QUANTITATIVE RISK ASSESSMENT FOR COLLISIONS INVOLVING DOUBLE HULL OIL TANKERS

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S A M Youssef, Ship and Offshore Research Institute, Pusan National University, Busan, Korea (*and Marine Engineering Technology Department, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*)**, S T Ince,** Ship and Offshore Research Institute, Pusan National University, Busan, Korea (*and Naval Architecture and Marine Engineering Department, Yildiz Technical University, Istanbul, Turkey*)**, Y S Kim** and **J K Paik**, Ship and Offshore Research Institute, Pusan National University, Busan, Korea, **F Chang**, Lloyd's Register, London, UK and **M S Kim**, Lloyd's Register Asia, Busan, Korea

SUMMARY

In recent decades, the safety of ships at sea has become a major concern of the global maritime industries. Ships are rarely subject to severe accidents during their life cycle. Collision is one of the most hazardous accidents, with potentially serious consequences such as the loss of human life, structural damage and environmental damage, especially if large tankers, LNG and/or nuclear-powered vessels are involved. This study presents a Quantitative Risk Assessment (QRA) for double hull oil tankers that have collided with different types of ships. The methodology used to perform the QRA is based on the International Maritime Organization's (IMO) definition of a Formal Safety Assessment (FSA). Using probabilistic approaches, ship-ship collision scenarios are randomly selected to create a representative sample of all possible scenarios. The collision frequency is then calculated for each scenario. As this is a virtual experiment, the LS-DYNA nonlinear finite element method (NLFEM) is used to predict the structural consequences of each scenario selected. In addition, the environmental consequences are estimated by calculating the size of each scenario's oil spill. To assess the economic consequences, the property and environmental damages are calculated in terms of monetary units. The total risk is then calculated as the sum of the resultant structural and environmental damages. Exceedance curves are established that can be used to define the collision design loads in association with various design criteria.

NOMENCLATURE

$B_i^{(1)}$	Breadth of vessel in ship class *i* in the waterway *1*
$B_j^{(2)}$	Breadth of vessel in ship class *j* in the waterway *2*
C	Collision consequences
D_1	Striking ship depth
D_2	Struck ship depth
D_{ij}	Geometrical collision diameter
d_1	Striking ship draught at time of accident
d_2	Struck ship draught at time of accident
$(d_2/D_2)/(d_1/D_1)$	Relative draught parameter
F	Collision frequency
$L_i^{(1)}$	Length of vessel in ship class *i* in the waterway *1*
$L_j^{(2)}$	Length of vessel in ship class *j* in the waterway *2*
L_2	Struck ship length
l_2	Distance from the foremost point of the struck ship to the impact point
l_2/L_2	Non-dimensional impact location along the struck ship length
PDF	Probability density function
$Q_i^{(1)}$	Traffic flow of ship class *i* in the waterway *1*
$Q_j^{(2)}$	Traffic flow of ship class *j* in the waterway *2*
R_A	Asset risk
R_E	Environmental risk
V_1	Striking ship speed at time of accident
V_2	Struck ship speed at time of accident
V_2 / V_1	Relative speed parameter
$V_i^{(1)}$	Velocity of vessel in ship class *i* in the waterway *1*
$V_j^{(2)}$	Velocity of vessel in ship class *j* in the waterway *2*
V_{ij}	Relative velocity of the two crossing vessels
Δ_1	Striking ship displacement
Δ_2	Struck ship displacement
Δ_2 / Δ_1	Relative displacement parameter
θ	Collision angle
ε_f	Fracture strain rate

1. INTRODUCTION

Despite the efforts made in recent decades to prevent accidents, they still occasionally occur and sometimes have serious consequences for the health and safety of people and for the surrounding environment. Accidents also have financial consequences for local communities close to the accident. Oil tankers may be subject to a variety of accidents such as collision, contact, grounding, fire, explosion and non-accidental structural failure. According to the accident database of the International Tanker Owners Pollution Federation (ITOPF), if acts of war are excluded, groundings and collisions are the most common causes of oil spills from tankers, combined carriers and barges [1]. Figure 1 shows the distribution of spills greater than 700 tonnes by cause for the 1970-2012 period.

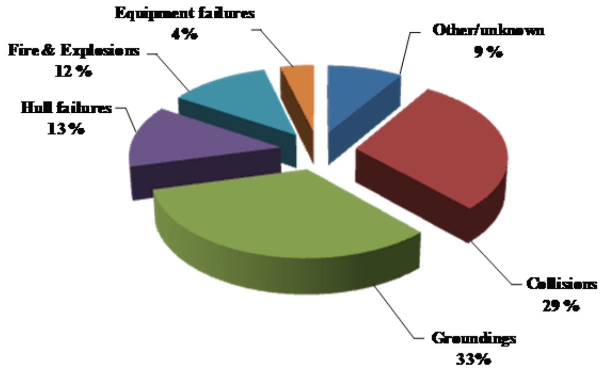

Figure 1: Incidence of oil spills greater than 700 tonnes by cause [1]

Figure 2: VLCC "Atlantic Empress" after collision [2]

Historically, the collision between the Very Large Crude Carrier (VLCC) "Atlantic Empress" and the fully laden supertanker "Aegean Captain" is one of the biggest ship-ship collision accidents. On 19 July 1979, as a result of this accident, the Empress sank after spilling 287,000 metric tonnes of crude oil into the Caribbean Sea and causing 26 fatalities [3]. Figure 2 shows the Atlantic Empress after collision, prior to sinking.

Ship-ship collision is one of the most hazardous accidents, with potentially serious consequences. It is very important to assess the potential risks in terms of both the probability of accidents and their consequences. By helping to develop acceptable design guidelines that satisfy all stakeholders, risk assessment results can be used to reduce the probability of accidents and ultimately minimize or prevent their consequences to ships and to the marine environment.

The main objective of the present study is to perform a Quantitative Risk Assessment (QRA) for double hull oil tankers involved in collisions in which they are struck by another ship; the study follows the International Maritime Organization's (IMO) probabilistically based Formal Safety Assessment procedure (FSA) [4]. The international shipping industry has begun to move from a reactive to a proactive approach to safety through the FSA, which considers risk in conjunction with the marine safety and the protection of the marine environment. Figure 3 presents the procedure for this study.

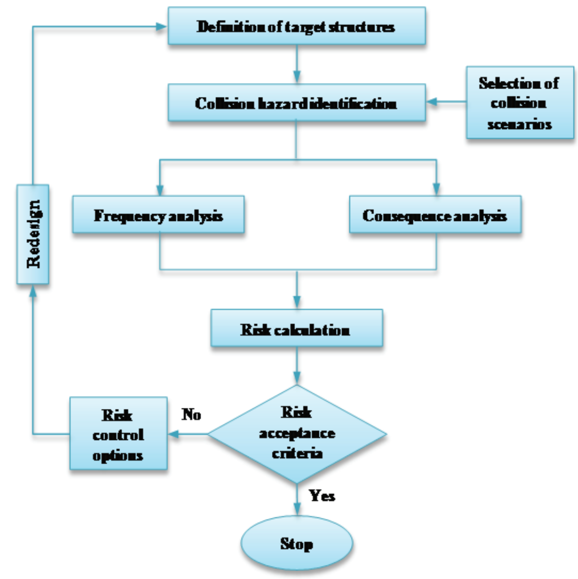

Figure 3: Quantitative collision risk assessment procedure considered in the present study

1.1 PROCEDURES OF THE STUDY

Quantitative risk assessment techniques can scientifically predict the probability of accidents and the extent of damages; this knowledge can in turn reduce the risk related to accidents. This study applies these techniques to a Suezmax-class double hull oil tanker. Thirty scenarios are randomly selected to represent all possible collision events, using a probabilistic method developed by Youssef et al. [5].

Generally, a risk has two components; frequency (i.e., the chance of something occurring) and consequences (i.e., the effects). The crossing collision model allows us to estimate the ship-ship collision accident frequency for each scenario, without taking into consideration a specific water area.

A full scale Suezmax-class double hull oil tanker is modelled as the struck ships, and in each scenario the striking ship has a different size and shape of bow portions. The selected collision scenarios are simulated using the nonlinear structural analysis computer program LS-DYNA [6]. The results of these simulations are used to calculate the structural consequences of the penetration of the striking bow into the struck ship's structure, the energy absorbed by the struck structure, the volume of structural damage and the estimated cost required to repair the damaged structure.

In addition, the size of the likely oil spill is estimated to assess the environmental damage and the corresponding costs of each scenario. Then, the risk is calculated as the product of the frequency and the consequences of the accidents estimated for each scenario. The risks to assets and to the environment are calculated. Based on the calculated risks, exceedance curves are established to define the collision design loads that should be considered during the accidental limit state design (ALS) of double hull oil tankers.

1.2 LITERATURE REVIEW

FSA was a focus of several academic articles before and after its formal adoption by the IMO. Rosqvist and Tuominen [7] considered the issue of confidence in FSA, using three case studies. RINA, the Royal Institution of Naval Architects [8], also published a collection of 15 papers on the subject, covering various aspects of this debate.

In recent years, quantitative risk assessment techniques (QRA) have been applied in different fields in the marine industries such as offshore units, oil and gas production industries, pipeline systems, marine traffic routes, maritime transportation systems and specific types of merchant ships.

Det Norske Veritas (DNV) [9], used a QRA study to estimate the risks associated with the marine transportation of oil, focusing on tankers travelling via established marine routes to and from the open ocean and the Kitimat Terminal in Canada; that study also assessed the risk of incidents occurring during loading and discharge operations.

The International Association of Oil & Gas Producers (OGP) [10], used QRA in a study of ship/installation collision risks in relation to activities within the offshore oil and gas exploration and production industry. In the assessment, they considered the basics of ship collision risk modelling, an overview of historical ship/installation collision information, passing vessel collisions, field related vessel collisions and risk reducing options.

Paik et al. [11] developed a methodology for the quantitative risk assessment of fires and explosions and applied it to a hypothetical floating, production, storage, and offloading unit (FPSO) using probabilistic approaches.

IMO has conducted very interesting FSA studies for container vessels [12], cruise ships [13], crude oil tankers [14] and Liquefied Natural Gas (LNG) carriers [15] that take into consideration collision, contact, grounding, fire, explosion and non-accidental structural failure (NASF) events.

In addition, Lois et al. [16] used the FSA technique in the cruise shipping industry; they considered the effect of human reliability, fire-fighting, and communication.

Cross and Ballesio [17] developed a quantitative risk assessment model for oil tankers that considered the effects of both the Class Society and tanker owners when evaluating risk tradeoffs, new designs, etc.

2. IDENTIFICATION AND MODELLING OF TARGET STRUCTURES

In the finite element analysis, a Suezmax-class double hull oil tanker plays the role of the struck ship. An as-built ship structural condition is assumed with as-built thicknesses that are free from any impairment. Table 1 indicates the principal dimensions of the object ship. The finite element model of the Suezmax-class double hull oil tanker is shown in Figure 4.

Table 1: Principal particulars of a Suezmax-class double hull oil tanker

Items	Dimension
Length overall (*m*)	272.0
Length between perpendiculars (*m*)	264.0
Moulded breadth (*m*)	48.0
Moulded depth (*m*)	23.7
Design draft (moulded) (*m*)	16.0
Deadweight (*DWT*)	157,500
Double side width (*m*)	2.64
Double bottom height (*m*)	2.64
Transverse frame spacing (*m*)	4.8

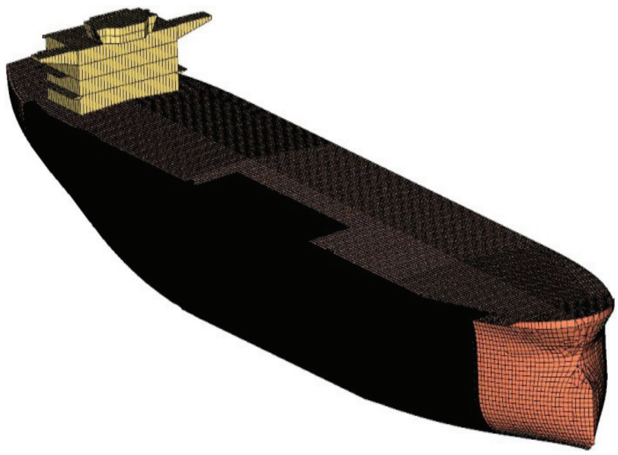

Figure 4: Struck ship finite element model

In this study, all of the panels and support members (i.e., webs and flanges) of the struck ship construction are modelled with Type 24-Elastic/Plastic Isotropic with piecewise linear plasticity; therefore, the strain rate effects and complete material fracture are measured using the Cowper-Symonds model. The fracture strain value ε_f = 0.1 is used in this study because it is commonly used in the material industry [18-23]. For the purpose of the current calculations, the bow structures of the striking ships are modelled and dealt with as having rigid stiffness, such that all of the collision energy will be absorbed by the struck ship structure. Hence, the use of an infinitely stiff striking bow can be accepted [24]. In practice, this scenario is relevant if the bow of the striking ship is relatively much stronger than the side of the struck ship [25].

The mesh density, element shape and mesh size are important, as the development of a fracture process starts at the uniform deformation and then extends over the whole component to a local necking in a very small area where extremely large strain values occur [26].

It is reasonable to focus only on the part of the collided structure that is close to the contact region.Therefore, a 200 mm element size is used in the vicinity of the collision damage (i.e., along the ship side plus parts of the deck and bottom) for all of the hull thicknesses, and coarse mesh is used in other areas to achieve acceptable computational time, as shown in Figure 4. Same mesh in the contact region was used before in the Ship Structures Committee Report SSC-437 [21].

The effect of the surrounding seawater is assessed using a virtual added mass to the struck ship that mimics surge, sway and yaw [21, 27]; this mass is calculated using a ship motions sub-program called MCOL [28]. This program is incorporated into the LS-DYNA program that determines the buoyancy forces using a linear restoring force approximation [28].

3. HAZARD IDENTIFICATION AND SHIP-SHIP COLLISION SCENARIOS SELECTION

Youssef et al. [5] developed an innovative method using probabilistic approaches to select a representative sample of possible ship-ship collision accident scenarios; the resulting sample is representative of all possible scenarios on the basis of random variables. Each scenario is defined by a number of the parameters that govern ship-ship collision accidents. Each parameter is a random variable with its own probability density distribution (PDF). As it is not practical to consider every possible scenario, the method proposed in Youssef et al. [5] is used in this study to select 30 scenarios. The striking ship type is considered one of the random variables. More details are available in Ref. [5]. The PDFs used are shown in Figure A.1 and the selected scenarios are listed in Table A.1.

As collisions are more common when vessels are sailing in well-trafficked routes such as ports, canals, rivers and narrow passages, it is assumed in the model that the struck ship speed is equal to two knots. Furthermore, the loading condition is assumed to be fully laden. The struck ship particulars (i.e., the target structure) are known and the striking ship particulars are based on the 30 selected collision cases given in Table A.1. The bow shape of the striking ship is determined for each case using the bow shape model produced by Lützen [29]. A sample of the striking bow portion's geometric model used in this study is shown in Figure 5.

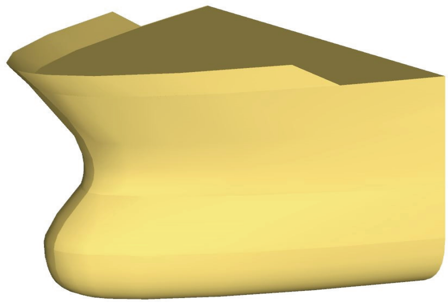

Figure 5: Striking ship bow model: Bulk carrier

4. COLLISION FREQUENCY ANALYSIS

The ship collision and grounding frequency models were initially proposed by Fujii and Tanaka [30] and Macduff [31], who defined the probability of an accident as

$$P = N_a \times P_c \quad . \qquad (1)$$

Given equation (1), the collision probability P can be estimated by two independent probabilities: the geometrical probability, N_a, (i.e., the number of collision candidates if no aversive measures are made by assuming blind navigator), which is dependent of the geometric parameters of the water area, vessel size, traffic volume, vessel speed etc.; and causation probability, P_c, which can be defined as the fraction of the accident candidates resulting in an accident or the probability of failing to avoid the accident while on a collision course.

Several models have been developed by researchers to estimate the ship-ship collision geometrical probability; for example, Fujii and Tanaka's model [30], Macduff's model [31], Pedersen's model [32], Roeleven et al. model [33] and Kaneko's model [34]. In this study, Pedersen's model [32] is used to calculate the geometrical probability of a vessel encountering one of the accidental scenarios. Pedersen defined the geometrical probability as the number of possible accidents per a unit of time, N_a. The model considers collisions the intersection of two waterways, as illustrated in Figure 6.

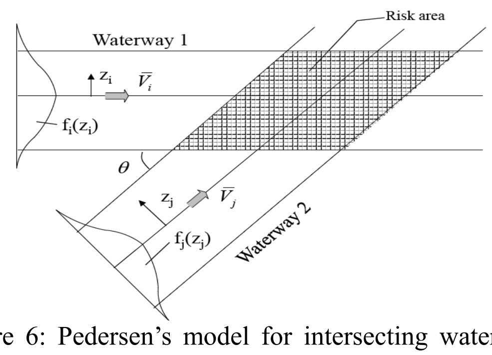

Figure 6: Pedersen's model for intersecting waterways, with a risk area for ship-ship collisions [32]

The ship in waterway 1 approaches the ship in waterway 2 with a relative velocity that can be described in equation (2),

$$V_{ij} = \sqrt{(V_i^{(1)})^2 + (V_j^{(2)})^2 - 2V_i^{(1)}V_j^{(2)} cos\theta} \, . \qquad (2)$$

Pedersen [32] defined the geometrical collision diameter (see Figure 7) in the following equation,

$$D_{ij} = \frac{L_i^{(1)}V_j^{(2)} + L_j^{(2)}V_i^{(1)}}{V_{ij}} sin\theta + B_j^{(2)} \left\{1 - \left(sin\theta \frac{V_i^{(1)}}{V_{ij}}\right)^2\right\}^{\frac{1}{2}} + B_i^{(2)} \left\{1 - \left(sin\theta \frac{V_j^{(2)}}{V_{ij}}\right)^2\right\}^{\frac{1}{2}} \, . \qquad (3)$$

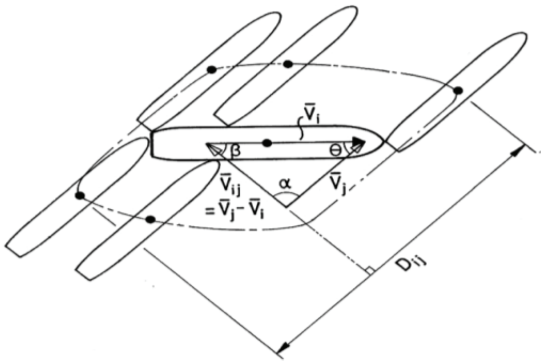

Figure 7: Definition of geometrical collision diameter [32]

Friis-Hansen et al. [35] conducted an analysis of grounding and ship-ship collision rates and the associated damage caused by collisions for specific geographical areas. In their study, the crossing angle θ was limited to an interval of [10˚; 170˚] because if it goes to zero, the length of the crossing goes to infinity. Based on this assumption and Pedersen's model, the number of crossing collision candidates, N_a, is determined as indicated in equation (4). This limitation of the collision angle is found to match the current studied scenarios (see Table A.1).

$$N_G^{crossing} = \sum_{i,j} \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} D_{ij} V_{ij} \frac{1}{sin\theta} \qquad \text{for } 10° < |\theta| < 170° \qquad (4)$$

Generally, Pedersen's model estimates the collision probability without relying on statistics and does not take into account the specific characteristics of the studied area. This model has been used in many recent publications, for example in Refs. [35-43]. Therefore, Pedersen's model is used in this study.

Our study assumes that several types of ships passing through waterway 1 will strike the model tanker ship (i.e., the target ship), which is passing through waterway 2. The relative velocity of the vessels, V_{ij}, the geometrical collision diameter, D_{ij} and the number of collision candidates, N_a, are calculated using equations (2), (3) and (4), respectively.

As indicated in equation (4), the traffic flow(s) Q (i.e., number of ships per unit time in each waterway) are calculated after investigating various world-wide fleet statistics. It is found that the number of world-wide fleets as Shipping Intelligence Network of Clarkson's database (SINC) [44]; considering all registered fleets excluding the fishing vessels and yachts, are about 56% of the IMO's database [45] in which all propelled sea-going merchant ships of no less than 100 GT are considered. In this study, it is assumed that the number of fleets as Clarkson's database will pass through virtual waterways 1 and 2 per year (about 160 passing vessels per day). The types of ships that are classified in Clarkson's database are grouped into six categories as per the types of ships classification described in Youssef et al. [5] and indicated in the second column of Table A.1.

The causation probability P_c (see equation (1)) can be estimated on the basis of available accident data collected in various locations and then transformed to the area of interest [46]. Various factors govern P_c, such as vessel type, manoeuvrability, weather conditions, navigators, navigation equipment, traffic perception, avoidance actions and communication [32, 47]. The causation probability values for crossing encounters in the literature have varied between 1.0×10^{-5} and 6.0×10^{-4}. Kujala et al. [47] summarised in a single table the various values of P_c from different research publications up to 2009. In Table A.2, this table is updated to cover most of the research on estimating the causation probability for cross collisions for the 1974 to 2012 period [31, 36-40, 48-51].

Using this research, Rosqvist et al. [36] calculated P_c to be equal to 5.1×10^{-4}; their study focused on the risk analysis of oil, chemical or gas tankers colliding with passenger vessels, freight vessels, or with each other, which match the scenarios in this study.

Therefore, Rosqvist's causation probability value is used in this study. The collision frequency $F_{Ship\text{-}Tanker}$ (i.e., the number of accidents per ship-year) is calculated by multiplying the number of collision candidates, N_a, with the related causation factor P_c for each collision scenario individually; the results are shown in Table A.3. Based on the current calculations, the total frequency is 3.09×10^{-3} per ship-year.

However, Eliopoulou and Papanikolaou [52] calculated the frequencies of various accidents for different sizes of tankers based on historical databases as part of the Pollution Prevention and Control project (POP&C) conducted at the National Technical University of Athens (NTUA). Loer and Hamann [53] used their analysis in the SAFEDOR project. Their analysis indicated that the frequency of Suezmax-class tankers involved in collision accidents is 3.05×10^{-3} per ship-year; thus, there is relatively good agreement between the frequency model used in this study and the historical data for Suezmax-class tankers.

5. COLLISION CONSEQUENCE ANALYSIS

5.1 COLLISION SIMULATIONS

To predict the consequences of the selected ship-ship collision scenarios (see section 3), numerical simulations using the nonlinear explicit finite element software LS-DYNA are conducted. The results of these numerical simulations can be considered virtual experimental data that is more cost effective than experimental tests using real structures [54, 55]. Figure 8 shows an example of a setup for collision scenario 15, which has the striking bow portion of a Bulk carrier strike the struck ship finite element model.

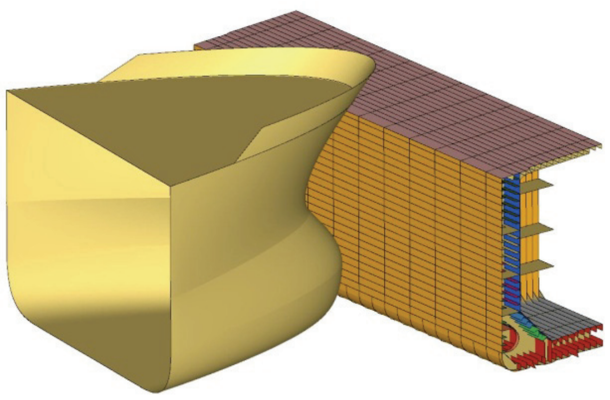

Figure 8: Example of a ship-ship collision finite element simulation

5.2 STRUCTURAL CONSEQUENCES

For the structural consequence analysis of a struck ship, it is useful to assess the internal mechanics of the damaged ship. Based on the collision simulation results generated by LS-DYNA, the transverse extent of the damage (i.e., penetration) to the struck ship structure and the energy absorbed by the struck ship structure is calculated for each collision scenario. For example, Figures 9 and 10 show the resultant collision force versus penetration and the absorbed energy versus penetration, respectively, for scenario 15.

Paik et al. [56] developed a method to determine a direct correlation between the absorbed energy capability and the damaged volume of the collided tanker's side structure. This method differs from the original Minorsky method [57] in its definition of the damaged volume. Paik et al. defined the damage volume as the space of the damaged side structure of the colliding vessel that approximately corresponds to the volume of the penetrated bow, whereas the original Minorsky method used the total volume of the affected structural members themselves. Paik et al. argued that the correlation method (empirically) accommodates the effects of side stringers, transverse webs and inner shell as well as outer shell and deck plate. Figure 11 shows a schematic drawing illustrating the definition of the damaged (shaded) volume using the method of Paik et al.

In the present study, the concept of Paik et al. [56] to measure the structural damage volume of the struck ship structure is applied. Table A.4 shows the values of the resultant damage (i.e., penetration), absorbed energy and the damage volume for each collision scenario based on the collision simulation results generated by LS-DYNA.

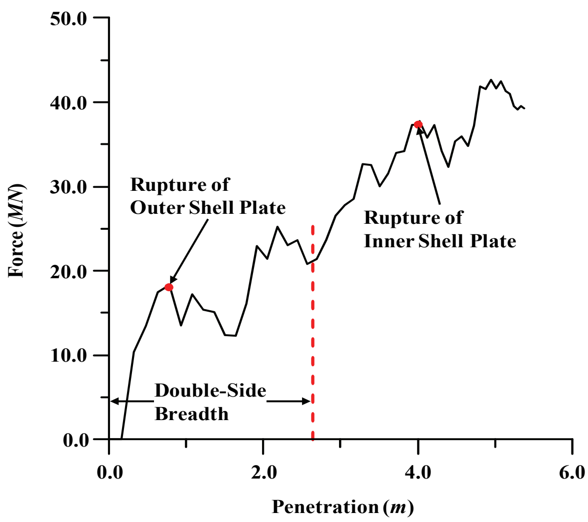

Figure 9: Collision resultant force versus penetration

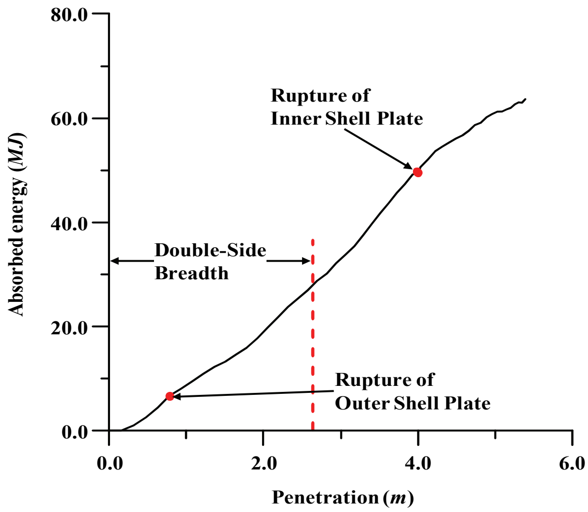

Figure 10: Collision energy absorption versus penetration

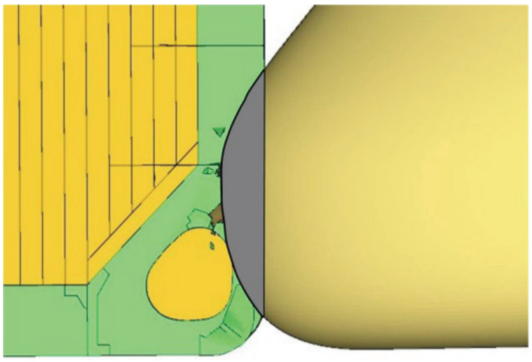

Figure 11: Definition of the structural damaged volume of the struck ship

5.3 ENVIRONMENTAL CONSEQUENCES

In addition to understanding the structural damage caused by a collision, tanker designers are also interested in obtaining a measure of the resultant environmental damage. The consequences of an oil spill depend on season, the location of the accident, the amount of spilled oil and its quality. In this study, the potential environmental damage is calculated in terms of the amount of oil spilled after the inner hull of the struck ship is breached. IMO [58] has developed guidelines for the oil outflow performance of double hull tankers, which are based on the following set of assumptions:

- an intact load condition shall be developed with the vessel at its maximum assigned load line with zero trim and heel;
- all of the cargo oil tanks shall be assumed to be filled to 98% of their capacities;
- all of the cargo oil shall be taken at a homogeneous density; and
- the entire contents of all of the damaged cargo oil tanks should be assumed to be spilled into the sea.

Given the above assumptions, the size of the potential oil spill is calculated in tonnes for each scenario in which the inner hull is breached; the cargo oil density is assumed to be 0.9 t/m^3 [58, 59]. Based on the collision simulation results, the inner hull is breached (i.e., oil outflow occurs) in 12 cases and the inner hull remains intact (i.e., zero outflow) in 18 cases. Table A.4 shows the amount of oil outflow in tonnes for each collision scenario. It should be noted that the amounts of spilled oil in scenarios 11 and 18 are larger than in the other scenarios. In these scenarios, the striking bow hit the side of the struck ship where the transverse bulkheads are located, thus rupturing the two cargo holds at the same time.

5.4 ECONOMIC CONSEQUENCES

Clearly, ship collisions have financial costs in addition to the loss of income and damage to the reputations of the shipping companies. In this regard, it is important to estimate the potential sequenced expenses related to the collisions' property and environmental damages.

5.4 (a) Damaged Property Repair Cost

Repair costs depend on damage location, damage size, material type, repair yard, etc. [37]. The property damage costs to the collided ship may include the amount of replaced steel, reparation costs of equipment and machinery, docking costs and the damaged cargo costs.
This study considers only the steel repair costs that can be estimated using the amount of ruptured steel in a unit tonne. The costs of repair can be calculated from the extent of the damage, assuming a steel density of 7.85 t/m^3 and a given material grade. For unscheduled repairs, such as those caused by incidents, shipowners and operators do not have the opportunity to choose the lowest cost yards in preferred locations. In the case of severe damages, they have to use the nearest shipyards (i.e., close to the location of the accident) to save the struck ship, regardless of the cost or quality of those services.

A study by Guarin et al. [60] that discussed risk modelling and cost-effectiveness analysis for RoPax ships, assumed that the price of steelwork in the construction process is 6,000 EUR per tonne (around 8,000 USD). In fact, the cost of steelwork in a repairing process is higher than in a new-building process, as the former job includes some additional work such as cleaning the areas and tanks around the damaged parts before starting high temperature jobs, determining the damaged area to be renewed based on the thickness measurement process, cutting the damaged parts and preparing the area where the new plates will be inserted. Therefore, this study assumes that the steelwork cost of a typical steel renewal job (i.e., full repair process) including cutting, building, and fitting of the damaged area, costs twice as much as in a new-building process (i.e., 16,000 USD).

Although the long-term trend in raw material prices is upwards, the cost of materials is only one of the costs; the other costs include equipment costs, energy use, labour costs (about 20% of the overall costs [61]), material transportation and manufacturing costs. Based on the current steel market, the steel plate price used in the shipbuilding industry is between 650 and 1,300 USD per tonne; the price varies depending on the place of origin, the quality and the steel grade. Overall, the cost of the steel represents about 8% of the full repair costs.

5.4 (b) Environmental Damage Costs

It is reasonable that most researchers directly relate the amount of oil spilled to the cost of the oil spills [59]. In the last decade, some studies have been carried out to estimate the cost of oil spills according to regression models based on large databases of oil spill incidents. For more details about the above studies, see Refs. [59, 62, 63]. Recently, Psarros et al. [63] proposed a relationship between the total unit cost and the amount of oil spilled according to a regression model based on a statistical analysis of the available data for oil spill costs (185 oil spill incidents in the 1970-2008 period),

$$\text{Total unit cost} = \frac{61{,}115}{w^{0.3528}} \text{ USD per tonne} \qquad (5)$$

where, w is the weight of the oil spill in tonnes. Based on equation (5), the total cost of the oil spill consists of clean-up expenditures (i.e., covering the removal of oil) and claims paid for compensation (i.e., property damage of economic users such as fisheries, tourism and recreational users). In this study, equation (5), as developed by Psarros et al. [63], is used to calculate the cost of the environmental damage in each scenario.

6. RISK CALCULATION

Practically, risk (R) can be defined as the product of frequency (F) and consequence (C), as follows [64]:

$$R = F \times C \,. \qquad (6)$$

To examine multiple types of scenarios, equation (6) can be expanded to cover all potential accident sequences, as follows [64, 65]:

$$R = \sum_i F_i \times C_i \;, \qquad (7)$$

where F_i is the frequency of the ith accidental scenario and C_i is the consequence of the ith accidental scenario. In this study, risk is calculated in two dimensions (i.e., risk elements); risk to assets and to the environment.

6.1 ASSET RISK

Risk to assets refers to possible damage to equipment and ship structures, which is usually expressed as a value of material damage. Asset risk can be defined as follows [64, 65]:

$$R_A = \sum_i F_i \times d_i \;, \qquad (8)$$

where F_i is the frequency of accident per ship-year of the ith accidental scenario and d_i is the extent of damage, which may be expressed in terms of the resultant penetration or damaged structural volume in the struck ship structure of the ith accidental scenario. In this study, equation (8) is used to measure the asset risk at which d_i is considered to represent the resultant penetration of the striking bow into the struck ship's structure. Table A.5 shows the calculated asset risk for each collision scenario as a unit of penetration per ship-year. The authors realize that the proposed unit for R_A is not informative in any context outside of the specific application of the presented study. However, it may be useful for creating collision design loads and some guidelines for preventing collisions.

To measure the asset risk in terms of the resultant structural damage volume, d_i (see equation (8)) is considered to represent the resultant damage volume of the struck ship's structure. Then, the asset risk can be presented as a unit of damaged volume per ship-year (see Table A.6).

Based on the damaged property repair cost analysis (see section 5.4 (a)), the asset risk, R_A, is calculated and presented in monetary units (USD per ship-year) for each collision scenario, as indicated in Table A.7. The total asset risk is found to be 1,440 USD per ship-year. In a real situation, the total asset risk is definitely higher than the calculated one in this study. Additional costs can come from the following sources:

- salvage operations,
- temporary repair costs before starting the permanent repairs or voyage costs to the shipyard,
- cost of cargo losses,
- renewal of the damaged pipes,
- damaged deck equipment,
- painting,
- docking and undocking operations,
- subsequent layover in dock per day,
- tank cleaning and gas free works,
- surveying by ship classification society representative,
- waiting times before docking, and
- other services.

6.2 ENVIRONMENTAL RISK

The quantified risk to the environment is usually expressed as the expected value of the amount of oil spilled per ship-year and can be defined by an equation similar to equation (8),

$$R_E = \sum_i F_i \times Q_i \;, \qquad (9)$$

where Q_i is the amount spilled during the ith accidental scenario in which the inner hull is breached. Environmental risk, R_E, is commonly measured in units of tonnes of oil spilled per ship-year, and is referred to in the literature as pollution risk [14, 65, 66]. In this study, equation (9) is used to measure the environmental risk, R_E, in terms of the expected amount of oil spilled per ship-year.

Table A.8 shows the measured environmental risk for each collision scenario in which the inner hull is breached; the risk is expressed in units of expected oil spilled per ship-year. The total environmental risk is 18 tonnes per ship-year. Interestingly, Eliopoulou and Papanikolaou [52] calculated the spillage rate of various accidents and different sizes of tankers based on historical databases and found that the spillage rate of Suezmax-class tankers involved in collision accidents after the US Oil Pollution Act (OPA90) is 20 tonnes per ship-year, which is in relatively good agreement with the current study. Loer and Hamann [53] used Eliopoulou and Papanikolaou's data in the SAFEDOR project.

Based on the environmental damage cost analysis (see section 5.4 (b)), the environmental risk, R_E, is calculated and presented in monetary units (USD per ship-year) for each collision scenario using equations (5) and (9), as indicated in Table A.9. The total environmental risk is 36,300 USD per ship-year.

7. SHIP-SHIP COLLISION DESIGN LOADS

An important step in the collision risk assessment is the determination of the collision design loads. Currently many industries are trying to generate diagrams of exceedance probability. In the current study, a probabilistic approach is used to establish the exceedance diagrams for the exceedance probability of collision versus the resultant penetration, damaged volume, absorbed energy and the amount of spilled oil.

Exceedance probability is defined on the basis of the cumulative frequency distribution of ship-ship collisions in conjunction with the characteristics of the collision loads identified in the LS-DYNA simulations.

To examine the accidental limit states associated with ship collisions, Paik et al. [23] identified three types of design criteria that are associated with damage to the struck side structure:

- rupture of outer side shell plate,
- penetration of the striking bow until the location of inner side shell plate equivalent to double-side breadth, and
- rupture of inner side shell plate.

In this study, the structural consequences for each scenario are evaluated with respect to the aforementioned three criteria. Figures 12 and 13 show the exceedance curves in terms of the exceedance of collision frequency versus the resultant penetration and the absorbed energy, respectively for the three design criteria. In addition, the exceedance of collision frequency versus the resultant structural damage volume are conducted and shown in Figure 14.

The exceedance diagrams can be used to define the ship-ship collision loads that can then be used as inputs into the structural design of double hull oil tankers. For example, if the designer decides to use 0.001 per ship-year as an exceedance value (i.e., the maximum tolerable risk), Figure 12 can be used to determine the approximate double side width that should be equal to or more than the 2.7 m at which the inner side shell plates start to rupture (i.e., oil outflow will occur). This example's recommended double side width (2.7 m) is close to the one currently used in the modelled Suezmax-class double hull oil tanker. This suggests that the current methods used in ship design are acceptable and reliable. This study also finds the exceedance curve of collision frequency versus the estimated steel repair cost analysis, shown in Figure 15.

Figure 16 represents the exceedance of collision frequency versus the amount of spilled oil; the diagram can be called an F-T diagram, which illustrates the cumulative oil spill size and frequency. This diagram may be useful in creating environmental risk evaluation criteria and guidelines such as developing an "as low as reasonably practical" (ALARP) area. Sames and Hamann [67] developed three approaches for setting an ALARP area to evaluate environmental risk using an F-T diagram. This study also determines the exceedance of collision frequency versus the estimated total oil spill costs, shown in Figure 17.

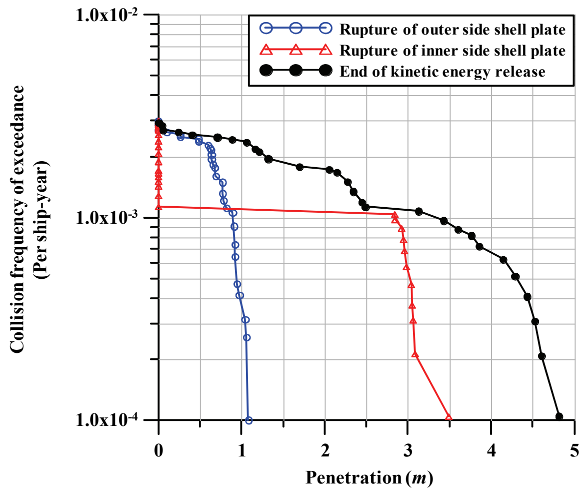

Figure 12: Collision exceedance curves in terms of exceedance of collision frequency versus penetration

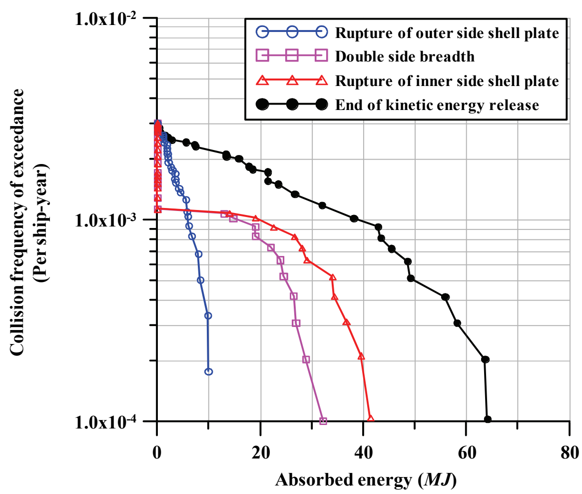

Figure 13: Collision exceedance curve in terms of exceedance of collision frequency versus absorbed energy

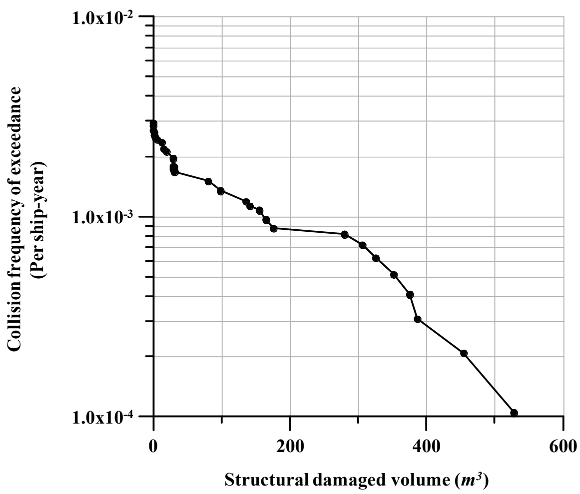

Figure 14: Collision exceedance curve in terms of exceedance of collision frequency versus volume of the structural damage

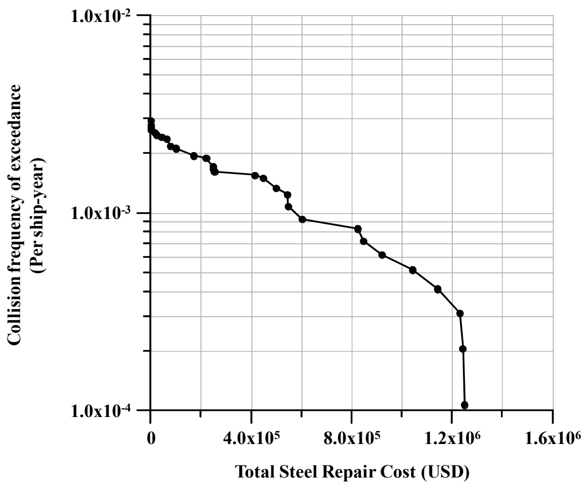

Figure 15: Collision exceedance curve in terms of exceedance of collision frequency versus the corresponding steel repair cost

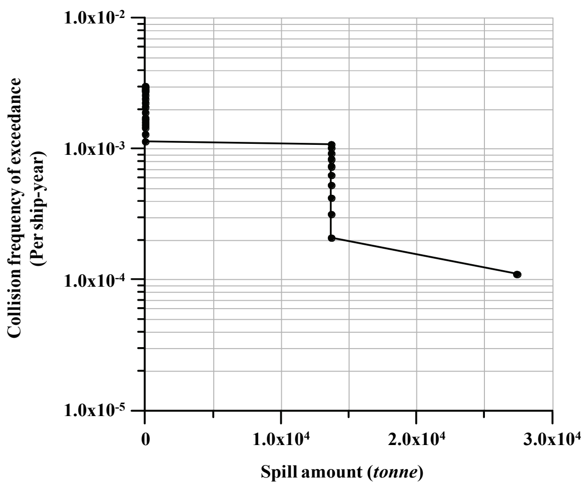

Figure 16: Collision exceedance curve in terms of exceedance of collision frequency versus the amount of spilled oil

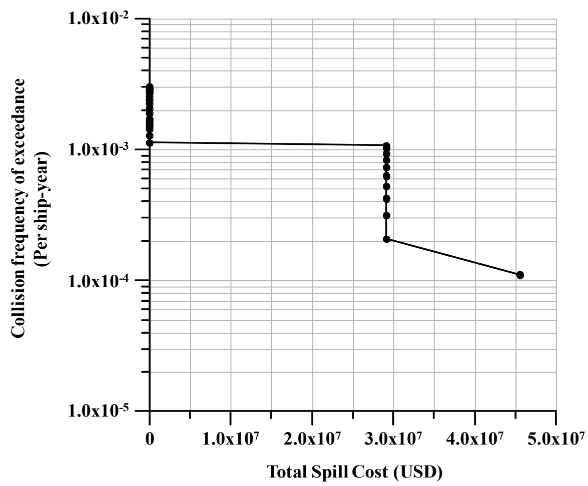

Figure 17: Collision exceedance curve in terms of exceedance of collision frequency versus the corresponding total oil spill cost

8. CONCLUSIONS

This study performed a quantitative assessment of ship-ship collision risk. A number of scenarios in which a full-scale Suezmax-class double hull oil tanker encountered different types of ships were considered. Following previous studies by the authors, probabilistic methods were used to select and define a limited number of probable collision scenarios using various random variables that affect accidents.

To estimate the frequency of accidents per ship-year for each scenario without taking into consideration a specific water area, the crossing collision model was used in conjunction with Pedersen's model [32]. The resulting total collision frequency analysis had relatively good agreement with the historical data for Suezmax-class tankers involved in collision accidents. Furthermore, it can be concluded that the collision frequency model of Pedersen is still reliable for different areas even for which statistics may not be available.

Numerical simulations using the nonlinear explicit finite element software LS-DYNA were conducted for each scenario to calculate the structural consequences in terms of the resultant penetration, absorbed energy, damage volume, and to evaluate the size of the oil spill.

As a product of frequency and consequence, the risk was calculated in two dimensions; risk to assets and to the environment. The authors realize that the proposed units of asset risk are not informative in any context apart from the specific application of this study. Therefore, the asset and environmental risks were presented in monetary units showing the economic losses caused by ship collision accidents; these units are understandable to the shipowners and operators.

Exceedance diagrams were established using a probabilistic approach. Collision design loads were developed in association with various collision design criteria using the exceedance diagram; these collision design loads should be useful in identifying the safety level against collision accidents in the early stages of ship structural design for double hull oil tankers. In addition, the developed diagram (F-T diagram), which represents the exceedance of collision frequency versus the amount of spilled oil, should be useful for developing environmental risk acceptance criteria and guidelines, such as developing as low as reasonably practical (ALARP) area.

9. ACKNOWLEDGEMENTS

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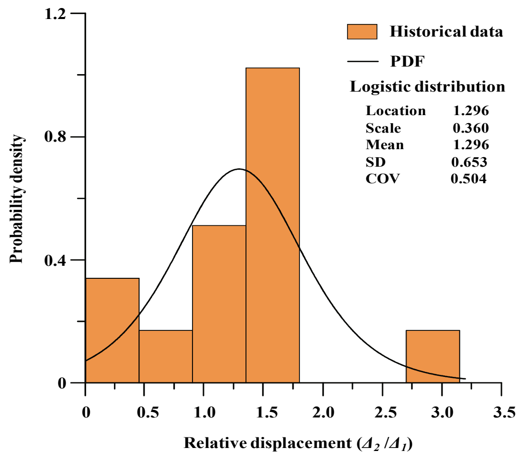
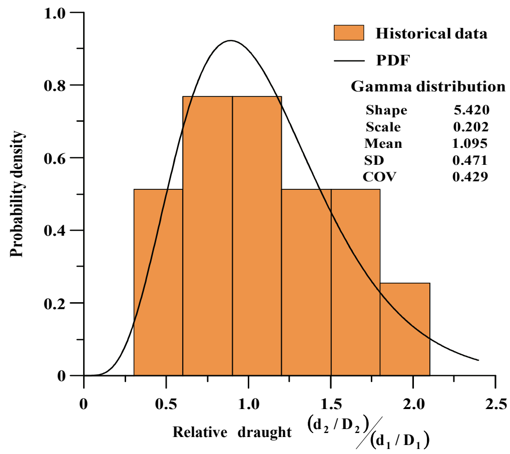
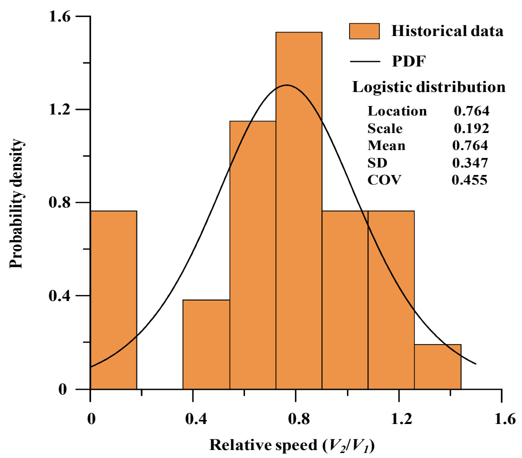
APPENDIX



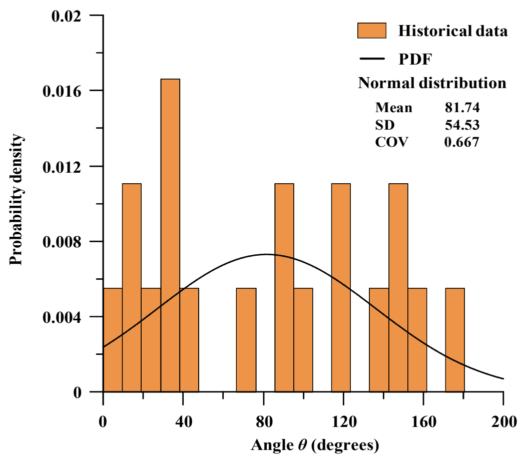
(a) PDF for relative displacement parameter



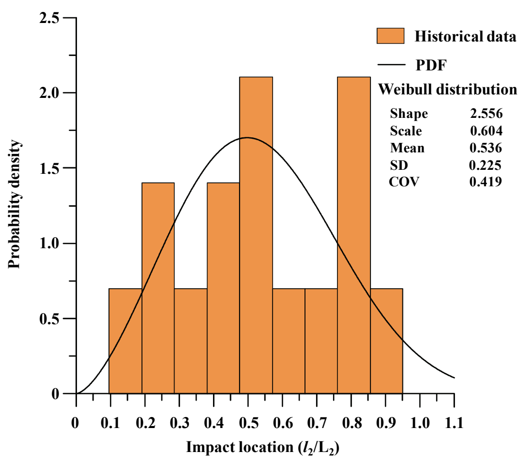
(d) PDF for relative draught parameter



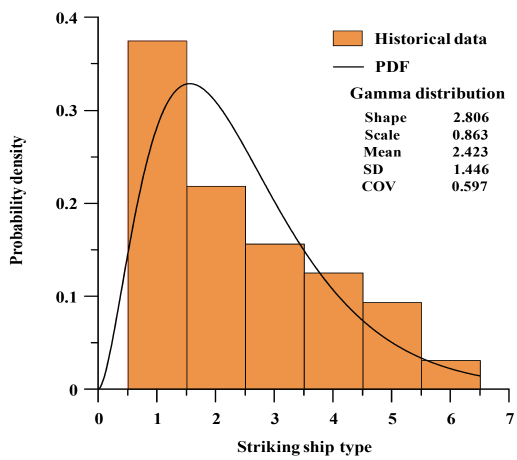
(b) Selected PDF for relative speed parameter



(e) PDF for collision angle parameter



(c) PDF for impact location parameter



(f) PDF for striking ship type parameter

Figure A.1: Probability density functions (PDF) versus collision parameters

Table A.1: Selected ship-ship collision scenarios

Scenario	Striking ship type	Δ_2 / Δ_1	V_2 / V_1	$(d_2 / D_2) / (d_1 / D_1)$	l_2/L_2	θ [°]
1	Container	0.875	0.332	0.910	0.145	10.0
2	Container	0.924	0.389	0.930	0.200	18.5
3	Container	0.969	0.435	0.950	0.238	25.8
4	Container	1.012	0.475	0.970	0.269	32.2
5	Container	1.054	0.510	0.990	0.296	37.9
6	Container	1.094	0.541	1.010	0.321	43.3
7	Container	1.132	0.571	1.031	0.343	48.2
8	Container	1.170	0.598	1.052	0.365	52.9
9	Bulk carrier	1.207	0.623	1.073	0.385	57.4
10	Bulk carrier	1.244	0.648	1.094	0.405	61.8
11	Bulk carrier	1.280	0.671	1.116	0.423	66.0
12	Bulk carrier	1.317	0.694	1.139	0.442	70.1
13	Bulk carrier	1.353	0.717	1.162	0.460	74.2
14	Bulk carrier	1.390	0.739	1.186	0.478	78.2
15	Bulk carrier	1.427	0.761	1.210	0.496	82.2
16	Bulk carrier	1.465	0.783	1.235	0.514	86.2
17	Bulk carrier	1.504	0.805	1.261	0.532	90.2
18	Bulk carrier	1.544	0.827	1.289	0.550	94.3
19	Tanker	1.585	0.850	1.317	0.568	98.5
20	Tanker	1.629	0.873	1.347	0.587	102.7
21	Tanker	1.675	0.898	1.378	0.606	107.1
22	Tanker	1.724	0.923	1.411	0.626	111.6
23	Tanker	1.776	0.950	1.446	0.647	116.4
24	Tanker	1.834	0.978	1.483	0.669	121.4
25	Cargo ship	1.899	1.009	1.524	0.692	126.9
26	Cargo ship	1.972	1.043	1.568	0.717	132.8
27	Cargo ship	2.059	1.081	1.617	0.744	139.3
28	Cargo ship	2.166	1.125	1.672	0.775	146.9
29	Other	2.311	1.179	1.735	0.810	156.0
30	Passenger	2.548	1.248	1.809	0.852	168.0

Table A.2: Summary of causation probability estimates for crossing ships

Value of P_c	Sea area	References that use the value	Remarks
1.11×10^{-4}	Dover Strait	Macduff 1974 [31]	Without Traffic Separation Scheme (TSS)
9.50×10^{-5}	Dover Strait	Macduff 1974 [31]	With Traffic Separation Scheme (TSS)
1.20×10^{-4}	Japanese straits	Fujii et al. 1983 [48]	
1.29×10^{-4}	Japanese straits	Fujii & Mizuki 1998 [39]	
1.30×10^{-4}	Spain-Canary Islands	Otto et al. 2002 [37] and Pedersen & Zhang 1999 [38]	Without taking into account the specific characteristics of the studied area [51]
8.48×10^{-5}	North Sea	Fowler & Sørgård 2000 [40]	In good visibility
6.83×10^{-5}	North Sea	Fowler & Sørgård 2000 [40]	In good visibility within Vessel Traffic Service (VTS) zone
5.80×10^{-4}	North Sea	Fowler & Sørgård 2000 [40]	In poor visibility
4.64×10^{-4}	North Sea	Fowler & Sørgård 2000 [40]	In poor visibility within Vessel Traffic Service (VTS zone)
5.10×10^{-4} ~ 6.00×10^{-4}	Gulf of Finland	Rosqvist et al. 2002 [36]	With mandatory reporting system, Vessel Traffic Service (VTS) and Automatic Identification System (AIS); at least one of the colliding vessels is a tanker
2.70×10^{-4}	Gulf of Finland	Hänninen and Kujala 2009 [49]	
1.04×10^{-5}	Gulf of Finland	Montewka et al. 2012 [50]	Based on the minimum distance to collision (MDTC) - approach

Table A.3: Collision frequencies (accidents per ship-year) for the thirty selected scenarios

Scenario	Frequency	Scenario	Frequency	Scenario	Frequency
1	8.44×10^{-5}	**11**	9.74×10^{-5}	**21**	1.63×10^{-4}
2	6.49×10^{-5}	**12**	9.91×10^{-5}	**22**	1.67×10^{-4}
3	5.97×10^{-5}	**13**	1.01×10^{-4}	**23**	1.72×10^{-4}
4	5.75×10^{-5}	**14**	1.03×10^{-4}	**24**	1.78×10^{-4}
5	5.66×10^{-5}	**15**	1.05×10^{-4}	**25**	6.43×10^{-5}
6	5.61×10^{-5}	**16**	1.06×10^{-4}	**26**	6.73×10^{-5}
7	5.59×10^{-5}	**17**	1.08×10^{-4}	**27**	7.14×10^{-5}
8	5.59×10^{-5}	**18**	1.10×10^{-4}	**28**	7.78×10^{-5}
9	9.37×10^{-5}	**19**	1.56×10^{-4}	**29**	1.50×10^{-4}
10	9.56×10^{-5}	**20**	1.59×10^{-4}	**30**	1.57×10^{-4}

Table A.4: Collision consequences for the thirty selected scenarios

Scenario	Penetration (*m*)	Absorbed Energy (*MJ*)	Damaged volume (m^3)	Size of Oil spill (*tonnes*)
1	0.040	0.356	0.001	Zero outflow
2	0.242	1.989	0.723	Zero outflow
3	1.214	7.175	15.379	Zero outflow
4	2.144	13.417	28.797	Zero outflow
5	2.054	15.812	29.522	Zero outflow
6	2.486	18.451	30.791	Zero outflow
7	3.124	21.446	80.269	13698.135
8	3.763	23.513	135.347	13698.135
9	3.603	42.855	176.211	13698.135
10	3.857	45.458	306.402	13698.135
11	4.147	48.620	351.879	27396.270
12	4.523	55.891	375.384	13698.135
13	4.605	64.080	454.045	13698.135
14	4.817	70.939	528.393	13698.135
15	5.383	63.646	556.312	13698.135
16	4.433	58.245	386.352	13698.135
17	4.288	49.129	325.446	13698.135
18	3.432	43.369	279.741	27396.270
19	2.450	38.154	164.246	Zero outflow
20	2.342	32.046	154.732	Zero outflow
21	2.274	26.703	140.836	Zero outflow
22	1.698	21.454	98.648	Zero outflow
23	1.321	17.704	29.425	Zero outflow
24	1.164	13.334	18.847	Zero outflow
25	1.060	7.390	12.646	Zero outflow
26	0.888	5.522	5.354	Zero outflow
27	0.709	2.742	2.992	Zero outflow
28	0.407	1.472	0.904	Zero outflow
29	0.053	0.600	0.012	Zero outflow
30	0.004	0.058	0.001	Zero outflow

Table A.5: Asset risk measured as penetration (meters per ship-year) for the thirty selected scenarios

Scenario	Asset risk	Scenario	Asset risk	Scenario	Asset risk
1	$3.41x10^{-6}$	**11**	$4.04x10^{-4}$	**21**	$3.71x10^{-4}$
2	$1.57x10^{-5}$	**12**	$4.48x10^{-4}$	**22**	$2.84x10^{-4}$
3	$7.24x10^{-5}$	**13**	$4.65x10^{-4}$	**23**	$2.27x10^{-4}$
4	$1.23x10^{-4}$	**14**	$4.95x10^{-4}$	**24**	$2.07x10^{-4}$
5	$1.16x10^{-4}$	**15**	$5.63x10^{-4}$	**25**	$6.82x10^{-5}$
6	$1.39x10^{-4}$	**16**	$4.72x10^{-4}$	**26**	$5.98x10^{-5}$
7	$1.75x10^{-4}$	**17**	$4.64x10^{-4}$	**27**	$5.06x10^{-5}$
8	$2.10x10^{-4}$	**18**	$3.79x10^{-4}$	**28**	$3.16x10^{-5}$
9	$3.38x10^{-4}$	**19**	$3.82x10^{-4}$	**29**	$8.04x10^{-6}$
10	$3.69x10^{-4}$	**20**	$3.73x10^{-4}$	**30**	$6.73x10^{-7}$

Table A.6: Asset risk measured as structural damage volume (cubic meter per ship-year) for the thirty selected scenarios

Scenario	Asset risk	Scenario	Asset risk	Scenario	Asset risk
1	6.73×10^{-8}	**11**	3.43×10^{-2}	**21**	2.30×10^{-2}
2	4.69×10^{-5}	**12**	3.72×10^{-2}	**22**	1.65×10^{-2}
3	9.18×10^{-4}	**13**	4.58×10^{-2}	**23**	5.06×10^{-3}
4	1.66×10^{-3}	**14**	5.43×10^{-2}	**24**	3.35×10^{-3}
5	1.67×10^{-3}	**15**	5.81×10^{-2}	**25**	8.13×10^{-4}
6	1.73×10^{-3}	**16**	4.11×10^{-2}	**26**	3.60×10^{-4}
7	4.49×10^{-3}	**17**	3.53×10^{-2}	**27**	2.14×10^{-4}
8	7.56×10^{-3}	**18**	3.09×10^{-2}	**28**	7.03×10^{-5}
9	1.65×10^{-2}	**19**	2.56×10^{-2}	**29**	1.81×10^{-6}
10	2.93×10^{-2}	**20**	2.47×10^{-2}	**30**	2.14×10^{-8}

Table A.7: Asset risk measured in USD per ship-year for the thirty selected scenarios

Scenario	Asset risk	Scenario	Asset risk	Scenario	Asset risk
1	6.24×10^{-2}	**11**	9.60×10^{1}	**21**	7.98×10^{1}
2	5.04×10^{-2}	**12**	1.17×10^{2}	**22**	4.06×10^{1}
3	3.64×10^{0}	**13**	1.17×10^{2}	**23**	2.89×10^{1}
4	1.20×10^{1}	**14**	1.11×10^{2}	**24**	1.38×10^{1}
5	1.32×10^{1}	**15**	1.23×10^{2}	**25**	6.13×10^{0}
6	1.35×10^{1}	**16**	1.34×10^{2}	**26**	2.76×10^{0}
7	2.19×10^{1}	**17**	9.43×10^{1}	**27**	1.49×10^{0}
8	2.36×10^{1}	**18**	8.84×10^{1}	**28**	1.03×10^{0}
9	4.83×10^{1}	**19**	9.23×10^{1}	**29**	4.97×10^{-2}
10	7.45×10^{1}	**20**	8.55×10^{1}	**30**	1.81×10^{-2}

Table A.8: Environmental risk in tonnes per ship-year for the thirty selected scenarios

Scenario	Env. risk	Scenario	Env. risk	Scenario	Env. risk
1	Zero outflow	**11**	2.670	**21**	Zero outflow
2	Zero outflow	**12**	1.360	**22**	Zero outflow
3	Zero outflow	**13**	1.380	**23**	Zero outflow
4	Zero outflow	**14**	1.410	**24**	Zero outflow
5	Zero outflow	**15**	1.430	**25**	Zero outflow
6	Zero outflow	**16**	1.460	**26**	Zero outflow
7	0.766	**17**	1.480	**27**	Zero outflow
8	0.765	**18**	3.020	**28**	Zero outflow
9	1.280	**19**	Zero outflow	**29**	Zero outflow
10	1.310	**20**	Zero outflow	**30**	Zero outflow

Table A.9: Environmental risk measured in USD per ship-year for the thirty selected scenarios

Scenario	Env. risk	Scenario	Env. risk	Scenario	Env. risk
1	Zero outflow	**11**	4,440	**21**	Zero outflow
2	Zero outflow	**12**	2,880	**22**	Zero outflow
3	Zero outflow	**13**	2,940	**23**	Zero outflow
4	Zero outflow	**14**	2,990	**24**	Zero outflow
5	Zero outflow	**15**	3,040	**25**	Zero outflow
6	Zero outflow	**16**	3,090	**26**	Zero outflow
7	1,630	**17**	3,150	**27**	Zero outflow
8	1,620	**18**	5,030	**28**	Zero outflow
9	2,730	**19**	Zero outflow	**29**	Zero outflow
10	2,780	**20**	Zero outflow	**30**	Zero outflow