

TANKER GROUNDING RESISTANCE

Jørgen Amdahl, Dept. of Marine Structures, The Norwegian Institute of Technology
Dag Kavlie, Dept. of Marine Structures, The Norwegian Institute of Technology
Atle Johansen, SINTEF, Structures and Concrete

ABSTRACT

A scenariobased design procedure for grounding and collision of tankers is outlined. It requires establishment of realistic accident scenarios for which the hull structural damage is calculated in order to determine possible puncturing of oil cargo tanks. A simulation model for the rigid body motion of a tanker during grounding is described, including a procedure for calculation of the contact force based on actual tanker bottom topology. Results from numerical analysis of two tankers illustrate the ideas behind the proposed procedure.

INTRODUCTION

The threat of pollution exists wherever tank vessels travel. Environmental protection has become an increasingly important issue internationally. As a reaction to the Exxon Valdez grounding we got the U.S. oil pollution act OPA 90, valid for all new tankers to call U.S. ports. The rules are rather primitive from a scientific point of view, simply specifying double hull for the entire ship. This has later been followed by similar international regulations issued by IMO.

There is, however, one important difference between the two. While OPA 90 specifies the double hull by given distances between inner and outer hull, IMO presents opening for alternative designs. Ships can be accepted provided it can be documented by a rational design procedure, that they have the same safety w.r.t. pollution as the conventional double hull. This will for example give an opening for the so-called middeck tanker, but also other designs.

The challenge is to develop a procedure for assessing the risk of oil pollution from a given design. This procedure must be approved by IMO. Rational design procedures against accidental loads is, however developed in related fields. In the design of offshore platforms, collision scenarios have to be considered. The aim of the present study is to discuss such a procedure, and present some elements that might constitute some first steps towards

development of a design oriented procedure against collision and grounding.

There are some basic features that we feel should be incorporated in such a procedure.

Realistic accident scenarios

Accident scenarios should represent situations that are as close as possible to those encountered by real ships. Accident statistics should be used to create the scenarios. Each scenario should be assigned a probability of occurrence. In the literature on grounding there is a tendency to concentrate on worst case accidents with an extremely small likelihood, i.e. knife like shape of sea bottom. Blunt shape of sea bottom is neglected, even if this is by far the most common in practice. The same goes with ship speed. Full speed grounding is assumed even if this is an extremely rare event, while drifting into rocks due to complex manoeuvring or loss of propulsion is much more common in real life.

Simulation of hull damage

A physically based simulation model for estimation of hull damage is important. The energy absorption of the hull structure must be realistically simulated. Horizontal as well as vertical extent of damage must be predicted for a given accident scenario. Some procedures previously presented are simply based on statistical data from accidents when it comes to evaluating damage length and penetration [1]. Particularly the latter is of vital interest when a double hull tanker is considered.

SUGGESTED DESIGN PROCEDURE FOR GROUNDING AND COLLISION

Grounding

A potential design procedure for grounding is sketched in Figure 1. It is closely related to the philosophy of designing according to the limit state of progressive collapse, which is extensively used for offshore installations.

The starting point is characterizing the ship by tank arrangement, principal dimensions, hull scantlings etc. In a grounding situation the ship is in a given load condition, (draught, trim) and exposed to associated still water bending moment and - shear force. The kinetic energy of the ship at the instant of grounding depends upon the total mass and speed.

The sea floor conditions at the site are obviously of paramount importance. These can vary from very soft conditions (clay, sand) to rigid objects like protruding rocks. At present very little information is available as to the distribution of soil conditions for different waters. Calculations have to be performed for selected conditions which may vary from knife-shaped rocks to shoals extending over the entire ship breadth. The shape of the obstruction in the longitudinal axis of the ship is also of importance.

For each of the grounding scenarios simulation of the ship rigid body motion is performed. Normally it will be sufficient to consider motion in the vertical plane, only (surge, heave, pitch). The rigid body motion depends upon the ship's mass of inertia and hydrodynamic properties, which in general may be influenced by shallow water effects. Furthermore, the contact force with the sea floor needs to be considered. This is created by plastic deformations of the bottom, potential cutting of bottom plating and friction. In particular, calculation of the contact force represents a challenge. Different sea floor conditions yield different deformation patterns resulting different demands on the calculation method. It is essential that the calculations reflect the actual topology of the ship bottom rather being based upon a generic structure.

A potential failure mode during grounding is overall collapse of the hull girder due to excessive bending moment or shear force. This has been studied for example by Terndrup Pedersen [2].

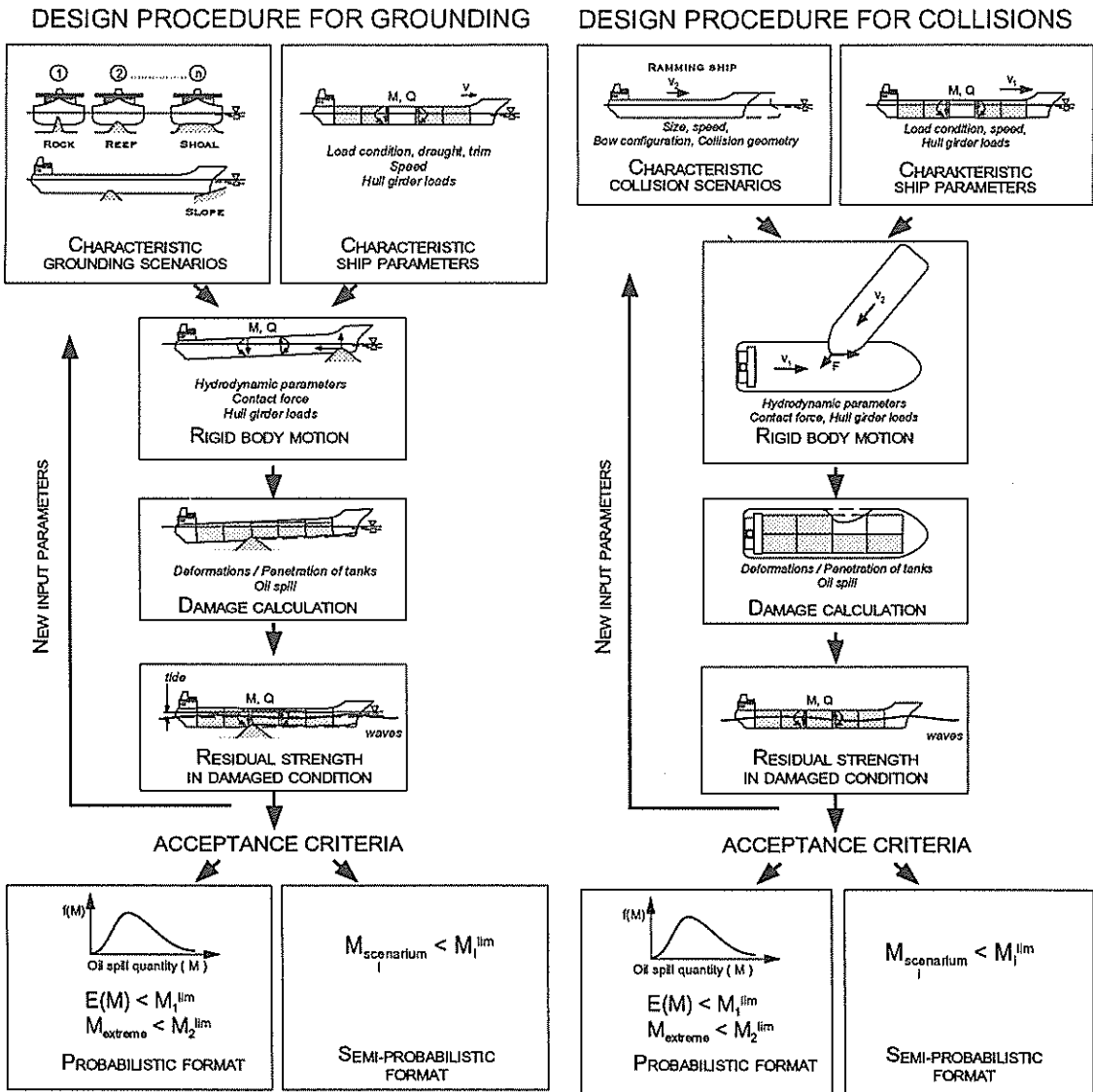


Figure 1 Suggested design procedure for grounding and collision

The simulation of the rigid body motion continues until the ship has been brought to rest or the obstruction has been passed. The key result is shape and amount of structural damage. Of primary importance with respect to oil spill is rupture/penetration of tanks carrying oil cargo. This constitutes the basis for calculation of oil outflow where hydrostatic balance etc. may be taken into account.

The next step in the procedure is assessment of the residual strength of the damaged ship. If the ship rests on the obstruction, further damage and additional hull girder loads may be caused by ebb tide and waves. Both waves and tidal changes may in itself cause additional oil spill. This is accelerated if the ship undergoes further damage.

Finally, the resulting damage/oil spill has to be evaluated against acceptance criteria. These may be expressed as limits to oil spill, both with respect to expected value as well as extreme value. For design purposes a semi-probabilistic format is useful, where a set of characteristic events are checked, rather than conducting full probabilistic analysis.

Obviously, there is a paucity of data describing the various grounding scenarios, especially with respect to sea floor conditions. Apart from carrying out surveys of actual conditions, screening of reported bottom damages could provide useful information. The benefit of analyzing a broad range of grounding scenarios is that the risk of creating sub-optimal solutions is minimized, i.e solutions which perform well for one particular grounding situation, but have poor properties for other events.

Collision

The design procedure for collisions follows the same principles outlined for grounding events. Most of the parameters governing grounding are relevant for collisions (tank arrangement, principle dimensions, load condition, speed etc.).

For the ramming ship the primary parameters are size and speed determining the kinetic energy, collision geometry (angle, longitudinal - and vertical positions of contact). The topology of the bow is crucial. A raked bow gives initial damage above still water load line. A bulbous bow may protrude forward of the forecastle deck. Bulbs tend to be very compact and is therefore inclined to penetrate deeply into the ship side with little damage to the bulb. Significant oil spill may result even for moderate collisions. From the point of view of oil spill prevention, softer bulb design is preferable. A possible solution is to introduce intentional imperfections, which do not affect the hydrodynamic properties and the resistance to lateral loads such as slamming, but trigger desirable axial, ductile collapse mechanisms in the bulb in the event of collision. It may also be argued that more frequent repair of bulbs due to damage in extreme weather should be accepted in light of the gain with respect to reduction of collision consequences.

The rigid body motion in collision is primarily governed by motion in the horizontal plane (surge, sway, yaw) and possibly roll. Closed form solutions for idealized events have been derived. Alternatively, numerical analysis may be performed, where the evolution of contact force can be traced more accurately. Again, the biggest challenge is to obtain a credible assessment of the contact force, which depend upon plastic deformations of both the ramming and the struck ship, friction etc.

Key results of the analyses are penetration and rupture of tanks, which form the basis for appraisal of oil spill. In principle, the residual strength of the damaged tanker under wave action may become critical. Further damage may cause increased spill. Most often, however, collisions may often occur in narrow and sheltered waters where wave effects are small compared to design values.

The acceptance criteria are similar to those described for grounding. Probably, it is easier in this case to quantify the expected frequency of the various collision scenarios enabling calculations both according to a probabilistic format and a semi-probabilistic format. The latter is probably more convenient for design purposes.

OUTLINE OF DAMAGE ASSESSMENT MODEL FOR GROUNDING

Even if the design procedures described above in principle are relatively straightforward, the practical execution of such analyses poses significant challenges. This is especially related to estimation of the damage to the bottom structure. Large plastic deformations, cutting of plating and transverse girders, friction and other extremely nonlinear effects need to be considered. In principle integrated analysis of the entire ship with a detailed modelling of the bottom structure taking sea-structure interaction into account could be performed. However, the demand for computer resources is still too high. Alternatively, the problem may be split into several sub-task, which may be solved sequentially:

- rigid body motion of the hull girder
- resistance to penetration of the bottom
- hull girder load-effect

By this strategy the complexity of each sub-task can be reduced significantly compared to the integrated approach. In addition it is easier to understand the governing physical effects at the different levels.

Rigid body motion

The rigid body motion of ships can generally be described by six coupled differential equations. In this context motions in the vertical plane will only be considered., in which case the problem reduces to three degrees of freedom, namely: surge, heave and pitch.

Furthermore, it is normal to assume that the hydrodynamic forces associated with surge motion are much smaller than the forces associated with heave and pitch so that the problem reduces to a coupled equation of motion for heave and pitch and an uncoupled equation for surge.

In a grounding situation the wave exciting forces can generally be assumed small. Thus, the exciting forces will be dominated by the grounding forces. As the ship moves over the obstruction as shown in Figure 2 the bottom plating with associated stiffeners, girders and floors will be displaced. The contact force has a lateral component as well as a horizontal component. The lateral component induces heave motion while both components contribute to the pitch exciting moment. This varies according to the location of contact relative to the ship centre of gravity.

In addition the lateral contact force induces a friction resistance which contributes to the pitch moment.

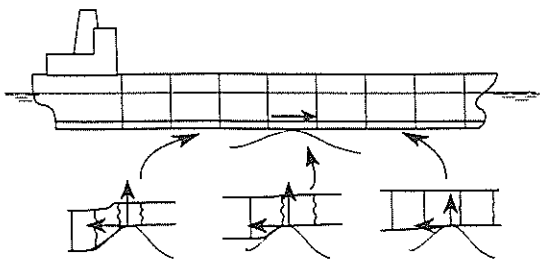


Figure 2 Model of the grounding process

With respect to the surge motion it is assumed that all hydrodynamic forces are small compared to the horizontal component of the grounding force and therefore can be neglected.

The equations of motion are simply solved by a numerical integration technique. The

major problem is related to determination of the grounding force which evolves during grounding and is not known a priori. The procedure adopted in the present study is based upon the following assumptions:

- The damage process is ductile and consists of deforming plastically the bottom structure a given distance according to the strength of the bottom and the rigid body motion of the ship. In the midship area it is assumed that both the lateral and horizontal components of the deformation force are fully determined by the amount of lateral indentation.
- The horizontal component of deformation force is calculated for various levels of lateral indentation. This analysis is carried out in two steps: First the obstruction is pressed into the structure up to the desired level of indentation. Next, it is moved in the longitudinal direction. For intermediate values of indentation depth the resistance is obtained by interpolation.

At each step in the simulation of the rigid body motion, the indentation of the obstruction into the bottom structure is calculated. This enables determination of the grounding force and the associated friction force. These forces are the input to simulation in the next time increment. The process is continued until the ship has come to a complete stop. The results of the calculations are damage in the forms of lateral indentations and plastic deformations/strains along the ship hull. The strains may be compared with a rupture criterion in order to determine whether puncturing of a cargo tank has taken place.

Resistance to lateral indentation of double bottom

The assessment of the resistance to lateral indentation for a double bottom is typically carried out in two ways:

- Nonlinear finite element analysis of a double bottom section, say within a tank.
- Synthesized resistance based upon nonlinear finite element - or simplified plastic analysis of double bottom components, e.g as described in [3].

The first method has the advantage that "all effects" are taken correctly into account. The other approach reduces the costs of computation considerably, but it may be difficult to define appropriate boundary conditions.

Finite element analysis of tanker bottom

Numerical analyses of the resistance to lateral indentation of the double bottom have been carried out for two tankers of 280,000 dwt and 36,000 dwt, respectively. The double bottom of the 280,000 dwt tanker is 4 m high and exceeds by far the present minimum requirements of IMO. It is primarily fitted with transverse girders and has only one longitudinal (centre) girder. Due to symmetry, only one quarter of the double bottom between centre line and the double side is modelled as shown in Figure 3. The lower section of the longitudinal bulkhead is included in the model along with the knee plates between the vertical - and bottom transverse girders.

The height of the double bottom of the 36,000 dwt tanker is 1.7 m. There is no longitudinal bulkheads. The girder system in the bottom is relatively homogeneous; the spacing between longitudinal girders is 3 m and the floor spacing is 2.4 m. As shown in Figure 4 the entire double bottom within a tank is modelled.

The analyses have been performed with the code DYNA3D, applying the 4 node shell element with a linear elastic- piecemeal plastic material model, where the stress strain relationships are matched with rule requirements to yield stress (245 MPa), ultimate stress (400 MPa) and rupture strain (0.2). Lateral indentation of the double bottom is simulated as an impact event assigning a kinetic energy to the impacting body sufficiently large to

penetrate the double bottom. In the present case the impact speed is 6 m/s. This may cause some dynamic magnification due to inertia forces, especially with respect to buckling of girder webs, but the effect is considered to be of secondary importance.

The rigid body representing the sea floor is assumed to be conical with a plane top section. Two different cone shapes are assumed:

Case I: Radius of top plane 1 m and cone angle 38.5° .

Case II: Radius of top plane 3 m and cone angle 11.9° for 280,000 dwt tanker

Radius of top plane 3.2 m , and cone angle 22.6° for 36,000 dwt tanker .

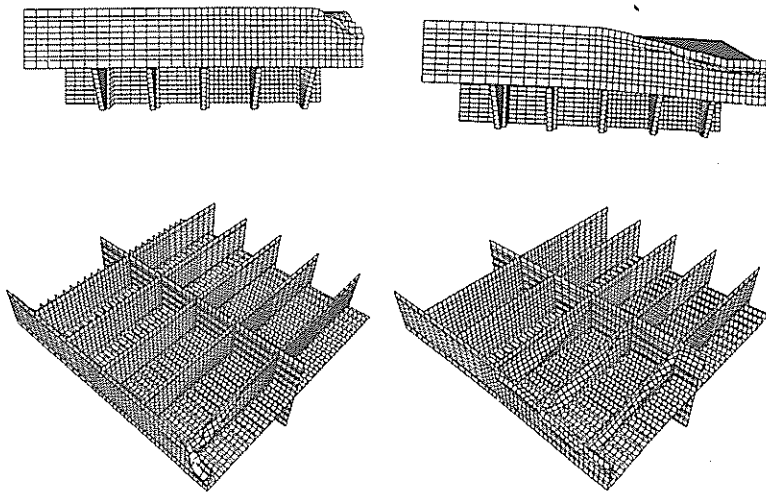


Figure 3 Finite element analysis of 280,000 dwt tanker

The results of the simulations are displayed in Figure 3 and 4. It is obvious that the shape of the obstruction has a significant influence on the resistance and the mode of deformation. In case I the deformations are very local and almost entirely confined to the volume described by the indented body. The displacement of the inner bottom is 90 mm and is purely elastic for the 280,000 dwt tanker and 170 mm with a strain of 0.1 for the 36,000 dwt tanker.

Rupture of the outer bottom occurs for 0.7 m (280,000 dwt) and 1.2 m (36,000 dwt) indentation. This causes an intermediate drop in the load-displacement curves, shown in Figures 5 and 6.

In case II the contact area becomes larger. The response of the girders now contains a significant contribution from the beam mode of deformation, which causes mobilization of the inner bottom plating. The maximum distortion and corresponding maximum strain in the inner bottom plating is 650 mm and 3.5% for the 280,000 dwt tanker and 1050 mm and 3.5% for the 36,000 dwt tanker. With the stress-strain curve adopted the tanks remain intact, but strain concentrations at welds and potential fatigue cracks may induce rupture. For both tankers the maximum strain in the outer plating is 13 %, below the rupture criterion presently used. Hence, a small cone angle reduces the strains level in the outer plating significantly.

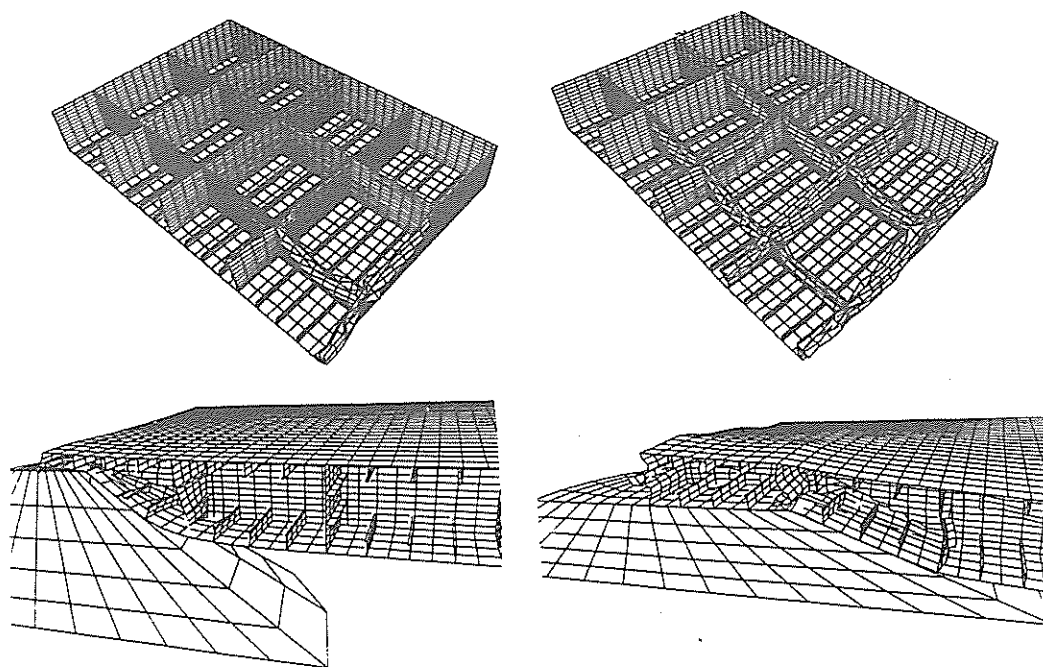


Figure 4 Finite element analysis of 36,000 dwt tanker

The absence of outer plating rupture, the increase of contact area and the earlier mobilization of the inner bottom all contribute to increase of the resistance to indentation as compared to case I. At one hand, the increased resistance is beneficial with respect to energy absorption. On the other hand, the distortion in the inner bottom plating may cause premature rupture of the tank and consequently oil outflow.

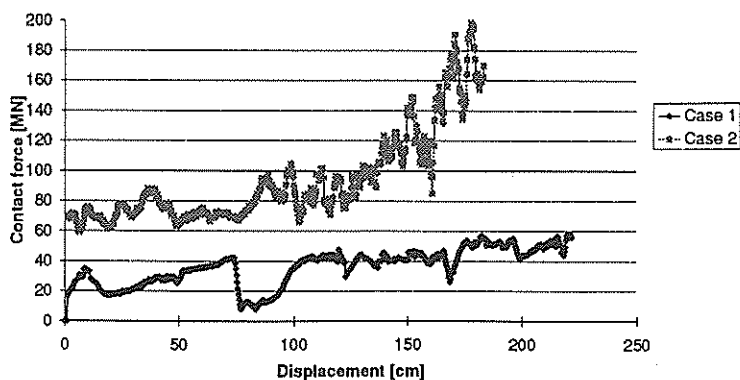


Figure 5 Force-indentation relationship for 280,000 dwt tanker

The CPU consumption a Cray-YMP super computer is typically in the range of 2-10 hours. This illustrates the heavy demands on computer capacity made by this calculations. The number of finite elements is approximately 10,000. Nevertheless, the element mesh is considered to be absolutely minimum for a reasonable representation of the deformation behaviour of the webs of the bottom girders.

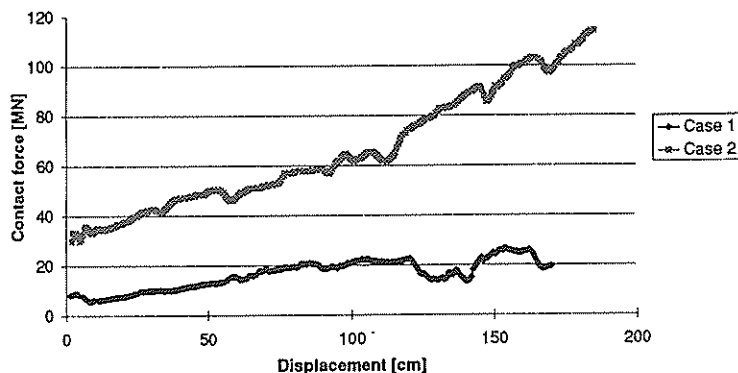


Figure 6 Force-indentation relationship for 36,000 dwt tanker

Horizontal component of crushing force.

Analysis of complete tanker bottom sections becomes very complex, even for the case of pure lateral indentation studied above. In order to cope with the longitudinal motion in grounding simplified procedures have to be adopted for estimating the axial component of the crushing force. A possible approach is to analyze representative isolated components or small systems by means nonlinear FEM and from these results conclude with respect to the behaviour of the total system. Analyses have been performed for an isolated longitudinal girder with associated bottom plating. The component is first subjected to lateral indentation and then the obstruction is moved parallel to the bottom plating simulating the passage of the obstruction. On the average it is found that the longitudinal force amounts to 15-20% of the lateral force.

Alternatively, the energy dissipation may be estimated by means of Vaughans method [4]. It is based upon a semi-empirical relationship between the energy dissipation and the volume of damaged material during the grounding process. From numerical simulations based on this approach the horizontal force comes out to be approximately 19- 29% of the lateral force, thus being in the same range as that obtained in numerical simulations.

In addition, the force caused by friction has to be included.

MODEL TESTS ON DOUBLE BOTTOM TRANSVERSE STRENGTH

In order to study the resistance to local deformation experiments with models of double bottoms have been carried out. The objectives of these tests are:

- Verify load-indentation relationships predicted by DYNA3D. It is of crucial importance to determine the amount of deformations transferred to the inner bottom.
- Check whether the stresses and strains predicted by DYNA3D comply with experimental values and can be used to predict the initiation of rupture. It is to be expected that local strains are very influenced by local weld geometry which is not captured by the element mesh used in the theoretical calculations.

The geometry of two of the models are shown in Figure 7. The models are at a scale of approximately 1:5 and represent two double bottom configurations; one with an even number of floors and girders and one which is predominantly transversely framed. Primary stiffeners are included, whereas secondary stiffeners are only modelled to a limited extent. Similar models are tested with double bottom height of 500 mm and 280 mm respectively.

The material used is ordinary ship steel plating.

The specimens are subjected to static, lateral indentation by a centrally located rigid body. A hexagonal truncated cone is selected to represent the sea floor.

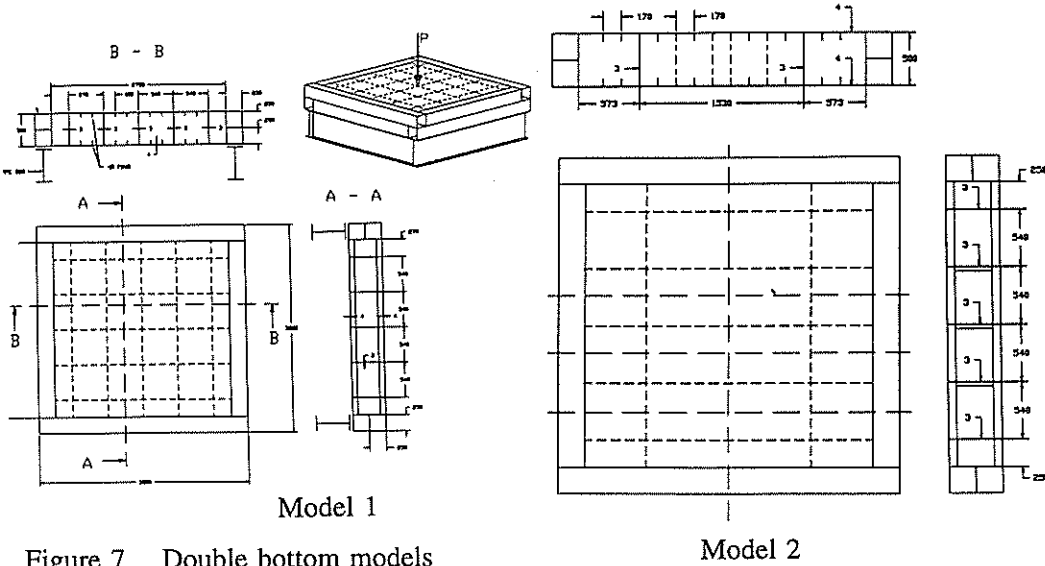


Figure 7 Double bottom models

Experimental results for double bottom height of 500 mm are shown in Figure 8. All models exhibit similar behaviour. The initial response is governed by buckling of girder webs. By further deformation cracking occurs in the outer plating. This causes a significant drop of the force, although a significant residual load carrying capacity remains parallel to cracks. As the deformations grow contact is made with the inner bottom plating which starts to deform and the resistance increases considerably. In all cases rupture takes place in the inner bottom, but the instant of initiation and amount of rupture depend very much on the actual weld quality. Space limitations did not always allow for continuous welding.

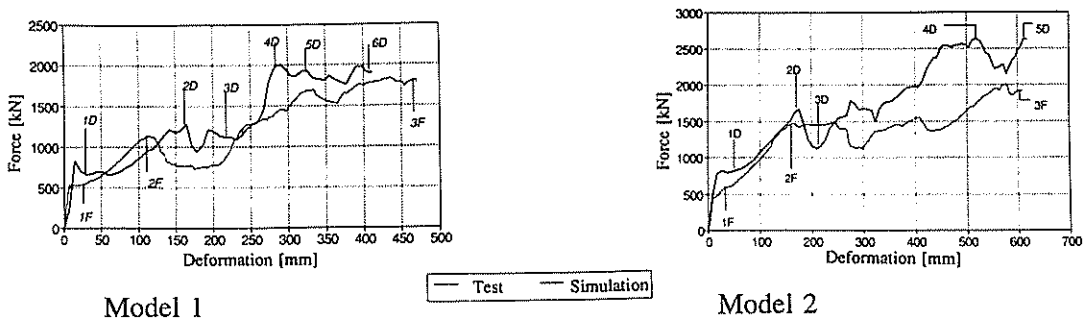


Figure 8 Results from tests and numerical analysis of double bottom models

For comparison, results from numerical analysis with DYNA3D are shown in Figure 8. In general the program is capable of tracing the collapse mode with good accuracy. The major reason for the deviation is related to the detrimental effect on the load carrying capacity from premature rupture in the outer plating, caused by weld discontinuities and/or geometric inaccuracies.

SIMULATION OF GROUNDING

Numerical simulation of the grounding process have been conducted for the 280,000 dwt tanker. The rigid body motion is simulated in the time domain as described above. The contact force depends upon the indentation of the obstruction into the double bottom and calculated on basis of fitted, nonlinear representations of the lateral force-indentation relationships obtained with DYNA3D. The horizontal force component is estimated by means of Vaughans method. In addition friction with a friction coefficient of 0.25 is assumed. The speed of the ship at grounding is 4 m/s. Both the cases of obstruction shape described previously are analyzed.

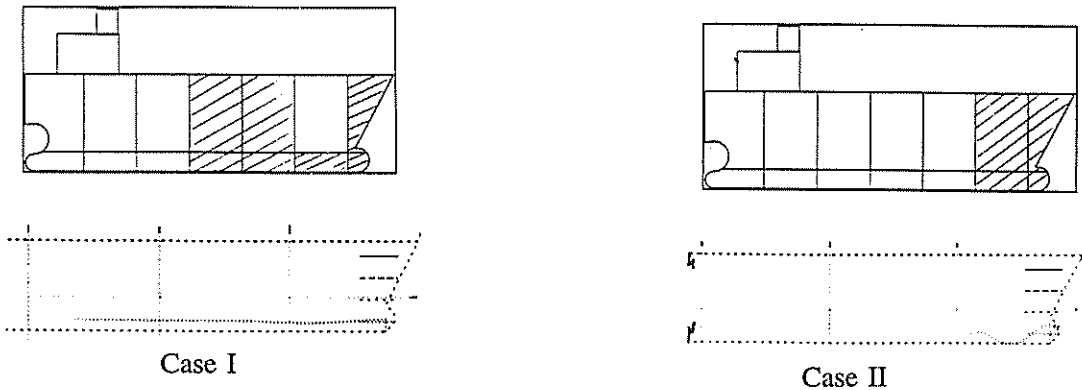


Figure 9 Simulation of damage to double bottom and cargo tanks

Figure 9 shows the resulting damage on the assumption that the top of the obstruction is 4 m above mean draught of the ship. It is seen that in case I the contact the ship is not subjected to notable pitch motion so that the obstruction more or less penetrates the bottom according to the relative indentation. In case II the contact force is much higher so that the ship responds by pitch, hence the indentation oscillates about a mean level, corresponding to the static equilibrium position. This reduces the amount of damage as concerns damage length and penetration depth. Particularly the latter is of vital interest as concerns penetration of inner bottom. Tanks that have been subjected to puncturing are schematically indicated by hatched areas in Figure 9.

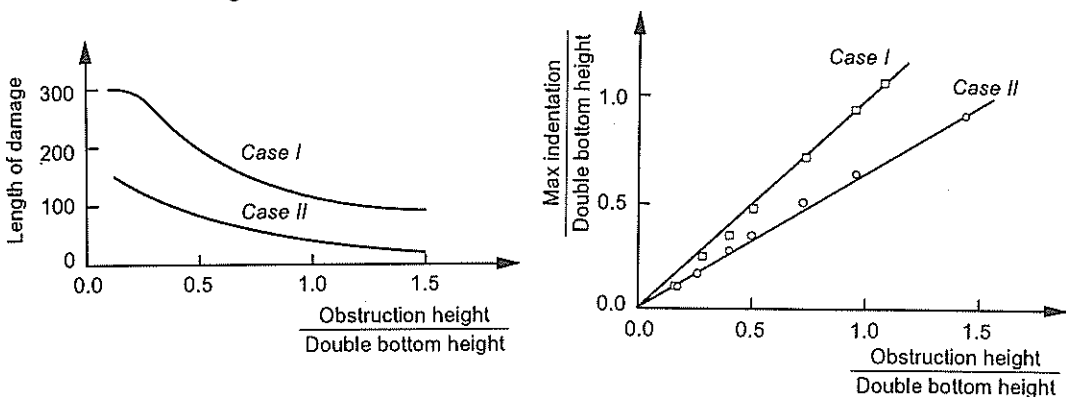


Figure 10 Grounding damage versus height of obstruction

Figure 10 shows the length of damage and maximum penetration as a function of obstruction height. Both the length and maximum depth of the damage depend heavily on the shape and height of the obstruction. Maximum indentation is largely governed by static conditions, but the distribution over length can vary significantly due to dynamic pitch and heave motion.

CONCLUDING REMARKS

The authors are the first to admit that a major effort still remains before we have all the elements required in a practical scheme for design against accidental load, i.e. grounding and collision. We hope that some ideas and procedures are presented that can form a basis for further work. We consider it to be a challenge for the ship design community to develop a rational design scheme. It is believed that this can be an important tool for building ships that have a safety performance superior to minimum requirements specified by regulations. The building cost may not necessarily be larger. An important question is how to most effectively increase the robustness in those parts of the ship which is most exposed to damage.

An important issue that we just have touched upon, is definition of realistic accidents scenarios. Here we believe that reports on accidents in the hands of classification societies and maritime authorities can be analyzed to form a basis for such scenarios.

Another major issue is to develop reliable simplified simulation especially of penetration depth. It is certainly not possible to run supercomputer analysis in order to determine this for each new ship to be considered. We still think that it is possible to combine insight in failure mechanisms gained by extensive analysis to construct simplified methods.

REFERENCES

- [1] DnV: "IMO Comparative Study on Oil Tanker Design. Analysis of Oil Outflow from Collision and Grounding Accidents", DnV Report 92-0042, Høvik 1992.
- [2] Pedersen, P.T: "Ship Grounding and Hull Girder Strength", The Technical University of Denmark, 1993.
- [3] Wierzbicki, T. and Thomas, P.: "Grounding Damage of Ships", *Structural Crashworthiness & Failure*, Elsevier Applied Science 1993.
- [4] Vaughan, H.: "The Tearing Strength of Mild Steel Plate". *J. of Ship Research*, March 1982.

