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Review

Review and application of ship collision and grounding analysis procedures

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ABSTRACT

It is the purpose of the paper to present a review of prediction and analysis tools for collision and grounding analyses and to outline a probabilistic procedure for which these tools can be used by the maritime industry to develop performance based rules to reduce the risk associated with human, environmental and economic costs of collision and grounding events. The main goal of collision and grounding research should be to identify the most economic risk control options associated with prevention and mitigation of collision and grounding events.

1. Introduction

The present paper reviews published research on procedures for reducing the high economic, environmental and human costs associated with ship collisions and grounding and outlines a probabilistic procedure by which the maritime industry can develop performance based rules to reduce the risk associated with collision and grounding events. The paper describes mathematically based procedures for identifying economic risk control options related to prevention and mitigation of damages due to collision and grounding events. Wang et al. [1] published in 2002 a review article in Marine Structures on the assessment of a ship's performance in accidents. Therefore, the main focus of the present paper is on more recently published research results.

The initial part of the paper reviews published research on acceptance criteria for costs associated with collision and grounding events. A first step for a rational reduction of risk related to hazards, such as collision and grounding, must be to establish a comprehensive risk evaluation criterion for ship

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design and for operations. Without a proper, generally agreed on evaluation criterion it is not possible to find the balance between safety in terms of risk reduction and the cost to the stakeholders.

Any risk evaluation criterion must include the probability of the considered hazard. Therefore, the second part of the paper is devoted to tools for determining the ship and route specific probability that collision, contact or grounding events will take place.

The probability of the occurrence of collision, Fig. 1, and grounding events may be computed from historical data, expert opinions and predictive calculations. Historical data provides realistic figures which are, nevertheless, difficult to use for future predictions since they are relevant to ship's structures which may differ from those used today, and they do not take into account the development in operational procedures and new navigational equipment. For these reasons, mathematical models for prediction of the frequency of hazard occurrence are an important first step for a rational risk assessment procedure. Such probabilistic analyses must involve identification of a number of different collisions and grounding scenarios, each associated with a probability level. The impact on the ship is then calculated as the sum of the products of the consequences related to each of these collision or grounding scenarios and the probability of their occurrence. It is a well known fact that usually the most cost-effective way to reduce risk is by reducing the probability that adverse events take place, see [2]. A number of frequency prediction models have been developed in recent years, which together with external energy analyses can be used to determine probabilistic distributions of energy released for crushing of structures.

The third step in the part of the risk analysis which deals with collisions, contacts and grounding hazards is to determine the consequences given that an event takes place. There is a wealth of literature which deals with the development of procedures for determining the structural damage to ships subjected to well defined collision and grounding events, see e.g. Samuelides [3] for a recent review. Mitigation of the further consequences of such accidents is today usually achieved by defining a certain distance between inner and outer watertight barriers, defining appropriate subdivisions for survival in case of flooding, appropriate arrangement of cargo and fuel tanks etc. However, again it is difficult to assume that the statistics from past collision and grounding events involving ships built several decades ago are adequate to be used to predict probabilistic damage distributions in new generations of megalarge container vessels, new generations of large LNG carriers, vessels carrying irradiated fuels, and large passenger vessels. Thus, with given distributions of energy for crushing of structures, rationally based procedures for crashworthiness calculations for the resulting probabilistic distribution of damages to present-day vessels are necessary tools for collision and grounding analyses.

The paper shows that the research community through the last decade has developed a number of basic analysis tools for collision and grounding analyses, see for instance the Proceedings of the

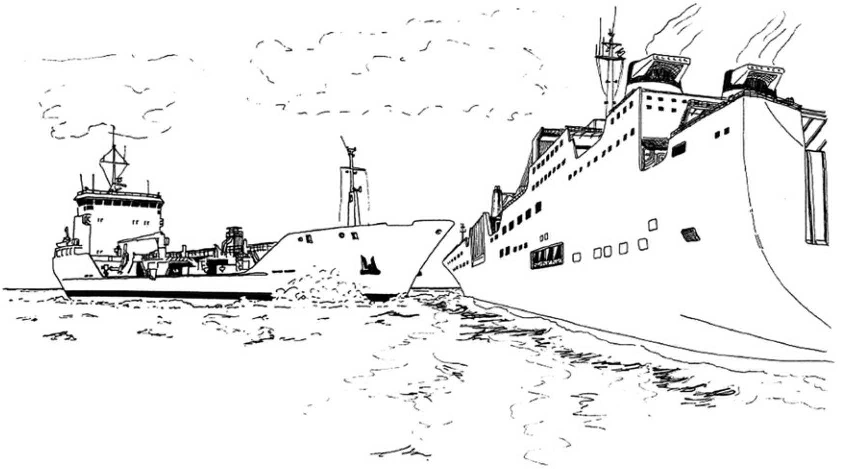


Fig. 1. Ship–ship collision.

International Conferences on Collision and Grounding of Ships held in San Francisco 1998, Copenhagen 2001, Izu 2004, Hamburg 2007, and Helsinki 2010.

In the present paper it is demonstrated that with a goal-oriented research and development effort, it should now be possible for maritime administrators and classification societies to derive performance based rational rules to reduce the risk associated with collision and grounding events. As a first step, this will require an assemblage of the developed analytical tools to make it possible to quantify potential collision, contact and ship grounding hazards in a rigorous way into a comprehensive suite of risk analysis programs.

Such risk analysis procedures are proposed being used in two ways. For ships where the consequences of collisions and grounding are large, such as passenger ships that carry thousands of lives [4], ships carrying cargo that is especially harmful to the environment [5], large LNG vessels [6,7], or ships representing high investments such as FPSOs [8], specific, rational, mathematically based risk assessment procedures should be developed along the same lines as currently done for offshore structures [9] or for large bridges crossing shipping lanes [10]. For such ships rational analysis procedures are needed to document that relevant measures to reduce the risk have been investigated and introduced.

For more standard types of vessels similar mathematical models should be used to outline Formal Safety Assessment procedures (FSA), see [11], in order to develop consistent, rationally based IMO and Classification rules which reflect the evolution of ship operation, design and materials. A number of FSA analyses following the procedure shown in Fig. 2 have been presented to IMO in recent years, see for instance Ref. [6]. Thus, the framework for collision and grounding risk evaluation exists. At present, it is the absence of agreed on, consistent, mathematically based analysis tools which makes the current risk analyses based on expert judgments and historically based comparisons somewhat subjective and often gives rise to discussions.

Whereas risks due to collisions and grounding are not yet explicitly considered in the design of ships - except for some special cases such as the class notation COLL from Germanischer Lloyd [12], the DNV rules for compressed natural gas carriers, the IMO rules for vessels carrying irradiated fuels, rules for bunker oil fuel tanks in large container ships, and a European agreement concerning international carriage of dangerous goods by inland waterways, see Ref. [13] - the situation is different within the offshore field. The offshore industry has established systematic assessment procedures for ship collisions against fixed platforms, Fig. 3, that address the probability of occurrence, risk ranking, structural analyses, and acceptance criteria. See e.g. API Recommended Practice [14] and a review in [9].

2. Risk acceptance criteria

Every year ship collisions and grounding events cause loss of hundreds of lives, economic losses, environmental damages and other unwanted events. It is indispensable that collision and grounding events are considered to be so rare that the benefit of the ship operation to the owner and the public exceeds their sensitivity to risk. Therefore, one of the many performance goals during the design phase

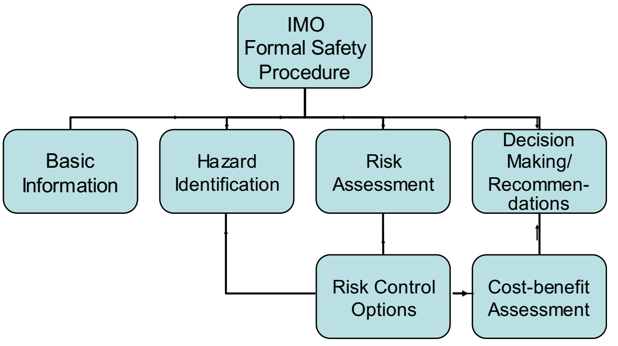


Fig. 2. Schematic representation of the IMO Formal Safety Procedure (FSA).

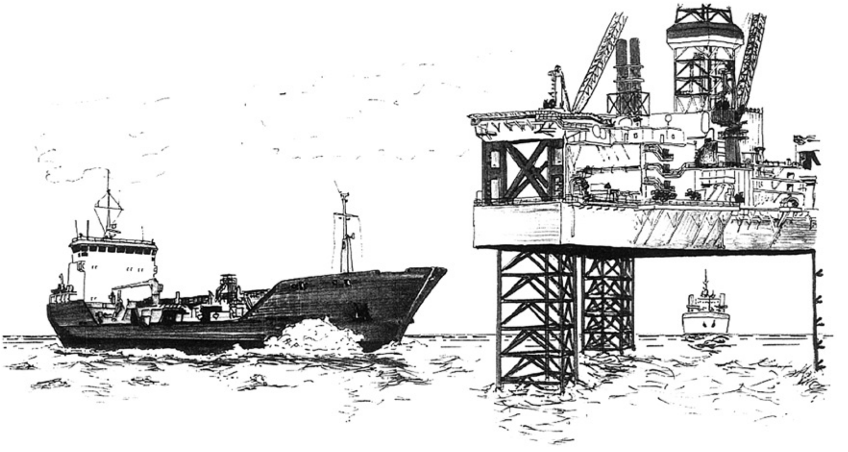


Fig. 3. Ship collision with offshore rigs and platforms.

of ships should be to ensure that serious accidents and service disruptions are low enough to be acceptable to all stakeholders, i.e. owners, the public and those responsible for public safety. On the other hand, the required risk levels should still allow construction and operation of the ship at feasible cost levels.

The risk involved in a given activity is a function of the possible hazards related to the activity and the probabilities and consequences related to these hazards.

Traditionally, risk acceptance criteria must be established for three main types of risks:

- Fatalities
- Pollution of the environment
- Loss of property or financial exposure

A much discussed problem with risk evaluation and risk mitigation measures is that the consequences may be of very different nature such as fatalities, pollution of the environment, and economic losses.

Criteria for regulation of the risk associated with fatalities have been analysed by Ditlevsen and Friis-Hansen [15] and a detailed proposal for consequence measurement of oil spill pollution is made by McGregor et al. [16]. In a very comprehensive report by Skjong [17] criteria used by IMO and other organisations for fatalities and for environmental damages caused by accidental release of oil and oil products are described in detail.

The acceptance criteria for fatalities are normally based on two principles:

- The individual fatality risk shall be approximately the same as typical for occupational hazards
- The frequency of accidents with several fatalities, that is the societal fatality risk, shall not exceed a level defined as unconditionally intolerable

The latter societal risk acceptance criterion must be introduced because society is more concerned about single accidents with many fatalities than many accidents with few fatalities per accident. To kill 100 people in one accident every 1000 years is considered more serious than to kill one person every ten years due to risk aversion of the society.

To risks which do not significantly exceed this upper bound the general ALARP (As Low As Reasonably Practicable) risk management shall be applied. Fig. 4 illustrates this criterion. Thus, in principle for all non-negligible risks, it is required that all possible measures for risk reduction should be identified and analysed and their societal value assessed.

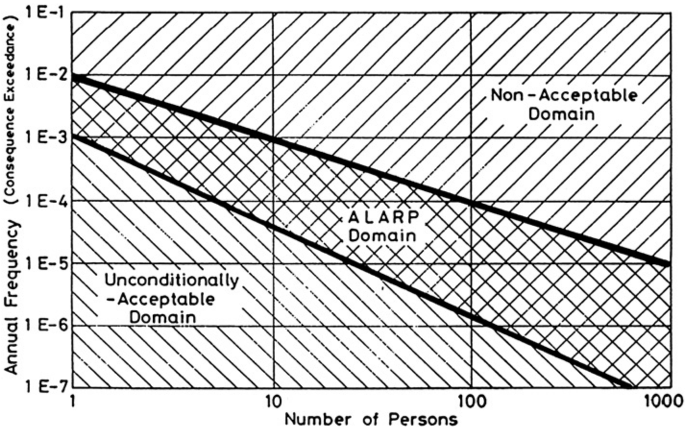


Fig. 4. Typical risk acceptance criterion, F–N diagram.

In the ALARP region an economic criterion can be applied to consider the effectiveness of safety measures or risk control options. That is, the additional cost of risk-reducing measures in the form of construction cost plus present value (PV) of operational costs is evaluated against the effect of the risk in the ALARP region. The condition for a decision to introduce a risk-reducing measure for fatalities used by IMO and IACS for rule making seems to be based on approximately three million US $ per fatality.

Similarly, ALARP criteria have been used by authorities to reduce accidental oil spills from tankers. Here the cost of preventing an oil spill accident must be based on the cost of oil, the clean-up cost, the environmental damage cost etc., see Sames and Hamann [18].

Authorities like IMO, IACS, and national administrations normally focus on these two types of risks one after the other. Thus, so far the ALARP principle has been applied separately to fatalities and to environmental impacts when considering new rules. The general economic costs associated with severe accidents have not been considered.

In the region where the ALARP principle governs, fatalities, environmental damage as well as economic loss could preferably be considered at the same time. Hence, evaluation criteria for making decisions related to risk reduction should have the form

$$Risk = SUM(P_i(H_i; C_i) * U(C_i)) \tag{1}$$

where the sum is over all the consequences C_i related to the hazard H_i and P_i is the probability of the ith consequence. The function U is a utility function which expresses the consequence in some common measure, such as monetary value. This translation of the different types of consequences into some other measure depends not only on the type of consequence of the hazard but also to whom it is a consequence. The utility function U must be different for those who have a direct interest in the activity, i.e. a gain from a successful operation, and for instance a third party such as the public who may only have the risk from the activity, as suggested by the risk Eq. (1). Such a summation will make more risk control options relevant and serve to improve safety of shipping.

With more than 1.5% of all ships involved in a serious and costly accident annually, the economic loss will have a significant influence in Eq. (1), and several risk mitigation measures, which for example improve navigation, will influence all three risk categories at the same time. Therefore, to improve marine safety the international marine community should standardise decisions concerning the elements in risk evaluation criteria for the ALARP region, such as Eq. (1), as far as possible in order to facilitate fair comparison between different control options.

Since the dominant risk contributors to ocean-going ships are collisions, contacts and grounding we shall in the following sections first describe how mathematical models can be established for prediction of the probability of such events. Thereafter, a number of sections are devoted to estimation of the structural consequences and the associated risk control options given that a collision, contact or grounding event takes place.

3. Probability of grounding and collision events

The most cost-effective way to reduce risk caused by collision and grounding is to reduce the probability of these events. It is a general principle that the most effective and least costly steps for safety provisions are as far back in the series of events as possible.

The limited number of consistent, research based analyses which have been performed on preventive measures related to reducing collision and grounding probabilities generally confirms that risk control options within this area are very cost-effective compared to most other risk-reducing measures introduced by maritime authorities.

In recent years, there has been a rapid development of new navigational systems. A growing number of Vessel Traffic Systems (VTS) are established around the world. An Automatic Identification System (AIS) has been introduced, and systems have been developed for access of AIS information through the Automatic Radar Plotting Aid (ARPA). Moreover, the Electronic Chart Display and Information System (ECDIS) with and without track control has been installed on new vessels, see Vanem et al. [19]. IMO has introduced requirements for new ships to fulfil particular manoeuvrability criteria and safe levels of manning are constantly discussed. It is generally agreed that all these activities have considerable influence on the probability of ship accidents in the form of collisions, contacts and grounding. However, so far very few rational analysis tools have been available to quantify the effect of these changes.

On this background researchers work on the development of rational, mathematically based models for determination of the probability of ship–ship collision, ship collisions with floating objects such as lost containers, Fig. 5, and grounding accidents.

3.1. Probability of ship–ship collisions

The main principle behind the most commonly used risk models is first to determine the number of possible ship accidents N_a, i.e. the number of collisions if no aversive manoeuvres are made. This number N_a of possible accidents, assuming blind navigation, is then multiplied by a causation probability P_c in order to find the actual accident frequency.

$$N_{ship\text{-}ship} = P_c N_a \tag{2}$$

Thus, the causation probability P_c is the fraction of the accident candidates that result in an accident. This probability depends on the navigators, their equipment, the manoeuvrability of the vessels, etc.

As an illustration of the principles behind the calculation of the number of possible ship collision candidates N_a, we shall consider two crossing waterways where the ship traffic is known and has been

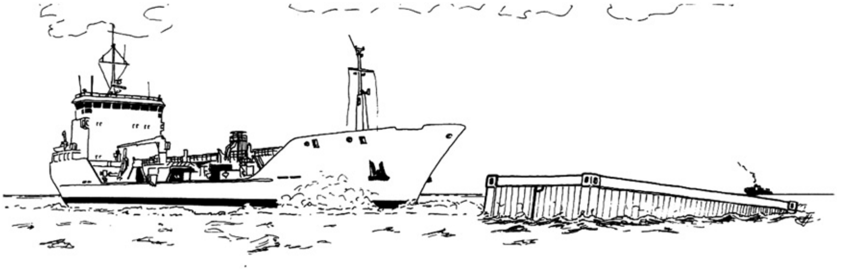


Fig. 5. Collision with floating object such as lost containers, small icebergs, etc.

grouped into a number of different ship classes, i and j, according to vessel type, displacement, length, loaded or ballasted, ship's speed, draught, ice class, with or without bulbous bow, etc.

Fig. 6 shows such two crossing waterways. A calculation model for the number N_a of possible events where two ships will collide in the overlapping waterway area Ω, if no aversive manoeuvres are made, is presented in [20]. By summing all the class "j" ships of waterway 2 on collision courses with all relevant class "i" ships during the time Δt, the following expression was derived for calculating the number of blind ship collisions in a time interval Δt:

$$N_a = \sum_i \sum_j \int \int_{\Omega(z_i z_j)} \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} f_i^{(1)}(z_i) f_j^{(2)}(z_j) V_{ij} D_{ij} \mathrm{d}A \Delta t \tag{3}$$

Here $Q_j^{(\alpha)}$ is the traffic flow (i.e. number of ships per unit time) of ship class j in waterway no. α (1 or 2), $V_j^{(\alpha)}$ is the associated speed. The lateral distribution of the ship traffic of class j in waterway α is denoted $f_j^{(\alpha)}$, D_{ij} is the geometrical collision diameter defined in Fig. 7, and finally the relative velocity is denoted V_{ij} .

The overall ship traffic data, $Q_i^{(\alpha)}$, for the considered geographical area divided into different vessel types and into different size categories can be obtained semi-automatically from AIS data collected in the region, see Aarsætter and Moan [21]. Similarly, the spatial distributions $f_j^{(\alpha)}$ can be collected from radar observations or from land based AIS stations.

The causation probability P_c can be estimated on the basis of available accident data collected in various locations and then transformed to the area of interest, see Kaneko [22] and Kaneko and Hara [23]. Another approach is to analyse the cause leading to human inaction or external failures and set up a mathematical model for these events. Among the few analytical models published so far for a rational calculation of the causation factor P_c are those based on a Bayesian network approach, see Friis-Hansen et al. [24], Itoh et al. [25], Ravn [26], and Jensen et al. [27], and on the fault tree approach to calculation of the probability of ship–ship collisions. These methods constitute a basis for possible future development of rational procedures for analyses of the effect of a number of risk control options.

By use of mathematical models such as those based on Bayesian networks it is possible to quantify the effect of improved manoeuvrability, two navigators on the bridge, AIS coupled to the radar, and the like.

In Fig. 8 a sketch of the starting point of a possible model is seen. A vessel with speed V_2 is on collision course with a ship with speed V_1. Given the weather condition it is possible to determine when the other vessel can be seen, either visionally or by radar. Thereafter, it is possible to calculate the time available for

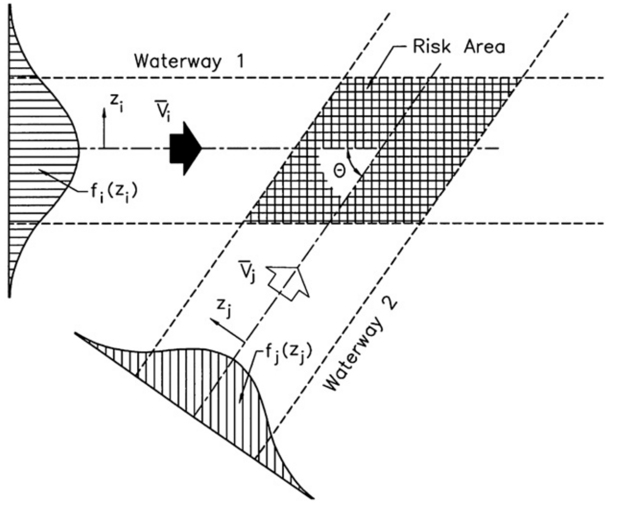


Fig. 6. Crossing waterways with risk area of ship–ship collision.

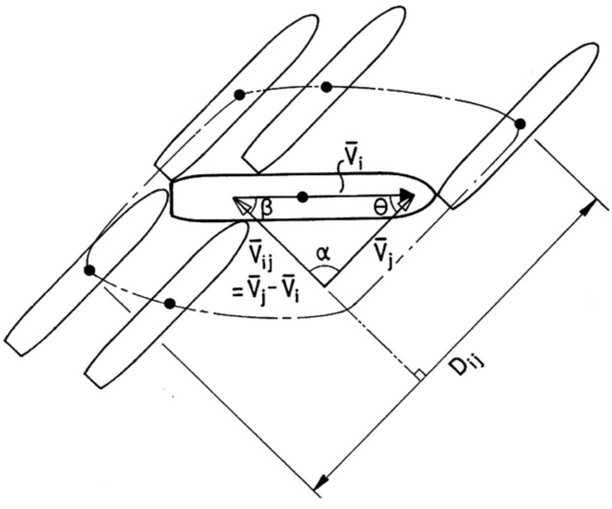


Fig. 7. Definition of geometrical collision diameter D_{ij}.

detection of the other vessel or object in order to make aversive action. This time for detection is limited by the time needed for manoeuvring, see Montewka et al. [28], and for planning the change of course. The visibility is a stochastic quantity and the probability of detection during the time available depends on a number of factors such as manning, bridge layout, AIS, etc. These interdependencies of stochastic elements make modelling of the causation probability suitable by Bayesian networks.

Collision models for meeting and for overtaking in parallel waterways and for contacts with floating objects, see Fig. 9, are just special cases for the procedure described by Eqs. (2) and (3). A similar procedure can also be used to determine the added probability of ship collisions in bends of the seaway where one of the vessels may not make the turn, provided that the causation probability of not following the bend route is compensated for by the fact that the navigator will normally check the position at regular intervals.

The probability that a ship has failed to change course at a turning point can for example be modelled as

$$P_T = P_0^{(d-a)/a} \tag{4}$$

where P_0 is the probability of omission to check the position of the ship, d is the distance sailed on wrong track and a is the average length between position checks by the navigator, often taken to be about eight ship's lengths.

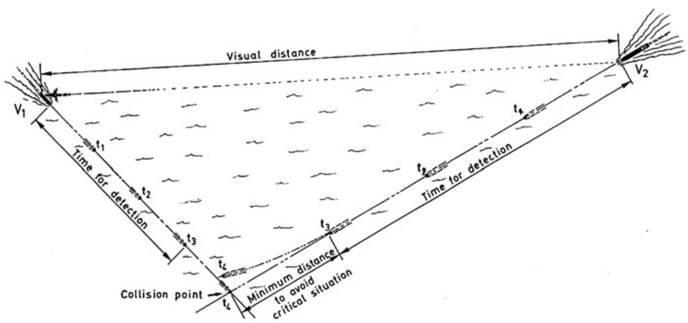


Fig. 8. Probabilistic space–time model used as a basis for derivation of causation probabilities using Bayesian networks.

An example of a rational risk based procedure has been an evaluation of the expected effect of using AIS as an integrated part of the navigational system, see Lützen and Friis-Hansen [29]. The evaluation was performed for vessels navigating on worldwide operational routes during the implementation phase before the full enforcement of AIS in July 2008. The risk-reducing effect of AIS was quantified by building a Bayesian network, facilitating an evaluation of the effect of AIS on the navigational officer's reaction ability in a potential, critical collision situation. The time-dependent change in the risk-reducing effect on ship collisions was analysed. Two different bridge systems were compared, a conventional bridge and a bridge equipped for solo watchkeeping. It was found that the risk-reducing effect on the collision risk of a full implementation of AIS could be significant independent of the bridge type.

With rational mathematically based analytical tools such as fault tree or Bayesian network based approaches it is possible to analyse the effect of Risk Control Options (RCO) as for example:

Change in collision probability due to change in route such as:

- Effect of vessel traffic separation schemes
- Effect of aids to navigation
- Effect of vessel traffic systems (VTS)
- Effect of Electronic Navigational Charts (ENC)
- Effects of pilots in open waterways
- Effect of weather and visibility conditions
- Effect of speed reduction
- Effect of better sea charts

Change in causation factor due to changes in human behaviour such as:

- Effects of manning
- Effect of simulator training [30]
- Effect of crew schedule to avoid fatigue of crew
- Effect of psychological screening of navigators

Changes in ship design such as:

- Effects of bridge layout and technical equipment such as radar systems
- Effect of GPS for position fixing and ECDIS
- Effect of AIS integrated with radar
- Effect of redundancy of navigational equipment
- Effect of ship's speed on causation factor (time to react), see Fig. 8
- Effect of improved manoeuvrability on causation factor (time to react)
- Effect of propulsion redundancy – twin screw vessels
- Effect of reduced probability of engine blackout or steering machine failure

3.2. *Probability of grounding and collision with fixed offshore structures*

To determine the probability of grounding another mathematical model needs to be developed and similar risk control options studied. The procedure should include power grounding where the ship is running on a ground with forward speed but also drift grounding for disabled ships.

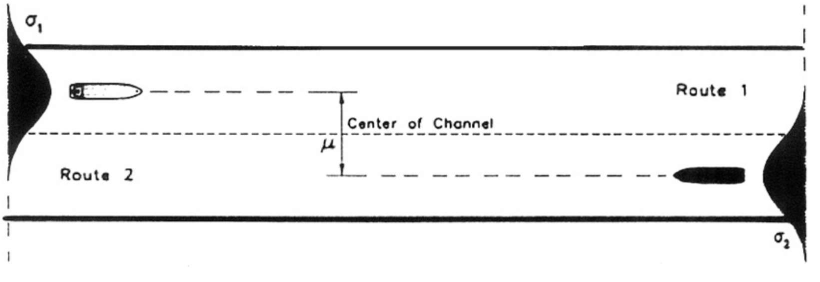


Fig. 9. Ship–ship collision model for straight waterways.

Models for calculation of the grounding probability P_g could be developed in a way similar to the method described above for ship–ship collisions, see Otto et al. [31]. The difference is that an obstacle, for example a rock, on which the ship grounds, is fixed in its position and that it is in most cases below the water surface. See Fig. 10.

Again ship traffic data needs to be collected for the number of ships and the spatial distribution in the vicinity of the most important coast lines, and a procedure should be developed for characterisation of these coast lines, i.e. distribution of rocks, bottom profile data, tide variations etc. As indicated in Fig. 10, for calculation of the probability of collision with an offshore structure and/or grounding, the collision model based on Eqs. (2) and (3) has to be augmented by an additional category of accident related to the probability that the vessel does not change course at bends on the shipping route, see Eq. (4), together with further categories related to drifting vessels due to steering machine failure or engine blackout. See [26] and [32].

Based on the principles for estimation of collision probabilities described above some procedures have been developed for calculation of collision probabilities in specific waterways where the ship traffic distribution is known. One such published procedure is the GRACAT software (Grounding and Collision Analysis Toolbox), see Friis-Hansen and Cerup-Simonsen [33].

Unfortunately, there are very few published procedures for calculation of the probability of grounding. This is an area in need for further research.

Possible risk control options related to reduction of the frequency of grounding events are similar to those given above for reduction of the probability of ship–ship collisions and contacts. Of course, the Electronic Chart Display and Information System (ECDIS) will mainly be effective in preventing grounding if it makes use of Electric Navigational Charts (ENC).

4. Probabilistic distribution of energy released for crushing in collisions and contacts

To determine the consequences of a given collision or contact the most important parameter will be the energy released to cause structural damage. Therefore, it is the aim of the external dynamic analysis to estimate the fraction of the initially available kinetic energy, which is released for rupture and plastic deformation in the vessels. In the case of two freely floating colliding ships, only part of the initial available kinetic energy will be spent in crushing of the bow of the striking vessel and the side structure

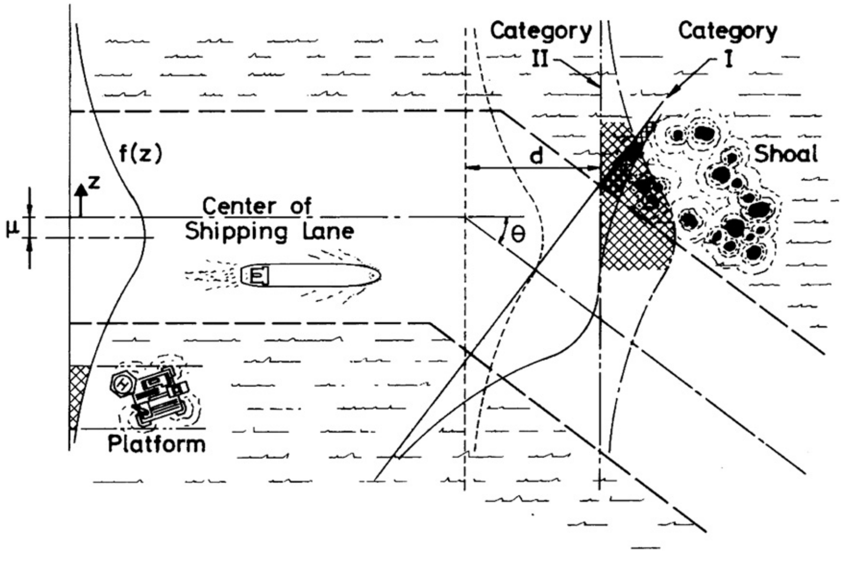


Fig. 10. Principles for estimation of probability of collision with offshore structures and grounding.

of the struck vessel. This separation of a collision analysis into an external energy analysis and a subsequent structural damage analysis was proposed by Minorsky [34] already in 1959.

Since the elastic energy stored in the hulls is normally small, see Ref. [35], the energy released for crushing can be approximated as the initial kinetic energy minus the kinetic energy of the floating vessel(s) after the collision or contact event.

The characteristics of the energy released for damage depend on various aspects for a given collision scenario, mainly the displacement and velocity of the struck and the striking vessel, the collision angle, the impact location and in some cases with sliding also the coefficient of friction, see Fig. 11.

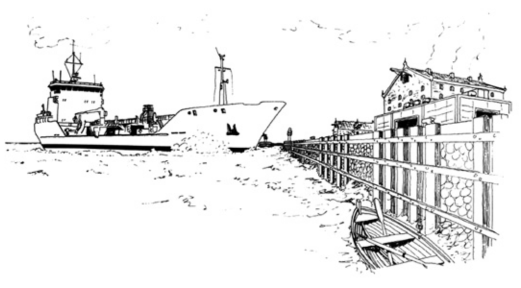
An analytical method for determination of the energy released for rupture and plastic deformation in the vessels in a given deterministic ship collision has been developed in Ref. [36]. Here the energy loss available for dissipation in structural deformations is given in closed-form expressions. The procedure is based on a 2D rigid body mechanism, where it is assumed that there is negligible strain energy for deformation outside the contact region and that this region is local and small. This implies that the collision can be considered as instantaneous and each body is assumed to exert an impulsive force on the other at the point of contact. The model includes friction between the impacting surfaces so that situations with glancing blows can be identified. At the start of the calculation, the ships involved can have forward motion, and the influences of the hydrodynamic forces due to the sudden de-acceleration of the involved vessels are in this model approximated by simple added mass coefficients. In Brown [37] this analytical method is compared to comprehensive time simulation results and good agreement is found. Tabri et al. [38,39] have demonstrated that the external dynamic behaviour measured in full-scale symmetric experiments can be modelled quite well by model experiments in a towing tank as well as by numerical procedures.

As an example, Fig. 12 shows the calculated energy released for crushing of two colliding identical supply vessels, at different collision angles and striking locations along the hull girder of the struck vessel. The results have been obtained by the analytical approach. From this figure it is seen that for given ship's speeds the impact location and angle distributions play a significant role for the amount of energy released for crushing of the two vessels.

The ship collision probability model, represented by Eqs. (2)–(4), and the above-mentioned analytical model for the energy released for crushing can be used, [40], to calculate collision probabilities and a set of energy reference values for a specific struck vessel on various shipping routes given a collision. The probabilistic distributions for ship's speeds, meeting angles and striking locations were derived from available casualty databases.

Recently, comparative numerical and experimental studies by Zhang and Suzuki [41] and Tabri et al. [42] have presented the secondary effect on the energy released for crushing due to sloshing in liquid filled tanks during ship collision.

For ships on different trades the probabilistic distribution of the energy absorbed by structural damage given a collision takes place can be described as a function of the displacement of the struck



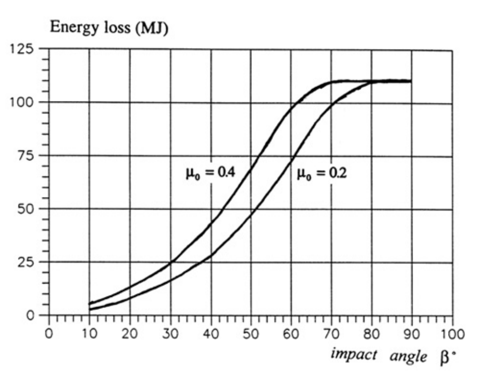


Fig. 11. Ship collision with rigid wall, structural damage or glancing depends on the coefficient of friction (analytical results, $\beta = 90^\circ$ is perpendicular to quayside).

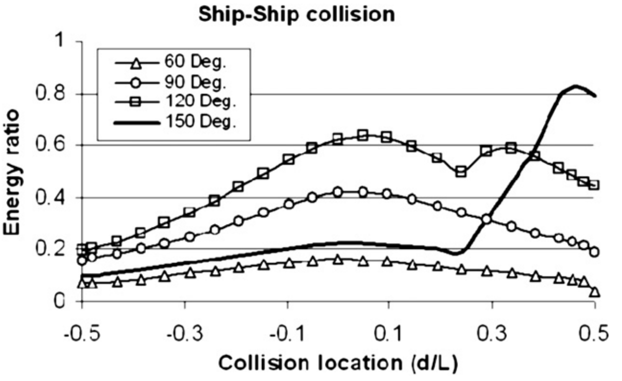


Fig. 12. Collision of two supply vessels, the energy ratio is the ratio between energy released for crushing and the total kinetic energy of the two ships before collision. The collision location is the ratio between the distance d measured from midship section of the struck ship and the struck ship length L, the collision angle $\beta = 60^\circ$, 90°, 120°, 150°, respectively [36].

vessel. For a striking location midship of the struck vessel the 25- and 90-percentile values of the energy to be absorbed are shown in Fig. 13. For other striking locations the calculated energy reference values will be smaller. It is noted that the calculated energy level is highly dependent on percentile values. It is also noted that the energy to be absorbed given a collision depends strongly on the sea route, i.e. on the distribution of striking vessels in the area. In calculations of the energy reference values for normal merchant vessels it might seem reasonable to choose the striking vessel from the world distribution. However, the world distribution reflects the large number of smaller vessels in local traffic worldwide. Therefore, for merchant vessels in international traffic the distribution of meeting ships will have larger displacements than the average world candidates, as clearly seen from Fig. 13. For vessels on fixed routes in trafficked areas, such as ferries crossing the Strait of Dover, it would be relevant to use route specific energy reference values. There is a need for more research on the distribution of energy reference values for typical shipping routes for tankers, bulk carriers, container vessels, etc.

5. Structural damage in given collision scenarios

When the probability of a collision and the probabilistic distribution of energy released for crushing of the striking and the struck vessels are known, the next step in a rational collision analysis procedure is to determine the resulting distributions of structural damages to the ships involved. Fortunately, within this area a number of efficient tools for crushing analyses have been derived. These tools make it possible to estimate structural damage distributions for specific ships on specific routes given that collision or grounding events have taken place.

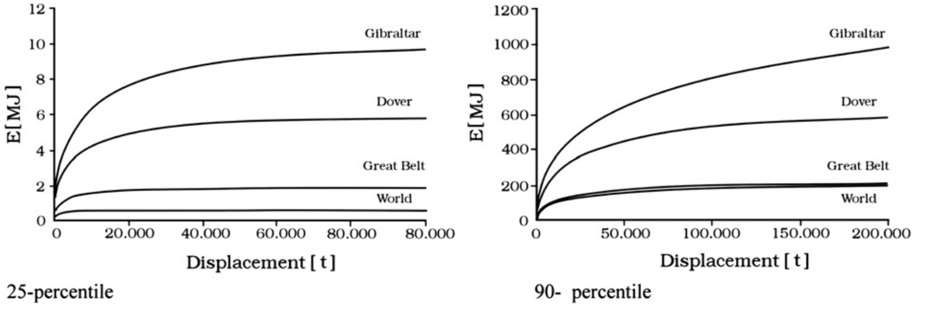


Fig. 13. The 25-percentile value (right) and the 90-percentile value (left) for energy to be absorbed amidships versus displacement and different shipping routes [40].

A recent review of finite element procedures for collision analyses has been presented by Samuelides [3]. Detailed finite element analyses are needed for the design of special-purpose ships built to withstand collisions and for verification of simplified methods. One of the challenges related to finite element analyses of the structural response in high energy collision scenarios is to determine the onset of fracture and the progress of fracture in large complicated welded ship's structures where the element size is relatively large compared to plate thicknesses. Progress on calculation models for the onset of fracture has been reported by Abramowicz and Cerup-Simonsen [43], Cerup-Simonsen and Törnqvist [44], Servis and Samuelides [45], Paik [46], Alsos et al. [47–49], Alsos and Amdahl [50], Ehlers et al. [51], Ehlers and Varsta [52], and Hogström et.al. [53]. So far the published research has mainly been devoted to fracture criteria for multi-axial stress and strain states. Modelling of fracture growth and the effect of cracks, welds and heat-affected zones has still to be dealt with in a consistent way.

For risk based analyses simplified, deterministic crushing analysis methods suited as procedures within Monte Carlo simulation schemes are needed for rapid calculation of the collision resistance and energy absorption in the ship's structures as function of penetration distances.

Several such simplified analysis tools for prediction of the damage to struck ships as well as striking ships have been developed, see Brown [37], Sajdak and Brown [54], Yamada and Pedersen [55] and [56], and Hong and Amdahl [57–59]. These tools all calculate the structural deformation for both the striking and the struck ship independently using rigid-plastic simplified analysis procedures. Thus, a rigid bulbous bow is assumed in order to estimate the structural resistance of a struck ship's side, see Fig. 14, and similarly a rigid struck ship's side is assumed to estimate the structural resistance of the bow of the striking ship.

For such simplified crushing analyses the ship's structures may be viewed as an assembly of plated structures such as shell plating, transverse frames, horizontal decks and bulkheads. Observations from full-scale ship accidents and model experiments reveal that the primary energy absorbing mechanisms of the side structure are as follows.

- Membrane deformation of shell plating and attached stiffeners
- Folding and crushing of transverse frames and longitudinal stringers
- Folding, cutting and crushing of horizontal decks
- Cutting or crushing of ship's bottoms
- Crushing of bulkheads

For calculation of crushing forces and energy absorption of ship's bows similar simplified methods for estimating mean axial crushing forces of plated structures can be applied. In Ref. [56] a benchmark study is presented of different simplified procedures for analysis of axial crushing of bulbous bows. A

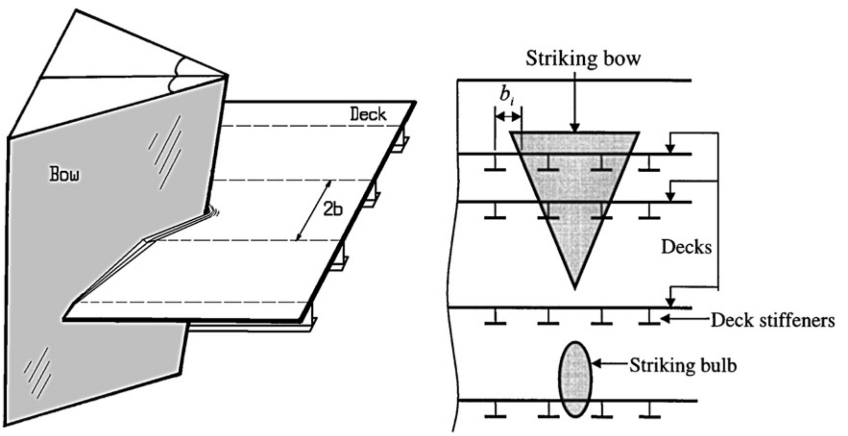


Fig. 14. Simplified structural models for estimation of crashworthiness of a ship's side for rigid bow penetration.

comparison of calculated results obtained from these procedures with comprehensive non-linear finite element analyses and a large number of experimental results for axial crushing of large-scale bulbous bow models prove that simplified methods are valuable for estimating the collapse load of bow structures subjected to extreme loads.

The fraction of energy absorbed by the bow of the striking ship varies and can be significant. The energy absorbed in the bow of a large striking ship with a longitudinally stiffened bow will normally be small, whereas the bow energy absorption for smaller striking ships against larger vessels and for striking ships with transversely stiffened bows will be significant and must be included in the damage analysis. See Ref.[54].

In order to compare typical collision energies needed for inner tank rupture on tankers or for inflow of water in a cargo hold of a bulk carrier with expected collision energies Fig. 15 can be considered. In this figure the 75 and the 90-percentile values for calculated collision energy reference values associated with collisions against the world fleet are depicted. In the same figure are sketched calculated energy absorption values until fracture of the inner hull for A: a 30,000 DWT tanker by Lehmann and Peschmann [60], B: a single hull 180,000 tons displacement single hull bulk carrier by Ozgus et al. [61], C: a 190,000 tons double hull bulk carrier by Ozgus et al. [61], D: a 280,000 DWT tanker by Shibue et al. [62], E: a 280,000 DWT tanker by Sano et al. [63], and F: a 300,000 DWT tanker by Kitamura et al. [64]. It should be noted that, as seen from Fig. 13, the collision reference energies for the world fleet are quite low compared to the reference energies for the major shipping routes where large tankers and bulk carriers normally trade. Thus, if a collision takes place, the probability is quite high that the inner tank of a double hull tanker will rupture or the cargo hold of a bulk carrier will be flooded.

By combining a ship collision probability model as described in Section 3.1, an analytical model for the external collision mechanics as described in Section 4, and simplified structural damage models for bow and side structures as described above in a comprehensive numerical Monte Carlo based ship - ship simulation model, probabilistic damage distributions can be calculated for existing as well as novel ship types.

In Fig. 16 such calculated probabilistic damage results are presented and the results are compared to IMO damage statistics. Here fifteen different specific vessels in worldwide traffic have been subjected to numerical damage analyses based on probabilistic input distributions of striking locations, angles and velocities, see Lützen [40]. The numerically obtained damage lengths and penetrations, the thin dotted lines, are compared with damage distributions obtained from damage databases collected during the Harder project, the bold lines. To account for the fact that not all accidents are properly registered, it is assumed that only one third of the penetrations smaller than 0.1B is reported to the international ship damage databases. On this assumption the simulated cumulative distribution

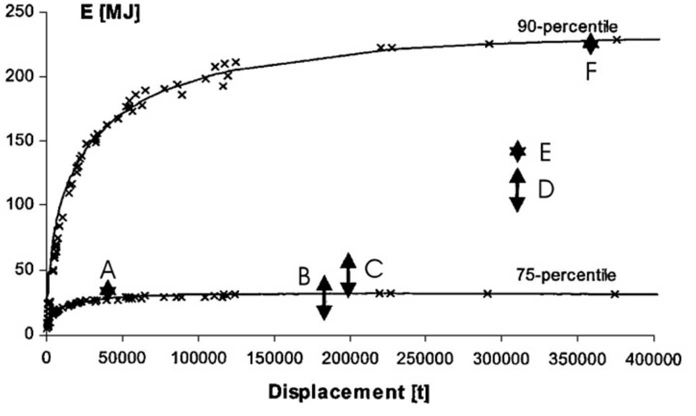


Fig. 15. Curves for 75 and 90 percentile energy reference values for collisions against the world ship size distribution. Included in the figure are examples on calculated energy absorption values until fracture of inner tank wall for double hull tankers represented by A, D, E and F, and for a single hull bulk carrier represented by B and a double hull bulk carrier represented by C.

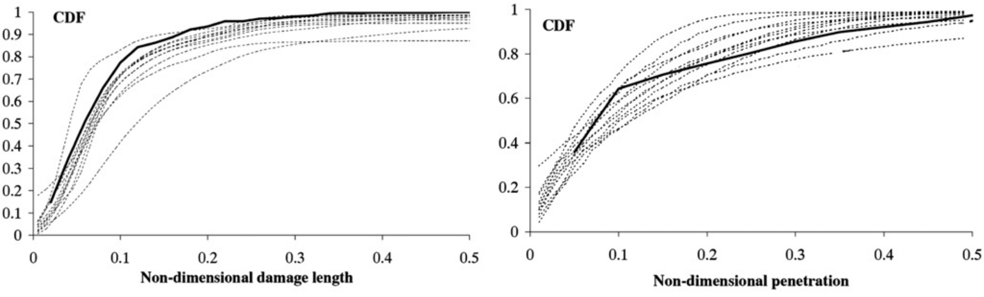


Fig. 16. Comparison of simulated cumulative distributions for non-dimensional damage lengths (damage/ship's length) and penetrations (penetration/ship's breadth) for 15 different ships (thin dotted lines) and observed data (full thick line) [40].

functions for the non-dimensional penetrations and for the non-dimensional damage lengths fit very well to the observed damages as shown in Fig. 16.

As indicated above, tools have been developed to determine the probability of having a collision on a given route and tools exist to determine the distribution of collision damages given a collision. An example of a rational analysis of a possible structural risk control option is the procedure applied by Yamada et al. [65] to determine the expected effect of buffer bow structures on the distribution of collision damages to struck tankers.

Furthermore, models have been developed for some important consequence analyses in the form of oil outflow, damage stability and hull integrity. Of course, these tools can be refined and made much more operational, and especially models for estimation of costs associated with collision accidents are needed in order to acquire better tools for determination of optimum risk reduction measures, see Vassalos [66].

Examples of structural Risk Control Options (RCO) which could be analysed to mitigate the risk associated with collisions:

1. Minimisation of damage extent in ship's side
   - Innovative double hull designs [67–71]
   - Steel sandwich panels [72]
   - Composite and sandwich panels
   - Pre-designed fracture points
   - Deformable inner barrier in tanks to prevent oil outflow [73]
   - Use of austenitic steel in inner and outer side shell structure [60]
2. Reduction of the striking vessel's bow stiffness (buffer bow) [65,74,75]

A further discussion on different measures to improve the crashworthiness of ship's structures is presented in Ref. [3].

6. Structural damage in given grounding scenarios

Grounding events may be powered groundings, see Fig. 17, or it may be drifting groundings. At the same time many quite different bottom types can be expected, for instance sandy or flat hard sloping bottoms, shoals, or different types of sharp rocks which may simply tear the bottom.

In the case of grounding on flat hard bottoms or sandy beaches the initial kinetic energy of the vessel will be spent on an initial inelastic impact phase, on lifting the ship and on friction between the ship and the sea bottom. This type of grounding will normally not lead to significant damage to the inner bottom of the vessel. However, due to the lifting of the vessel, see Fig. 18, possibly in combination with additional hull girder loading due to change in tide and wave action, this type of grounding can easily cause excessive hull girder shear loads and bending moments. See Brown et al. [76] and Alsos and Amdahl [50]. Analyses [32] have shown that for grounding on plane soft or hard grounds the induced

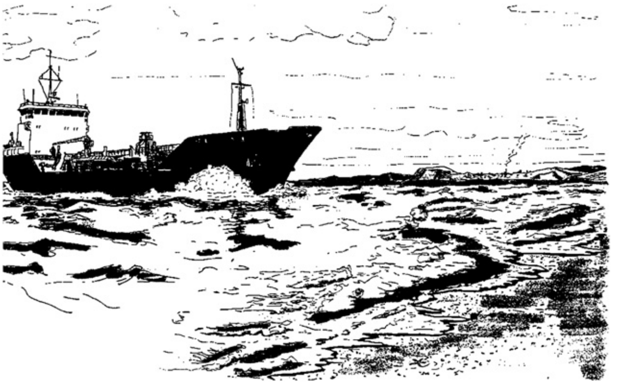


Fig. 17. A powered grounding scenario.

hull sectional forces increase strongly with ship's size, and the possibility exists that the hull girder breaks due to grounding induced sectional shear forces or bending moments, see Fig 19.

Grounding on uneven rock bottoms will normally cause local damage to the double bottom structure, see Fig. 20, and the major part of the initial kinetic energy will be absorbed through plastic deformation as in the case of collision events. For analysis of this type of grounding it is convenient to distinguish between grounding on large rounded shoals which cause significant plastic deformation over a significant width of the double bottom, but not much tearing, on one hand, and grounding on sharp rocks which cause extensive tearing of a narrower segment of the bottom structure.

Hong and Amdahl [58,59] and Alsos and Amdahl [50] have recently established a simplified procedure for calculation of the sliding resistance for grounding on circular cylindrically or spherically shaped shoals. Their procedure is based on a calculation of the forces F_R associated with a vertical indentation of the shoal into the ship's bottom using the tools developed for collision analysis. By assuming a uniform pressure distribution between the shoal and the ship's bottom the horizontal force component F_x can easily be estimated. The effect of a Coulomb frictional coefficient μ is added to this expression and the total sliding friction becomes

$$F_{xtot} = F_x + \mu F_z = F_x + 1/2 \mu F_R \tag{5}$$

A comparison with numerical FEA shows a very good accuracy of this Minorsky [34] type of simplification.

For grounding on sharp rocks where the kinetic energy of the vessel is absorbed mainly by raking and tearing of the double bottom a number of empirical expressions have been derived for the average horizontal reaction forces, F_{xtot} . These simplified expressions involve flow stress of the material, rupture strains, width of the tearing object, damage height and equivalent thickness of the bottom structure including transverses and longitudinal webs and stiffeners, see Cerup-Simonsen et al. [77].

Due to the large variation of grounding scenarios and bottom types, it seems difficult to establish a Monte Carlo type of simulation procedure for prediction of bottom damages from grounding on rocky bottoms, like the procedure indicated above for prediction of side damages due to ship–ship collisions. Instead rational models for translation of historical data for prediction of grounding damages to novel ship types have been proposed in recent years.

In order to translate historical damage data into data which can be representative of ships of today for grounding on shoals or sharp rocks dominated by bottom raking, it may be assumed that the kinetic energy of a ship is totally dissipated by friction and destruction of the ship's bottom structures. Thus, we have

$$\frac{1}{2} M \cdot V^2 = F_{xtot} \cdot L_{dam} \tag{6}$$

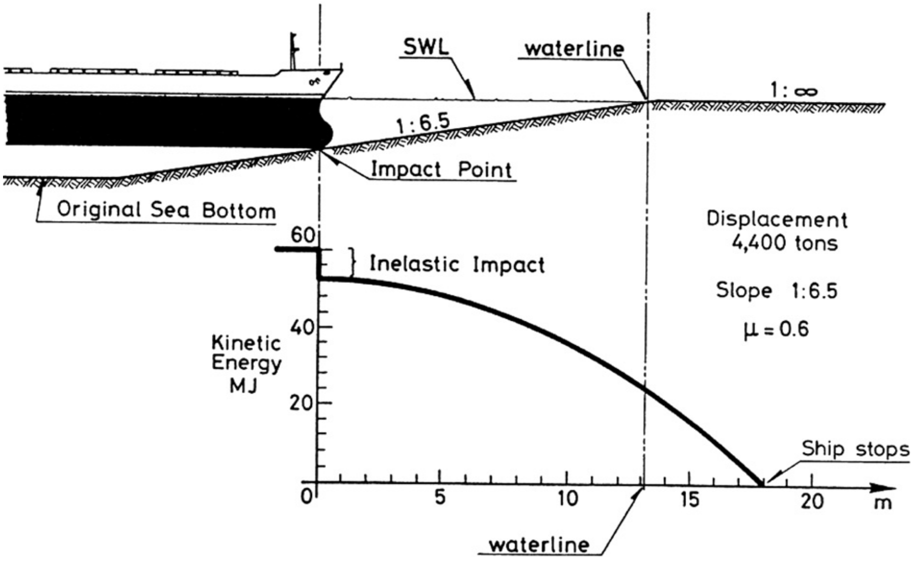


Fig. 18. Energy dissipation during powered grounding on a flat sand or rock bottom [32].

where M is the ship mass including the added mass effect, V is the grounding speed, F_{xtot} is the average horizontal grounding force, and L_{dam} is the damage length of the ship's bottom.

For two different ships, the ratio between the relative grounding damage length, i.e. the grounding damage length normalised by the ship's length (L_{dam}/L), can be expressed as [78]:

$$\frac{(L_{dam}/L)_1}{(L_{dam}/L)_2} = \frac{M_1}{M_2} \cdot \left(\frac{V_1}{V_2}\right)^2 \cdot \frac{L_2}{L_1} \cdot \frac{F_{2xtot}}{F_{1xtot}} \tag{7}$$

where the subscripts represent the different ships. The major difficulty of this procedure is to determine the horizontal grounding forces F_{1xtot} and F_{2xtot} since these forces depend on factors, such as rock

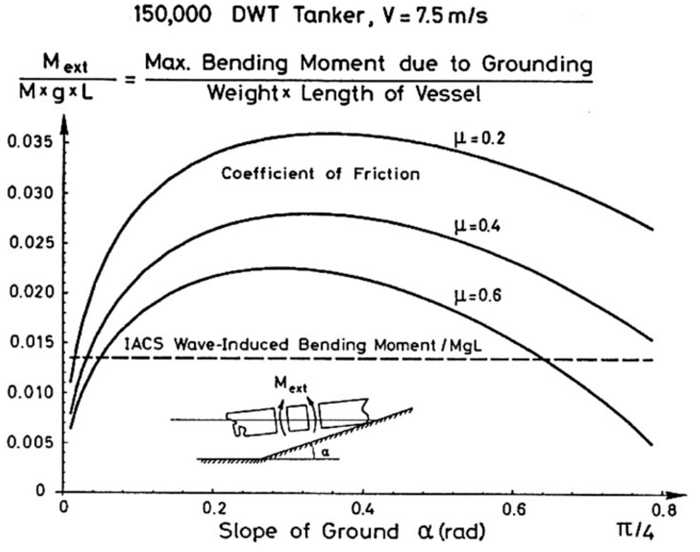


Fig. 19. Midship bending moment due to grounding as a function of slope of ground [32].

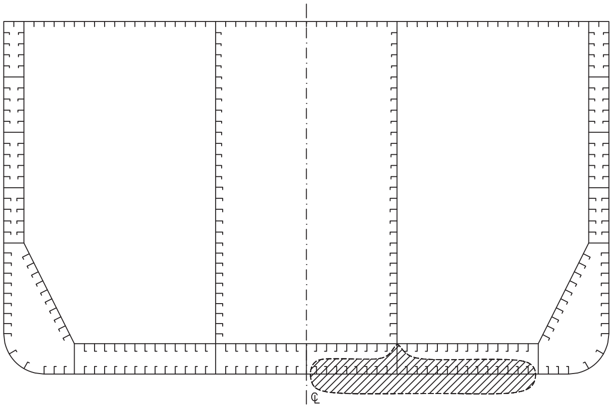


Fig. 20. Resulting double bottom damage of a powered grounding of a tanker on a rocky bottom.

shape, rock elevation and the structural design, Ref. [71]. It is often assumed that vertical indentation of a rock into the ship's bottom is proportional to the ship's draught. This means that ships with larger draught suffer larger vertical penetration. Therefore, also a larger damage width will be created for a larger draught of a ship. On this assumption application of Eq. (6) will also show that for example large tankers are subject to a higher probability of large relative damage lengths than that of smaller tankers, as shown in Fig. 21 from Ref. [78].

Hence, this figure shows that the fundamental assumptions behind the IMO recommendations for grounding damage distributions for tankers may not hold since the distributions for grounding damages do not scale linearly with the ship main dimensions. A comparison with existing statistical grounding damage data for cargo ships validates the derived analytical expressions and the main conclusions.

In another application of the procedure briefly described above, Cerup-Simonsen et al. [77] developed a proposal for new grounding damage rules for High Speed Craft (HSC). They base their formulation on a Grounding Damage Index (GDI) which can be used to compare the raking damage of different vessels. For HSC very little accident data exists and since ship grounding is highly stochastic in nature, they used a Monte Carlo simulation procedure for calibration of their model such that it

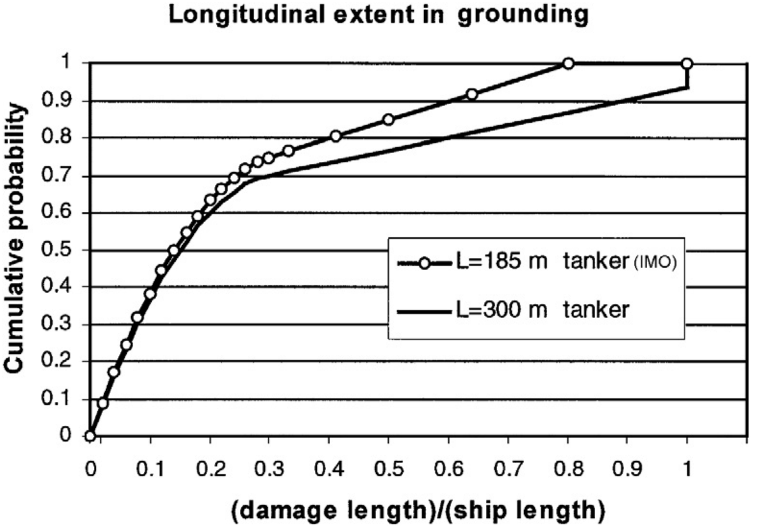


Fig. 21. The translated cumulative grounding damage length probabilities obtained by Eq. (7) for two different tanker sizes [78].

accurately produced the damage statistics for conventional ships. The same procedure was then used to produce the damage statistics for HSC. The result is a formula fitted to the statistical data which expresses the rule damage length as a function of the ship's kinetic energy, the raking resistance of the bottom, the width and height of damage in the rule and the probability of survival.

The procedure proposed in [77] is an example of a development of rationally based criteria for estimation of grounding damages once grounding has taken place. It is easy to use and it is possible to use the approach as a design tool to improve the grounding resistance of a given new type of vessel and to compare the resistance between different types of vessels.

Examples of structural Risk Control Options (RCO) related to grounding are as follows.

- Increased scantlings in the double bottom
- Increased double bottom height
- Varying double bottom height such that the double bottom height is higher in the forward part of the ship
- Middecks in tankers to reduce oil outflow
- Unidirectional stiffened hull to delay fracture

Mitigation of the consequences of grounding accidents is normally achieved through definition of a certain double bottom height, see Paik [68], through appropriate arrangement of cargo and fuel tanks, and through a limitation of tank sizes, see Tavakoli et al. [79].

7. Conclusions and further work

Accident statistics show that collision and grounding events are some of the most frequent causes of serious accidents at sea and therefore also the most important elements in any risk summation procedure for ships.

Collision and grounding safety is at present implemented in the maritime industry by compliance with prescriptive, history-driven rules and regulations used by designers and operators and verified by classification societies and Port State Control. Thus, the development of these rules is motivated by accidents and implemented to satisfy societal concerns following the event of past accidents.

However, rational risk based analysis procedures have been used with success in connection with design and approval of offshore structures and large bridges crossing international waterways. Therefore, it seems appropriate that the international shipping community should also standardise decisions concerning elements in risk acceptance criteria. That is, establish agreement on a general form of risk criteria such as Eq. (1) and then establish a suite of connected rational tools for

- Estimation of the grounding and collision probability
- Models for calculation of the resulting grounding and collision damage
- Analysis of the conditions of the damaged vessels
- Estimation of costs associated with the accidents

With such tools it is possible to facilitate increased collision and grounding safety through rational selection and development of different risk control options.

It has been the purpose of the present paper to demonstrate that the research community has developed much of the needed basic research work. What is still needed is a concerted effort to identify gaps in our knowledge and then to integrate this knowledge into risk based procedures for ship operation and ship design. The goal should be development of new rules based on international formal safety assessment analysis (FSA). A number of FSA analyses following the procedure described in Fig. 2 have been presented to IMO in recent years, see for instance Ref. [6]. Thus, the framework for collision and grounding risk evaluation exists. At present, it is the absence of agreed on, consistent, mathematically based analysis tools which makes the current risk analyses based on expert judgments and historically based comparisons somewhat subjective and often gives rise to discussions.

A framework for introduction of such rational procedures for grounding and collision safety exists within IMO and the classification societies.

The International Maritime Organization (IMO) is developing “Goal Based Standards” (GBS) for new ship constructions. By the concept of Goal Based Standards, IMO attempts to define certain “high level” goals that must be met. Since this effort is still at an early stage, the current discussions at IMO could be extended to the performance of ship’s structures in collisions and groundings.

Traditionally, IMO and various maritime administrations have not developed structural standards. Instead, they have relied on classification societies to develop such standards. The recent Common Scantling Rules developed by the International Association of Classification Societies (IACS) have resulted in new structural design codes for tankers and bulk carriers. The development of these common rules clearly shows the tendency of moving towards limit state design. Therefore, a logical future step should be to consider also the most important Accidental Limit States (ALS), including collisions and groundings, in these Common Structural Rules.

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