

# Predicting Probabilistic Collision Damage Extents for Tanker Oil Outflow Assessment and Regulation

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## ABSTRACT

*This paper presents the most recent improvements and application of the Simplified Collision Model SIMCOL, developed under SNAME Ad Hoc Panel #6 for the rapid prediction of collision damage in probabilistic analysis. IMO's ongoing transition to probabilistic performance-based standards requires the ability to predict the probabilistic environmental performance and safety of specific ship designs. Current IMO 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, and applied identically to all ships without consideration of their structural design. They do not consider the effect of structural design or crashworthiness on damage extent. SIMCOL provides a means to correct this deficiency. SIMCOL's ability to predict probabilistic damage in real world collision scenarios is demonstrated by application to two reference tanker structural designs, and comparison to the IMO damage pdfs. The comparison is excellent when the struck ship is a single hull tanker consistent with the single hull MARPOL tankers represented by the IMO statistics, and because of the physics-based models used in SIMCOL, it is reasonable to extrapolate this performance to today's double hull tankers.*

## NOMENCLATURE

$x, y$  - coordinates, ship center of gravity (m)  
 $G$  - ship center of gravity  
 $\theta$  - ship heading (degrees)  
 $\phi$  - 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<sup>2</sup>)  
 $m_s$  - ship mass (kg)  
 $I_{s33}$  - yaw mass moment of inertia (kg-m<sup>2</sup>)  
 $\mathbf{X}$  - location and orientation of ships in the global system,  $\mathbf{X} = \{x, y, \theta\}^T$   
 $\mathbf{V}_s$  - ship velocity,  $\mathbf{V}_s = \{u, v, \omega\}^T$   
 $\tau$  - time step (seconds)  
 $\mathbf{F}$  - forces exerted on the ships in the global system,  $\mathbf{F} = \{F_x, F_y, M\}^T$   
 $\mathbf{V}'$  - ship acceleration,  $\mathbf{V}' = \{u', v', \omega'\}^T$   
 $R_T$  - damaged volume of structural members (m<sup>3</sup>)  
 $A$  - damaged area of the decks or bottoms swept by each striking bow segment (m<sup>2</sup>)  
 $t$  - total thickness of impacted decks or bottoms (m)  
 $\xi, \eta$  - local struck ship coordinate system, origin at midship of struck side (m)  
 $l$  - strike location in local ship coordinate system (m)  
 $D$  - effective depth of the striking ship bow contacting a longitudinal bulkhead (m)  
 $t$  - thickness of a longitudinal bulkhead, deck, bottom or stringer (m)

$CD_L$  - longitudinal crush distance of the longitudinal bulkhead within the current time step  
 $b$  - breadth of the deck, bottom or stringer between supports (m)  
 $S_b$  - material flow stress =  $(\sigma_y + \sigma_u)/2$   
 $\epsilon_{ij}^p$  - plastic strain rate  
 $v_{ij}$  - material flow velocity  
 $\epsilon_e^p$  - effective plastic strain  
 $\sigma$  - effective stress  
 $E$  - strain energy absorption rate per unit volume

## 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 2000a). The primary reason for this exclusion is that no definitive theory or data exists to define this relationship.

This paper presents the most recent improvements and application of the Simplified Collision Model SIMCOL, developed under SNAME Ad Hoc Panel #6 for the rapid prediction of collision damage in probabilistic analysis (Brown 2000b, 2001a, 2001b, 2002a, 2002b, 2002c, 2002d).

The probabilistic analyses use independent variables specified by probabilities and pdfs and dependant variables specified by parametric equations as a function of the independent variables. These independent and dependent variables describe the striking ship and collision scenario parameters necessary for probabilistic analyses. The independent variables include type and displacement of striking ship; speed of the struck ship; speed of the striking ship; impact location; and collision angle. The dependent variables include striking ship principal characteristics and striking ship bow half-entrance angle (HEA). The struck ship is described by constant parameters including type (double or single hull); principal characteristics (LBP, B, D, T,  $\Delta$ ); 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.

Table 1. Struck Ship Principle Characteristics

Principle Characteristic	DH150	SH100
Deadweight, tonnes	150000	100000
Length $L$ , m	264	222
Breadth $B$ , m	48	42
Depth $D$ , m	24	20.3
Draft $T$ , m	16.8	13.35
Double Bottom Ht $h_{db}$ , m	2.32	NA
Double Hull Width, $W$	2	NA
Displacement, tonnes	178867	110015

The struck ships used in this paper include a 150000 dwt double-hull tanker (DH150) and a 100000 dwt single-hull tanker (SH100). Both vessels' principal characteristics are consistent with the 150000 dwt and 100000 dwt reference tankers in the IMO Interim Guidelines (IMO 1995). The baseline structures are designed using

SAFEHULL (ABS 2002c). Table 1 and Table 2 list the SH100 and DH150 representative tanker design characteristics.

Table 2. Struck Ship Structural Characteristics

Ship	DH150	SH100	
Web Frame Spacing $L_s$ , m	3.3	5.015	
Smeared Thickness $t_h$ , mm	Deck	47.32	36.27
	Inner Bottom	26.92	NA
	Bottom	28.29	44.2
	Stringers	3@15.34	NA
Smeared Thickness $t_v$ , mm	Side Shell	21.92	26.78
	Inner Skin	22.94	NA
	Bulkhead	22.28	27.82
Web Thickness $t_w$ , mm	Upper	12	15
	Lower	18	15

## DESCRIPTION OF SIMCOL

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 sub-models: an internal sub-model and an external sub-model. Figure 1 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.

The external dynamics sub-model uses a global coordinate system shown in Figure 2. In Figure 1 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:

$$\mathbf{X}_{n+1} = \mathbf{X}_n + \mathbf{V}_{sn} t \quad (1)$$

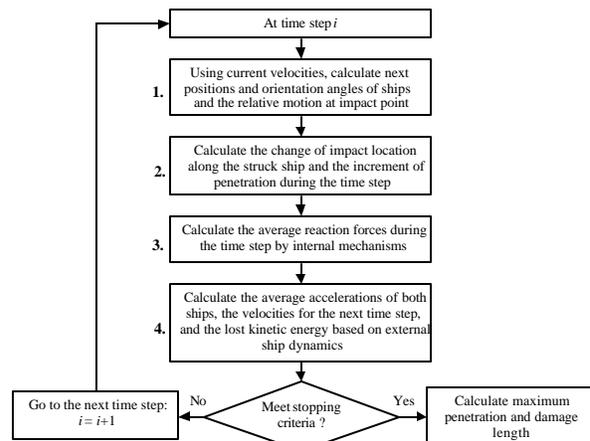


Figure 1. SIMCOL Simulation Process

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:

$$\mathbf{V}'_s = \frac{\mathbf{F}}{\mathbf{M}_{VJ}} \quad (2)$$

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

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

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

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

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

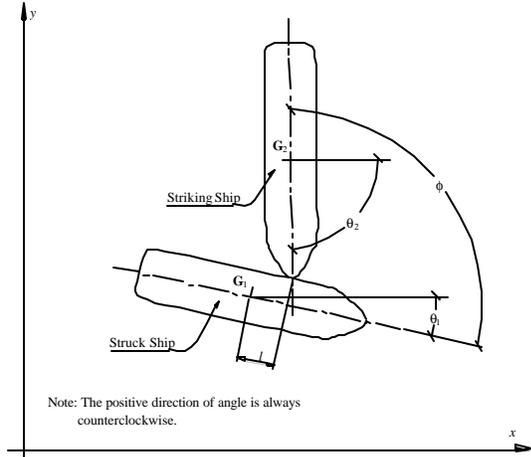


Figure 2. SIMCOL Global Coordinate System

The internal sub-model calculates the struck ship deformation resulting from the ships' relative motion, and calculates the average internal forces and moments generated by this deformation over the time step. Refer to Figure 1, Steps 2 and 3. The internal sub-model determines reacting forces, perpendicular to the centerline of the struck vessel, from side and longitudinal 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. These mechanisms and models are described in prior papers and reports on SIMCOL (Brown 2000a and Brown 2002a).

Since the last version of SIMCOL, a series of finite element analyses using LSDYNA was performed to select and fine-tune the various energy coefficient correlations used for component crushing and tearing analyses with particular attention to longitudinal extent of damage (Sajdak 2004).

The internal sub-model determines absorbed energy and forces from the crushing and tearing of decks, bottoms and stringers (horizontal structures) in a simplified

manner using an energy coefficient formulation from Paik & Pedersen (1996). The Minorsky equation (1959) was used in previous versions of SIMCOL for these calculations. The Paik & Pedersen (1996) energy coefficient is based on crushing and folding and cutting and tearing damage modes of plated structures. The energy coefficient formulation is derived from Amdahl's (1983) theoretical and experimental work and is given by:

$$E_{coef} = (1.9514 \cdot (\frac{t}{b})^{0.5} + 0.3661 \cdot \frac{t}{b}) \cdot S_o \quad (5)$$

Step 2 in the collision simulation process calculates damaged area and volume in the struck ship horizontal structure given the relative motion of the two ships in a time step calculated in Step 1 by the external sub-model. Figure 3 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 3. The shaded area in Figure 3 shows the damaged area of decks and/or bottoms during the time step. Coordinates of the five nodes in the  $\xi-\eta$  system at each time step are derived from the penetration and location of the impact, the collision angle,  $\phi$ , and the half entrance angle,  $\alpha$ , of the striking bow.

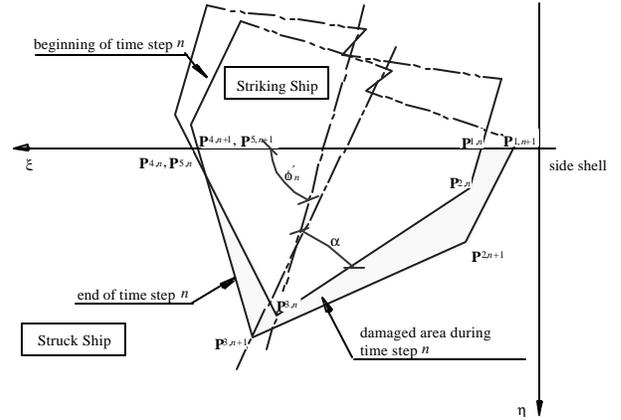


Figure 3. Sweeping Segment Geometry

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 reaction 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:

$$\Delta KE_{1,n} = E_{coef} \times R_{1,n} = E_{coef} \times A_{1,n} \times t \quad (6)$$

Forces and moments acting on other segments are calculated similarly.

In a ship to ship collision, where the struck ship has forward speed or the collision occurs at an oblique angle, the striking ship both penetrates into the struck ship and crushes structure longitudinally, parallel to the struck ship centerline. Determination of reacting forces, parallel to the centerline of the struck vessel, from the crushing and tearing of side and longitudinal bulkhead (vertical) structures is accomplished using the Minorsky (1959) energy coefficient correlation as modified by Reardon and Sprung (1996).

Step 2 in the collision simulation process also calculates the longitudinally (parallel to struck ship centerline) damaged volume of the vertical structure (side and longitudinal bulkheads) in the struck ship given the relative motion of the two ships in a time step calculated in Step 1 by the external sub-model. The damaged volume is given by Equation (7) and is only considered after the longitudinal bulkhead or side shell has ruptured.

$$R_T = D \cdot t \cdot CD_L \quad (7)$$

The energy absorbed by longitudinal damage of vertical structure is then:

$$\Delta KE_i = 47.1 \times 10^6 \times R_i \quad (8)$$

where the  $47.1 \times 10^6$  is the Reardon and Sprung (1996) energy coefficient for steel structures.

Determination of the absorbed energy and forces from the longitudinal (parallel to struck ship centerline) deflection and damage to transverse bulkheads and web frames (transverse structures) are determined using a plasticity flow membrane approach recently developed by Sajdak (2004) and incorporated in SIMCOL.

Initially the transverse structure is isolated using rigid-diaphragm boundary conditions yielding an idealized transverse bulkhead (idealized plate with the use of structural smearing techniques) where the span is bounded by longitudinal bulkheads and the height is bounded by structural decks. Using the rigid-diaphragm boundary condition, the transverse plate is assumed to absorb energy independent of other contacted structure. Making use of this independence, the plate is laterally deformed by the striking ship. To determine the absorbed energy in the plastic deformation of the plate it is subdivided into eight or twenty-five (depending on contact scenario) flat panel regions which approximate the transverse bulkhead deflection as shown in Figure 4, Figure 5 and Figure 6. Each of the regions is evaluated for the energy absorbed by plastic membrane stretching. Determining the energy absorbed in each region (both rectangular and triangular regions) is accomplished by developing velocity flow field equations for each region in a co-rotational system.

The velocity flow fields for each region ( $v$ ) are substituted into the plastic strain rate – velocity relation, Equation (9). The plastic strain rate is used to determine the effective plastic strain, Equation (10), and the effective plastic strain is multiplied by the material yield strength to provide the energy absorption rate per unit volume for the region, Equation (11).

$$\mathbf{e}_{ij}^p = \frac{1}{2} (\mathbf{n}_{i,j} + \mathbf{n}_{j,i}) \quad (9)$$

$$\mathbf{e}_e^p = \sqrt{\frac{2}{3}} \mathbf{e}_{ij}^p \cdot \mathbf{e}_{ij}^p \quad (10)$$

$$E = s \mathbf{e}_e^p \quad (11)$$

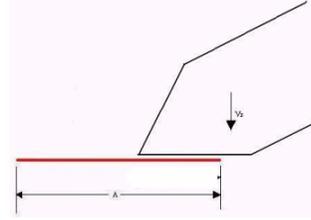


Figure 4. Transverse Bulkhead Contact Scenario 2

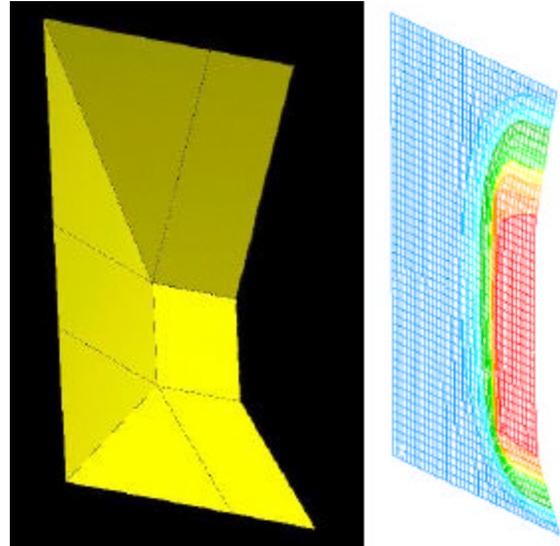


Figure 5. Transverse Bulkhead Deflection

The energy absorption rate per unit volume for each region is integrated over the volume of the region and then over the duration of the time step to yield the total energy absorbed through plastic deflection over the time step.

The energy for each region is summed to provide the total energy absorbed by the plate over the time step and the reactive force for the plate is added to the side shell, bulkhead and web forces and the forces from each ruptured longitudinal bulkhead. Internal forces and moments are calculated for the struck ship in the local coordinate system, i.e. the  $\xi$ - $\eta$  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.

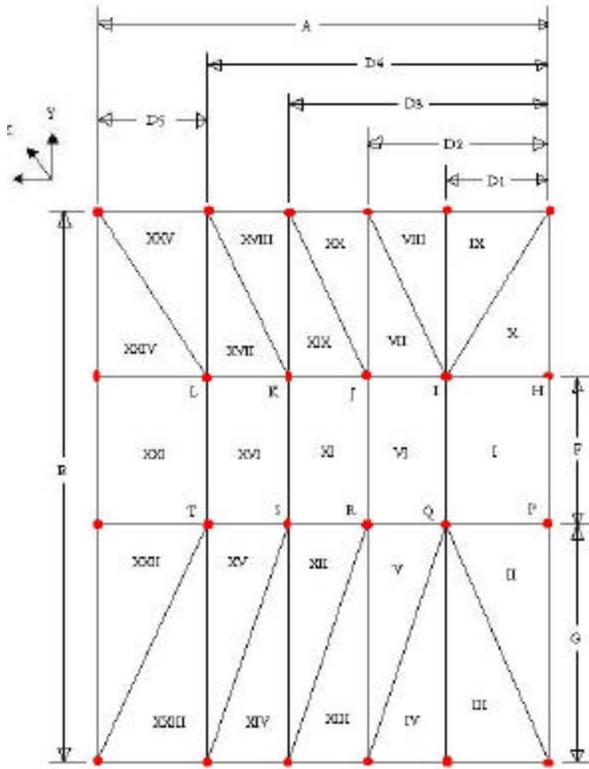


Figure 6. Transverse Bulkhead 25 Region Model

## 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 ( $\phi$ ), 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 inde-

pendent 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 7 provides a framework for defining the relationship of scenario variables. Figure 8 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 9 shows the worldwide distributions of displacement for these ship types. Table 3 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 10 and regression equations are summarized in Table 4.

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.

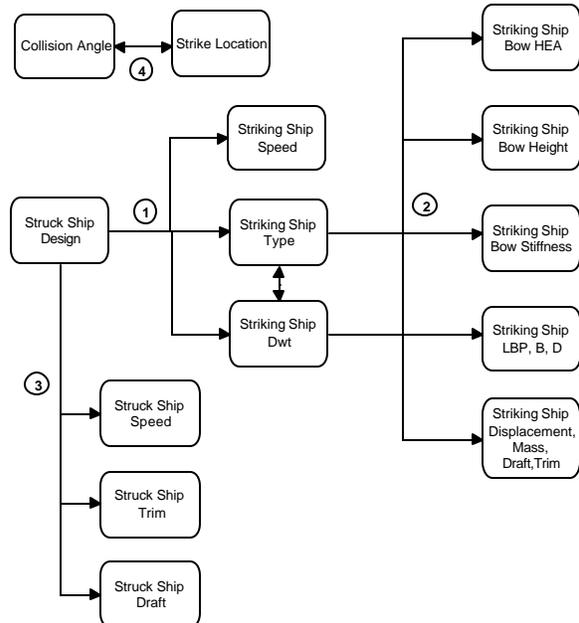


Figure 7. Scenario Variable Relationships

Figure 11 is a plot of striking ship speed data derived from the Sandia Report (1998) and limited USCG tanker-collision data (USCG 1991). Figure 12 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.

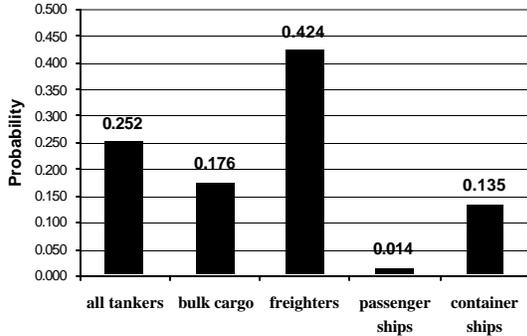


Figure 8. Struck Ship Encounters

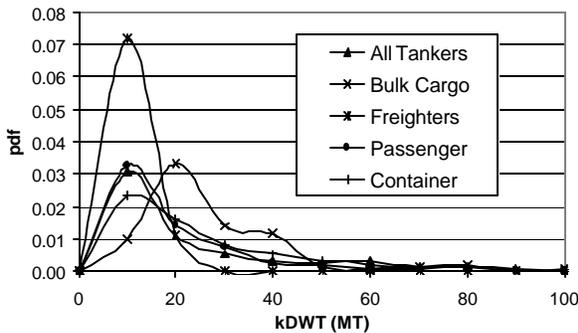


Figure 9. Worldwide Displacement Distribution

Table 3. Displacement Regression Curve Parameters

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

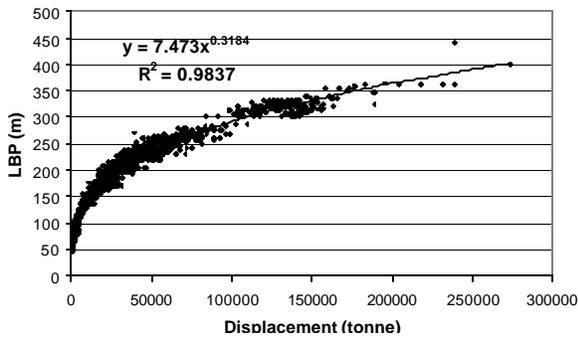


Figure 10. Striking Ship Length vs. Displacement

A Normal distribution ( $\mu = 90$  degrees,  $\sigma = 28.97$  degrees) is fit to collision angle data derived from the Sandia Report (1998), and is used to select collision an-

gle 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.

Table 4. Principle Characteristic Regression Summary

Ship Type	LBP		Beam		Draft		Bow Height		HEA
	Coef	Power	Coef	Power	Coef	Power	Coef	Power	
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

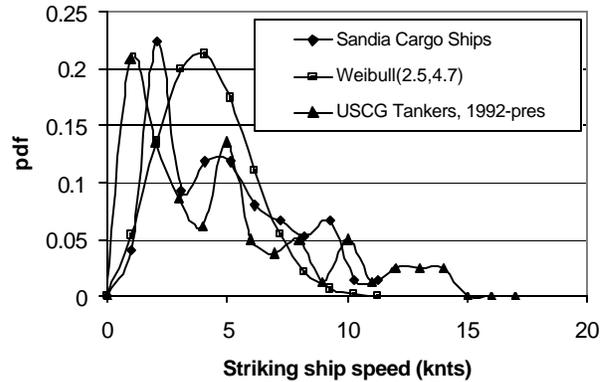


Figure 11. Striking Ship Speed pdf

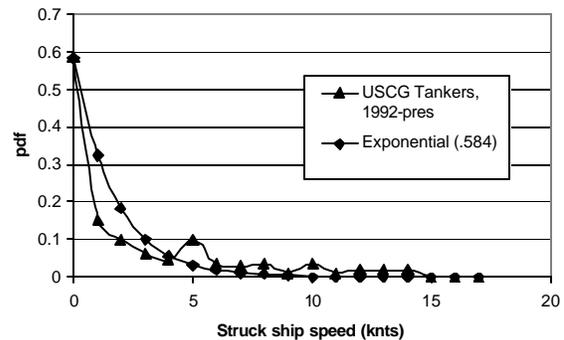


Figure 12. Struck Ship Speed pdf

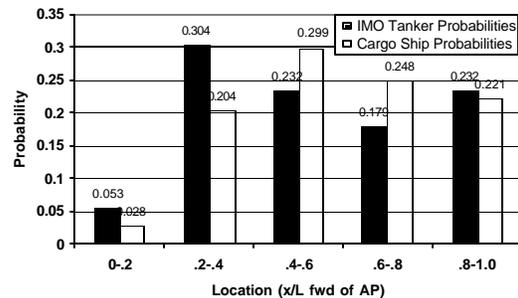


Figure 13. Longitudinal Damage Location

The current IMO pdf for strike longitudinal location specifies a constant value over the entire length of the struck ship, IMO (1995). The constant pdf was chosen for convenience and because of the limited avail-

able data. Figure 13 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.

## RESULTS OF PROBABILISTIC ANALYSES

Probabilistic analyses of the IMO representative single-hull and double-hull vessels (SH100 and DH150) are performed using SIMCOL and 10000 probabilistic striking ship contact scenarios developed from the probabilistic data described in the previous section by Brown (2002). Figure 14 and Figure 15 show the probabilistic damage extent distribution functions (penetration and longitudinal extent of damage) for the SH100 and DH150 compared to the MARPOL 73/78 (IMO 1995) and HARDER Project (Mains 2001) reported probabilistic damage extent distribution functions.

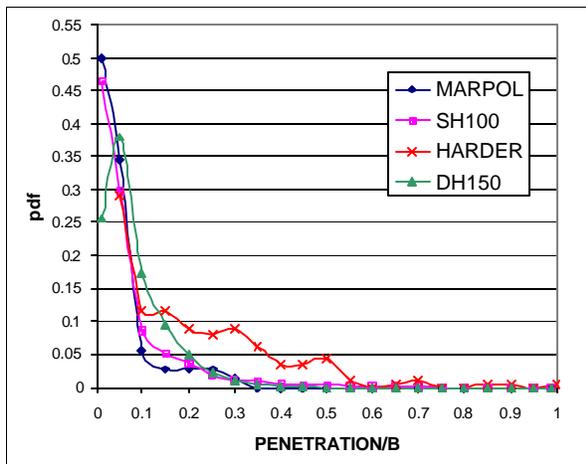


Figure 14. SIMCOL Penetration pdfs for SH100 and DH150 Compared to MARPOL and Harder Data

The MARPOL data was compiled using historical damage statistics for collisions of single hull tankers 30,000 dwt and above. The HARDER data contains the original MARPOL data and a collection of more recent collision events involving both single and double hull vessels. As expected, the SIMCOL SH100 analysis provides a better fit to the MARPOL probability density functions collected for single hull vessels and the more modern DH150 analysis aligns closer to the HARDER data of more recent ship collisions. For either analysis, the maximum variation between SIMCOL results and the MARPOL or HARDER data is less than 10%.

Table 5 provides the mean values of damage penetration, longitudinal extent of damage for both the

SH100 and DH150 probabilistic analyses and the mean values of damage penetration, longitudinal extent of damage for the MARPOL historical damage statistics and the HARDER data.

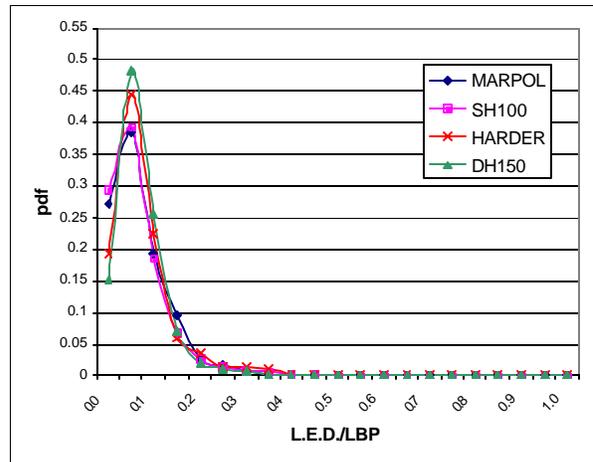


Figure 15. SIMCOL Longitudinal Damage Extent pdfs for SH100 and DH150 Compared to MARPOL and Harder Data

Table 5. Mean Damage Values

Data	Mean Results	
	Penetration/B	LED/LBP
SH100	0.0696	0.0304
MARPOL	0.0502	0.0688
DH150	0.2131	0.0755
HARDER	0.0772	0.0723

## CONCLUSIONS

A simplified model for the prediction of damage in ship collisions (SIMCOL) is presented. Recent improvements to SIMCOL are described including new energy coefficient formulations, consideration of deformable bows, and a plasticity flow membrane approach for calculating absorbed energy in longitudinal deformation of transverse bulkheads and transverse webs.

Validation of SIMCOL is performed by comparing probabilistic penetration and longitudinal damage results from SIMCOL to both MARPOL and HARDER Project damage pdfs. Good agreement is obtained.

Future work can now address the final steps in the progression towards IMO implementation originally proposed by SNAME Ad Hoc Panel #6 (for collision). Although SIMCOL is a simplified code, its worldwide use by working engineers in satisfying regulatory requirements is not practical. A simpler parametric formulation (set of equations) for relating probabilistic damage and ultimately oil outflow or flooding to ship structural design is required. A process for the development of this relationship is illustrated in Figure 16

(Brown 1996 and Brown 2000a). Response surface modeling techniques can be used to establish simple mathematical relationships between damage extent pdfs and (struck) ship structural design variables in the final steps of this process.

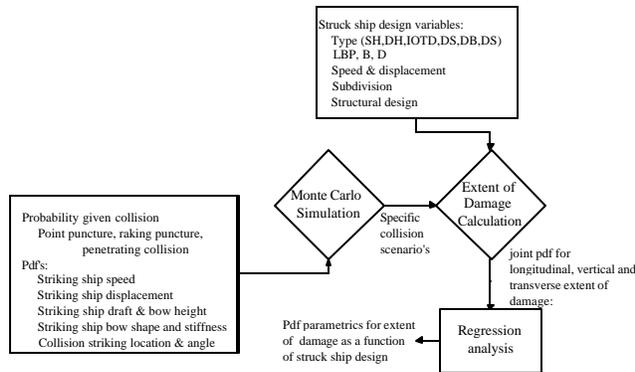


Figure 16. Process to Predict Probabilistic Damage (Brown 2000a)

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