Prediction of Structural Response in Grounding - Application to Structural Design

K. K. Tikka, Webb Institute (M)
Y. J. Chen, American Bureau of Shipping (SM)

ABSTRACT

A considerable amount of work has been done during the past ten years to develop methods to predict structural response in collision and grounding. The objective of the research is to improve structural design by taking into account accident loads. To achieve the goal, simplified methods must be available to analyze designs in largely varying accident scenarios. The paper assesses to what extent this goal has been achieved in grounding research and identifies required future work. The past work in structural response in grounding is reviewed. The paper tests an existing simplified method against results from numerical studies, model testing and actual grounding data. It assesses the range of applicability of the method for predicting grounding response in varying grounding scenarios. An evaluation of the relative impact of grounding parameters on damage extents, and a study of the performance of varying structural configurations within the applicability of the simplified method is presented.

Presentation

INTRODUCTION

The past regulatory actions to mitigate oil pollution in the case of a collision or grounding by design have been focusing on subdivision of tankers, but it is generally recognized that the ship structural design is also important as it affects the extent of damage in an accident. However, the technology to account for accidental loads in structural design has not been available for designers or regulators. Significant amount of work has been done in this area in the past ten years, and the objective of the work presented in this paper was to investigate tools currently available to study structural response in grounding. The emphasis was on simplified methods.

First past research work was reviewed and summarized. A simplified method was then selected for further evaluation. The performance of the method in predicting structural response in three validation cases was investigated. A sensitivity analysis was carried out to study the effect of changes in input parameters on the results. Finally a number of structural modifications were analyzed in four grounding scenarios using the selected method.

Conclusions were made on the state-of-the art of the development of simplified methods as well as on the applicability of the selected method for design and regulatory work. Recommendations were made for future work.

REVIEW OF PAST WORK

Structural response in grounding involves the global behavior of the vessel relative to the obstruction as well as the global and local structural behavior. The past research summarized below has provided insight into the significance of the various factors and has advanced the development of simplified methods applicable to structural design and regulatory use.

The research on structural behavior in grounding started with the empirical work of Card in the 1970's [Card 1975], and has since then evolved into large numerical simulations and experiments, and finally to development of simplified methods applicable to structural design.

Card's empirical work was based on a survey of 30 grounding incidents in the U.S. waters from January 1969 to April 1973. In each of these cases, the extent of damage was analyzed to determine the effectiveness of a double bottom in reducing pollution. He concluded that fitting tankers with a B/15 high double bottom would have prevented 27 of the 30 oil spills.

A few years later, Vaughan [1978] proposed a simplified method to predict energy absorption in a grounding damage. Similar to a well-known method developed by Minorsky for collision [Minorsky 1959], the Vaughan method is based on the assumption that the energy absorption can be characterized by the volume of distortion and by the area of torn plate.

It wasn't until a decade later following the Exxon Valdez accident that ship structural response in grounding became an active area of research. The focus of the research has been to improve tanker designs to prevent and mitigate oil outflow in grounding.

In 1991, the Japanese Association for the Structural Improvement of the Shipbuilding Industry (ASIS) started a seven-year research project on "Protection of Oil Spills from Crude Oil Tankers." This research project has supported large-scale grounding experiments [Ludolphy, Wevers and Vredeveldt 1995], model grounding experiments [Kuroiwa, et. al., 1992], and numerical simulations [Kuroiwa 1996]. The project developed the finite element method coupled with ship motion analysis to a level where a fairly accurate simulation of a real grounding accident is possible. However, the application of the finite element method to study design alternatives is not practical, except in research and development environment, because the analysis is time consuming and it requires a high level of expertise.

Wang, Ohtsubo and Liu [1997] proposed a simplified method for calculating the grounding strength of bottom structures. Their method considers four primary failure modes: stretching failure of transverse structures, denting, tearing and concertina tearing failure of bottom plates. A relatively simple mathematical formulation is given for each failure mode and the grounding damage is calculated by combining the failure modes. Global dynamics of the ship are simplified: only horizontal motions are considered. Resistance during grounding is considered to be periodic following the periodicity of the structure: a period lasts from one transverse structure to the next. The method is elegant in its simplicity, but the assumptions in the method limit its direct application to raking type damage only.

In the United States, the Carderock Division of the Naval Surface Warfare Center (NSWCCD) has conducted grounding experiments, and the MIT-Joint Industry Project on Tanker Safety has developed computationally efficient models of tanker bottom structural members.

The NSWCCD tests were carried out on a conventionally framed double-hull design and on the Advanced Double Hull (ADH) design (ADH is a "unidirectional" design) [Rodd 1996]. The results from the experiments can be used for validation of simplified methods.

MIT-Joint Industry Project on Tanker Safety began in 1992, and it resulted in a computer program DAMAGE (Damage Assessment of Grounding Events) [Little, et. al., 1996], which can be used to predict structural damage in grounding. The project carried out significant research on plastic energy dissipation by the ship's structure, fracture and tearing processes of steel plates, and the contact and friction phenomena between the obstruction and stiffened panels to provide verification for the computational models.

The theory of grounding on a conical rock (pinnacle) adopted by DAMAGE is largely based on the doctoral dissertation of Simonsen at the Technical University of Denmark [Simonsen 1997]. Simonsen's work presents mathematical models for grounding response on soft seabed and on a rock pinnacle. An earlier work at the same university by Pedersen [1994] studied a vessel grounding on sand, clay or rock sea bottoms.

The program DAMAGE was selected for further testing and analysis, because it has the widest range of applicability of the published simplified methods. It is available in a user-friendly program that allows prediction of structural damage for a large range of structural arrangements and grounding scenarios. Its major limitations are in regards to the type of the obstruction (pinnacle only), and to the structural model (the structure is modeled for the cargo block only).

DAMAGE

The theory behind the models in DAMAGE can be found in [Simonsen and Wierzbicki 1996] and in [Simonsen and Wierzbicki 1997]. Simonsen presented verification of the theory by comparing calculated results with the US Navy 1/5-scale grounding experiments and with an actual grounding of a VLCC [Simonsen 1998]. The predicted energy absorption and the penetration of fracture were compared with the experimental measurements. The difference was in the order of 5 percent for the energy absorption and 15 percent for the fracture penetration. A fairly good agreement was found between predicted and actual observed damage extents. The importance of taking into account ship motions was illustrated.

The software DAMAGE contains closed form solutions for the resistance of each structural element. It is a PC-based program operating in the Windows environment. The ship's structure is modeled by selecting typical ship structural members from a menu. The model includes the complete cargo block without the bow and the stern of the ship. The computation is carried out in a stepwise manner by moving the ship forward and, at each time step, finding the rock penetration and static equilibrium of the ship. The program can be run in a coupled or uncoupled mode. The coupled mode takes into account ship motions. The uncoupled mode ignores the effect of ship motions. In the coupled mode, sway and yaw motions are neglected. Heave, roll and pitch motions are calculated based on static equilibrium using a simplified model. Surge motion is calculated based on energy balance. The motions, rock penetration, structural reaction force and plating status (ruptured or not) are output for each time step.

Brown and his students at MIT used DAMAGE to simulate grounding damage data for a MARPOL tanker [Sirkar, et. al., 1997]. They developed probability density functions for damage extents based on the generated data and compared them with the probability density functions used in "Interim Guidelines for the Approval of Alternative Tanker Designs under Regulation 13F of Annex I of MARPOL 73/78" (*IMO Guidelines*) [IMO 1996]. The agreement between the points generated by DAMAGE and the functions in *IMO Guidelines* was good with some exceptions (for example the damage width prediction was not satisfactory). In a 1998 paper [Rawson, et. al. 1998] they presented a similar analysis for a double-hull tanker and a midship tanker and demonstrated the use of the program in a methodology to compare tanker designs.

Brown's work has illustrated the potential that the program DAMAGE has for use in a design and regulatory environment. This paper presents further validation work for the program as well as an evaluation of its performance in comparing structural alternatives.

VALIDATION OF DAMAGE

Available validation cases were limited to the ones used in the past by Simonsen to verify his theory. The cases include a grounding of a VLCC off the coast of Singapore, large-scale tests in the Netherlands, and model tests at Carderock. It is recognized that more validation cases are needed to properly evaluate the applicability of DAMGE to predict structural response in various grounding scenarios.

VLCC Grounding

A VLCC grounded on the *Buffalo Reef* off the coast of Singapore on January 6, 1975. The speed of the vessel at the time of grounding was approximately 12 knots and the bottom rupture extended approximately 180 meters aft of the bow along the centerline. The width of the rupture varied from 3 to 5 meters. The depth of the indentation was 2 to 3 meters. The input for DAMAGE is shown in Table 1, and the output is shown in Table 2.

LBP [m]	304	Beam, B [m]	53.4
Displacement [ton]	273,000	Draft, T [m]	19.8
Impact Velocity [knot]	12.0	Depth, D [m]	25.7
Rock Elevation [m]	4.40	Rock Tip Radius [m]	1.0
Rock Eccentricity [m]	5.0	Rock Semi-Angle [deg]	50

Table 1: Principal Input for VLCC

Run Mode	Coupled (Note 2)
Total Energy Dissipation [10^9 J]	5.475
Total Damaged Hull Length [m]	176.86
Damaged Width [m]	3.4-4.0
Maximum Penetration [m]	4.01

Table 2: Principal Output for VLCC

DAMAGE predicted the damage length quite accurately: the difference between the calculated damaged hull length of 177 meters and the observed damage length of about 180 meters is only 1.7%. However, since the actual transverse location of the rock is unknown, the effect of the changes in the rock eccentricity (e) was studied and the results are shown in Figure 1.

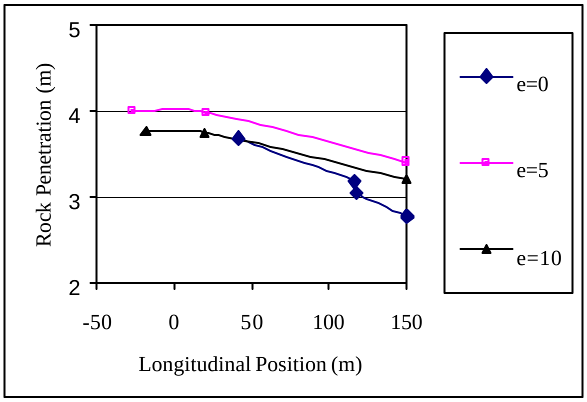


Figure 1: Rock Penetration as a Function of Rock Eccentricity

As the rock moves away from centerline the effect of ship motions increases. At e= 0 the damage length is 108 meters, and at e=10 meters the damage length is 168 meters.

Kuroiwa applied the finite element method to simulate the same grounding accident [Kuroiwa 1996]. He simulated about 15 seconds of the grounding. The simulated damage extent was reported to compare well with the observed damage extents. The simulation results (duplicated from Kuroiwa's paper) are used here in lieu of actual observations to compare with forces predicted by DAMAGE. Figures 2-4 present the comparison of DAMAGE results with the simulation results.

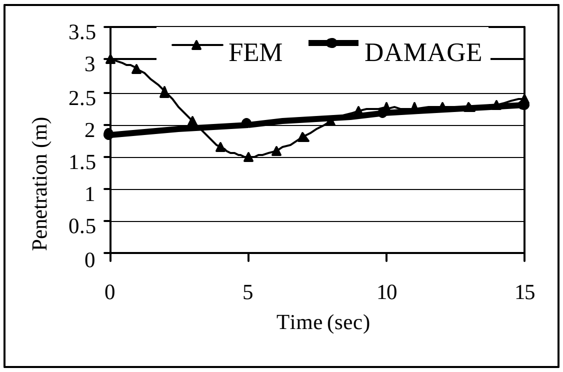


Figure 2: Vertical Penetration for DAMAGE and Simulation

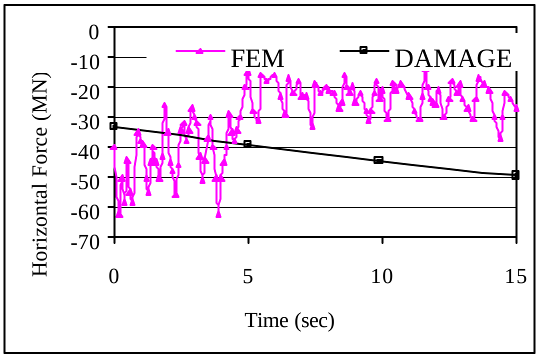


Figure 3: Horizontal Contact Force During Grounding

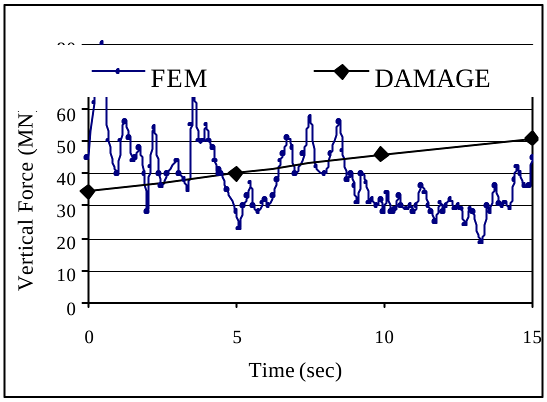


Figure 4: Vertical Contact Force During Grounding

It can be seen from the figures that DAMAGE does not predict the minima and maxima of the forces nor the initial penetration predicted by simulations, but the average forces and penetration are in reasonable agreement with simulation results. The trend in the horizontal force predicted by DAMAGE is different from the one predicted by the finite element analysis

***NSWCCD* Tests**

The Carderock Division of the Naval Surface Warfare Center (NSWCCD) conducted a series of 1:5 scale grounding experiments on a conventional double-hull design and on a unidirecitionally framed design [Rodd 1996]. The models, which consisted of two compartments, were attached to railcars. They were released down a ramp to strike an artificial rock. One of the models had a conventional double-hull design and the others had a "unidirectional" design with differences in stiffener spacing and plating thickness.

The test vehicle was trimmed to an angle so that the rock would enter the structure approximately 5 cm below the inner bottom, and at the aft bulkhead the penetration would be equal to twice the double bottom height.

Results of the conventional double-hull test were compared with the results of the computer program DAMAGE. The DAMAGE input is shown in Table 3. Thickness of the transverse bulkheads is increased to account for the effect of stiffeners. Since the models were fixed to railcars, DAMAGE calculations were done in an uncoupled mode (Note 1).

Figure 5 shows the comparison of the measured and the predicted horizontal force and Figure 6 shows the same comparison for the vertical force. DAMAGE prediction agrees remarkably well with the measured values, which were obtained from [Simonsen 1998].

Table 3: Principal Data Used in DAMAGE for the Four Tests

Parameter	NSWCCD
Length Between Perpendiculars (m)	7.32
Breadth, B (m)	2.54
Displacement (tons)	223
Ship Velocity (knots)	14
Trim Angle (degree)	3.38
Rock Elevation (m @ amidships)	0.375
Rock Tip Radius (m)	0.17
Rock Semi-Apex Angle (degree)	45
Double Bottom Height (m)	0.38
Plate Thickness of Inner Bottom(mm)	3.0
Plate Thickness of Shell (mm)	3.0
Plate Thickness of Girders (mm)	2.3
Plate Thickness of Floors (mm)	2.3
Pl. Thickness of Trans. Bhd (mm)	6.0
Material Yield Strength (Mpa)	283
Material Ultimate Strength (Mpa)	345
Fracture Strain	0.22

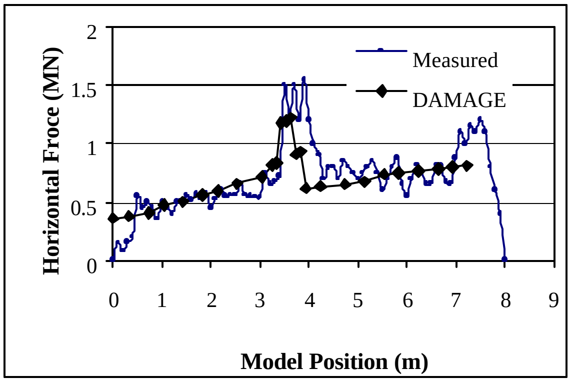


Figure 5: Horizontal Contact Force During Grounding

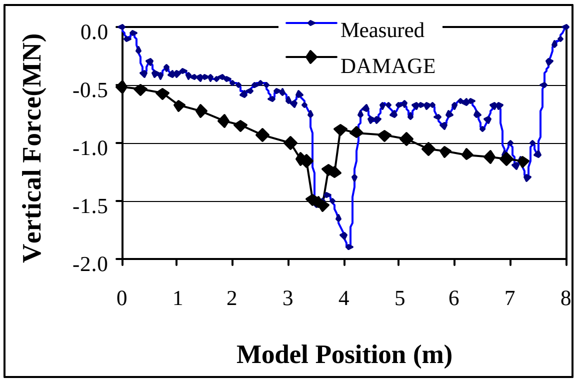


Figure 6: Vertical Contact Force During Grounding

ASIS Tests

The Association for Structural Improvement of Shipbuilding Industry (ASIS) conducted large-scale grounding tests with an inland waterway tanker in the Netherlands in 1994 and 1995. A test section was attached to the tanker and run aground on an artificial rock. Input for DAMAGE is shown in Tables 4 and 5.

Table 4: ASIS Test Setup

Ship Length, L [m]	68.3	Specimen Double Bottom Height [mm]	750
Ship Beam, B [m]	9.4	Specimen Bottom Thickness [mm]	5
Rock Apex Angle	49	Specimen Inner Bottom Thickness [mm]	5
Rock Height [m]	1.5	Specimen Floor Spacing [mm]	1250
Rock Tip Radius [m]	0.60	Specimen Girder Spacing [mm]	3500
Specimen Length [m]	7.15	Specimen Stiffener Spacing [mm]	250
Specimen Length [m]	5.5	Specimen Stiffener Depth [mm]	150

Table 5: ASIS Test 2 Grounding Scenarios

Rock Elevation [m]	1.31
Impact Velocity [m/s]	4.06
Mass [ton]	678.8
Trim [deg]	1.208
Rock Eccentricity [m]	1.75

The results calculated by the program DAMAGE were compared with experimental results. Figures 7-9 show the comparison of the results for ASIS test 2. Global ship motion effects are included in the calculations.

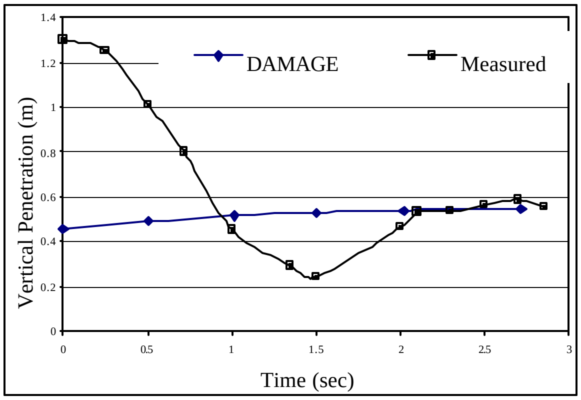


Figure 7: Comparison of Vertical Penetration (ASIS Test No.2)

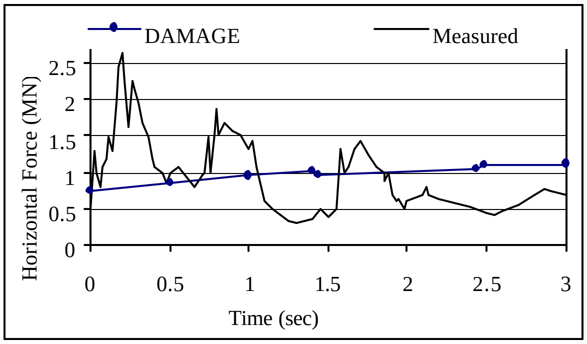


Figure 8: Comparison of Horizontal Forces (ASIS Test No.2)

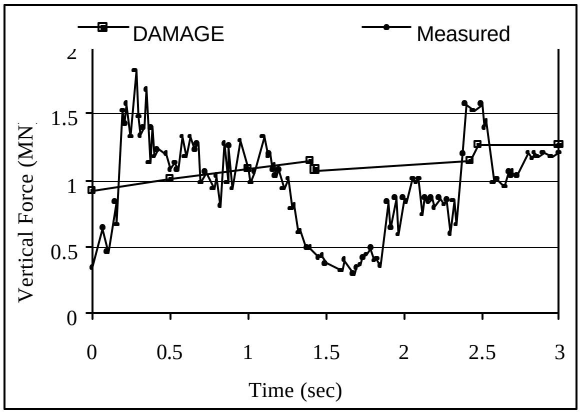


Figure 9: Comparison of Vertical Forces (ASIS Test No.2)

DAMAGE does not predict minima or maxima for either the penetration or the forces, but it seems to predict the average values satisfactorily. The same observation was made when DAMAGE results were compared with simulations for the VLCC grounding.

Large differences in the penetration at the initial stages of grounding are probably due to simplifications in the global motion calculations.

SENSITIVITY ANALYSIS OF DAMAGE RESULTS TO GROUNDING SCENARIOS

The sensitivity of DAMAGE results to changes in grounding parameters, including global ship characteristics, ground characteristics and their interaction, was studied. The grounding parameters and their initial values are shown in Table 6.

Table 6: Sensitivity Analysis Input Data

Young 's Modulus [MN/m^2]:	200,000	Poisson Ratio	0.3
0.2% Yield Stress [MN/m^2]	262.83	Specific Work of Fracture [KJ/m^2]	200
LBP (m)	304	Breadth [m]	53.4
LCF (- aft of MS (m)	-4.4	Depth [m]	25.7
Breadth of Flat Bottom	48.4	Draft [m]	19.8
Number of Tanks	3 x 5	Cargo block length [m]	220
Displacement (Mtons)	273,000	Waterplane Area [m^2]	12,600
GM_T (m)	5.3	GM_L (m)	330
Ship Velocity [knots]	12	Trim Angle [deg]	0
Rock Type	Pinnacle	Rock Tip Radius [m]	1.0
Rock Semi-Apex Angle [deg]	45	Friction Coefficient	0.4
Rock Eccentricity [m-CL]	5.0	Rock Elevation [m-BL]	4.4
Bulkhead Position (- aft of MS) [m]	[132] ~ [77] ~ [49.5] ~ [22] ~ [-33] ~ [-88]		
Bottom Type	Single Bottom		
Bulkhead plate[mm]	20	Bottom Plate [mm]	35
Transverse Frame Spacing [mm]	5000	Longitudinal Stiffener Spacing [mm]	1000

The analysis was based on the following principles:

1) Only one parameter is changed at a time. Other parameters are kept at their initial values.

2) The results are characterized by three parameters: total energy dissipation, total damaged hull length, and the maximum penetration during grounding.

3) DAMAGE run mode is "coupled", i.e., the global motions are included.

The analysis studied the sensitivity of the results to:

- The ground characteristics
- The parameters defining the ship-ground interaction
- The global ship parameters
- The bottom structural design
- The material characteristics.

In DAMAGE the ground is characterized by the rock tip radius and semi-apex angle, which define the shape of the rock. The ship-ground interaction is defined by the rock eccentricity (i.e. the distance from centerline), rock elevation, ship velocity, trim angle and friction coefficient. Global ship parameters include displacement, breadth of flat bottom, transverse and longitudinal metacentric height, longitudinal center of floatation, and waterplane area coefficient.

At the local level the following structural details were investigated: longitudinal stiffener spacing, thickness of outer bottom, spacing of longitudinal girders and transverse floors, and characteristics of longitudinal girders and transverse floors. The material characteristics were defined by 0.2% yield stress and specific work of fracture.

As can be expected the results are very sensitive to the rock elevation, rock shape and transverse location, ship velocity and displacement. The results were found sensitive also to the value of the friction coefficient (Note 2), and the trim angle.

Surprisingly, the tank spacing as well as the characteristics of both the transverse bulkhead and the longitudinal bulkhead had very little effect on damage results. The results were not very sensitive to the material characteristics either.

The longitudinal center of floatation and both the longitudinal and the transverse metacentric height had little effect on damage results.

Damage results were sensitive to the thickness of the outer bottom. Reducing the spacing and increasing the scantlings of longitudinal girders and transverse floors also affected damage results, but not as effectively. The same applies to longitudinal stiffeners. Table 7 summarizes the analysis.

Table 7: Summary of Damage Results Sensitivity Analysis

Increasing the Value of the Parameter	Changing of Damage Results (m)		Sensitivity
	Damaged Length	Max. Penetration	Sensitive=S Insensitive=I
Rock Eccentricity	Increase	Decrease	S
Ship Velocity	Increase	Increase	S
Rock Elevation	Decrease	Increase	S
Longitudinal Metacentric Height	Decrease	Increase	I
Transverse Metacentric Height	Decrease	Increase	I
LCF moves aft	Increase	Decrease	I
Waterplane Area Coefficient	Decrease	Increase	I
Friction Coefficient	Decrease	Decrease	S
Stiffener Size	Decrease	Decrease	I
Rock Tip Radius	Increase	Increase	S
Rock Semi-apex angle	Decrease, then increase	Increase, then decrease	S
Thickness of Outer Bottom	Decrease	Decrease	S
Displacement	Increase	Increase	S
Spacing (longitudinal and transverse)	Increase	Increase	I
Longitudinal Girders	Decrease	Decrease	I
Transverse Floors	Decrease	Decrease	I
Number of Ttransverse Bulkheads	Decrease	Insensitive	I
Number and Location of Longitudinal Bulkheads	Insensitive	Insensitive	I
Trim Angle	Increase	Decrease	S

STRUCTURAL MODIFICATIONS

Based on the above analyses DAMAGE was found to provide a good tool for comparative studies, and it was used to investigate the effect of a number of structural modifications in selected grounding scenarios. A 150,000DWT double-hull tanker was used as the base ship. The principal dimensions of the base ship are shown in Table 8, and the tank arrangement data is shown in Table 9. Dimensions of the bottom structure are given in Table 10.

Table 8: Principal Dimensions of Baseship

Length Overall [m]	274.50
Length Between Perpendiculars [m]	261.00
Breadth [m]	50.00
Depth [m]	25.10
Double Bottom Height [m]	3.34
Lightship Weight [ton]	24,116

Table 9: Detailed Tank Arrangement Data of Baseship

Number of Tanks Longitudinally	7
Length of Cargo Block [m]	202
Thickness of Longitudinal Bulkheads [mm]	15.5
Thickness of Transverse Bulkheads [mm]	16.5
Stiffeners - Longitudinal Bulkheads [N=25]	450x100x12.5/19
Stiffeners - Transverse Bulkheads [N=50]	700x200x13/22

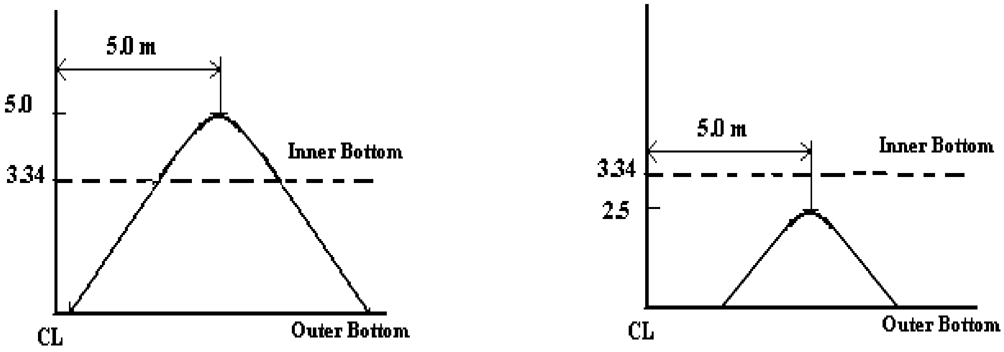
Table 10: Bottom Structure Data of Baseship

Keel Plate Thickness [mm]	18.5
Transverse Floor Spacing [mm]	5200
Transverse Floor Thickness [mm]	17.5
Longitudinal Web Spacing [mm]	17850
Longitudinal Web Thickness [mm]	47.00
Outer Bottom Thickness [mm]	17.00
Inner Bottom Thickness [mm]	17.00
Outer Bottom Stiffeners, Longitudinal [N=50]	600x150x12.5/23
Inner Bottom Stiffeners, Longitudinal [N=40]	600x125x12.5/22
Center Vertical Keel Thickness [mm]	46.0

Four different grounding scenarios were selected: one with a high rock elevation (HE), one with a mediate rock elevation (ME), one with a low rock elevation (LE), and one with a sharp tip (ST). The rock eccentricity was set to be 5 meters. The definition of these four grounding scenarios is shown in Table 11 and Figure 10.

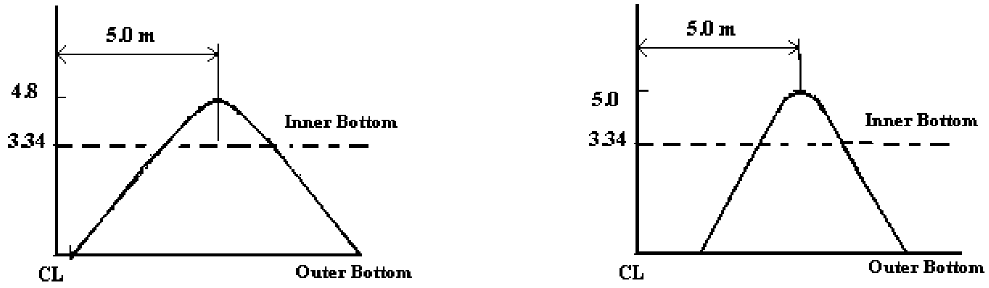
Table 11: Definition of Grounding Scenarios

Scenario	Rock Tip Radius	Semi-Apex Angle	Elevation	Eccentricity
HE	1.0 m	45	5.0 m	5.0 m
LE	1.0 m	45	2.5 m	5.0 m
ME	1.0 m	45	4.8 m	5.0 m
ST	1.0 m	30	5.0 m	5.0 m



Scenario: HE

Scenario: LE



Scenario: ME

Scenario: ST

Figure 10: Sketch of Four Grounding Scenarios

Two velocities were used in the analysis: 14 knots and 7 knots to represent a service speed and port speed of a tanker.

In order to investigate the effectiveness of different structural designs to the grounding accidents, a total of nine different structural designs were modeled, using the American Bureau of Shipping SafeHull software. The structural dimensions in these nine designs met the minimum classification requirements, except for the scantling, which was studied. All of the nine designs satisfied the ABS Rules (97/98). The structural differences in the designs were either in the plate thickness or in the structural spacing (Table 12).

The modifications in Designs 1-3 were:

1) An increase in the outer bottom plate thickness from 17mm to 25mm (Design #1);

2) An increase in the inner bottom plate thickness from 17mm to 25mm (Design #2); and

3) An increase in both the outer bottom and the inner bottom plate thickness from 17mm to 25mm (Design #3).

Consequently, the scantlings of stiffeners along the outer bottom and inner bottom were changed. Comparing to the original design, these modifications increase the longitudinal structural steel weight for unit length from 17371 tons to 17837 tons, 17932tons, and 18398 tons respectively.

Table 12: Differences of The Structural Designs

H_{DB}: Double Bottom Height; T_{OB}: Thickness of Outer Bottom; T_{IB}: Thickness of Inner Bottom; S_{TF}: Spacing of Transverse Frames; S_{LG}: Spacing of Longitudinal Bottom Girder

Design Number	H_{DB} (mm)	T_{OB} (mm)	T_{IB} (mm)	S_{TF} (mm)	S_{LG} (mm)	Weight (Ton)	Weight Increase
#0(Original)	3340	17	17	5200	17850	17371.83	-----
# 1	3340	**25**	17	5200	17850	17837.04	2.68%
# 2	3340	17	**25**	5200	17850	17932.99	3.23%
# 3	3340	**25**	**25**	5200	17850	18398.21	5.91%
# 4	3340	17	17	5200	**8925**	17416.98	0.26%
# 5	3340	17	17	5200	**5950**	18637.00	7.28%
# 6 (Note 3)	3340	17	17	**4457**	17850	16711.97	-3.80%
# 7	**3000**	17	17	5200	17850	17380.90	0.05%
# 8	**3500**	17	17	5200	17850	17457.96	0.50%

The modifications in Designs 4 and 5 were:

1) An additional longitudinal girder (Design #4);

2) Two additional longitudinal girders (Design #5).

The above modifications change the spacing of the longitudinal girders, the dimensions of the bottom plate, side shell, inner skin bulkhead, etc. The increase in the longitudinal structural steel weight for one additional bottom girder (Design #4) was only 45 tons, and for two additional bottom girders (Design #5) 1265 tons.

In Design #6 the spacing of transverse floors was decreased from 5200 mm to 4457 mm increasing the number of frames in a tank from 6 to 7. This modification causes the dimensions of other structural components to decrease. Accordingly, the longitudinal structural steel weight in this modification is 66 tons less than the original design (Note 3).

The modifications in Designs 7 and 8 are:

1) A decrease in the double bottom height from 3340 mm to 3000mm (Design #7);

2) An increase in double bottom height from 3340mm to 3500mm (Design #8).

These two modifications cause little change to other structural components. The structural steel weight increased only 9 tons for Design #7, and 86 tons for Design #8.

Damage Results for Different Structural Designs

A total of 72 grounding cases, 9 different structural designs under 8 different grounding scenarios were analyzed using the program DAMAGE.

1) High rock elevation: At service speed, designs 1, 3, 4, 5, and 8 show better performance than the original design in preventing inner bottom plating from rupture. In design #5 (two additional longitudinal girders), design #3 (increased plating thickness) and design #8 (increased double bottom height) the inner bottom rupture is significantly reduced. At port speed, all design modifications perform better than the original except design #7 (reduced double bottom height).

2) Medium rock elevation: At service speed, no inner bottom plating rupture occurs for designs #5 (additional girders) and design #8 (increased double bottom height). All design modifications perform better than the original except design #7 (reduced double bottom height) at both speeds.

3) Low rock elevation: No design had rupture of the inner bottom. At service speed, all designs have a ruptured outer bottom throughout the cargo block. In this kind of raking scenario, the structural modifications have little impact on the damage extent.

4) Sharp rock tip: At service speed the rock penetrated through the entire cargo block for all designs. At port speed, designs 1, 2, 3, 5 and 6 had reduced outer bottom and inner bottom rupture. This was the only grounding scenario where the increased double bottom height did not reduce the inner bottom rupture significantly.

Among all the nine selected designs, the design #5 with two additional longitudinal girders shows the best performance in preventing inner bottom plate rupture and oil outflow in the selected grounding scenarios. Design #7 with the reduced double bottom height has the worst performance. In the low-obstruction raking scenario all the designs have similar performance and no oil outflow. If the tanker meets a high-elevation, sharp-tip grounding scenario at service speed, serious damage will occur in all selected designs. Even if the tanker meets the grounding scenario at the lower speed, all designs will have serious inner bottom plate rupture.

Although adding longitudinal girders seems to be the best modification in preventing inner bottom plate from rupturing in the eight selected grounding scenarios, it is not the most effective design. It has the heaviest structural steel weight among the selected designs.

If the damage extent is studied as a function of the structural steel weight, design #8 with the increased double bottom is found to be effective in terms of a slight increase in steel weight, but a significant reduction in ruptured inner bottom length in most studied scenarios. This observation is tied to the selected grounding scenarios, particularly to the height of the obstruction relative to the ship bottom. It would be interesting to repeat Card's 1975 empirical study using DAMAGE in a probabilistic analysis to investigate the effect of the double bottom height in all possible grounding scenarios. Since changes in the subdivision have an impact on other characteristics of the vessels as well, such as stability and cargo capacity, the study should be supported by an intact and damage stability analysis.

Increasing outer bottom plating thickness was found to be effective in reducing inner bottom rupture. It would be interesting to validate this observation using different methods to predict damage extent. The next step would be again to carry out a probabilistic study.

Increasing the thickness of both the outer and inner bottom plating reduces the ruptured length more, but at the cost of increased weight.

It must be noted that the weight changes were based on the longitudinal structure only and the changes in transverse structure (design #6) were not properly accounted for. It should be also kept in mind that the design performance in this study was measured in terms of the extent of structural damage. The changes in the damage extent may have no effect on the oil outflow since it is a function of the damage location and the tank subdivision as well.

CONCLUSIONS

The research on predicting structural response in grounding has provided tools that can be used in comparing structural alternatives. However, to confirm that the conclusions on the performance of design alternatives are correct, the methods must be tested further. This is a challenge since finding detailed data on actual groundings necessary for validation is difficult.

The software DAMAGE has the widest applicability of the published simplified methods. It is easy to use and the computation is fast. DAMAGE provides a good tool for probabilistic analysis involving large amounts of input and output data. The main limitations of DAMAGE are the type of the obstruction (pinnacle only) and the omission of the bow structure in the model.

The validation cases used in this study indicate that DAMAGE predictions on the average values of penetration and internal forces are good. DAMAGE predicted longitudinal damage extent well in the studied cases. Further review is recommended on the prediction of structural component response to confirm that DAMAGE is an accurate tool for structural design evaluation.

The study of structural modifications was limited to only eight grounding scenarios and the conclusions from it cannot be generalized. However, this type of deterministic investigation provides additional insight into the effects of the scenarios and the structural modifications, which can be lost in a probabilistic study. Deterministic studies can be used to help design probabilistic studies on the effects of structural modifications. That should be the next step after the validation of the method is completed.

The study found that even small changes in a traditional structural arrangement, such as the height of the double bottom or the thickness of the bottom plate, can have a significant effect on damage extent, and further study is recommended to identify the effect of simple structural modifications on the expected oil outflow from tankers.

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NOTES

(1) In DAMAGE, the "Coupled" calculation mode considers global motions(surge, heave, pitch, and roll), and the "Uncoupled" mode ignores all ship motions except surge.

(2) Based on the results of other work, the friction coefficient is typically assumed to be 0.3 or 0.4.

(3) The weight in the analysis accounts for the longitudinal structure only. The effect of a larger number of transverse floors is not taken into account.

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