Brown, A.J., Moon, W., Louis, M., "Structural Design for Crashworthiness in Ship Collisions", SNAME Annual Meeting T&R 2002 and *SNAME Transactions* ***110***, pp. 499-512, 2002.

Structural Design for Crashworthiness in Ship Collisions

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ABSTRACT

This paper describes the application of a simplified collision model to optimize crashworthiness in a tanker structural design. The objective of this optimization is to minimize mean collision damage penetration over a probabilistic sample of 10000 collision scenarios. The simplified collision model (SIMCOL) is used in a Monte Carlo simulation to predict mean probabilistic damage penetration. All designs must meet minimum regulatory and class requirements, but structural crashworthiness is not currently regulated. Additional crashworthiness, beyond that resulting from other requirements, is an option for the owner/operator that may be driven by their desire to reduce liability in a collision. Selection of a particular design depends on the decision-maker's preference for cost and crashworthiness. By performing a series of optimizations, varying the structural weight constraint, this becomes a probabilistic multi-objective (penetration and weight) optimization. The product of this optimization is a non-dominated (ND) frontier that specifies mean damage penetration as a function of structural weight. The non-dominated frontier is an excellent tool for selecting a preferred level of crashworthiness. It provides a picture of the optimum cost/crashworthiness trade-off. Trends in structural parameters over the non-dominated frontier also provide excellent guidance on where to place added weight for optimum crashworthiness.

NOMENCLATURE

x, y - coordinates, ship center of gravity (m)
G – ship center of gravity
θ - ship heading (degrees)
ϕ - collision angle (degrees)
a_{11} - added mass in the surge direction (kg)
a_{22} - added mass in the sway direction (kg)
a_{33} - yaw added mass moment of inertia (kg-m^2)
m_s - ship mass (kg)
I_{s33} - yaw mass moment of inertia (kg-m^2)
X - location and orientation of ships in the global system, $\mathbf{X} = \{x, y, \theta\}^T$
$\mathbf{V}_s$ - ship velocity, $\mathbf{V}_s = \{u, v, \omega\}^T$
τ - time step (seconds)
F - forces exerted on the ships in the global system, $\mathbf{F} = \{F_x, F_y, M\}^T$
V' - ship acceleration, $\mathbf{V'} = \{u', v', \omega'\}^T$
R_T - damaged volume of structural members (m^3)
A - damaged area of the decks or bottoms swept by each bow segment (m^2)
t - total thickness of impacted decks or bottoms (m)
ξ,η - local struck ship coordinate system, origin at midship of struck side (m)
l – strike location in local ship coordinate system (m)

INTRODUCTION

The International Maritime Organization (IMO) is responsible for regulating the design of oil tankers to provide for ship safety and environmental protection. Their ongoing transition to probabilistic performance-based standards requires the ability to predict the probabilistic environmental performance and safety of specific ship designs. IMO's first attempt to apply a probabilistic methodology to tankers was in response to the US Oil Pollution Act of 1990 (OPA 90). In OPA 90 the US required that all oil tankers entering US waters must have double hulls. IMO responded to this unilateral action by requiring double hulls or their equivalent. Equivalency is determined based on probabilistic oil outflow calculations specified in IMO (1995). These regulations use probability density functions (pdfs) to describe the location, extent and penetration of side and bottom damage. These pdfs are derived from limited historical damage statistics (IMO 1989), and applied identically to all ships without consideration of their structural design.

A major shortcoming in IMO's current oil outflow and damage stability calculation methodologies is that they do not consider the effect of structural design or crashworthiness on damage extent (Brown 1996, Sirkar 1997, Rawson 1998, Brown 2000). The primary reason for this exclusion is that no definitive theory or data exists to define this relationship.

This paper describes the application of a simplified collision model to optimize crashworthiness in a tanker structural design. The objective of this optimization is to minimize mean collision damage penetration over a probabilistic sample of 10000 collision scenarios. Feasible designs must satisfy minimum ABS standards with a specified constraint on structural weight.

By performing a series of optimizations, varying the structural weight constraint, this becomes a probabilistic multi-objective (penetration and weight) optimization. The product of this optimization is a non-dominated (ND) frontier. A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists which is better in one objective attribute and at least as good in all others. If one of the objective attributes is cost, the preferred design should always be a non-dominated solutions where the best performance (crashworthiness) is provided for a given cost.

In this optimization, structural weight is used as the cost metric and mean probabilistic damage penetration is used as the crashworthiness metric. All designs must meet minimum regulatory and class requirements, but structural crashworthiness is not currently regulated. Additional crashworthiness beyond that resulting from other requirements is an option for the owner/operator that may be driven by their desire to reduce their liability in a collision. Selection of a design depends on the decision-maker's preference for cost and added crashworthiness. The non-dominated frontier is an excellent tool for making this choice. It provides a picture of the optimum cost/penetration trade-off.

None of the designs on the ND frontier can be identified as "the best". Selection of the preferred design is up to the customer, but the ND frontier provides the customer with important information to make this selection: 1) the engineer can assure the customer with confidence that non-dominated designs have been identified; 2) the non-dominated frontier provides a perspective on the entire design space; and 3) some designs stand out as providing good value given a range of acceptable cost. This perceived value is affected by the shape of the frontier and cannot be rationally determined a priori.

Problem and Process

The optimization problem described in this paper is defined as follows:

- Objective: Maximize tanker crashworthiness by minimizing mean damage penetration over 10000 collision scenarios generated using a Monte Carlo simulation. The simulation assumes random collisions with a worldwide population of ships.
- Constraints: Designs must satisfy ABS rules and have less than a maximum specified structural weight. By varying the structural weight constraint, this becomes a multi-objective optimization.
- Collision scenario variables:
  - Independent - specified by probabilities and pdfs: type and displacement of striking ship; speed of the struck ship; speed of the striking ship; impact location; and collision angle.
  - Dependent - specified by parametric equations as a function of the independent variables: striking ship principal characteristics and striking ship bow half-entrance angle (HEA).
- Ship design parameters:
  - Constant struck ship parameters - The struck ship in this optimization is a 150000 dwt double-hull tanker. Its principal characteristics are consistent with the 150000 dwt reference tanker in the IMO Interim Guidelines (IMO 1995). Table 1 and Table 2 list the baseline tanker design characteristics. Constant struck ship parameters are: type (double hull); principal characteristics (LBP, B, D, T, Δ); transverse web spacing; description of primary subdivision (number and location of transverse bulkheads, number and location of longitudinal bulkheads including the side shell); material grades of side shell, longitudinal bulkheads, decks, bottom and webs; number, width, location, and material of side stringers; side shell supports including decks, bottom, and struts; web stiffener spacing and supported length; strut material, area, radius of gyration, and critical length. The baseline structure is designed using SAFEHULL (ABS 2002c).
  - Optimized struck ship parameters (Table 3) – smeared plate thickness of: side shell, inner side, longitudinal bulkheads, decks, bottom, inner bottom, stringers, upper and lower transverse webs.

Table 1. Struck Ship Principal Characteristics

Deadweight, tonnes	150,000
Length *L*, m	264.00
Breadth *B*, m	48.00
Depth *D*, m	24.00
Draft *T*, m	16.80
Double Bottom Ht h_{DB}, m	2.32
Double Hull Width *W*, m	2.00
Displacement, tonnes	178,867

Table 2. Struck Ship Structural Characteristics

Ship		150,000 dwt double hull tanker
Web Frame Spacing L_s, m		3.30
Smeared Thickness t_h, mm	Deck	47.32
	Inner Bottom	26.92
	Bottom	28.29
	Stringers	3 ◊15.34
Smeared Thickness t_v, mm	Side Shell	21.92
	Inner Skin	22.94
	Bulkhead	22.28
Web Thickness t_w, mm	Upper	12.00
	Lower	18.00

Table 3. Optimized Design Parameters

Design Variable	Baseline (mm)	Design Range – Smeared Scantling Values (mm)
$t_{OuterHull}$	21.92	20.0-60.0
$t_{InnerHull}$	22.94	20.0-60.0
t_{Deck}	47.32	30.0-60.0
$t_{InnerBottom}$	26.92	20.0-40.0
t_{Bottom}	28.29	25.0-40.0
$t_{Stringer}$	15.34	10.0 - 50.0
$t_{WebUpper}$	12.0	5.0 - 25.0
$t_{WebLower}$	18.0	5.0 - 25.0

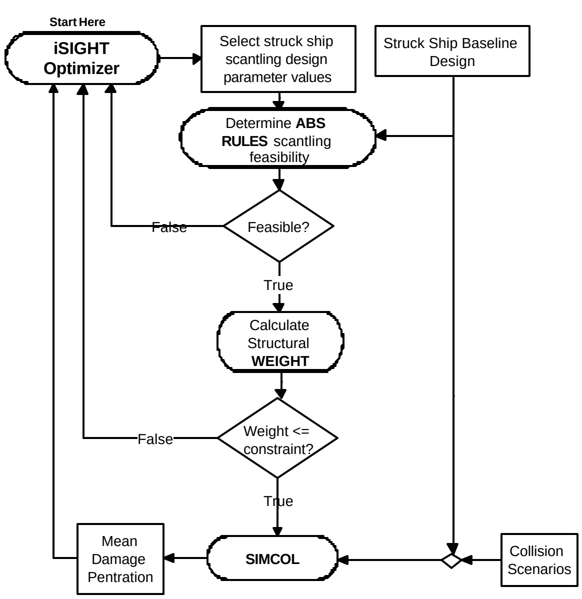

Figure 1. Optimization Process

Figure 1 illustrates the overall process used to perform the optimization. The program iSIGHT is used to link the simulation codes, and to execute the codes in a prescribed manner while analyzing and monitoring the results (Engineous Software 1998).

Optimization of the struck ship scantlings is accomplished using a simplified ABS required midship scantling calculation, a weight estimate calculation and a probabilistic damage penetration calculation in a genetic algorithm optimization performed by iSIGHT. Input data for this optimization includes a baseline set of struck ship design-parameter values and 10000 random collision scenarios. In each design iteration, iSIGHT chooses new values for the struck ship scantlings listed in Table 3, assesses their structural and weight feasibility, and calculates their resulting mean damage penetration using a simplified collision model (SIMCOL) and the random collision scenarios. The ABS module calculates required midship scantlings and section-modulus for the design. If the offered scantlings or section modulus fail to satisfy the ABS requirement or if the offered structural weight exceeds the maximum weight constraint, the design is infeasible. iSIGHT continues without calculating damage for this design. If the design is feasible, the 10000 collision cases are run in SIMCOL and a value for mean damage penetration is returned to iSIGHT. The genetic algorithm considers this result and selects another design for assessment. This is continued, building a population of designs progressing towards the non-dominated frontier. In the process iSIGHT gathers data relating mean damage penetration to the structural design parameters. It uses this data to build a response surface model (RSM) or approximation to this functional relationship. When this approximation becomes sufficiently accurate, iSIGHT uses it in the place of actually calculating damage. This saves time in the optimization process.

SIMCOL

The Simplified Collision Model (SIMCOL) used to calculate collision damage in the iSIGHT structural optimization was developed under the sponsorship of SNAME Ad Hoc Panel #6 and the Ship Structure Committee (SSC) (Chen 2000, Crake 1995).

SIMCOL uses a time-domain simultaneous solution of external ship dynamics and internal deformation mechanics similar to that originally proposed by Hutchison (1986). SIMCOL includes two primary submodels: an internal sub-model and an external sub-model. Figure 2 shows the SIMCOL simulation process. The internal sub-model performs Steps 2 and 3 in this process. It calculates internal deformation due to the relative motion of the two ships, and the internal reaction forces resulting from this deformation. The external sub-model performs Steps 1 and 4 in this process.

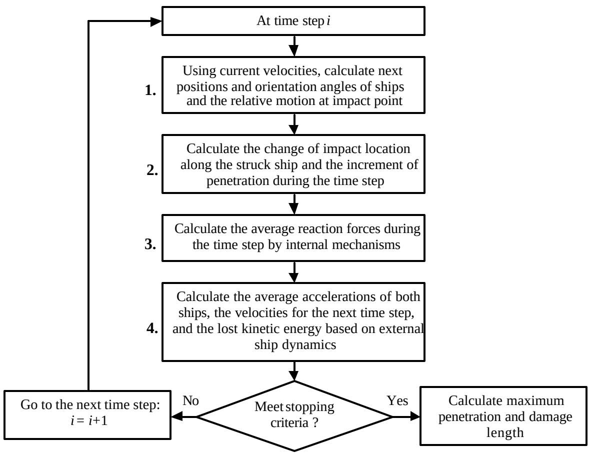

Figure 2. SIMCOL Process

The external dynamics sub-model uses a global coordinate system shown in Figure 3. In Figure 2 Step 1, the velocities calculated in the previous time step are applied to the ships to determine their positions at the end of the current time step:

$$\mathbf{X}_{n+1} = \mathbf{X}_n + \mathbf{V}_{sn} t \tag{1}$$

In Steps 2 and 3, the Internal Model calculates the compatible deformation, and the average forces and moments generated by this deformation over the time step. In Step 4, these forces and moments are applied to each ship. The new acceleration for each ship is:

$$\mathbf{V}_s' = \frac{\mathbf{F}}{\mathbf{M}_{VJ}} \tag{2}$$

where the virtual mass, $\mathbf{M}_V$, for each ship in this system is:

$$\mathbf{M}_{Vq} = \mathbf{M}_{ship} + \mathbf{A}_q = \begin{bmatrix} m_{V11} & m_{V12} & 0 \\ m_{V21} & m_{V22} & 0 \\ 0 & 0 & I_{V33} \end{bmatrix} \tag{3}$$

$$= \begin{bmatrix} m_s + a_{11}\cos^2 q + a_{22}\sin^2 q & (a_{11} - a_{22})\cos q \sin q & 0 \\ (a_{11} - a_{22})\cos q \sin q & m_s + a_{11}\sin^2 q + a_{22}\cos^2 q & 0 \\ 0 & 0 & I_{s33} + a_{33} \end{bmatrix}$$

The new velocity for each ship at the end of the time step is then:

$$\mathbf{V}_{s,n+1} = \mathbf{V}_{s,n} + \mathbf{V}_s' t \tag{4}$$

The internal sub-model determines reacting forces from side and bulkhead (vertical) structures using specific component deformation mechanisms including: membrane tension; shell rupture; web frame bending; shear and compression; force required to propagate the yielded zone; and friction (Rosenblatt 1975 and McDermott 1974). It determines absorbed energy and forces from the crushing and tearing of decks, bottoms and stringers (horizontal structures) using the Minorsky (1959) correlation as modified by Reardon and Sprung (1996). Total forces are the sum of these two components. The striking ship bow is assumed to be rigid and wedge-shaped with upper and lower extents determined by the bow height of the striking ship and the relative drafts of the two ships. Deformation is only considered in the struck ship.

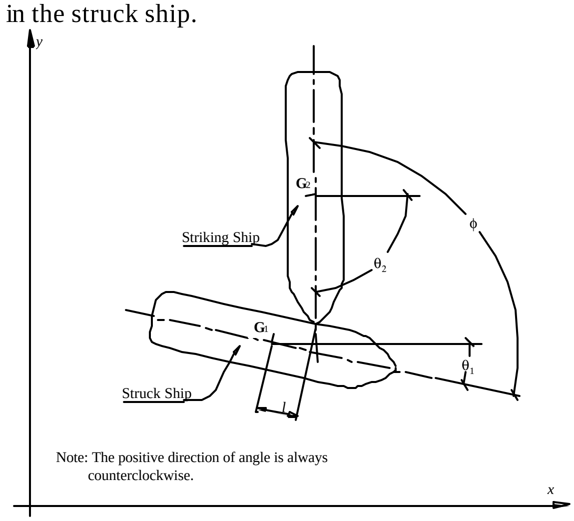

Figure 3. SIMCOL global coordinate system

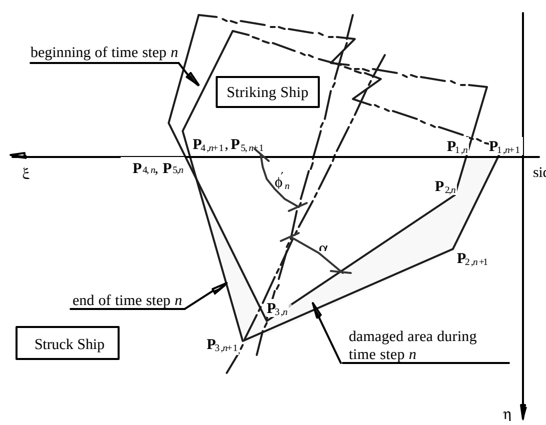

Figure 4. Sweeping segment method

Step 2 in the collision simulation process calculates damaged area and volume in the struck ship given the relative motion of the two ships calculated in Step 1 by the external sub-model. Figure 4 illustrates the geometry of the sweeping segment method used for this calculation in SIMCOL. The intrusion portion of the bow is described with five nodes, as shown in Figure 4. The shaded area in Figure 4 shows the damaged area of decks and/or bottoms during the time step. Coordinates of the five nodes in the local ship system at each time step are derived from the penetration and location of the impact, the collision angle, ϕ, and the half entrance angle, α, of the striking bow.

The damaged plating thickness t is the sum thickness of deck and/or bottom structures that are within the upper and lower extents of the striking bow. Given the damaged material volume, the Minorsky force is calculated based on the following assumptions:

- The resistant force acting on each out-sweeping segment is in the opposite direction of the average movement of the segment. The force exerted on the struck ship is in the direction of this average movement.
- The work of the resistant force is done over the distance of this average movement.
- The total force on each segment acts through the geometric center of the sweeping area.

The energy absorbed is then:

$$\Delta KE_{1,n} = 47.1\times10^6 R_{T1,n} = 47.1\times10^6 A_{1,n}\ t \qquad (5)$$

Forces and moments acting on other segments are calculated similarly. The total exerted force, $\mathbf{F}_n$, is the sum of the forces and moments on each segment. These forces are added to the side shell, bulkhead and web forces. Internal forces and moments are calculated for the struck ship in the local coordinate system and converted to the global system. The forces and moments on the striking ship have the same magnitude and the opposite direction of those acting on the struck ship.

COLLISION SCENARIOS

Collisions are a high consequence, low probability event. Because of this high consequence, most collisions involve litigation and sometimes years of legal proceedings. The focus of these proceedings is frequently on human error vice a precise technical analysis of what happened and what resulted. For these reasons, complete technical data describing the struck and striking ship, the collision event, and the resulting damage is very difficult to obtain even when it exists.

Data required by SIMCOL to describe the collision event includes:

- Struck ship design parameters
- Struck ship variables – speed, trim, draft or displacement
- Event variables - collision angle (ϕ), strike location (l)
- Striking ship variables – type, displacement, speed, length, beam, bow half-entrance angle (HEA), draft at bow

Except for the struck ship design parameters, these are all random variables with varying degrees of dependency, some discrete and some continuous. Struck and striking ship speed, collision angle, striking ship type and striking ship displacement are treated as independent random variables in the scenarios. Other striking ship characteristics are treated as dependent variables derived from the independent variables based on relationships developed from worldwide ship data (Brown 2001, Brown 2002a, Brown 2002b).

The data used to determine the probabilities and probability density functions necessary to define these random variables were obtained from a number of sources including Sandia National Laboratories (1998), Lloyds (1993), ORI (1980) and ORI (1981).

Figure 5 provides a framework for defining the relationship of scenario variables. Figure 6 provides probabilities of the struck ship encountering specific ship types. These probabilities are based on the fraction of each ship type in the worldwide ship population in 1993 (Lloyds 1993). Each of the general types includes a number of more specific types. Figure 7 shows the worldwide distributions of displacement for these ship types. Table 4 provides parameter values for regression curves of these distributions. Simple power function regression curves were developed from the Lloyds data for length, beam, draft, and bow height as a function of striking ship type and displacement. Typical principal characteristic data are shown in Figure 8 and regression equations are summarized in Table 5.

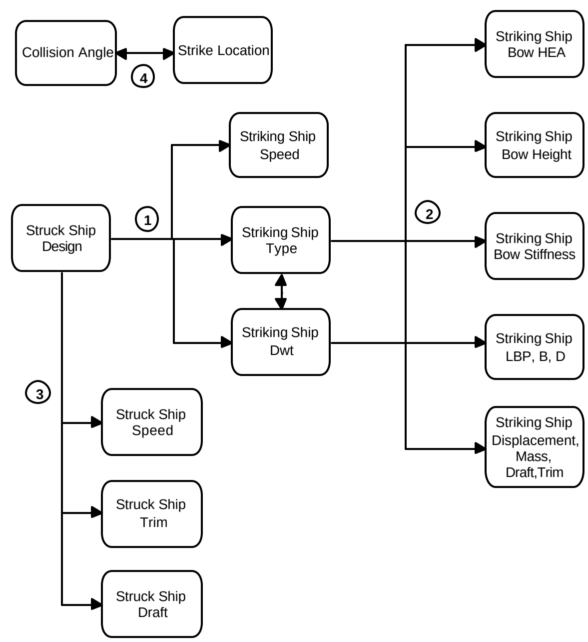

Figure 5. Collision Event Variables

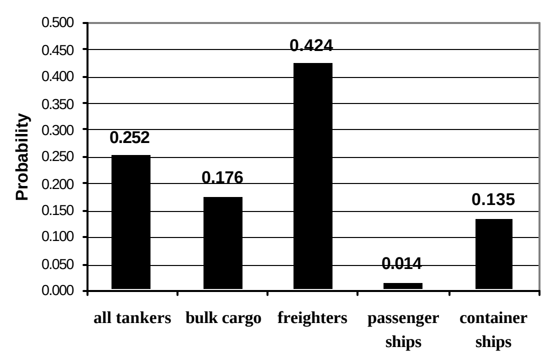

Figure 6. Striking ship type probability

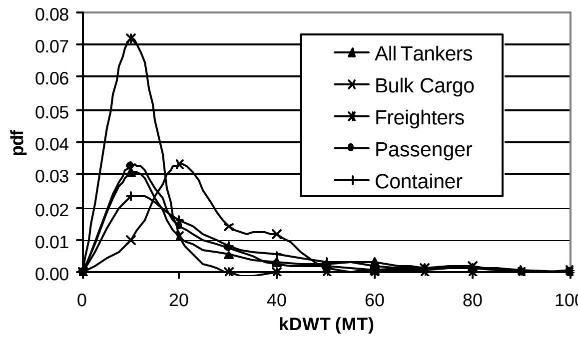

Figure 7. Striking Ship Displacement, Worldwide

Table 4. Striking Ship Type and Displacement

Ship Type	Probability of Encounter	Displacement pdf	Weibull a	Weibull b	Mean (kMT)	s (kMT)	Displacement Range (MT)
Tanker	0.252	Weibull	0.84	11.2	12.277	14.688	699-273550
Bulk carrier	0.176	Weibull	1.20	21.0	19.754	16.532	1082-129325
Freighter	0.424	Weibull	2.00	11.0	9.748	5.096	500-41600
Passenger ship	0.014	Weibull	0.92	12.0	12.479	13.579	997-76049
Container ship	0.135	Weibull	0.67	15.0	19.836	30.52	1137-58889

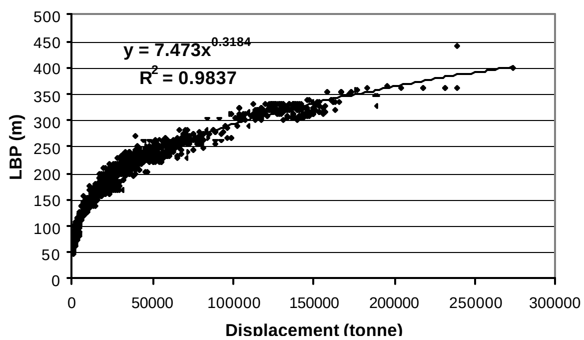

Figure 8. Worldwide Tankers: Length vs. Displacement

Table 5. Striking Ship Characteristics

Ship Type	LBP		Beam		Draft		Bow Height		
	Coef	Power	Coef	Power	Coef	Power	Coef	Power	HEA
Tanker	7.473	.3184	1.1507	.3237	.5746	.2972	.6712	.3200	38
Bulk carrier	6.598	.3317	.9569	.3366	.5466	.3030	1.305	.2611	20
Freighter	6.927	.3249	1.7215	.2725	.4744	.3197	.7406	.3211	20
Passenger ship	8.223	.2991	1.9688	.2555	.8894	.2098	1.1317	.2582	17
Container ship	5.486	.3526	1.9603	.2648	.5964	.2843	.7460	.3173	17

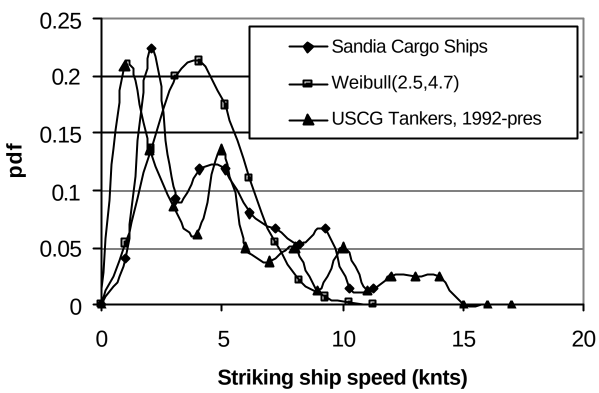

Figure 9. Striking Ship Speed (knots)

Collision speed is the ship speed at the moment of collision. It is not necessarily related to service speed. It depends on actions taken just prior to collision. Collision speed data is collected from actual collision events.

Figure 9 is a plot of striking ship speed data derived from the Sandia Report (1998) and limited USCG tanker-collision data (USCG 1991). Figure 10 is a plot of struck ship speed derived from the USCG tanker collision data (USCG 1991). The struck ship collision speed distribution is very different from the striking ship speed distribution. Struck ships are frequently moored or at anchor as is indicated by the significant pdf value at zero speed.

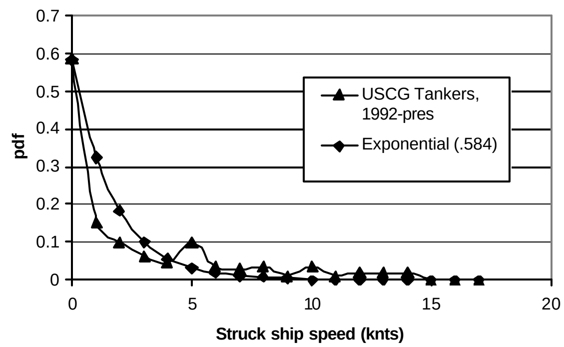

Figure 10. Struck ship speed (knots)

A Normal distribution (μ = 90 degrees, σ = 28.97 degrees) is fit to collision angle data derived from the Sandia Report (1998), and is used to select collision angle in the Monte Carlo simulation. At more oblique angles, there is a higher probability of ships passing each other or only striking a glancing blow. These cases are frequently not reported.

The current IMO pdf for strike longitudinal location specifies a constant value over the entire length of the stuck ship, IMO (1995). The constant pdf was chosen for convenience and because of the limited available data. Figure 11 shows a bar chart of the actual data used to develop the IMO pdf, IMO (1989), and data gathered for cargo ships in the Sandia Study. This data does not indicate a constant pdf. The IMO data is from 56 of 200 significant tanker-collision events for which the strike location is known. The Sandia data indicates a somewhat higher probability of midship and forward strikes compared to the IMO data. The IMO tanker probabilities are used here.

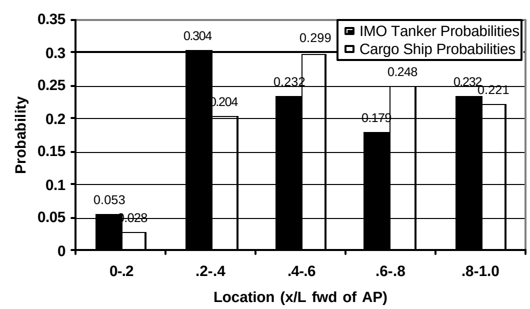

Figure 11. Longitudinal Damage Location

ABS COMPLIANCE

Structural feasibility of the designs is assessed using American Bureau of Shipping (ABS) Rules (ABS 2002a, ABS 2002b) to calculate minimum midship net scantlings and section modulus. The double hull tanker structural design is modeled as a rectangular box with no camber, zero bilge radius and no hoppers or stools. Table 6 lists the rules applied in the ABS Feasibility Module calculations to determine minimum required net scantlings.

Table 6. ABS (2002a, 2002b) Net Scantlings

Component	**ABS Rules**
Inner bottom plate thickness	5-1-4/7.3.2
Outer bottom plate thickness	5-1-4/7.3.1
Outer side shell plate thickness	5-1-4/5.3 5-1-4/9.1
Inner side plate thickness	5-1-4/5.5 5-1-4/13.1
Deck thickness	5-1-4/3.1 5-1-4/9.3
Centerline bottom girder	5-1-4/7.7.1 5-1-4/7.7.4
Side bottom girder	5-1-4/7.7.2
Longitudinal bulkhead	5-1-4/5.5 5-1-4/13.1
Transverse web	5-1-4/11.7
Transverse bulkhead thickness	5-1-4/13.3
Side stringer	5-1-4/11.9
Hull girder vertical bending moment	3-2-1/3.3 5-1-3/3.1 5-1-3/7.3 Taggart (1980)
Hull girder section modulus	3-2-1/3.7.1 3-2-1/5.5 5-1-4/3.1
Corrosion allowance	5-1-2/Table 1

The required net plate thickness is multiplied by a smearing ratio to account for stiffeners. Typical smearing ratios were calculated for the components listed in Table 6 by taking the average component value for a sample of double hull tankers around 150000 dwt. This avoids the explicit calculation of stiffener scantlings. Each offered plate thickness is compared to the required ABS thickness to assess feasibility. Minimum required upper transverse web section modulus and lower transverse web section modulus are also calculated and compared to the offered values. Finally, required hull girder section modulus and offered section modulus are calculated and compared, where the assumed total bending moment includes still water and wave bending moments. The still water bending moment is calculated using an estimation formula from Taggart (1980):

$$M_{sw} = C_s L^{2.5} B(C_B + 0.5) \qquad (6)$$

A corrosion allowance is added to the offered plate thickness before structural weight is calculated.

STRUCTURAL WEIGHT CALCULATION

Longitudinal steel volume per unit length is calculated for each plate section, summed and multiplied by the density of steel to give the weight per unit length. Upper and lower transverse web volume and weight are also calculated per unit length and added to the longitudinal weight to give a total weight per unit length.

A weight distribution equation taken from Watson (1998) based on midship weight per unit length is used to extrapolate this weight to a full bare hull structural weight less transverse bulkhead structure:

$$W_s = (0.715C_B + 0.305)LW_{pm} \qquad (7)$$

where:
W_s = weight of ship structure less transverse bulkhead structure
W_{pm} = weight per unit length of structure
L = LBP

Transverse bulkhead weight is calculated based on plate thickness, smearing ratio, number of bulkheads and principal characteristics. This weight is added to the longitudinal bare hull weight to give a total bare hull weight. Finally a correlation factor of 1.17 is applied to account for brackets and other miscellaneous structure.

RESULTS

Figure 12 shows weight and mean damage penetration values for the total population of feasible ships calculated by the optimization. The lower boundary of these points is the non-dominated (ND) frontier of minimum penetration for a given structural weight. Designs above this frontier are inferior designs.

Figure 13 shows the 43 designs that define the non-dominated frontier. The baseline design, developed using SAFEHULL Phase A, has a hull structural weight of 23000 MT. Based on the ABS equations used in the optimization, 12 designs were found with a slightly lower structural weight, 22360 MT being the minimum non-dominated design. The other designs on the non-dominated frontier represent the best (minimum mean damage penetration) combination of design scantlings for a given structural weight.

Figure 14 shows how side-shell thickness increases along the non-dominated frontier with increased weight. Each point in this curve has a corresponding point in Figure 13 (they are the same designs). Similar curves are provided for the other scantling design parameters in Figure 16 through Figure 22.

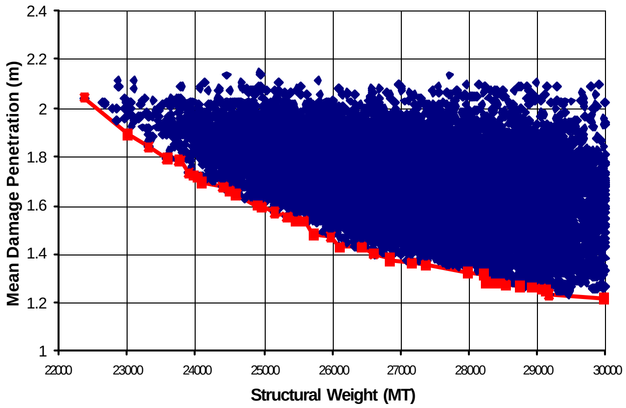

Figure 12. Penetration vs. Weight Design Space

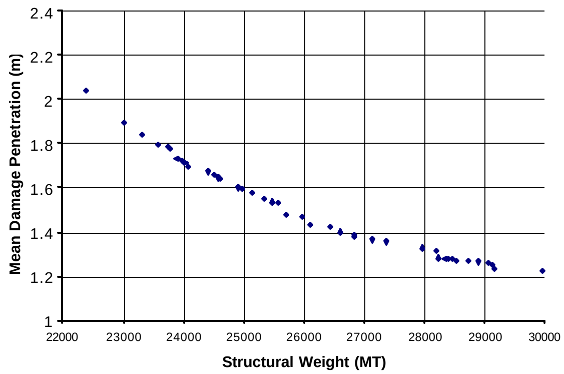

Figure 13. Penetration vs. Weight Non-Dominated Frontier

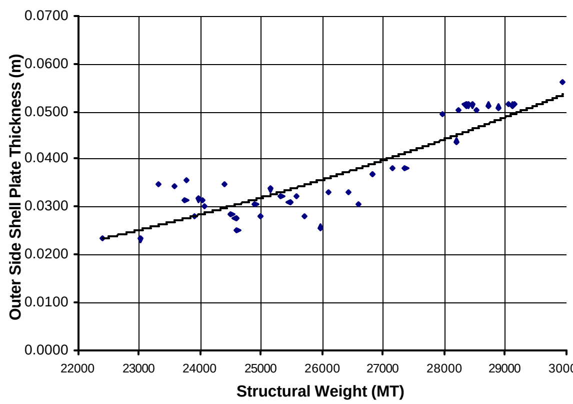

Figure 14. Non-Dominated Side Shell Thickness vs. Weight

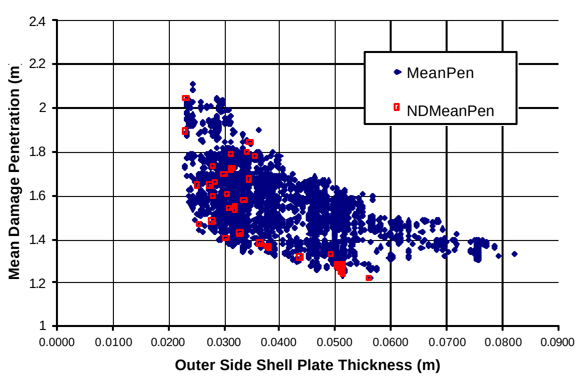

Figure 15. Penetration vs. Side Shell Thickness

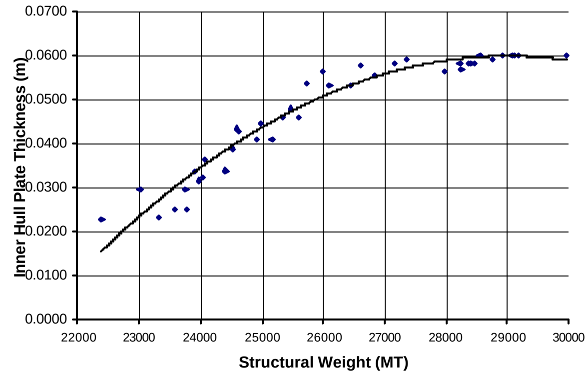

Figure 16. Non-Dominated Inner Side Thickness vs. Weight

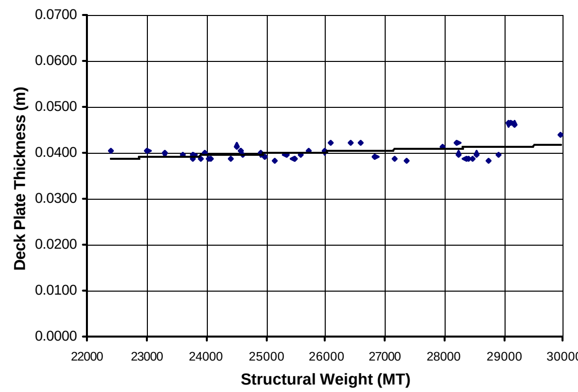

Figure 17. Non-Dominated Deck Thickness vs. Weight

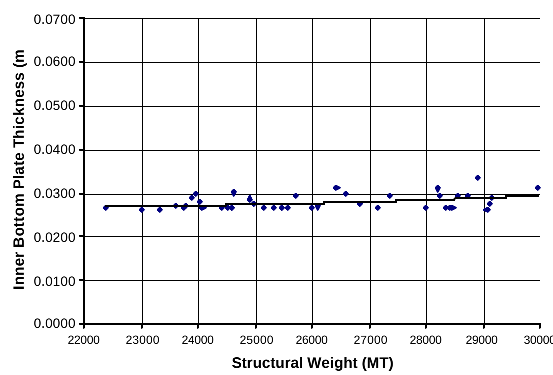

Figure 18. Non-Dominated Inner Bottom Thickness vs. Weight

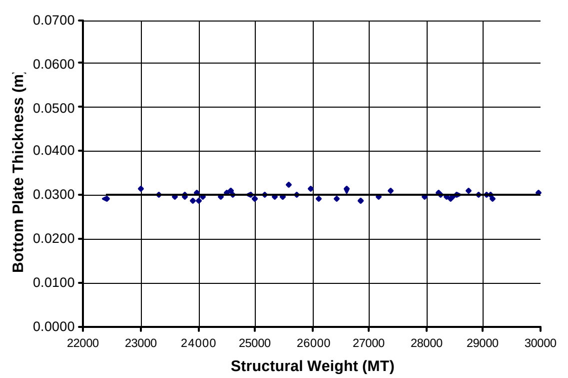

Figure 19. Non-Dominated Bottom Thickness vs. Weight

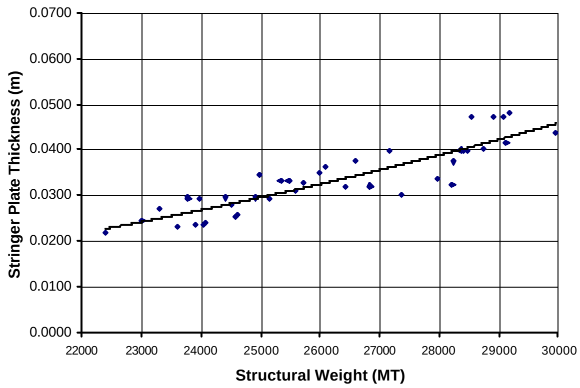

Figure 20. Non-Dominated Stringer Thickness vs. Weight

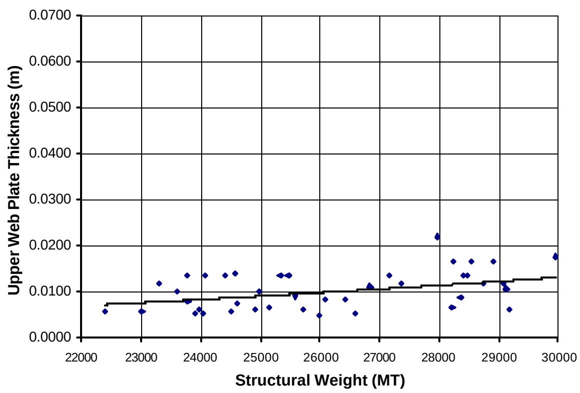

Figure 21. Non-Dominated Upper Web Thickness vs. Weight

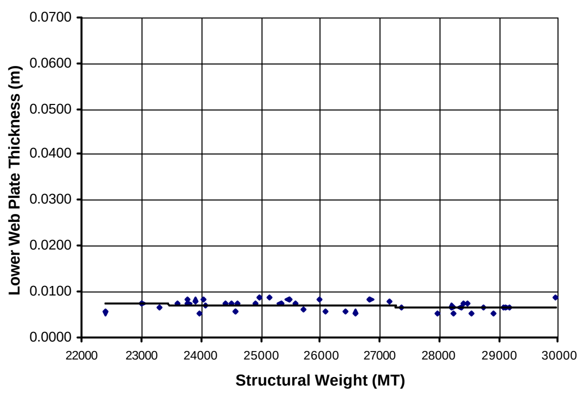

Figure 22. Non-Dominated Lower Web Thickness vs. Weight

Figure 15 shows mean damage penetration as a function of side shell thickness. The non-dominated designs from Figure 14 are indicated with squares. The lower boundary (frontier) in Figure 15 represents the best possible designs for a given side shell thickness, but these designs are not necessarily the best designs for a given weight. Other scantlings, particularly inner side thickness (Figure 16), are also increased as structural weight is added, maintaining a minimum weight balance to improve crashworthiness.

Side shell thickness (Figure 14) and inner side thickness (Figure 16) increase over their full range (20-60 mm) as structural weight is increased. Inner side thickness reaches its maximum constraint at a weight of 28500 MT.

Deck thickness (Figure 17), inner bottom thickness (Figure 18) and upper web plate thickness (Figure 18) increase only slightly above their ABS minimum values. Side stringer thickness (Figure 20) shows a modest increase. Bottom plate thickness (Figure 19) and lower web thickness (Figure 22) remain at their minimum ABS required values.

The struck ship in this optimization is much larger than most striking ships in the 10000 collision scenarios. As a result, the struck ship bottom is rarely contacted and its scantlings have little effect on damage penetration. The struck ship deck, inner bottom and lower web are contacted more often than the bottom, but still infrequently.

CONCLUSIONS

This paper describes the application of a simplified collision model and probabilistic description of collision scenarios to optimize crashworthiness in a tanker structural design. The optimization methodology includes three important components necessary to assist the customer in selecting the preferred design. These are:

- An efficient and effective search of design space for non-dominated designs. This is accomplished by the multi-objective (weight and crashworthiness) genetic optimization.
- Well-defined and quantitative measures of objective attributes. Structural weight is a reasonable cost metric for commercial designs. Crashworthiness is calculated efficiently using the simplified collision model (SIMCOL).
- An effective format to describe the design space and to present non-dominated concepts for rational selection by the customer. Figure 14 through Figure 22 provide a graphic description of the design space relative to crashworthiness, allowing the customer to select their preferred option with confidence.

The use of a simplified collision model (SIMCOL) is essential in this application because of the large number of probabilistic damage calculations required.

Damage penetration for this struck ship design is most sensitive to side shell, inner side and stringer scantlings. Crashworthiness was not sensitive to the other design parameters investigated. Future work will investigate additional design parameters such as web spacing, material types, number of side stringers and double side spacing.

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