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A Probabilistic Model of Flooding Loads on Transverse Watertight Bulkheads in the Event of Hull Damage

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Watertight bulkheads (WTBs) are crucial to ship survivability in the event of hull damage. Current design standards for WTBs are empirical and prescriptive in nature. However, damage-causing events and damaged ship response exhibit significant variabilities and uncertainties. Hence, the design and assessment of WTBs should be performed in a probability-based format. This paper outlines, as an essential input to reliability analysis, the development of a physically based probabilistic model of transverse WTB loads. Poisson arrival is assumed for damage events, and the maximum life-time load effect envelope on the WTB in damaged condition is derived. The emphasis of this paper is on the probabilistic modeling of loads; hence, simple phenomenological expressions of load components are used to underline the cause and extent of randomness in WTB loads. A response surface type approach is suggested for determining ship-specific model parameters. A large RO/RO vessel with side shell breach below the waterline is used for illustrating the application of the proposed methodology; randomness is considered in ship hydrostatic properties, damage location, length of breach, occurrence and duration of damage events, the environment, curve fitting, and modeling errors. Probabilistic estimates of the maximum load components are obtained through Monte Carlo simulations. These are compared with available code-prescribed design values.

Introduction

SUBSTANTIAL WORK has been performed on the reliability of primary ship hull structures (e.g., ISSC 1991, Wang et al 1994, Guedes Soares & Garbatov 1996, Mansour et al 1997, Ayyub et al 2000); however, reliability of such structures as bulkheads and decks has so far not received comparable scrutiny. Watertight bulkheads (WTBs), which constitute structural boundaries to vital spaces, are crucial for ship survivability in the event of damage involving hull breach. Significant loads on WTBs are likely to occur in damaged condition, and failure of these structures could initiate progressive flooding of vital spaces and may ultimately lead to loss of the ship. Damage-causing scenarios include collision, grounding, on-board explosions, weapons effects, and extreme wave environments.

Although the structural loading or reliability of WTBs has not been addressed in a probabilistic format in any significant way in the literature, the dynamic response and survivability of damaged ships (particularly RO/RO ships) nevertheless have attracted considerable research in recent years. It is clear that the estimation of response of a damaged ship requires intricate physical models that include nonlinearities due to large-amplitude motions of the ship (Chan et al 2002), the effect of water in a flooded compartment on motions (Yildiz 1983, Chan et al 2002), the influence of ingress and egress of water through the breach on motions (Vassalos & Jasionowski 2002), coupling of six degree-of-freedom responses in oblique seas (Chan et al 2002), and the effect of listing of ships on roll motions (D'Este & Contento 2000). The last mentioned

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reference also indicates that roll damping characteristics may not be constant for damaged ships with the same displacement irrespective of the list.

Appraisal of current WTB design practices

Current design standards for watertight bulkheads are based on historical practices and are empirical and prescriptive in nature. For example, the US Navy's DDS 079-1 (NSEC 1975) prescribes design loads on watertight boundaries due to flooding. The ship is assumed to start at the limiting draft with full load including full tanks. The extent of damage is prescribed according to ship type and overall length (e.g., 15% of length between perpendiculars [L_{BP}] for combatants over 300 ft long). For ships without side-protective systems, shell-to-shell flooding is assumed. For determining the total head of water on the WTB, the trim is determined first. The heel, roll, and wave action are determined as in the following: (1) a static heel of 15 deg is assumed as a result of unsymmetrical flooding, (2) the roll angle is determined as an empirical function of displacement, and (3) a further head of 4 ft is assumed to account for wave action.

Similar prescriptive and experience-based rules are used in the design of commercial vessels. For example, Part 5, Chapter 3, Section 3, Subsection 5.7.3 of ABS Steel Vessel Rules (ABS 2003) provides design pressures for transverse bulkheads of bulk carriers. The nominal pressure for watertight requirements in a flooded condition may be taken as 70% of the nominal pressure calculated for a cargo hold assumed as a ballast tank filled up to the freeboard deck. The nominal pressure for a cargo hold assumed as a ballast tank is given as

$$P_i = \rho g(\eta + k_u h_d) + P_0 \tag{1}$$

where P_0 = pressure setting on pressure/vacuum relief valve less 2.07 N/cm^2, ρ = density of water, g = acceleration due to gravity, η = the depth of tank, k_u = load factor, h_d = the dynamic head, given by:

$$h_d = k_c(\eta a_i / g + \Delta h_i) \tag{2}$$

in which k_c = correlation factor, a_i = resultant acceleration, Δh_i = head due to roll and pitch.

It is, however, recognized that a change in the design philosophy of ships in the event of damage from an experience-based approach to a more analytical format is imperative (e.g., Vassalos et al 1997, Hockberger 1999).

The need for probabilistic modeling

There are significant variabilities/uncertainties in the events that lead to ship hull damage, in the description of such damage, and in the response of the ship once such damage occurs. For example, Brown (2002) analyzed Lloyd's Worldwide Ship data and a Sandia National Laboratory report (that included US Coast Guard data) on ship collisions, and reported that struck ships are frequently moored or anchored. Further, struck ship speed can be modeled by an exponential random variable with mean 1.7 knots, the collision angle may be modeled as a normal random variable with mean 90 deg and standard deviation 28.97 deg, and the longitudinal strike location may be best modeled as uniformly distributed, although the Sandia report favored a relatively higher probability of midship and forward strike. This may be compared with the findings of TDC (1995), who analyzed Lloyd's Register of Shipping (LRS) and International Maritime Organization (IMO) data and concluded that the longitudinal location of damage was uniformly distributed on the struck ship. Analyzing collision scenarios with Monte Carlo simulations, Brown (2002) concluded that "probabilistic damage extents are very sensitive to striking ship displacement, striking ship speed and collision angle."

Tagg et al (2002) analyzed 216 damage events from IMO and other databases to obtain statistical estimates of vertical extent of collision damage, and found that the overall damage height above the waterline could be described as a normal random variable with mean 4 m and standard deviation 4.8 m. On closer analysis they found that, for a given length of the struck ship, this distribution remained normal; the mean of the distribution decreased with increasing struck ship length.

Otto et al (2002) studied a 16,000-ton "example Ro-Ro passenger ferry" (with length between perpendiculars 173.0 m, breadth 26.0 m, depth 15.7 m) operating on a 700-nm route between Cadiz and the Canary Islands with 240 voyages per year and 25 hours per trip. They used data from Spanish port statistics to generate traffic data for their analysis and found that the annual collision frequency was 0.0429, with equal likelihood that the example ferry was the striking or the struck vessel. This agrees with the 4.3% per year (based on Det Norske Veritas [DNV] data) and the 5% per year (based on LRS data) estimates reported in TDC (1995). It may be concluded from the work of Otto et al (2002) that the collision damage length on the example ferry was an exponential random variable with mean about 3.5 m. This also agrees qualitatively with TDC (1995) (who analyzed IMO and LRS data) where the distributions of the collision damage longitudinal breach and collision damage transverse penetration exhibit similar exponential characteristics. The grounding frequency of the example ferry in Otto et al (2002) was computed as 0.00578 per year. The authors assumed that damage length, depth, and height (in collision or grounding) were statistically independent of each other; this assumption however is not expected to hold in all situations.

Zhu et al (2002) analyzed damage incidents during 1990–1999 (inclusive) for RO/RO and merchant navy ships with lengths greater than 100 m from Lloyd's Registry damage database and concluded that grounding rate was approximately 0.02 per year, which was "about half the incident rate for ship collision." The difference with the findings of Otto et al (2002) above may be noted in this regard. Zhu et al (2002) further found that grounding damage location was more likely to be the midship and the midship to fore regions of the ship. It may also be concluded from their paper that damage length was exponentially distributed with mean 0.13 times the ship length, and damage width was exponential with mean 0.26 times the ship breadth. These exponential distributions, of course, need to be truncated at 1.0 on the right as a practical matter. The above findings again agree qualitatively with those of TDC (1995) (who analyzed IMO and LRS data) where the significant positive skewness in each of the distributions of the grounding damage longitudinal breach and grounding damage vertical penetration is apparent.

It is therefore clear that ship damage must be described in probabilistic terms. Consequently, it is imperative that the assessment and design of WTBs be performed in a reliability framework. This will have the following desirable effects: (1) WTB reliability can be made consistent with that of the primary ship structure; (2) explicit determination of WTB reliabilities will enable the calibration of new reliability-based design rules; and (3) a reliability-based approach can reduce weight and cost if current standards for WTB design are overly conservative; alternately, a reliability-based assessment can provide a strong justification for increasing strength and cost (Pires et al 2000a). Similar concerns about the design of marine structures in general have been expressed recently by the International Ship and Offshore Structures Congress Committee on Design Principles and Criteria (ISSC 1997).

This paper crafts a methodology for determination of loads on WTB within a probabilistic framework. A simple physically based model that describes loads on transverse WTBs in terms of variables describing ship geometry, hydrostatic properties, the seastate, and the location, extent, and frequency of damage is used. The probabilistic nature of the loads is established by considering randomness in the above variables and in the modeling and curve-fitting errors. This probabilistic load model, in turn, may be used in a full reliability-based design or assessment of WTB structures in damaged condition.

The probabilistic framework for describing WTB loads is discussed in the next section. Following that, equations are developed for loads on transverse watertight bulkheads based on a simple phenomenological model. The emphasis of this study is on randomness in the loads on transverse bulkheads; consequently, a simple damage model is adopted. Detailed mechanistic models for loads based on a complex and possibly nonlinear response of a damaged ship in seas are beyond the scope of this study.

Approach to probabilistic load modeling

Unlike the prescriptive nature of existing rules, the probabilistic modeling of WTB loads should have a clear analytical and physical basis. Ideally, the load model (1) should be physically based and rational, (2) should have explicit functional dependence on damage-related variables, as well as on hydrostatic and environmental descriptors, and (3) should use only easily available/quantifiable parameters. These would enable the model to be applicable to ships of different sizes and classes, as well as to different types of damage-causing events. These would also allow sensitivity analyses of the loads and WTB reliability in terms of the damage variables, and would accommodate future refinements when new information becomes available.

Based on the requirements listed above, the authors believe that a combination of analytical and response surface-based approaches would be most appropriate. The basic steps are:

1. Identify all relevant variables and select the important ones to be considered in the model.
2. Identify distinct components of loads acting on the WTB and develop a rational load combination scheme.
3. Develop a simplified description of hull damage in terms of the damage-related variables.
4. Establish, from physical considerations, the functional dependence of each load component on the damage variables. These relations should ideally be valid for all ships of a given class subject to a given type of damage. If necessary, use a response surface type approach to determine unknown parameters of the functions. Also estimate the error statistics in estimating these parameters.
5. Finally, identify or establish the probabilistic description of each of the variables in step 1. Include correlation wherever appropriate. Obtain load statistics using Monte Carlo simulations with an appropriately defined algorithm.

Loads on transverse WTBs in damaged condition

Loads on WTBs depend on a range of variables, including ship geometry, environment, and type of damage. These variables can be conveniently grouped in the following categories:

1. Geometry-related variables, **G**, describing ship type and loading. These include dimensions, hydrostatic properties, subdivision, and construction of the ship, type of cargo, and loading pattern.
2. Damage-related variables, **D**, describing cause, extent, and location of hull damage. These depend on whether the damage is caused by accidents (collision, grounding), internal explosions, weapons effects (mines, torpedoes, etc.), or extreme natural hazards. These also include the frequency of such damages and the duration of damage events (i.e., the time interval to mission completion, repair, or rescue).
3. Environment-related variables, **E**, describing wave environment and length of exposure. These include wave height, period, and relative wave direction during and after the occurrence of damage.

The generalized load vector on transverse watertight bulkheads at a location $\mathbf{x}$ and time τ can be represented as arising from two distinct sources:

$$\mathbf{F}(\mathbf{x}, \tau) = \mathbf{F}^L(\mathbf{x}, \tau) + \mathbf{F}^H(\mathbf{x}, \tau) \tag{3}$$

We emphasize that equation (3) shows a vector addition of loads. The superscripts L and H stand for "liquid" and "hull," respectively, as described in the following. In the most general case, $\mathbf{F}^L$ and $\mathbf{F}^H$ are stochastic in both space and time. The first term, $\mathbf{F}^L$, represents the effect of liquids, which may be ingressed water (in damaged condition) or liquid cargo (in intact condition), in direct contact with the bulkhead. $\mathbf{F}^L$ has static as well as dynamic components and generally acts normal to the WTB. The dynamic components may include direct wave action, inertial forces due to motion of the ship, and sloshing. The second term, $\mathbf{F}^H$, represents loads that derive from hull girder response (in intact or damaged conditions) and generally act in the plane of the WTB. These are caused by hull girder bending and torsion, as well as those resulting from dynamic effects, such as springing, whipping, and slamming caused by the environment and weapons loads.

From the point of view of WTB design or assessment, the maximum value of an appropriately defined load effect, $Q_{\max,t}(\mathbf{x})$ (a scalar, such as maximum pressure head, maximum bending moment, or maximum principal stress, etc.), at a given location x, produced by the loads $\mathbf{F}$ during the life (t) of the ship is of concern. The subscript "max,t" denotes the maximum value attained during [0, t]. $Q_{\max,t}(\mathbf{x})$ may occur either in damaged (D) or intact (I) condition:

$$Q_{\max,t}(\mathbf{x}) = \max \begin{cases} Q^{L,I}_{\max,t}(\mathbf{x}) + Q^{H,I}_{\max,t}(\mathbf{x}) \\ Q^{L,D}_{\max,t}(\mathbf{x}) + Q^{H,D}_{\max,t}(\mathbf{x}) \end{cases} \tag{4}$$

where the superscript "L, I" denotes liquid loads in intact condition, and similarly for the other three superscripts. The load combination in equation (4), by requiring "max,t" in each case instead of "arbitrary point in time" values for the accompanying loads, is somewhat conservative. But it should be noted that significant positive correlation may exist between $Q^{H,D}(\mathbf{x}, \tau)$ and $Q^{L,D}(\mathbf{x}, \tau)$ especially if damage is caused by extreme natural hazards or erroneous loading.

Among the four load-effect components in equation (4), this paper focuses only on $Q^{L,D}_{\max,t}(\mathbf{x})$. For one, it is reasonable to assume that most critical out-of-plane loads on WTBs occur in damaged, rather than intact, condition, that is, $Q^{L,D}_{\max,t}(\mathbf{x}) > Q^{L,I}_{\max,t}(\mathbf{x})$. For another, granted that a completely rigorous analysis would require the determination of which of the hull-induced load effects, $Q^{H,D}_{\max,t}(\mathbf{x})$ or $Q^{H,I}_{\max,t}(\mathbf{x})$, is more critical on transverse WTBs, the hull-induced loads are believed to have a marginal contribution to the total load effect on transverse WTBs anyway. This last assertion is known to generally hold at least in intact condition; whether it holds in every damaged condition in the light of possible local redistribution of stresses due to side-shell breach is ignored here and the focus henceforth is exclusively on the dominant component $Q^{L,D}_{\max,t}(\mathbf{x})$.

$Q^{L,D}_{\max,t}(\mathbf{x})$ depends on **G**, **D**, and **E**, the damage-, geometry-, and environment-related variables, respectively. Owing to the randomness in these variables, it is clear that $Q^{L,D}_{\max,t}(\mathbf{x})$ is random in nature. In order to derive the probabilistic description of transverse WTB loads, an accurate probabilistic description of **G**, **D**, and **E** and an accurate model of how these variables affect WTB loads are required. The standard convention of using uppercase letters for random variables and corresponding lowercase letters for their realizations have been used in this paper as much as practicable.

Now, a ship may be subject to several damage events during its lifetime. For example, TDC (1995) report that annual probability of ship collision worldwide is 4.3% (based on DNV data) or 5% (based on LRS data). Suppose that $N(t)$ damage events occur during the service life, t, at random times $T_1, T_2, \ldots, T_N$. The time-dependent reliability of the WTB is then given by:

$$\mathrm{Rel}(t) = P[S(\mathbf{x}, T_i) > Q^{L,D}_{t_i}(\mathbf{x}), \quad \forall \mathbf{x} \in \Omega, \quad \text{and} \quad \forall T_i < t; \; i = 1, \ldots, N(t)] \tag{5}$$

where S is the random strength of the WTB (possibly deteriorating with time); $Q^{L,D}_{t_i}(\mathbf{x})$ is the load effect at location **x** due to the damage event at time T_i; and Ω is the set of critical locations on the WTB. An example of WTB reliability assessment, based in part on the proposed methodology, under one damage event and without considering strength deterioration may be found in Pires et al (2000b).

The lifetime maximum load effect at a location **x** is:

$$Q^{L,D}_{\max,t}(\mathbf{x}) = \max_{i=1,2,\ldots,N(t)} \{Q^{L,D}_{T_i}(\mathbf{x}; \mathbf{G}_i, \mathbf{D}_i, \mathbf{E}_i)\} \tag{6}$$

where it is emphasized that the load effect at the ith damage event depends on the values of the geometry-related, the damage-related, and the environment-related variable at the time T_i of the damage. We assume that (1) hull damage events are sufficiently rare and the duration of damage event is negligible compared to the life of the ship, (2) after each damage event the hull can be repaired to an intact condition provided the ship is not lost, and (3) the occurrence (or nonoccurrence) of damage in past voyages does not affect the likelihood of future damages. Hull damage events then occur according to a homogeneous Poisson process with constant rate λ so that the probability distribution function of the maximum load effect evaluated at any q,

$$F_{Q^{L,D}_{\max,t}}(q; \mathbf{x}) = \frac{1}{c} \sum_{n=1}^{\infty} \frac{1}{n!} e^{-\lambda t} (\lambda t)^n \prod_{i=1}^{n} F_{Q^{L,D}_{t_i}}(q; \mathbf{x}, \mathbf{D}_i, \mathbf{G}_i, \mathbf{E}_i) \tag{7}$$

The constant c is simply $P[N(t) \geq 1]$; it is included to ensure proper normalization because the case of damage-induced loads due to no damage event is degenerate. $F_{Q^{L,D}_i}(q; \mathbf{x}, \mathbf{D}_i, \mathbf{G}_i, \mathbf{E}_i)$ is the probability distribution of the load effect due to the ith damage event. Although the random variables **G**, **D**, and **E** are assumed to be statistically independent in different damage events, significant dependence may exist among them in the same damage event, owing, for example, to the possibilities that in a more extreme environment or due to an unfavorable cargo loading pattern the extent of damage may be higher.

We now turn to estimating the properties of $Q^{L,D}(\mathbf{x})$ for any i; the subscript i is omitted when there is no scope of confusion. Consistent with existing design practices, we describe $Q^{L,D}(\mathbf{x})$ and $Q^{L,D}_{\max,t}(\mathbf{x})$ in terms of equivalent pressure head of water in the remainder of this paper.

Loads due to ingressed seawater

For a damaged and flooded compartment, $Q^{L,D}(\mathbf{x})$ is the result of seawater ingress, and it depends on several components:

$$Q^{L,D} = f(T, \Delta T, \Delta h_{\mathrm{heel}}, \Delta h_{\mathrm{trim}}, \Delta h_{\mathrm{roll}}, \Delta h_{\mathrm{pitch}}, \Delta h_{\mathrm{wave}}, \ldots) \tag{8}$$

where T = draft of intact ship, ΔT = parallel sinkage, Δh_{heel} = additional water head due to heel of the damaged ship, Δh_{trim} = additional water head due to trim of the damaged ship, Δh_{roll} = additional water head due to roll of damaged ship, $\Delta h_{\mathrm{pitch}}$ = additional water head due to pitch of the damaged ship, Δh_{wave} = additional water head due to direct wave pile up. Components due to sway, heave, and so forth also should be included in a more detailed analysis.

The original (intact) draft depends only on ship type and loading (**G**) and not on location (**x**), damage (**D**), and environmental (**E**) variables. The parallel sinkage, however, depends on the ship type and loading as well as on the damage variables. Heads due to heel and trim at a point depend on **G**, **D**, and also on location **x** of the point in consideration. The heads due to roll and pitch (equation 8) arise from the external environment and are time dependent. Heads due to roll and pitch motions at a point, **x**, depend on **G**, **D**, **E**, as well as on the location of the point. Finally, the additional head due to direct wave pile up (if any) is conservatively given by the largest wave amplitude during the damage event and depends on the sea state and the duration of the damage event, ΔV_i:

$$\Delta h_{wave} = \zeta_{a,\max} = \max\{\zeta_a(t; \mathbf{E}_i), \quad t \in (T_i, T_i + \Delta V_i)\} \tag{9}$$

where ζ_a is wave amplitude. In the following sections, the proposed methodology for obtaining probabilistic estimates of maximum WTB loads will be illustrated using a simplified large RO/RO vessel. We reiterate that the focus is more on the probabilistic framework than on the mechanistic intricacies, such as nonlinear dynamic effects. Simple expression of loads in terms of damage-related variables are adopted wherever appropriate. Special care is taken to include only readily available geometric, environmental, and hydrostatic properties in the analytical expressions so that (1) they are acceptable and easy to use, and (2) they can be general enough to have applicability over several classes of ships.

A numerical example on ship damage and resultant loads

The example RO/RO vessel mentioned above is described in Fig. 1. It has a double bottom at elevation 5.5 ft and has six compartments created by five transverse watertight bulkheads at −420 ft, −240 ft, −85 ft, 120 ft, and 265 ft (centerline = 0 ft, aft positive). The ship does not have any *watertight* longitudinal bulkhead. The nominal volume permeability of these compartments can be taken as 0.9. The hydrostatic response of the intact and the damaged ship is computed using the proprietary software GHS (Creative Systems, Inc. 1999). Relevant hydrostatic properties of the vessel in intact condition are given in Table 1.

Description of damage

The following simplifying assumptions are made about hull damage:

1. The damage occurs in the form of a breach in the side shell (consistent with Wiernicki [1986], who reports that 58% of structural damage pertains to the side shell and another 19% to the framing). The breach occurs below the waterline, which is a conservative assumption.
2. Asymmetric flooding is assumed to be absent. This is consistent, for example, with the US Navy's design philosophy (NSEC 1975) that longitudinal watertight bulkheads are to be avoided, otherwise counterflooding measures are installed. This assumption removes Δh_{heel} from equation (8).
3. Once the ship is damaged, it is assumed to stop or lose main propulsion if it was already not stationary. In a regular sea, this will cause the ship to attain a beam sea configuration. This is consistent with the observation in Brown (2002) that roughly half the collision accidents occur when the struck ship is stationary. Consequently, Δh_{pitch} may be assumed as zero in equation (8). This is also consistent with load cases 5 and 6 among the loading patterns listed in the ABS rules for bulk carriers (ABS 2003).
4. The flooding occurs almost instantaneously, that is, rate-dependent phenomena (such as those discussed in Vassalos and Letizia 1998) are neglected. The time dependence of Δh_{roll} and Δh_{wave} may be eliminated by replacing them with their respective maximum amplitudes (cf. equation 9). This is a conservative assumption.

The above assumptions may be relaxed in a more rigorous analysis.

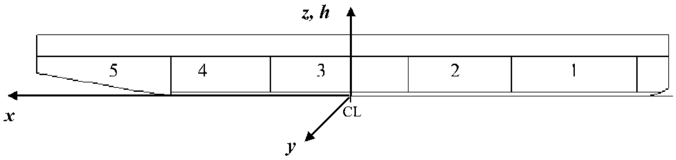

Fig. 1 Simplified geometric model of RO/RO ship (with major watertight compartments numbered)

Table 1 Nominal hydrostatic properties of the RO/RO ship

Geometric Property	Nominal Value
Length, L	900 ft (274 m)
Breadth, B (at midsection)	100 ft (30.5 m)
Height, H	90 ft (27.4 m)
Draft, T (at midsection)	33 ft (10.1 m)
Displacement, Δ	60,000 LT (5.9×10^5 kN)
Waterplane area, A_w	80,000 ft^2 (7,436 m^2)
Longitudinal center of flotation, L_{CF} (from amidships)	44.3 ft aft (13.4 m aft)
Moment to trim per unit length, M_{TL}	132,000 LT-ft/ft (1.31×10^6 kNm/m)
Transverse metacentric height, H_{GM}	5.5 ft (1.7 m)

The contributors to flooding load therefore reduce to:

$$Q^{L,D} = f(T(\mathbf{G}), \Delta T(\mathbf{G}, \mathbf{D}), \Delta h_{\text{trim}}(\mathbf{G}, \mathbf{D}, \mathbf{x}), \Phi^*(\mathbf{G}, \mathbf{E}, \mathbf{x}), \varsigma_{a,\max}(\mathbf{E})) \tag{10}$$

where Φ^* = maximum roll amplitude and $\zeta_{a,\max}$ = maximum wave amplitude during a damage event.

Based on the above simplifications, ship damage can be completely quantified by (1) X_D, the longitudinal location of the center of damage, (2) L_D, the length of damage, and (3) L_F, the flooded length. It should be noted that the three variables above are not all independent. For example, L_F depends on damage location as well as size, and also on the geometric variables, **G**, such as ship subdivision.

The functional dependence between each of the load components T, ΔT, and Δh_{trim} and the variables **G, D,** and **E** is determined in a response surface type analysis, as described next. Damaged ship response is analyzed for all possible values of x_D and l_D, subject to the following restrictions:

1. n_1 equally spaced values of x_D along the length of the ship are used.
2. For each value of x_D, n_2 equally spaced values are used for l_D subject to the following restrictions: (a) $x_D \pm l_D$ is within the ship's length, and (b) l_D is less than $l_{D\max}$. The limit $l_{D\max}$ is chosen so that three-compartment flooding is prevented. This ship sinks if any three compartments as defined in Fig. 1 flood.

Two sets of values of n_1 and n_2 are adopted in the analysis: (1) $n_1 = 10$, $n_2 = 10$, giving 100 points, and (2) $n_1 = 100$, $n_2 = 100$, giving 9,928 points. Figures 2 and 3 pertain to the first set ($n_1 = 10$, $n_2 = 10$). Least square analyses (Mandel 1964), nevertheless, are performed on both sets of results and are described in the following. The effect of the number of compartments flooded (one or two in this case) is also highlighted in the figures.

Parallel sinkage as a function of damage

While computing the final equilibrium position of a damaged ship, it is convenient to first determine the parallel sinkage due to lost buoyancy; following this, the associated hydrostatic properties are computed, the rotational restraints are removed, and the heel and trim angles are computed.

The buoyancy lost due to ingressed seawater is compensated by an increased draft. To a fairly accurate estimate, the parallel sinkage is given by Lewis (1988):

$$\Delta T = \frac{\nu'}{A'_w} = \frac{P\nu}{A_w - \mu_s a} \tag{11}$$

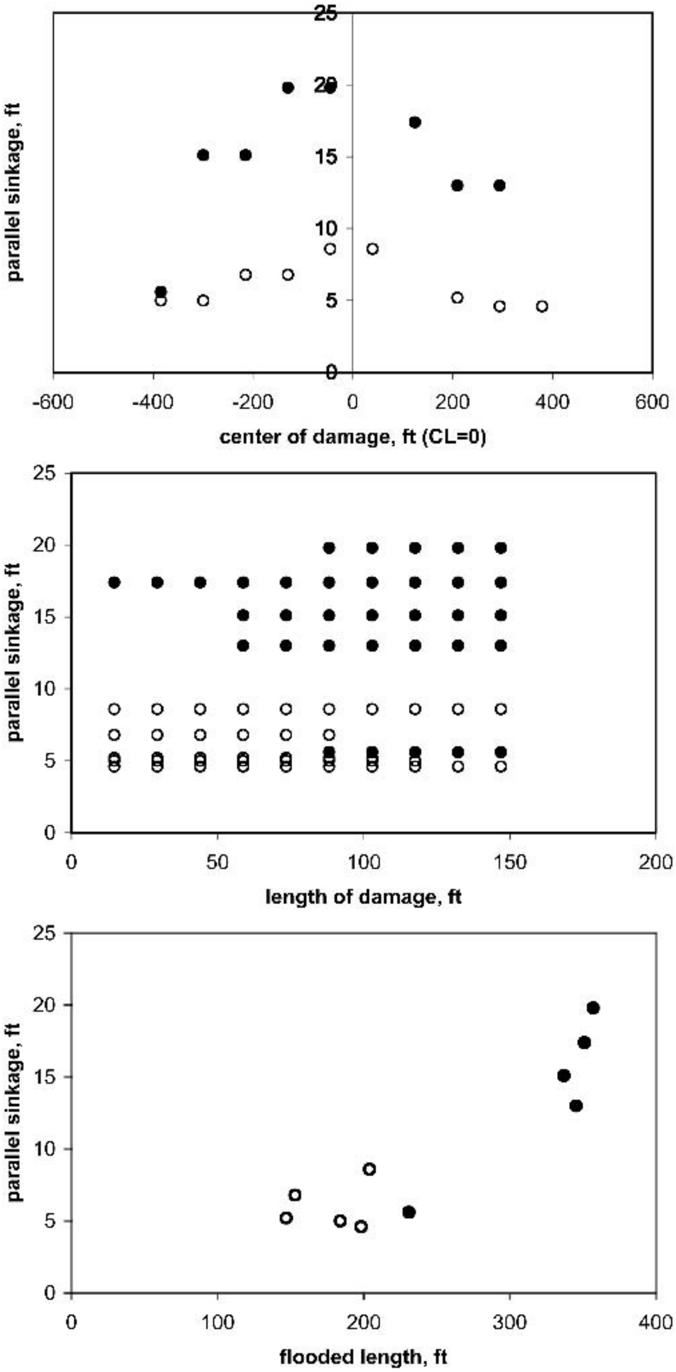

Fig. 2 Sinkage as a function of the damage parameters (○ = one-compartment flooding, ● = two-compartment flooding)

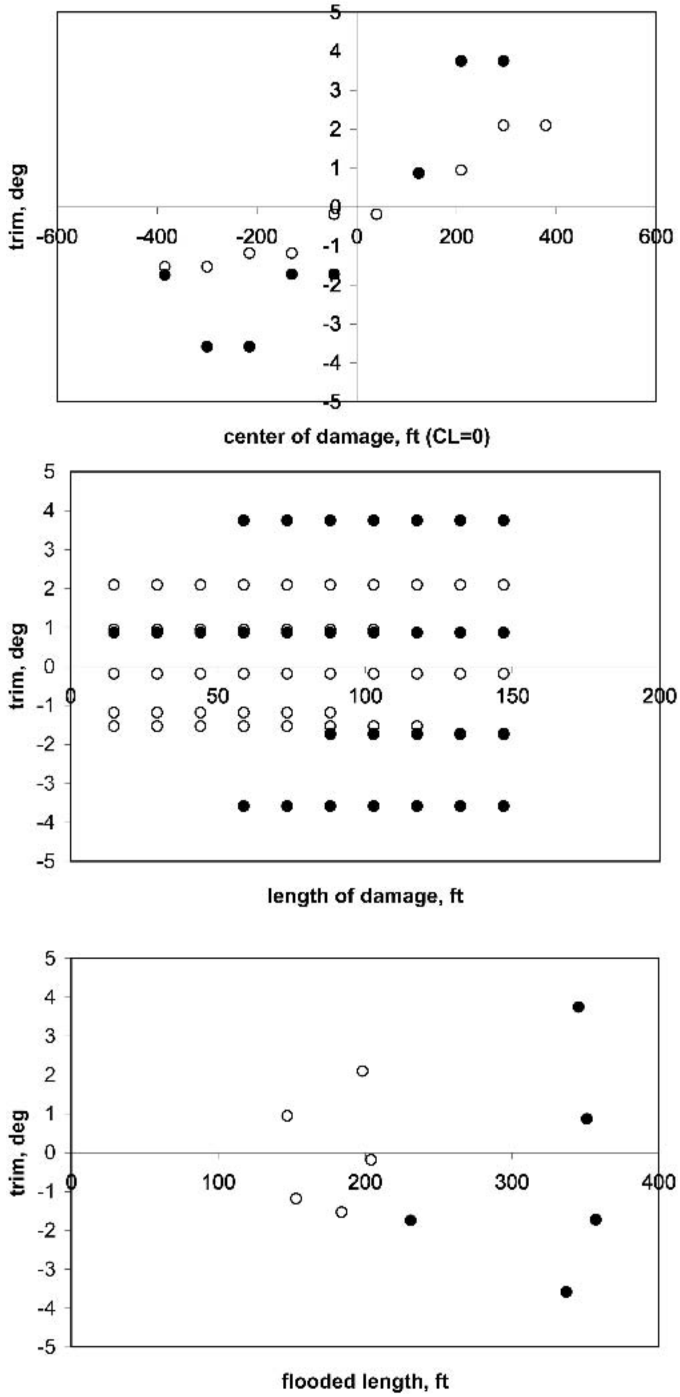

Fig. 3 Trim as a function of the damage parameters (○ = one-compartment flooding, ● = two-compartment flooding)

where $\nu' =$ volume of ingressed water, $A'_w =$ reduced waterplane area, $\nu =$ volume of damaged compartment up to the new waterline, $a =$ horizontal cross-sectional area of damaged compartment at the new waterline, $P =$ volume permeability of damaged compartment, $\mu_s =$ surface permeability of damaged compartment.

Parallel sinkage as functions of damage location and damage length for the example RO/RO vessel are shown, respectively, in Fig. 2 *a* and *b*. It is clear that sinkage is not strongly dependent on either variable. This is consistent with equation (11), which indicates that sinkage depends primarily on the volume of ingressed seawater and not specifically on damage location. It is much easier to estimate the flooded length of a damaged ship instead of the flooded volume. The flooded length, L_F, is therefore chosen as the damage-related variable here at a cost to accuracy. We now propose that parallel sinkage is a function of geometry and damage-related variables and not of environment-related variables; in particular, ΔT is a function of L_F, L, B, T, and A_w. The following functional form, with two undetermined dimensionless constants, is therefore adequate:

$$\Delta T = \alpha_{11} \frac{PLBT}{A_w} \left(\frac{L_F}{L}\right)^{\alpha 12} \tag{12}$$

where α_{11} and α_{12} are nondimensional constants obtained from nonlinear regression analysis.

A least square analysis of the data gives the following results: $\alpha_{11} = 2.0$ and $\alpha_{12} = 1.6$ with $n_1 = 100$, $n_2 = 100$. These are expected to be valid for large RO/RO vessels in general but are likely to be different for other classes of ships.

Trim angle as a function of damage

After computing the parallel sinkage due to damage, the ship is allowed to rotate about its transverse axis. At equilibrium, the moment introduced by the ingressed seawater is balanced by the ship's weight, and the trim is given fairly accurately by Lewis (1988):

$$\text{trim} \times M_{TL} = \nu\rho g\bar{x} \tag{13}$$

where trim = vertical distance between points on the base plane at fore and aft perpendiculars, M_{TL} = moment required to trim the ship per unit vertical distance from its original intact position (M_{TL} has dimensions of force), ν = volume of ingressed sea water, ρ = density of seawater, g = acceleration due to gravity, $\bar{x}$ = longitudinal distance between the center of gravity of the ingressed water and the ship's original center of flotation.

The added head due to trim on a transverse bulkhead located at x is:

$$\Delta h_{\text{trim}}(\mathbf{G}, \mathbf{D}, x) = x \sin(\Theta(\mathbf{G}, \mathbf{D})) \tag{14}$$

where Θ is the trim angle. Trim angle as functions of damage location and damage length are shown, respectively, in Fig. 3 *a* and *b*. Like sinkage, trim is found to be almost independent of damage length. Unlike sinkage, however, it is clear that trim is strongly dependent on damage location. For completeness, the relation between trim angle and the flooded length is shown in Fig. 3*c*. Even though a degree of dependence between $|\theta|$ and l_F is evident, this is ignored in the scope of this work.

As in the case of parallel sinkage, we propose that the trim angle is a function of geometry- and damage-related variables and not of environment-related variables. In particular, we propose that Θ is a function of X_D, L, B, T, L_{CF}, and M_{TL} . The following functional form, with two undetermined constants, is therefore adequate:

$$\Theta = -\alpha_{21} \frac{P\rho gBT}{M_{TL}} L_{CF} + \alpha_{22} \frac{p\rho gLBT}{M_{TL}} \left(\frac{X_D}{L}\right) \tag{15}$$

The numerical values are $\alpha_{21} = 2.3$ and $\alpha_{22} = 10.35$ for $n_1 = 100$, $n_2 = 100$. These are expected to be valid for large RO/RO vessels in general but are likely to be different for other classes of ships.

Roll response of a damaged ship

The roll motion of the damaged ship is idealized as a damped single degree of freedom oscillation under a sinusoidal moment. Following Lewis (1989), we assume that the maximum roll amplitude during a damage event is given by:

$$\Phi^* = \frac{\exp[-k(T+\Delta T)/2]}{\sqrt{(1-\Lambda^2)^2 + \nu_\phi^2 \Lambda^2}} k\varsigma_{a,\max} \tag{16}$$

where Λ = frequency ratio = ω/Ω_D (in which ω = wave frequency and Ω_D = roll natural frequency of the damaged ship), k = wave number = ω^2/g, and ν_ϕ = damping factor. Finally, $\zeta_{a,\max}$ is the largest wave amplitude occurring during the damage event, given by equation (9). Note that the roll response in damaged condition is likely to be significantly different from that in intact condition and may be attributed to the fact that quantities such as ν_ϕ, Ω_D, and draft are generally affected by ship damage.

The head due to roll is then given by:

$$\Delta h_{\text{roll}}(\mathbf{G}, \mathbf{D}, y) = y \sin(\Phi^*(\mathbf{G}, \mathbf{D})) \tag{17}$$

where y is the transverse distance from the ship's centerline.

Probabilistic modeling of transverse WTB loads in damaged condition

The load models developed in the previous section for the example RO/RO vessel will now be analyzed for obtaining probabilistic estimates of the maximum lifetime loads on transverse WTBs in damaged condition. The sources of randomness in the loads are discussed in detail next.

Sources of randomness

The sources of randomness in WTB loads due to ship damage can be grouped into the following categories:

1. Randomness in **G, D,** and **E:** Randomness in **G** occurs due to variabilities in ship loading. Randomness in **D** is due to uncertainties/variabilities in cause, type, location, and source of damage, and in the duration of the damage event. Randomness in **E** results from wave height, period, relative direction, and so forth being random processes.
2. Error in ship response modeling, $\mathbf{B}_{\text{error}}$: The computed ship response deviates from the actual due to several reasons, such as model idealization, numerical errors, and so forth.
3. Curve-fitting error, $\boldsymbol{\varepsilon}_{\text{fit}}$: A least-square equation usually simplifies the relation between the dependent and the independent variables, and thus introduces error in the prediction.

The model predicted loads given by equation (10) are functions of the random quantities **G, D,** and **E**. In addition, sinkage, trim, and roll amplitudes (regarding equations 12, 15, and 17) are functions also of the least square coefficients and random curve-fitting errors. Finally, the model predicted loads are related to the actual loads through the use of modeling error variables:

$$Q = Q_{\text{model}} \cdot B_{\text{error}} \tag{18}$$

where B_{error} is the relevant modeling error variable. Therefore, the head of water at a transverse distance y (from the longitudinal centerline) on a bulkhead located at x_b from amidships is:

$$H(x_b, y) = H_x(x_b) + y \sin \Phi^* \tag{19}$$

where $H_z(x_b)$ is the component that varies longitudinally given by:

$$H_x(x_b) = T + \left\{\alpha_{11}\frac{PLBT}{A_w}\left(\frac{L_F}{L}\right)^{\alpha 12}\cdot\exp[\varepsilon_{\text{fit}_1}]\right\}B_1 + x_b\sin\left[\left\{-\alpha_{21}\frac{P\rho gBT}{M_{TL}}L_{CF}+\alpha_{22}\frac{P\rho gLBT}{M_{TL}}\left(\frac{X_D}{L}\right)+\varepsilon_{\text{fit}_2}\right\}B_2\right] + \varsigma_{a,\max} \tag{20}$$

and Φ^* is the maximum roll amplitude given by:

$$\Phi^* = \frac{\exp\left(-\frac{1}{2}\frac{\omega^2}{g}(T+\Delta T)\right)}{\sqrt{\left(1-\frac{\omega^2}{\Omega_D^2}\right)^2+\nu_\phi^2\frac{\omega^2}{\Omega_D^2}}}\frac{\omega^2}{g}\varsigma_{a,\max}B_3 \tag{21}$$

Note that, by definition, the maximum roll amplitude, Φ^*, is a nonnegative quantity. As noted previously, the uppercase letters P, D_0, A_w, L_F, M_{TL}, X_D, ΔT, and Ω_D are used in place of their lowercase counterparts in equations (20) and (21) as they are now treated as random variables. It is important to note that x_b, the location of the affected bulkhead, is a function of the location and the size of damage as well as the ship subdivision and geometry. The curve-fitting errors, $\varepsilon_{\text{fit}_1}$ and $\varepsilon_{\text{fit}_2}$, pertain to the formulas developed for sinkage and trim, respectively. In the present model, modeling errors, represented by random variables, $B1$, $B2$, $B3$, respectively, are assumed to be present only in sinkage, trim, and roll angle computations.

Monte Carlo simulations for maximum WTB loads in damaged condition

Recall that the loads on transverse WTBs in damaged condition as given in equations (19) through (21) pertain to one damage event. The objective in probability-based design and assessment, on the other hand, is to estimate the maximum load during the ship's design/remaining life (equation 6). Hence, this section describes a Monte Carlo simulation–based approach for obtaining the probabilistic estimate of the lifetime maximum load on transverse WTBs in damaged condition. The simulation scheme is described in Fig. 4. A total of N_{MCT} time histories are generated for the ship. For each time history, the occurrence of damage events are simulated as Poisson arrivals; the interarrival times $\Delta\tau$ are i.i.d. exponentials. This is continued until the design/remaining life of the ship, t, is exhausted. For each damage event, the geometric, damage, and environmental random variables are simulated from their appropriate distributions, and the resultant WTB loads are computed. For each time history, the maximum WTB loads (h_z and ϕ^*) are recorded, and the statistics of the maximum loads are analyzed after the N_{MCT} trials are over. The location of the affected bulkhead is not considered so that the envelope to the maximum loads can be obtained. Those time histories where no damage event occurs are discarded because the objective is to determine the statistics of the maximum loads (cf. equation 7); hence, the statistical results in the following should be qualified as conditional on at least one damage event occurring during the ship's lifetime.

The statistical properties for the random variables considered in the present analysis including their sources are listed in Table 2. Reasonable values have been assumed for those properties that

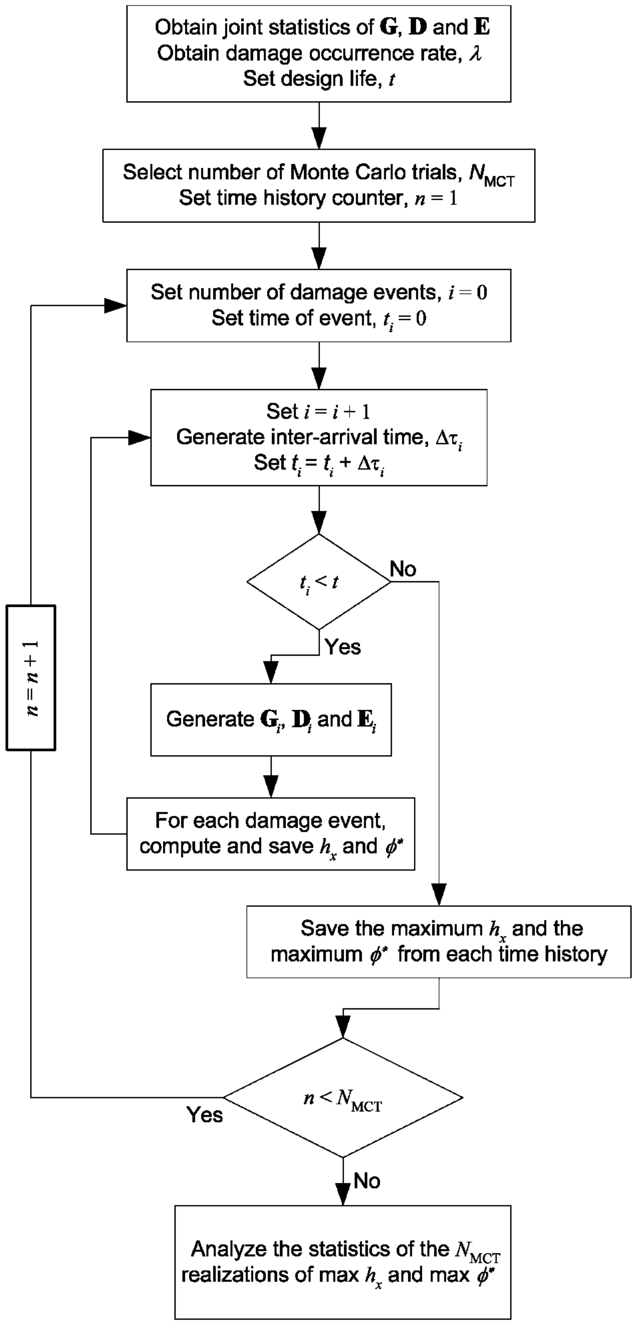

Fig. 4 Maximum lifetime loads on watertight bulkheads in damaged condition through Monte Carlo simulation

were not available to the authors and are indicated as such in Table 2. All random variables are mutually independent unless explicitly mentioned in Table 2. Among the geometric variables in the model, only T, A_{w,P,Ω_D}, M_{TM}, and ν_ϕ are considered as random variables in this analysis. A moderately high correlation has been assumed between undamaged draft and undamaged waterplane area. A large uncertainty has been assumed in Ω_D, the natural roll frequency in damaged condition that is consistent with the findings of the references listed at the beginning of Section 1. The mean of Ω_D has been taken to be about half of ω_0, which

Table 2 Statistical properties of geometric environmental and damage variables used in Monte Carlo simulations

Variable	Distribution	Parameters*	Correlation*	Remarks
Draft, T	Normal	$\mu = 31$ ft (9.45 m), $V = 5\%$		(a), (b), (c)
Waterplane area, A_w	Normal	$\mu = 80{,}000$ ft^2 (7,436 m^2), $V = 5\%$	ρ between D_0 and A_w is 0.6	
Permeability, P	Normal	$\mu = 0.7$, $V = 20\%$		(a), (b)
Damaged natural frequency, Ω_D	Lognormal	$\mu = 0.13$ rad/s, $V = 50\%$		(a), (b), (c)
Moment to trim per unit length, M_{TL}	Lognormal	$\mu = 10{,}500$ LT ft/in. (1.26×10^6 kNm/M), $V = 5\%$		(a), (b)
Damping factor, ν_ϕ	Lognormal	$\mu = 0.15$, $V = 20\%$		(b)
Longitudinal center of damage, X_D	Uniform	$\Delta = -l/2$ to $l/2$		(d)
Length of damage, L_D	Truncated exponential	$\mu = 0.08\ l$, $\Delta = 0$ to $0.16\ l$		(e)
Damage occurrence rate, λ	Deterministic	0.10 per year		(f)
Ship lifetime, t	Deterministic	20 years		
Duration of damage event, ΔV	Lognormal	$\mu = 1$ day, $V = 50\%$		(b)
Significant wave height, H_s	Lognormal, if $H_s < 6.6$ ft (2 m)	$\mu = 5.6$ ft (1.70 m), $V = 67\%$		(g)
	Weibull, if $H_s > 6.6$ ft (2 m)	$\mu = 5.1$ ft (1.55 m), $V = 66\%$ (i.e., $\alpha = 1.55$)	Expressed through conditional statistics of T_p	
Peak period, T_p	Lognormal	$\mu' = 1.59 + 0.42\ \ln(h_s + 2)$, $\sigma'^2 = 0.005 + 0.085\exp(-0.13\ h_s^{1.34})$; h_s in m, t_p in s		
Wave height, ζ_a	Rayleigh	σ^2 given by Bretschneider spectrum		
Sinkage curve-fitting error, ε_{fit_1}	Normal	$\mu = 0$, $\sigma = 0.28$		(h)
Sinkage curve-fitting error, ε_{fit_2}	Normal	$\mu = 0$, $\sigma = 1.03$		(h)
Sinkage modeling error, B_1	Lognormal	$\mu = 1.0$, $V = 5\%$		(i)
Trim modeling error, B_2	Lognormal	$\mu = 1.0$, $V = 5\%$		(i)
Roll modeling error, B_3	Lognormal	$\mu = 0.95$, $V = 3\%$		(i)

*μ = mean; V = coefficient of variation; σ = standard deviation; ρ = correlation coefficient; Δ = range; α = shape parameter; μ' = mean of ln( ); σ'^2 = variance of ln( )

(a) Statistical properties of the hydrostatic variables are based on the trim and stability booklet of the RO/RO ship. Note that mean values are not necessarily equal to the respective nominal values. However, these statistics are only for illustration purposes and should not be used without verification.

(b) Distribution type (i.e., normal or lognormal, etc.) has been assumed.

(c) Correlation coefficient has been assumed.

(d) Based on Brown (2002), TDC (1995), and Wiernicki (1986).

(e) Based on Otto et al (2002), Zhu et al (2002), and TDC (1995).

(f) Assumed to be the sum of frequencies of collision, grounding, fire, slamming, and other damages and that these lead to partial flooding. Collision and grounding frequencies are taken to be 5% per year and 2% per year, respectively, based on Otto et al (2002), Zhu et al (2002), TDC (1995). The remaining frequencies have been assumed.

(g) The wave statistics are based on Haver and Nyhus (1986). Uppercase letters denote random variables, and corresponding lowercase letters denote their realizations.

(h) Estimated from the data generated for this paper. Normal distribution is commonly assumed for curve fitting error.

(i) Based on errors associated with other similar models listed in Nikolaidis and Kaplan (1991). Lognormal distribution is commonly assumed for modeling errors.

is the nominal value in undamaged condition given by $\omega_0 = \sqrt{[g\ (h_{GM})/r_\phi]}$ (where h_{GM} = transverse metacentric height, g = acceleration due to gravity, r_ϕ = radius of gyration about the longitudinal axis). The independent damage variables, X_D and L_D are considered as random variables in this analysis. As stated previously, the right limit on L_D is chosen so that three-compartment flooding is prevented. The dependent damage variable, L_F, is therefore also a random variable. A large uncertainty has been assumed in the duration of the damage event, ΔV.

The environmental variables in the model are ω and $\zeta_{a,\max}$; both are determined from the prevailing wave spectrum during the damage event. The ship's composite route scatter diagram is given in terms of the long-term joint distribution of the significant wave height, H_s, and peak spectral period, T_p; the distribution is based on the model in Haver and Nyhus (1986), as shown in Table 2. For purposes of illustration, a simple wave spectrum using only these two parameters, namely, the Bretschneider spectrum, is adopted (Goda 2000):

$$S(f) = 0.257\,\frac{h_s^2}{t_s^4 f^5}\exp\left[-1.03\left(\frac{1}{t_s f}\right)^4\right], \quad t_s \simeq t_p/1.1 \qquad (22)$$

where h_s is in meters, t_s is in seconds, and f is in hertz. Statistics of the short-term wave period, T_0, and wave amplitude, ζ_a, corresponding to specific realizations of H_s and T_p are then found from m_0 and m_2, the area and the second moment of the spectrum, respectively. In particular, the average period is $\overline{T}_0 = \sqrt{m_0/m_2}$; and the variance of ζ_a, assuming it is Rayleigh distributed, is $\sigma^2_{\zeta_a} = m_0(2 - \pi/2)$. The distribution of maximum wave amplitude during a damage event is then determined in this analysis as (cf. equation 9):

$$F_{\zeta_{a,\max}}(h) = \left[1 - \exp\left\{-\frac{h^2}{2m_0}\right\}\right]^{n_w}, \quad n_w = \Delta\nu/\overline{T}_0 \qquad (23)$$

It is assumed that the random wave heights that occur during a damage event are mutually independent and that they are identi-

Table 3 Statistics of lifetime maximum loads H_x and Φ^*

		Height of Maximum Flooding Water, H_x				Maximum Roll Amplitude Φ^*				
N_{mct}	N_D	μ (ft)	σ (ft)	g_3	g_4	μ (deg)	σ (deg)	g_3	g_4	ρ between H_x and Φ^*
1,000	883	54.3	8.79	0.369	3.18	0.179	0.185	2.35	11.9	0.214
10,000	8,679	54.1	9.04	0.329	3.20	0.191	0.210	2.82	16.3	0.251
100,000	86,543	54.1	9.12	0.311	3.17	0.193	0.215	3.06	20.4	0.248
1,000,000	864,520	54.1	9.11	0.309	3.18	0.193	0.214	3.13	24.6	0.250

μ = mean; σ = standard deviation; ρ = correlation coefficient; g_3 = coefficient of skewness = $E[Y-\mu]^3/\sigma^3$; g_4 = coefficient of kurtosis = $E[Y-\mu]^4/\sigma^4$.

cally distributed provided the sea state stays unchanged during the damage event. Finally, the wave frequency, ω, in equation (21) is simply given by the average period: $\omega = 2\pi/\bar{T}_0$.

The curve fitting errors, $\varepsilon_{\mathrm{fit1}}$ and $\varepsilon_{\mathrm{fit2}}$, are zero mean random variables and usually taken to be normally distributed. The three modeling error random variables, B_1, B_2, and B_3, are each lognormal as modeling uncertainties commonly are, and their statistics are adopted based on uncertainties in similar models used elsewhere in the literature (Table 2).

Table 3 lists the first four moments of H_x and Φ^* obtained from 1,000, 10,000, 100,000, and 1 million Monte Carlo simulations outlined in Fig. 4, each starting with the same seed; the numerical convergence is found to be rapid for the first three moments. A moderate correlation is observed between the two random variables. Approximately 86.4% of the simulated time histories, denoted by ND in Table 3, were found to yield at least one damage event; this is in fact an estimate of c in equation (7) and agrees with the theoretical result of $c = 1 - \exp(-\lambda t)$.

Figure 5 shows the histograms of H_x and Φ^* drawn from the 1,000 simulation case used in Table 3. The distribution of H_x is seen to be slightly skewed to the right (corroborated by coefficient g_3 in Table 3) with a kurtosis slightly higher than the Gaussian shape. The exponential nature of the distribution of maximum roll amplitude, on the other hand, is clearly visible.

An accurate determination of the probability distribution that best fits the data is crucial to a full characterization of the loads and to the subsequent structural reliability analysis. In order to select the best probability distribution for the simulated data, chi-squared goodness of fit tests were performed for the two load components. The candidate distributions were normal, lognormal, Weibull, exponential, gamma, and Gumbel. The same set of data as in Fig. 5 was used for the purpose (883 realizations each); 10 equiprobable intervals were chosen in each case, and statistics were adopted from the 1 million simulation case. The gamma distribution was clearly the best for H_x, yielding a total chi-squared statistic of 10.95 and a level of significance of 27.9% with 9 degrees of freedom. For Φ, the exponential distribution was clearly the best, yielding a total chi-squared statistic of 14.25 and a level of significance of 11.4% with 9 degrees of freedom. A confirmation of the above goodness of fit is shown in Fig. 6, where the gamma distribution function for H_x and the exponential distribution for Φ^* are plotted with respective statistics taken from Table 3 (the 1 million simulation case).

Finally, the above probabilistic estimates of maximum flooding water level are compared with design values given by naval (NSEC 1975) and commercial (ABS 2003) rules outlined in the "Appraisal of current WTB design practices" section. As stated in assumption 2 in the "Description of damage" section, heel due to

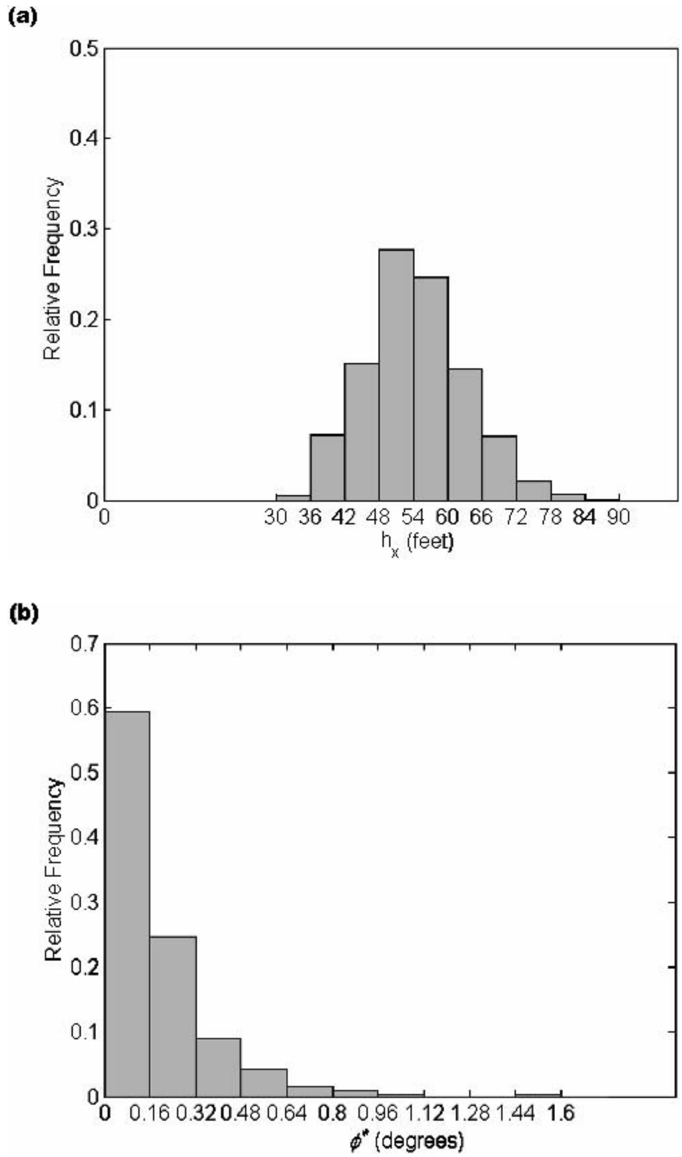

Fig. 5 Relative frequency histogram for maximum lifetime loads on watertight bulkheads (883 realizations each)

asymmetric flooding is neglected. Hydrostatic analysis of the example RO/RO vessel yielded the highest flooding water level at any transverse bulkhead due to trim and sinkage as 75 ft (two-compartment flooding). Per NSEC (1975) procedure, the design

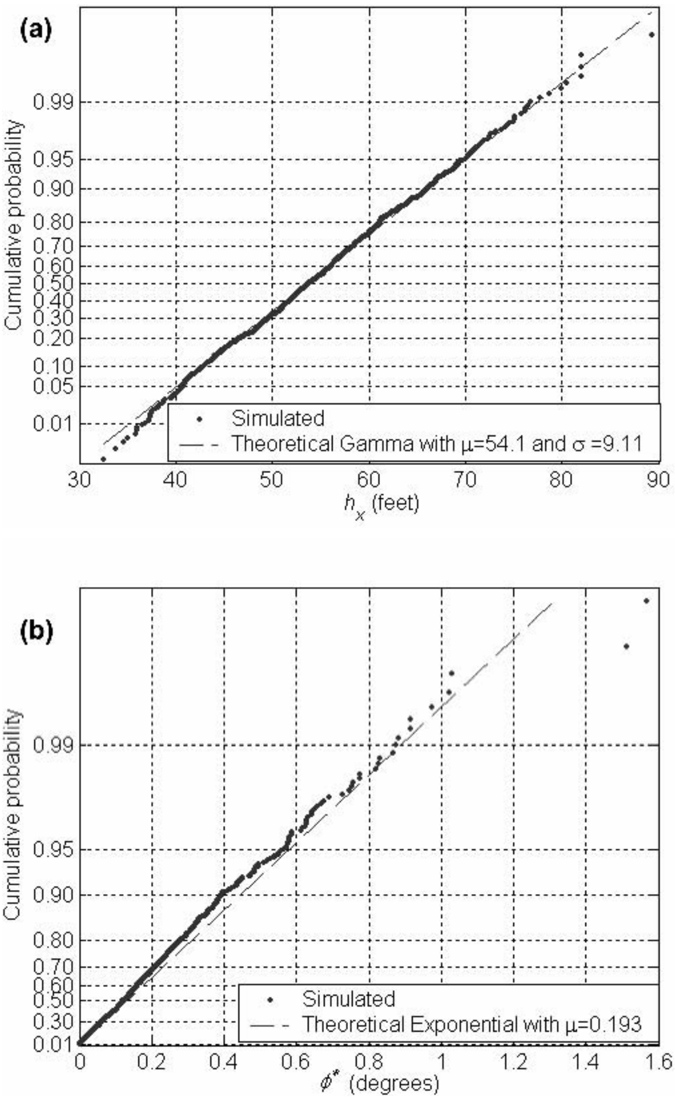

Fig. 6 Comparison of simulated data with best fit theoretical distributions

roll amplitude of a damaged ship with displacement 60,000 Lt is 6 deg; adding 4 ft due to direct wave action, this gives the highest water level on the transverse WTB near the side shell as 84 ft. ABS rules for vessels intended to carry ore or bulk cargoes (492 ft or more in length) are used to determine maximum water level at an intact transverse bulkhead. As stated in assumption 3 listed in the "Description of damage" section, pitch motion due to waves is assumed zero. Hydrostatic analysis of the RO/RO ship gives a maximum trim of 3.75 deg (two-compartment flooding). The maximum water level at the forward most transverse bulkhead in a ballast tank near the side shell due to static water head, trim, roll, and wave-induced pressure (inertia and added pressure head) is determined as 81 ft. The prescribed roll angles in both design documents is significantly to the right of the distribution of Φ derived above. Although the two design heads are remarkably close to each other and it is interesting to note that they are located in the right tail of the probability distribution of H_x, a systematic study over a large population of ships is required before a generalization of this observation can be attempted.

Conclusion and future work

A rational probability-based method for modeling flooding load on transverse watertight bulkheads was presented in this paper. This model is general and can be expanded to different classes of ships and different damage scenarios. Complete phenomenological expressions were derived for simplified cases; the methodology was illustrated using a generic RO/RO ship. Unlike existing prescriptive rules for WTB design against accidental flooding, the proposed method establishes explicit dependence of flooding loads on ship damage parameters, environmental variables, and ship hydrostatic properties. Consequently, probabilistic estimates of flooding loads can be estimated from first principles by considering randomness in the above parameters and can be incorporated in a full reliability analysis of WTB structures. A detailed numerical example demonstrated the proposed methodology: correlation among hydrostatic properties, a random rate of occurrence and duration of damage events, randomness in location and size of damage, a long-term joint probability distribution of environmental parameters, dependence between damage duration and maximum wave loads, and random modeling errors were considered. Statistics of lifetime maximum loads on transverse WTBs were obtained through Monte Carlo simulations: correlation among load components was not ignored and their probability distributions were estimated. These were then compared with code predicted nominal values.

Further work is required in the following areas:

1. More sophisticated hydrostatic modeling including more subdivisions and side protection, asymmetrical flooding, and heel response is required. In-plane loads on transverse WTBs from the hull girder in damaged condition needs to be considered. Dynamic effects, including pitch, sway, surge motions, and rate effects, need to be considered as well.
2. More detailed damage description needs to be incorporated. Statistics of geometric properties in damaged state, such as roll damping factor and roll natural frequency, need to be derived.
3. Sensitivity analyses of various sources of randomness need to be studied systematically, particularly in the context of reliability of transverse WTB structures.

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