

# Performance Based Criteria for Ship Collision and Grounding

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*It is the purpose of the present paper to outline a probabilistic procedure whereby the maritime industry can develop performance based rules to reduce the risk associated with human, environmental and economic costs of collision and grounding events and identify the most economic risk control options associated with prevention and the initial phases of the events.*

## KEY WORDS

Risk analysis; Ship Collisions; Grounding,

## INTRODUCTION

The annual frequency of serious ship accidents has been increasing in recent years. According to statistics from Det Norske Veritas (Editorial 2008) then a ship is twice as likely to be involved in a serious grounding, collision or contact accident in 2008 as it was in 2003. In addition the economic cost per accident also increased significantly during the same time period. Although collisions, grounding and contact events account for 60% of the most costly ship accidents IMO and Classification rules for building vessels do not explicitly refer to these accidents.

Due to the high economic, environmental and human costs for ship collisions and grounding it is the purpose of the present paper to outline a probabilistic procedure whereby the maritime industry can develop performance based rules to reduce the risk associated with collision and grounding events and identify economic risk control options related to prevention and structural damages.

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 design and operations. Without a proper evaluation criterion it is not possible to find the balance between safety in terms of risk reduction and the cost to the stakeholders. Such an evaluation criterion will give hard as well as soft boundaries for the choice of risk control options.

Any risk evaluation criterion must include the probability of the considered hazard. Therefore, the second step is to develop tools to determine the statistical probability that collision and grounding events will take place. Probabilistic analyses must involve identification of a number of different collision and grounding scenarios, each one 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 times the probability of its occurrence.

The probability of the occurrence of collision and grounding events may be computed from historical data, expert opinions and predictive calculations. Historical data provide realistic figures which nevertheless are difficult to use for future predictions since they are relevant to ship 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 is an important first step for a rational risk assessment procedure and procedures for selection of the most effective risk control options. A number of frequency prediction models have been developed during recent years.

Usually the most cost effective way to reduce risk is by reducing the probability that adverse events take place.

The third step in that part of the risk analysis which deals with collisions and grounding hazards is to determine the consequences given that an event takes place. Mitigation of the consequences of such accidents is to day usually achieved through defining a certain distance between inner and outer bottom, defining appropriate subdivisions for survival in case of flooding (Zhang et.al. 2004), appropriate arrangement of cargo and fuel tanks etc. It is difficult to assume that the statistics from the past collision and grounding events are sufficient to be used to predict probabilistic damage distributions in new generations of mega large container vessel or for the new generations of large LNG carriers (Vanem et..al. 2007a), vessels carrying irradiated fuels and large passenger vessels (Vanem and Skjong 2004, Vassalos 2008). 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.

The paper shows that the research community has developed a number of basic analysis tools for:

- Criteria to regulate the risk associated with fatalities and to some extent oil pollution from tankers (Ditlevsen and Friis-Hansen 2005; Skjong 2008; Vanem et al 2007a and b; Sames and Hamann 2008).
- Prediction and measures for reduction of the probability of collision and grounding events (Friis-Hansen and Pedersen 1998, Friis-Hansen et al 2004, Kaneko 2004; Lützen and Friis-Hansen 2003; Vanem et al 2007c; Itoh et al 2007, Ravn 2008)
- Derivation of damage distributions from collision and grounding scenarios using mathematical models (Amdahl et al 1995, Pedersen et al 1996, Lützen 2001, Tagg et al 2002, Pedersen & Li 2008)
- Small- and large-scale collision and grounding experiments (Sterndorff and Pedersen 1996; Törnquist and Simonsen 2004)
- Prediction and measures for reduction of collision and grounding damages (Brown 2002; Lützen et al 2000; Otto et. al 2002; Tagg et al 2002; Yamada et al 2007 and 2008; Zhang 1999)
- Prediction of consequences following collision or grounding in the form of stranding, oil outflow, capsize, hull girder failure, residual stability in waves etc. (Tavakoli et al 2008, Vasalos 2008)
- Examples of actual ship designs with improved structural resistance to collision or grounding (Vredevelt et al 2004; Yamada et al 2008; Ehlers et al 2007; Zhang et al 2004)

In spite of these comprehensive research results the role of IMO, classification societies, and other regulatory bodies in developing safer ships based on rational risk assessment has not yet been formulated. The assemblage of the developed analytical tools to make it possible to quantify potential ship – ship collision events and ship grounding hazards in a rigorous way into a comprehensive suite of programs and procedures is still missing. 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 rules to reduce the risk associated with collision and grounding events.

Such rules are proposed used in two ways. For ships where the consequences of collisions and grounding are large such as passenger ships that carry thousands of lives or ships carrying cargo that is especially harmful to the environment, large LNG vessels etc. rules should be developed for specific rational mathematically based risk assessment procedures. Such procedures are proposed developed for each project along the same lines as currently done for offshore structures or large bridges. For more normal types of vessels then similar mathematical models should be used to outline formal safety assessment procedures (See IMO MSC83/INF.2) in order to

develop consistent, rationally based rules which reflects the evolution of ship operation, design and materials.

Whereas risk due to collisions and grounding are not yet explicitly considered in design of ships except for some special cases such as the class notation COLL from Germanischer Lloyd (2004), the DNV rules for compressed natural gas carriers, IMO rules for vessels carrying irradiated fuels, rules for bunker oil fuel tanks in large containerships, and a European agreement concerning international carriage of Dangerous goods by inland waterways, see Samuelides et al (2008), then the situation is different within the offshore field. The offshore industry has established systematic assessment procedures for fixed platforms that address the probability of occurrence, risk ranking, structural analyses, and acceptance criteria.

As an example API recommends evaluating the structural performance of (fixed) platforms that suggest a high risk to life safety and/or the possibility of failure when there is a fire, blast or accidental collision loading. An API Recommended Practice (2000) specifies the following assessment tasks for evaluating the events (fire, blast, and accidental loading) that could occur to the platform over its intended service life and service function(s):

1. Assign a platform exposure category for the platform
2. Assign risk levels to the probability of the event
3. Determine the appropriate level of risk for the selected platform and event
4. Conduct further study or analyses to better define the risk, consequence and cost of mitigation
5. Reassign a platform exposure category and/or mitigate the risk or the consequence of the event
6. Assess structural integrity if the platform is considered high-risk

A summary of offshore design codes that are related to design of offshore structures against ship collision is presented in Wang and Pedersen (2007).

A procedure for design against ship collisions of large bridges crossing ship lanes is presented in Pedersen 2002.

## RISK ACCEPTANCE CRITERIA

Every year ship collisions and grounding cause loss of hundreds of lives, economic loss, environmental damage and other unwanted events. Therefore, one of the many performance goals during the design phase of ships should be to ensure that serious accidents and service disruptions are low enough to be acceptable to owners, the public and those responsible for public safety.

It is indispensable that collisions 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. That is, the design of the ship must meet risk levels which are judged to be so low that risks are of little concern to users and 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 the hazards. 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. In order to solve this problem and to introduce evaluation criteria for making decisions related to risk reduction a common measure such as monetary values are often introduced. Thus a risk definition could have the form:

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

where the sum is over all the consequences  $C_i$  related to the hazard  $H_i$  and  $P_i$  is the probability of the  $i$ 'th consequence. The function  $U$  is a utility function which expresses the consequence in some common measure, such as the 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 should also depend on 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.

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

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

In a very comprehensive report by Skjong (2008) criteria used by IMO and other organizations 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 and moreover the general ALARP (As Low As Reasonably Practicable) risk management shall be applied. Fig. 1 illustrates the principle of this criterion.

The last-mentioned 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 1 person every 10 years due to risk aversion of the society.

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, see Fig. 1. 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 3 million US \$ per fatality.

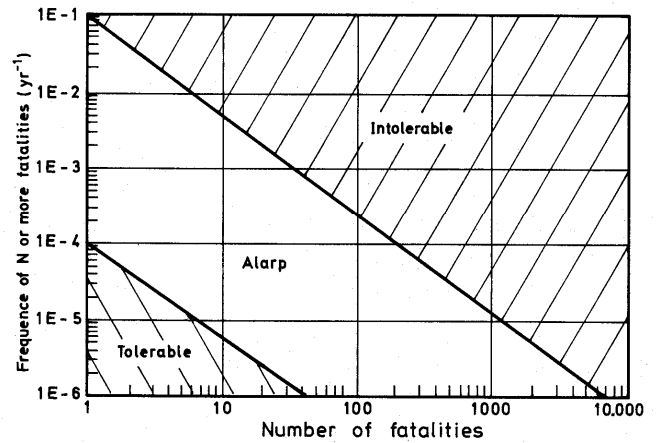


Fig. 1 Typical risk acceptance criterion, F-N diagram (Pedersen 2002).

Similarly, ALARP criteria have been used by authorities to reduce accidental oil spills from tankers. Here the cost for preventing an oil spill accident must be based on the cost of oil, the clean up cost, the environmental damage cost etc. (Sames and Hamann 2008)

Authorities like IMO, IACS, national administrations etc. normally focus on these two types of risks. That is, mandatory, generic rules and regulations are sought developed based on criteria for fatalities on one hand and on the other hand generic rules are imposed to limit environmental (oil spill) impacts.

Thus, so far the ALARP principle has been applied separately for fatalities and for environmental impacts when considering new rules. The general costs associated with severe accidents have not been considered. For the operational phase the International Safety Management (ISM) code could be an instrument to assess this risk level.

In the region where the ALARP principle governs fatalities, environmental damage as well as economic loss should be considered at the same time, 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.

To improve marine safety the international marine community should standardize decisions concerning the elements in risk evaluation criteria for the ALARP region such as Eq. (1) as far as possible in order to facilitate comparison between different control options.

Since the dominant risk contributor for ocean going ships is collisions and grounding we shall in the following sections first describe how mathematical models can be established for prediction of the frequency of such events. Thereafter, a number of sections are devoted to estimation of the structural consequences for the vessel given that a collision or grounding event has taken place.

## PROBABILITY OF GROUNDING AND COLLISION EVENTS

The most cost-effective way to reduce risk caused by collision and grounding is by reducing 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 event-chain as possible.

The limited number of analyses which have been performed on preventive measures related to reducing collision and grounding probabilities generally show 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 VTS systems are established around the world. Automatic Identification System (AIS) have been introduced, and systems have been developed for access of AIS information through the Automatic Radar Plotting Aid (ARPA). ECDIS with and without track control have been installed on new vessels. IMO has introduced requirements for new ships to fulfill particular maneuverability criteria. It is generally agreed that all these activities have considerable influence on the probability of ship accidents in the form of collisions and grounding. But so far very few rational analysis tools to quantify the effect of these changes have been available.

It is with this background that a number of researchers have worked on development of rational models for determination of the probability for ship collision and grounding accidents.

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

$$N_{ship-ship} = P_c N_a \quad (2)$$

The causation probability  $P_c$  is the fraction of the accident candidates that result in an accident.

## Probability of ship-ship collisions

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

Fig. 2. shows such two crossing waterways. In Pedersen et al (1996) is presented a calculation model for the number  $N_a$  of possible events where two ships will collide in the overlapping area  $\Omega$  if no aversive maneuvers are made. By summing all the class "j" ships of waterway 2 on collision courses with all relevant class "i" ships during the time  $\Delta t$  the following expression can be applied to calculate the number of blind ship collisions in a time interval  $\Delta t$  :

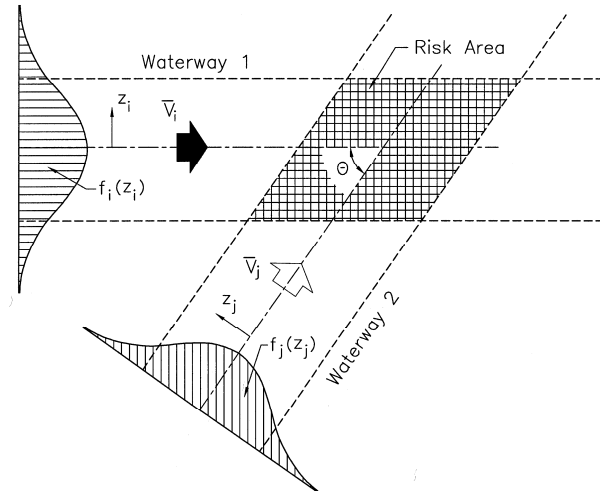


Fig. 2. Crossing waterways with risk area of ship-ship collision.

$$N_a = \sum_i \sum_j \int_{\Omega(z_i, z_j)} \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} \cdot f_i^{(1)}(z_i) f_j^{(2)}(z_j) V_{ij} D_{ij} dA \Delta t \quad (3)$$

Here  $Q_j^{(\alpha)}$  is the traffic flow (i.e. number of ships per unit time) of ship class  $j$  in waterway no.  $\alpha$ ,  $V_j^{(\alpha)}$  is the associated speed. The lateral distribution of the ship traffic of class  $j$  in waterway  $\alpha$  is denoted  $f_j^{(\alpha)}$ ,  $D_{ij}$  is the geometrical collision diameter defined in Fig. 3, and finally the relative velocity is denoted  $V_{ij}$ .

The overall ship traffic data 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. Similarly the spatial distributions  $f_j^{(a)}$  can be collected automatically from land based AIS stations. See Fig. 4.

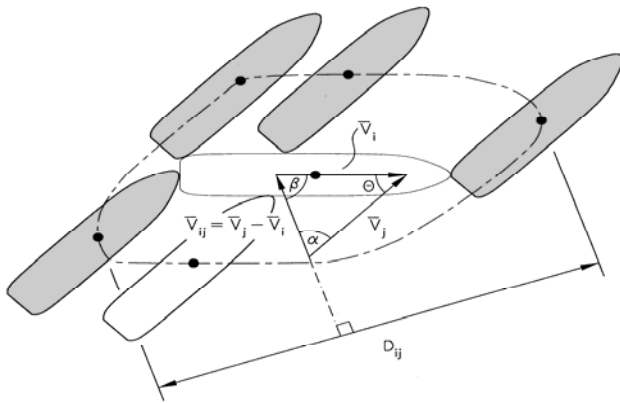


Fig. 3. Definition of geometrical collision diameter  $D_{ij}$ .

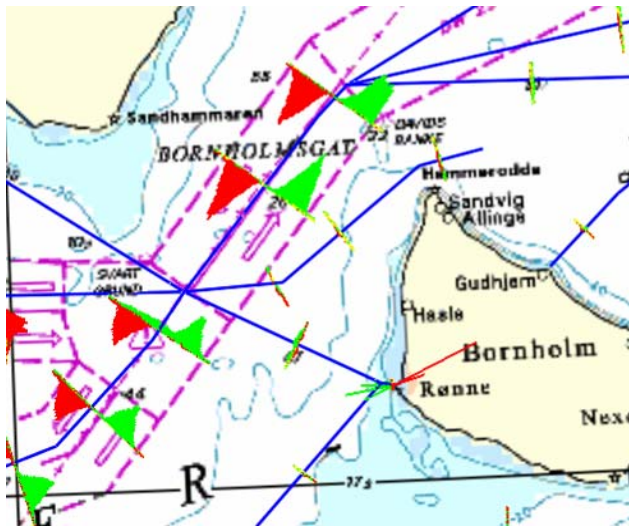


Fig. 4 AIS data used to determine lateral distribution of ship traffic after traffic separation. (Courtesy E. S. Ravn, Technical University of Denmark)

The causation probability  $P_c$  can be estimated on the basis of available accident data collected at various locations and then transformed to the area of interest, see Kaneko and Hara (2007). Another approach is to analyze 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 (Friis-Hansen and Pedersen 1998 and Itoh et al 2007, and Ravn 2008) and the Fault Tree approach for

calculation of the probability of ship-ship collisions. These methods constitute a basis for a possible future development of rational procedures for analyses of the effect of risk control options.

One example on an application 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 (Lützen and Friis-Hansen 2003). The evaluation was performed for vessels navigating in world-wide 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 analyzed. Two different bridge systems were compared, a conventional bridge and a bridge equipped for solo watch keeping. 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.

There is no reason why similar procedures cannot be used for evaluation of other types of risk control options which can influence the collision probability. Examples could be:

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.
- The effect of redundancy of navigational equipment.
- Effect of ship speed on causation factor (time to react, see Fig. 5)
- Effect of improved maneuverability on causation factor (time to react)
- Effect of reduced probability of engine blackout or rudder failure

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

- Effect of vessel traffic separation schemes, see fig. 6
- 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

Change in causation factor due changes in human behavior such as:

- Effects of manning
- Effect of simulator training
- Effect of psychological screening of navigators

There is a need for further research to establish reliable and rational mathematical models for estimating the frequency of collision and grounding events as function of traffic separation

schemes, aids to navigation, bridge manning, training of navigators and new bridge components for safer navigation.

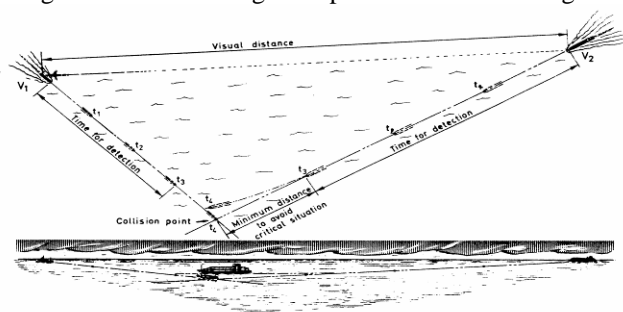
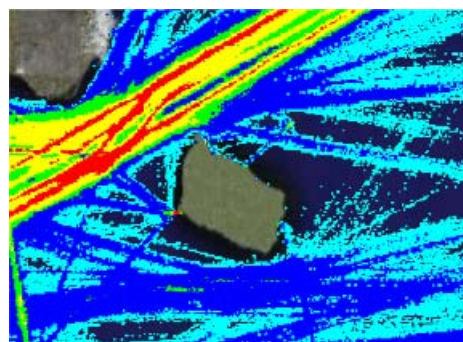
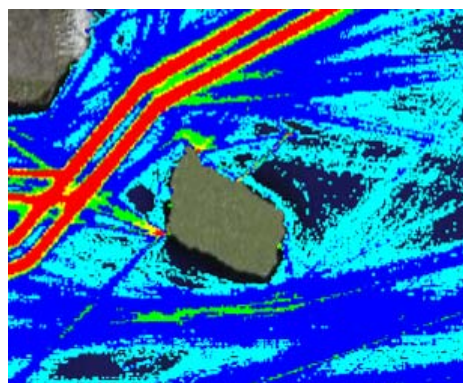


Fig. 5. Space-time model used as a basis for derivation of causation probabilities using Bayesian networks.



Before traffic separation



After traffic separation

Fig. 6. The effect of routing measures in the sea area between Sweden and the Danish island Bornholm in the Baltic. Traffic before and after implementation of traffic separation (Courtesy E. S. Ravn, Technical University of Denmark)

### Probability of grounding and collision with fixed offshore structures

To determine the probability of grounding another mathematical model need to be developed and similar risk control options studied. The procedure should include power grounding where

the ship is running a ground with forward speed but also drift grounding for disabled ships.

Such a model for calculation of the grounding probability  $P_g$  could be developed in similar way to the method described above for ship-ship collisions. 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. 7.

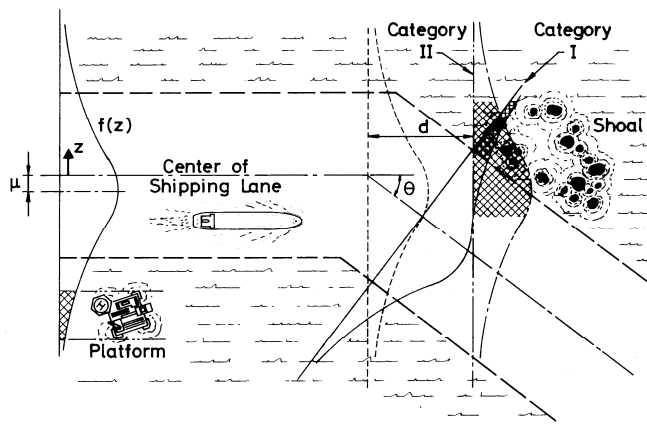


Fig. 7. Principles for estimation of probability for collision with offshore structures and grounding.

Again ship traffic data need to be collected showing the number of ships in the vicinity of the most important coast lines, and a procedure should be developed to characterize these coast lines. i.e. distribution of rocks, bottom profile data, tide variations etc. As indicated in Fig. 7 for calculation of the probability for collision with an offshore structure and/or grounding the collision model based on Eqs. (2) and (3) has to be augmented with a category 2 type of accident related to the probability that the vessel does not change course at bends in the shipping route together with further categories related to drifting vessels due to steering machine failure or engine black out. See Pedersen (2002).

Based on the principles for estimation of collision probabilities described above some computer programs have been written for calculation of collision probabilities in specific waterways where the ship traffic distribution is known. Among such available analytical tools to estimate the collision risk is the program GRISK developed by Technical University of Denmark (DTU) and Gatehouse. This software is a successor of the GRACAT software (Grounding and Collision Analysis Toolbox), see Friis-Hansen and Cerup Simonsen (2002). The features in GRISK are also important elements in the ongoing development of the IALA Waterway Risk Assessment Program IWRAP Mk2. Fig. 9 shows how the seabed topography can be introduced in the GRISK program.



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



Fig. 8. Defining grounds or depth curves with polygons in the GRISK program.

### PROBABILISTIC DISTRIBUTION OF ENERGY RELEASED FOR CRUSHING IN COLLISIONS

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

The characteristics of the energy released for damage depend on various aspects for a given collision scenario, namely the displacement and velocity of the struck and the striking vessel, the collision angle, the impact location and the coefficient of friction between the two vessels.

An analytical method for determination of the energy released for rupture and plastic deformation in the vessels in a given deterministic ship-ship collision has been developed by Pedersen and Zhang 1998. Here the energy loss for dissipation in structural deformations is given in closed-form expressions.

The procedure is based on a 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 are supposed to have forward motion, and the influences of the hydrodynamic forces due to the sudden deceleration of the involved vessels are in this model approximated by simple added mass coefficients.

Fig. 9 shows the calculated energy released for crushing of two colliding RoRo vessels, both with an initial speed of 10 knots, at

different collision angles and striking locations along the hull girder of the struck vessel. From this figure it is seen that for given ship speeds the assumed impact location and angle distributions play a significant role for the amount of energy released for crushing of the two vessels.

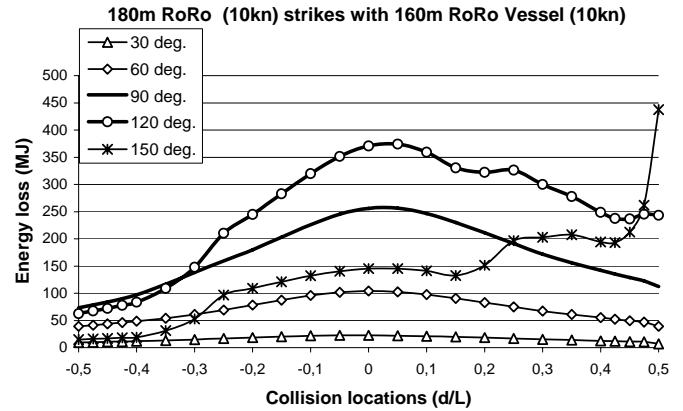


Fig. 9. Energy loss of a 180 m RoRo ferry striking a 160 m RoRo vessel at different collision angles and locations.

Based on the mathematical model for analysis of the probability of collision presented here and the above mentioned analytical model for the energy released for crushing a set of energy reference values have been calculated in Lützen (2001) for specific struck vessels in various shipping routes around the world using assumed probabilistic distributions for ship speeds, meeting angles and striking locations.

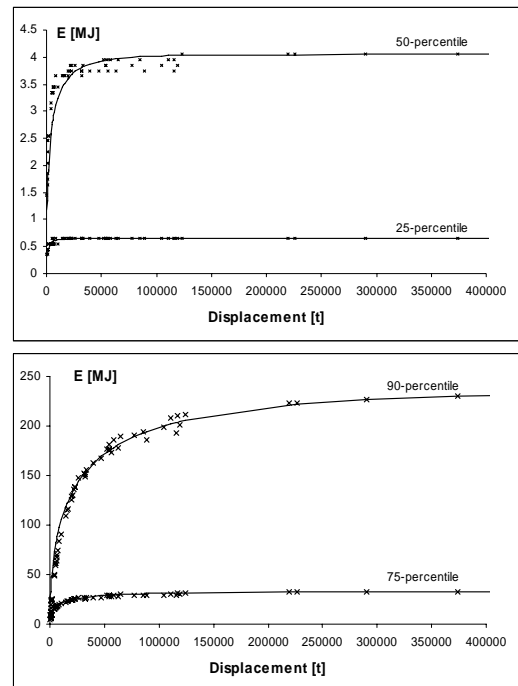
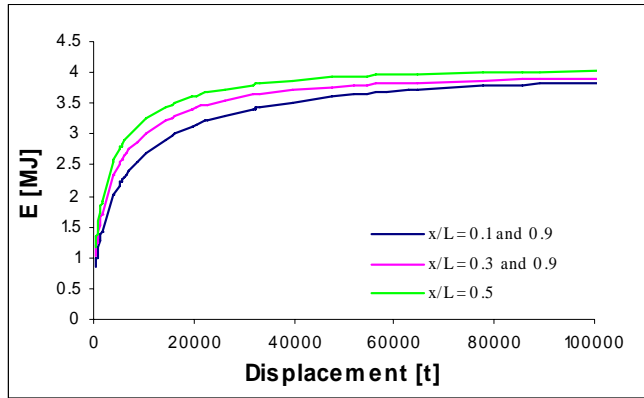
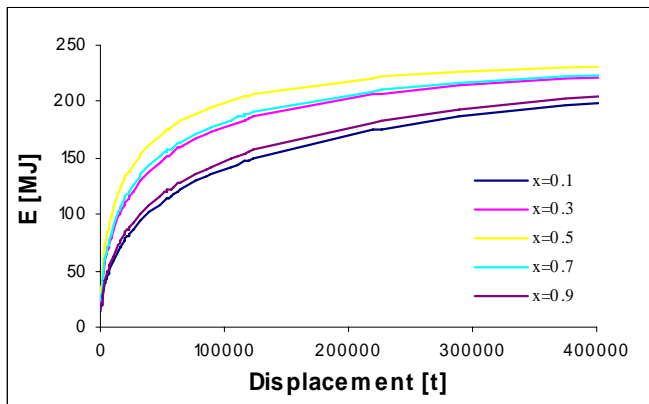


Fig. 10. The 25- 50-75 and 90 percentile value for energy to be absorbed amidships versus displacement of struck vessel given a collision takes place. (Lützen 2001)

For world wide trade the probabilistic distribution of the energy absorbed by structural damage given a collision takes place can be described as function of displacement of the struck vessel. For a striking location amidship of the struck vessel the 25-, 50-, 75- and 90-percentile values of the energy to be absorbed are shown in Fig. 10. For other striking locations the calculated energy reference values are given in Fig. 11. It is noted that the calculated energy level is highly dependent on percentile values.



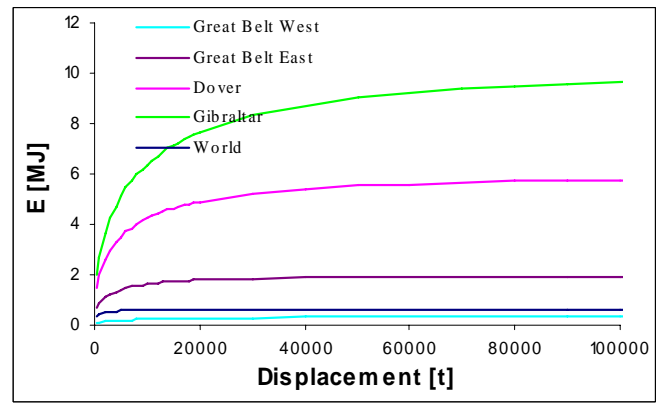
50-percentile



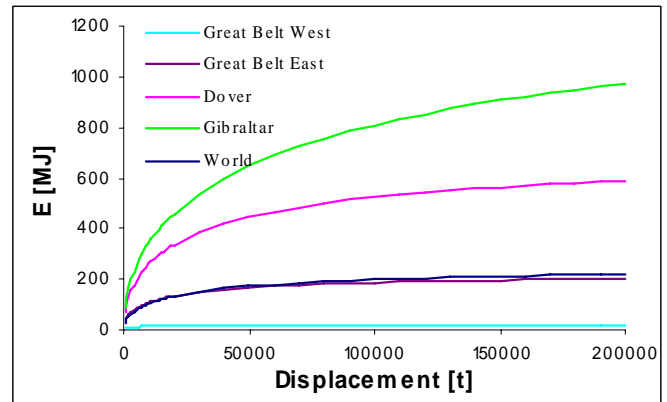
90-percentile

Fig. 11. The 50-percentile value (upper) and 90-percentile value (lower) for energy to be absorbed as function of displacement of struck vessel and the striking location. (Lützen 2001).

Fig. 12 shows 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. But when calculating the energy reference values it seems reasonable to choose the striking vessel from the world distribution for several reasons. The world distribution relates to the average collision candidates, whereas the distribution from specific routes represents the ships for that particular area only. However, for vessels in fixed routes in trafficked areas, it would be more relevant to use route specific energy reference values.



25-percentile



90-percentile

Fig. 12. The 25-percentile value (upper) and the 90-percentile value (lower) for energy to be absorbed amidships versus displacement and different routes. (Lützen 2001).

## STRUCTURAL DAMAGE IN GIVEN COLLISION SCENARIOS.

Knowing the probabilistic distribution of energy released for crushing the next step in a rational collision analysis procedure is to determine the resulting distributions of structural damages on the ships involved.

Here simplified, deterministic crushing analysis methods suited as procedures within Monte Carlo simulation schemes are needed for rapid calculation of the collision forces and the resulting energy absorption in the ship structures as function of penetration distances.

Several such simplified analysis tools to predict the damage of struck ships as well as striking ships have been developed (See Friis-Hansen and Cerup Simonsen 2002, Lützen et al 2000,



Brown 2002, Sajdak and Brown 2005, and Yamada et al 2007). These tools all calculate the structural deformation for both the striking and the struck ship independently using rigid-plastic simplified analysis procedures. That is, a rigid bulbous bow is assumed in order to estimate the structural resistance of a struck ship side, see Fig. 13, and similarly a rigid struck ship side is assumed to estimate structural resistance of the bow of the striking ship.

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

- 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 bottoms
- Crushing of bulkheads

By analyzing damage resistance of each basic structural element and adding their contributions together, the total collision resistance and dissipated energy of ship sides can be determined. See Fig. 13.

For calculation of crushing forces and energy absorption of ship bows similar simplified methods to estimate mean axial crushing forces of plated structures can be applied, see Pedersen et. al. 1993. In Yamada and Pedersen (2008) a benchmark study is presented of different simplified procedures for analysis of axial crushing of bulbous bows. A 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 a bow structures subject to extreme loads. However, it should be emphasized that the limit analysis is an approximate method. A basic assumption is that the material is perfectly plastic without strain hardening or softening.

As an example of the level of accuracy which can be achieved by the calculation method and the formula used in the simplified procedure SSCAT (Yamada & Pedersen 2007) we can consider a case where the developed tool was verified by comparison with detailed FEA results for a collision scenario, see Fig. 14, where a VLCC in ballast condition collides perpendicularly with the mid part of another D/H VLCC in fully loaded condition. The calculations are performed for a standard bow and for a softer (buffer), bow on the striking tanker.

The calculated combined contact force and the total absorbed energies are shown in Fig. 15. The horizontal axis shows the total displacement of both ships, which is nearly equal to the change in distance between the centers of gravity of the ships.

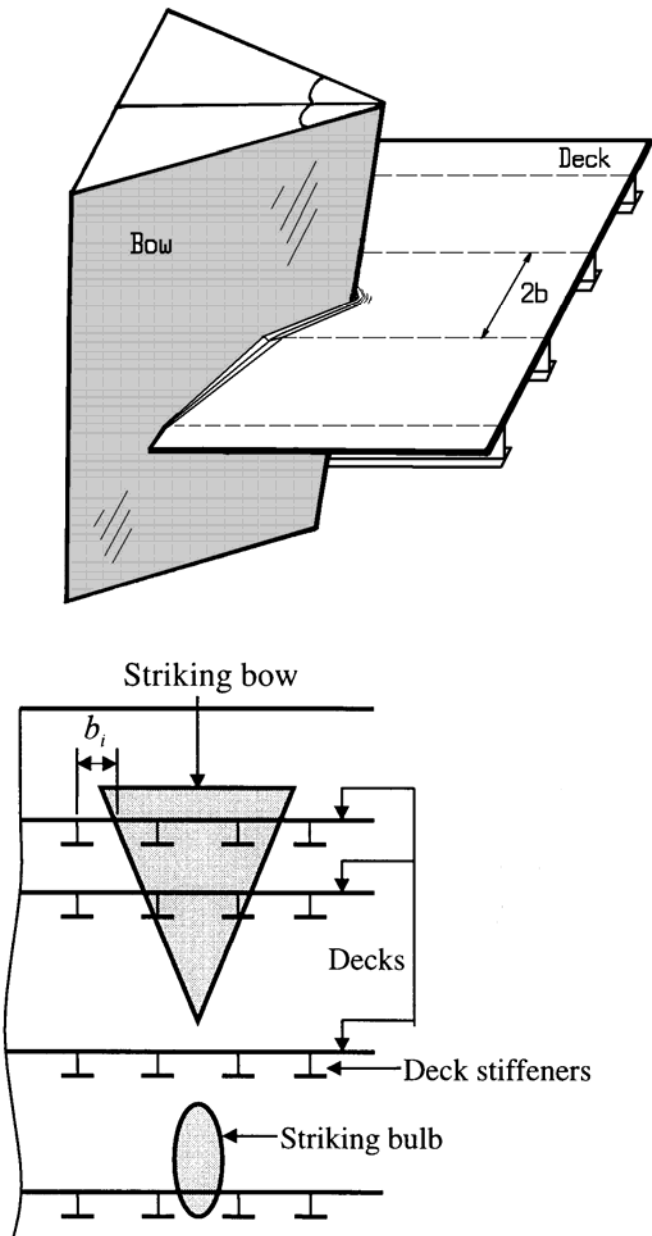


Fig. 13. Simplified structural model for estimation of crashworthiness of a ship side for rigid bow penetration. (Zhang 1999)

For such simplified crushing analyses the ship structures may be viewed as an assembly of plated structures such as shell plating,

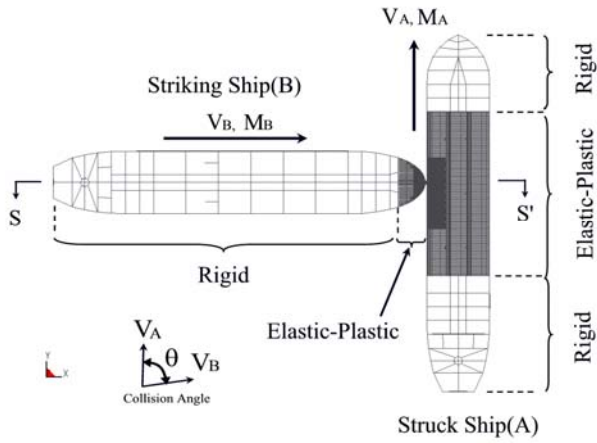


Fig. 14. Illustration of FEA analysis of a collision (Yamada et al 2008)

seen in that a simplified procedure such as SSCAT gives relatively good estimates of the mean contact force and especially the absorbed energy as function of the penetration.

In Lützen (2001) probabilistic results from comprehensive numerical Monte Carlo based simulations of ship collisions is presented. Here fifteen different struck vessels in world wide traffic have been subjected to numerical damage analyses based on input distributions of striking locations, angles and velocities using a simplified structural damage model. The numerically obtained damage lengths and penetrations are compared with damage distributions obtained from damage databases collected during the Harder project. To account for the fact that not all accidents are properly registered it is assumed that only one third of the penetrations smaller than  $0.1B$  are reported to the international ship damage databases. With this assumption the simulated cumulative distribution functions for the non-dimensional cumulative distribution functions for the non-dimensional damage lengths fits very well to the observed damages as shown in Fig. 17.

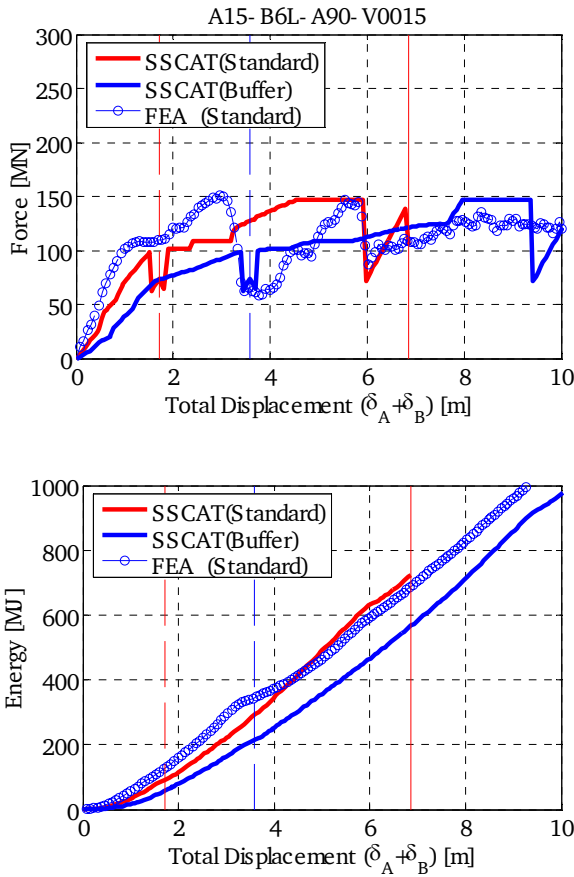


Fig. 16. Combined force-displacement and energy-displacement curves for a standard ship bow and a soft (buffer) bow calculated by a simplified method (SSCAT). FEA results are the case for standard bow. (Yamada et al 2007)

These curves are compared with results obtained by FEA where the striking ship is equipped with a standard bow structure. It is

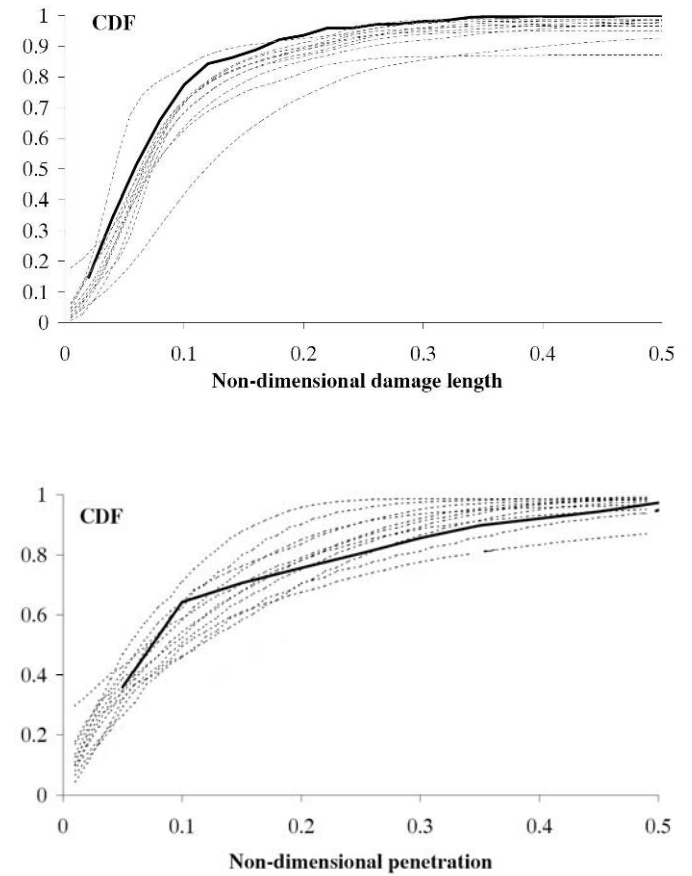


Fig. 17. Comparison of simulated cumulative distributions for non-dimensional damage lengths and penetrations for 15 different ships (thin dotted lines) and observed data (full thick line). (Lützen 2001).

As an example of a rational analysis of a possible structural risk control option a similar procedure has been applied by Yamada et al (2007) to determine the expected effect of buffer bow structures on the distribution of collision damages to struck tankers.

As indicated then we now have the tools to determine the probability of having a collision on a given route and we have tools to determine the distribution of collision damages given we have a collision and also models for some important consequences 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 get better tools for determination of optimum risk reduction measures, see Vassalos (2008).

## STRUCTURAL DAMAGE ESTIMATES IN GIVEN GROUNDING SCENARIOS

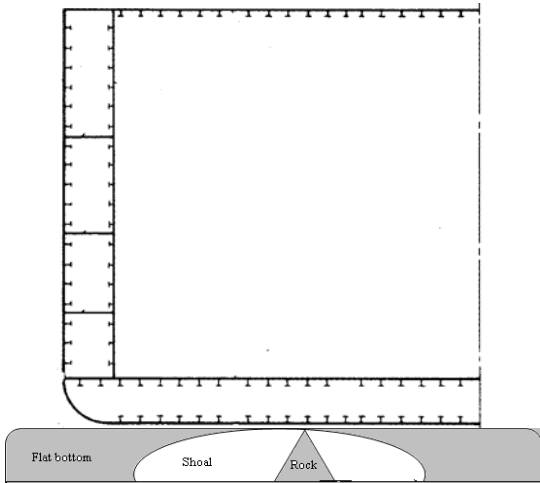


Fig. 18. Powered grounding on inclined slopes,, shoals or sharp rocks.

Grounding events may be powered groundings or it may be drifting groundings. At the same time many quite different grounding scenarios can be expected for instance on sandy or flat hard slopping bottoms, on shoals, or on different types of sharp rocks. See Fig. 18.

In the case of grounding on flat hard bottoms or sandy beaches the initial kinetic energy of the vessel will be spent in lifting the ship and on friction between the ship and the sea bottom. This type of grounding will normally not lead to significant damage of the inner bottom on the vessel. However, due to the lifting of the vessel, see fig. 19, possibly in combination with additional hull girder loading due change in tide and wave action then this type of grounding can easily cause excessive hull girder shear

loads and bending moments.. See Pedersen (1994), Sterndorff and Pedersen (1996); Simonsen and Pedersen (1997), Brown et al (2004), and Alsos and Amdahl (2008). The analyses (Pedersen 1994) have shown that for grounding on plane soft or hard grounds the induced hull sectional forces increase strongly with ship size.

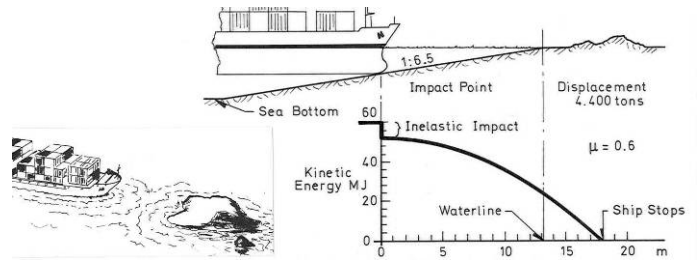


Fig. 19. Powered grounding on a flat sand or rock bottom.

Grounding on uneven rock bottoms will normally cause local damage to the double bottom structure and the major part of the initial kinetic energy will be absorbed through plastic deformation as in the case of collision events. Simonsen (1997a and b). 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. See Fig. 20.

Alsos and Amdahl (2008) 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 bottom using the tools developed for collision analysis. Assuming a uniform pressure distribution between the shoal and the ship bottom the horizontal force component  $F_x$  can easily be estimated. The effect of Coulomb friction is added to this expression and the total sliding friction becomes

$$F_{xtot} = F_x + \mu F_z = F_x + \frac{1}{2} \mu F_R \quad (4)$$

A comparison with numerical FEA shows a very good accuracy of this Minorsky 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. (Pedersen and Zhang 2000a and b; Simonsen and Törnquist 2004).

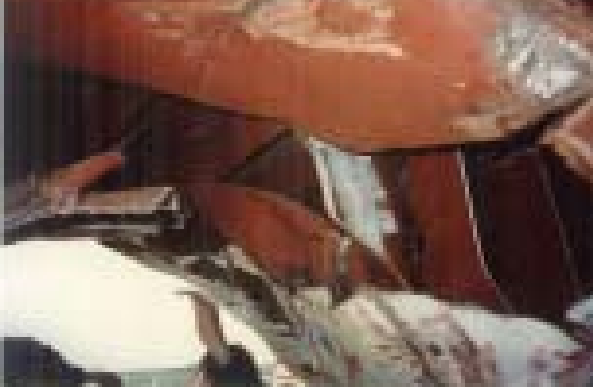


Fig. 20. Tearing damage of a double bottom

In order to translate historic damage data into data which can be representative for 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

$$\frac{1}{2} M \cdot V^2 = F_{xtot} \cdot L_{dam} \quad (5)$$

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 normalized by the ship length,  $(L_{dam} / L)$ , can be expressed as

$$\frac{(L_{dam} / L)_1}{(L_{dam} / L)_2} = \frac{M_1}{M_2} \cdot \left(\frac{V_1}{V_2}\right)^2 \cdot \frac{L_2}{L_1} \cdot \frac{F_{2xtot}}{F_{1xtot}} \quad (6)$$

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

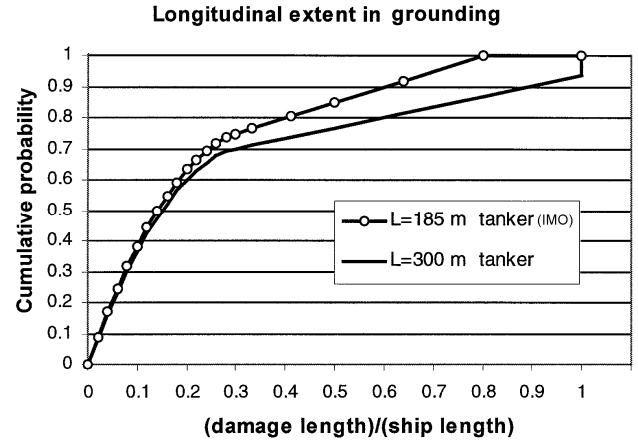


Fig. 21. The translated cumulative probabilities obtained by the present method for longitudinal extent with different ship sizes in grounding (Pedersen and Zhang 2000a)

That is, the analytical expressions for raking damages caused by grounding on irregularly shaped rocks show that larger ships will suffer relatively larger grounding damages. The analysis shows that the fundamental assumptions behind the IMO recommendations for grounding damage distributions for tankers do 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, Simonsen and Törnqvist (2004a) have developed a proposal for new grounding damage rules for High Speed Crafts (HSC). They based 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 exist and since ship grounding is highly stochastic in nature they used a Monte Carlo simulation procedure to calibrate their model such that it 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 express the rule damage length as function of the ship 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 by Simonsen et al (2004b) is an excellent 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.

Mitigation of the consequences of grounding accidents is normally achieved through definition of a certain double bottom

height, through appropriate arrangement of cargo and fuel tanks and through a limitation of tank sizes.

## CONCLUSIONS AND FURTHER WORK

Accident statistics show that collision and grounding events are some of the most frequent causes for serious accidents at sea and therefore also the most important element 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. That is, the development of these rules is motivated by accidents and implemented to satisfy societal concerns following the event of 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 also should standardize decisions concerning elements in risk acceptance criteria. That is, establish an agreement on a general form of risk criteria such as Eq. (1) and then establish rational tools for

- Estimation of the grounding and collision probability
- Establish models for calculation 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 a rational selection and development of different 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, see for instance the Proceedings of the International Conferences on Collision and Grounding of Ships held in San Francisco 1998, Copenhagen 2001, Izu 2004, Hamburg 2007 and the next is planned for Helsinki in 2010, where many tools are made available to investigate various aspects of damage due to collision and grounding.

What is still needed is a concerted effort to identify gaps in our knowledge and then to integrate the knowledge into risk based procedures for ship operation and ship design. The goal should be development of new rules based an international formal safety assessment analysis (FSA) including the normal elements in the form of expert judgment, identification of hazards, evaluation of risk control options and costs and benefits.

A framework for introduction of such rational procedures for grounding and collision safety exists.

The International Maritime Organization (IMO) is developing "Goal Based Standards" (GBS) for new ship constructions. Traditionally, IMO and various maritime administrations have not developed structural standards. Instead, they have relied on classification societies to develop such standards. However, through GBS, IMO is attempting to define certain "high level" goals that must be met. Since this effort still is in its early stages, the current discussions at IMO could be extended to the performance of ship structures in collisions and groundings.

Furthermore, 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), which includes collisions and groundings, in these Common Structural Rules.

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