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## **EXPERIMENTAL AND NUMERICAL SIMULATION OF DOUBLE HULL STRANDING**

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### **Load effect analysis of ship grounding and collision**

The grounding process of a ship is in general very complex. Large plastic deformations may spread over a large portion of the bottom structure. The amount of deformation at each specific point depends upon both the resistance to penetration of the bottom relative to the shape of the sea floor as well as the hydrodynamic stability of the ship. The lateral component of the contact force causes both a heave and a pitch motion. A significant amount of energy may also be dissipated in friction between the bottom plate and the sea floor.

The problem becomes even more complex if rupture occurs so that the sea floor starts to tear open the outer plating.

To take all effects into account nonlinear finite element analysis with a detailed modelling of the entire damaged area should be performed. However, the size of the problem precludes this with present computational capabilities.

The problem becomes significantly simpler if the post-grounded condition is considered. The following topics should then be addressed:

- i) local deformation of the double bottom in the affected tank
- ii) analysis of the hull girder and progressive collapse analysis of damaged tank section

### **Local deformation**

The deformations in the vicinity of the contact point will be very severe with local buckling and crumpling of floors and girders and membrane straining of bottom plating. The latter may be limited by fracture causing a significant change of the deformation pattern in this mode.

The nature of deformation is such that a very detailed nonlinear FE analysis should be carried out. For successful use they should be able to trace deformations in girders and floors

forces along the hull girder for the ship in grounded condition. This can be done by means of a calculation of equilibrium of weights, hydrostatic loads and reaction forces along the hull girder. A computer program VESIM (12) dedicated for analysis of oil tankers will be used for this purpose.

The bending moments and shear forces at each end of the damaged compartment can be calculated for different equilibrium positions corresponding to tidal variations. These force histories can then be applied to a more detailed model of the compartment. In this way it can be checked whether the ultimate collapse strength of the hull girder will be exceeded where the detrimental effect of lateral indentation of double bottom members is included.

### Postgrounding scenarios

The major attention in the study of grounding has been directed towards ships running aground at service speed. The background for this is that even if this is a rare event, the consequences are large and the challenge to predict damage difficult.

On the other hand what happens if the ship in grounded condition is subjected to swells or tidal variation should be included as a separate accident scenario. It may result in a major marine disaster, like Amoco Cadiz, where the ship drifted ashore. Failure of machinery or manoeuvring system occurs first. Even if the stranding action itself is not subjecting the ship to any extensive damage, wave and tidal variations may do so.

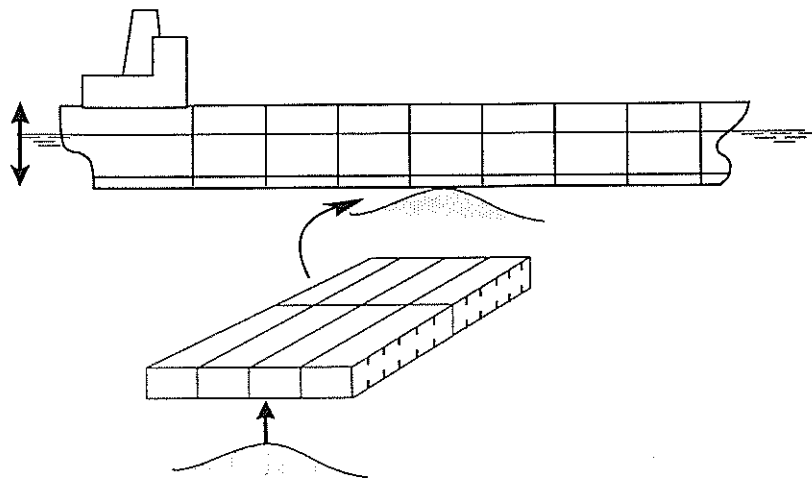


Figure 2. Post-grounding model.

### Experimental studies of transverse strength.

In order to study local deformation experimental tests with models of double bottoms are carried out. The objectives of these tests are to verify the theoretical calculations carried out with DYNA3D. Of crucial importance is to determine the amount of deformations transferred to the inner bottom and to assess when rupture is likely to occur. For the latter purpose the

plate thicknesses should be as large as possible, however, available jack capacity restricts plate dimensions to 3-4 mm.

The geometry of the first model is shown in Figure 3. It is approximately a 1:5 scale model of an actual double bottom with a relatively large number of longitudinal girders. Longitudinal stiffeners on the inner and outer plating are modelled. However, no secondary stiffeners are included on the girders and floors. The significance of this depends upon the strength of actual girder web stiffeners. The peak capacity is underestimated, but for weak stiffeners the buckle will propagate across the stiffeners and the shear force drops rapidly to the level of an unstiffened web. For strong stiffeners the post-buckling strength is underestimated as well.

All connections in the inner plating are fully welded, while availability prevents welding of longitudinal stiffeners to the floors.

The geometry of the second model is shown in Figure 4. The overall dimensions and plate thicknesses are the same as for model 1, but the number of longitudinal girders are reduced from five to three. This is more representative for typical tanker double bottoms having greater stiffness in the transverse direction. Furthermore, secondary stiffening is included on the three middle floors. To reduce the fabrication costs local stiffening is only provided for every second longitudinal, except for the center floor, which is stiffened at every longitudinal.

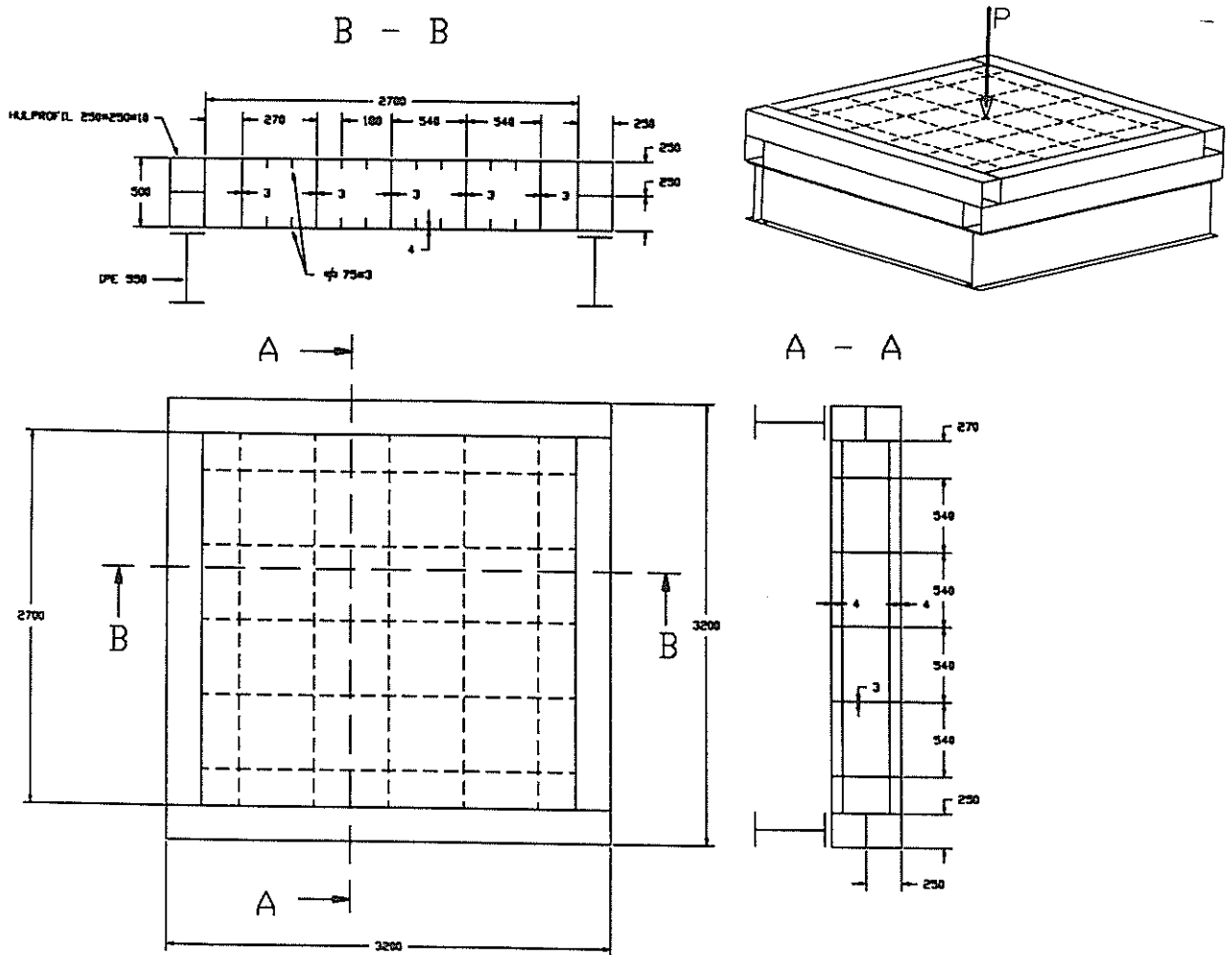


Figure 3. Double bottom test model 1

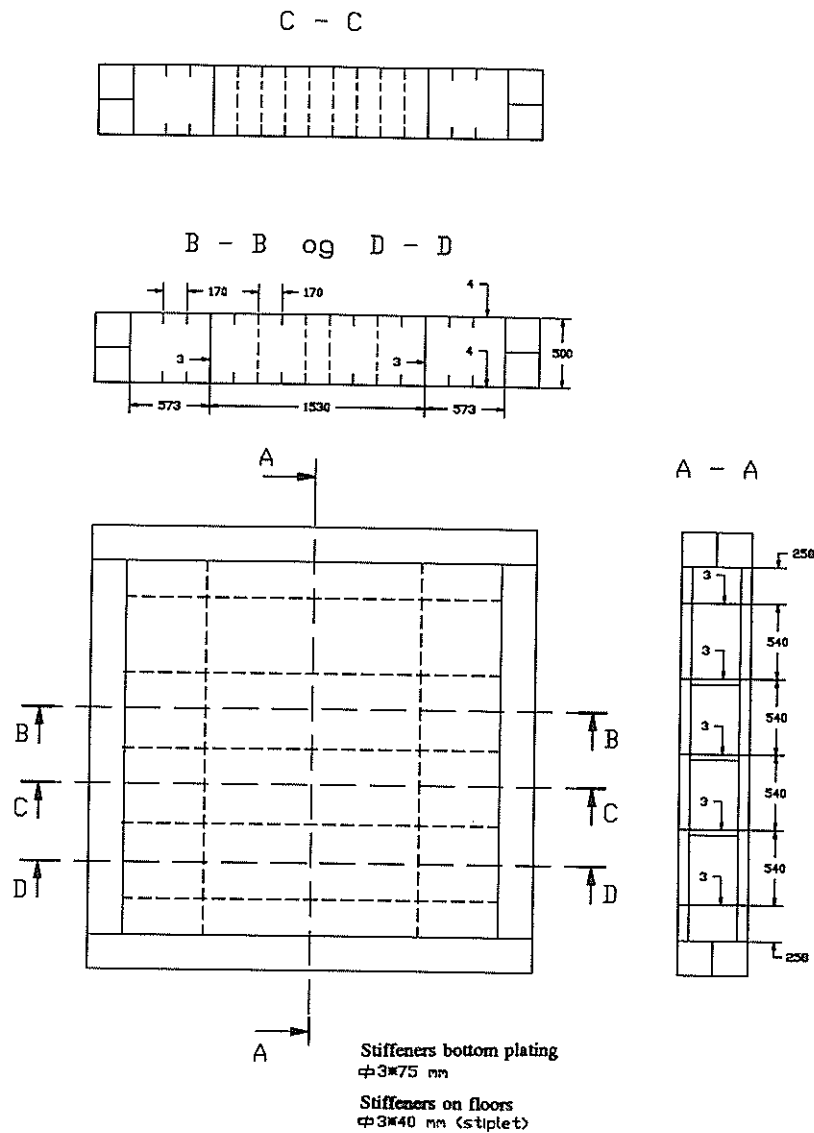


Figure 4. Double bottom test model 2

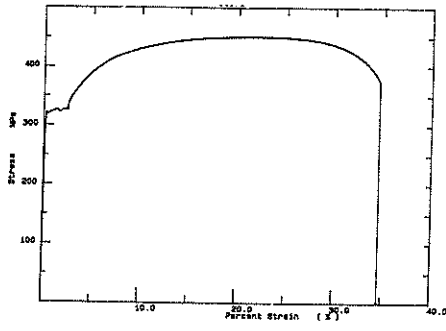
The test with model 1 shows that fracture initiates at discontinuities in the welds in the outer bottom. On the other hand, the inner bottom suffers relatively little damage before fracture occurs. Hence, first priority is given to welding of the outer bottom in model 2. By cutting the inner plate into three pieces it is also possible to perform continuous welding of longitudinals but the connections to the floors can not be welded.

Plates of ship quality grade A are used in bottom plating, floors and girders. Flat bars of grade A are used in stiffeners. Stress-strain curves from tension coupon tests are given in Figures 6 and 7.

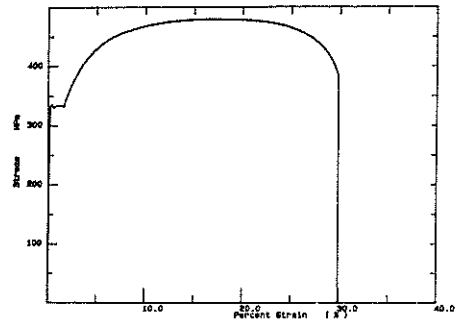
The models are attached to strong box-girders which constrain inward displacements and placed on deep I-girders.

The specimens are subjected to static, lateral indentation by a centrally located rigid body. The hexagonal truncated cone shown in Figure 8 is selected to represent the sea floor.

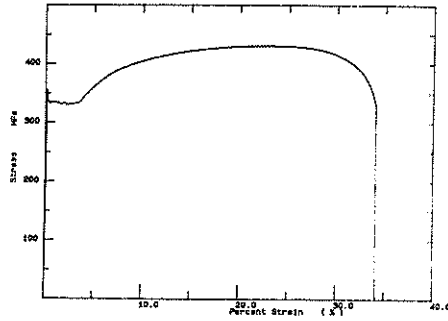
Apart from measuring the lateral load-indentation relationship strains are recorded at 13 positions by means of high performance strain gauges.



Bottom plating

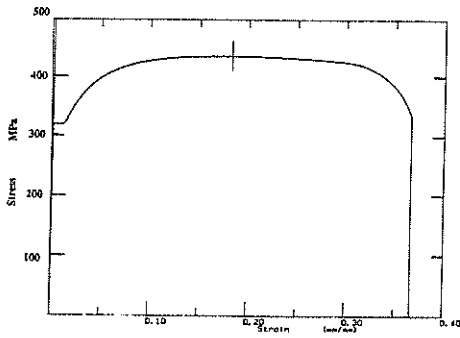


Floors/girders

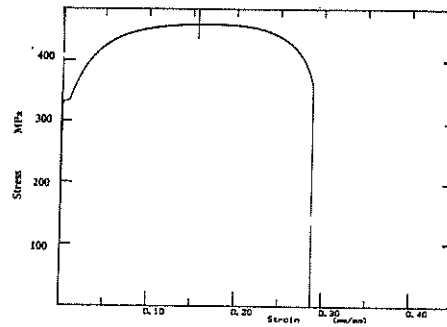


Stiffeners

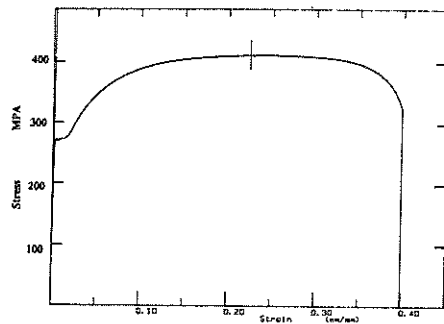
Figure 5 Stress-strain relationships for material in model 1



Bottom plating



Floors/girders



Stiffeners

Figure 6 Stress-strain relationships for material in model 2

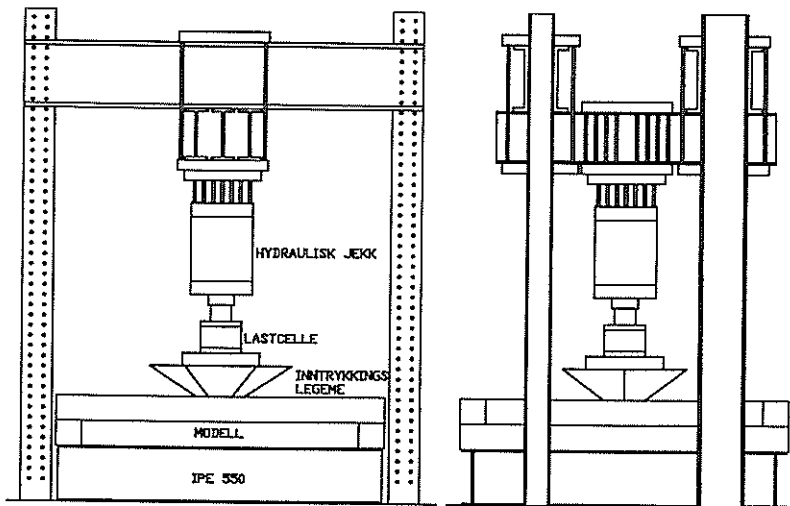


Figure 7. Double bottom test arrangement

### Experimental results

Load-lateral indentation relationships are given for the two models in Figures 8 and 9. The curves are quite similar both with respect to shape and magnitude.

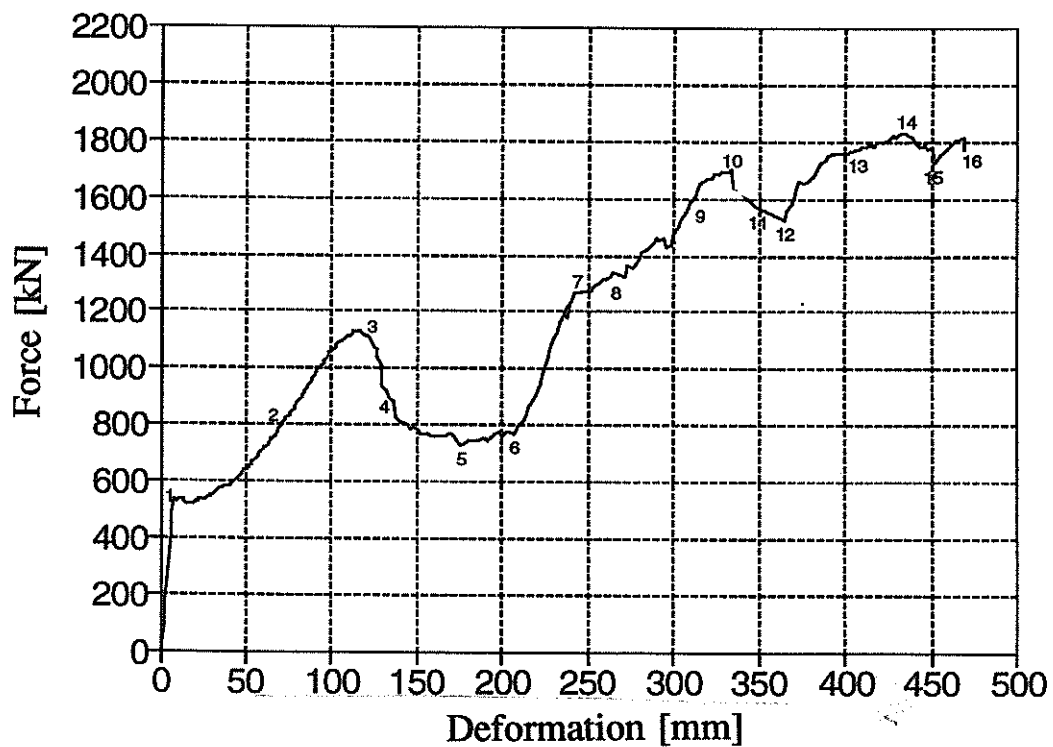


Figure 8 Load versus lateral indentation for model 1

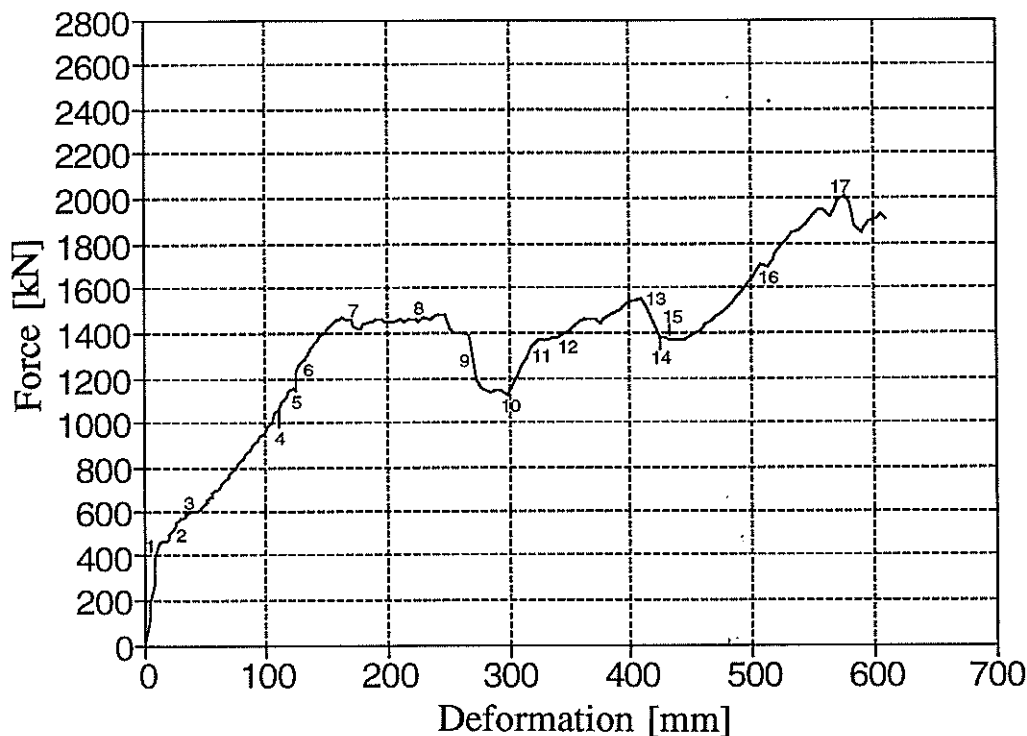


Figure 9 Load versus lateral indentation for model 2

The following observations made during tests refer to points indicated on the load displacement curves:

**Model 1**

- 1 Buckling of the cross-joint between the center girder and floor
- 3 Fracture in outer bottom plate close to next but center floor. The crack first follows the floor then turns in the direction of a girder.
- 6 Increase in stiffness as more girders and floors come into contact with the indenter
- 10 Drop in load carrying probably caused by extensive cracks in floors and girders
- 12 Activation of inner bottom by direct contact with the indenter
- 15 Fracture in inner bottom

**Model 2:**

- 1 Local failure of floor under the contact point
- 7 Fracture in outer plating at center floor. The crack grows in longitudinal direction.
- 9 Load drop probably caused by crack in transverse direction in outer plating.
- 10 Increase in stiffness due to direct contact between indenter and the two next floors.
- 13 Load drop probably due to extensive cracking of floors and girders
- 15 Increase in stiffness due to direct contact with inner bottom
- 17) Fracture in inner bottom along center girder in longitudinal direction

For both models the mode of deformation is very local. The predominant part of the deformations take place inside the floors and girders surrounding the contact area. Once these

members come into direct contact with the indenter the deformations spread to the adjacent sections.

### Computer simulation of double bottom strength.

For simulation of local resistance to lateral indentation the computer code DYNA3D is used. The indentation of the sea floor is simulated as an impact problem assigning a kinetic energy to the impacting body sufficiently large to penetrate the double bottom.

The 4 node Belytschko-Lin-Tsay shell element is used in the analyses. A piecewise linear, isotropic strain hardening material is assumed based on strain-stress relationships from tension coupon tests. Fracture is simulated by a drop in the effective stress to 10 % of the ultimate stress. To avoid very abrupt changes in stiffness a linear reduction is performed once the ultimate stress is attained.

As a first step the sensitivity of the results with respect to fineness of the element mesh and the speed of the indenter is studied.

Figure 10 shows results from simulation of axial impact on a cruciform joint for three different mesh fineness. All edges are restrained to displace in the axial direction only. Side edges are fully clamped. The speed of the indenter is 3 m/s.

The load-displacement relationship depends strongly on the mesh fineness. The coarse mesh yields significantly higher peaks as well as average compressive stress, while the intermediate - and the fine mesh yield comparable results. This is also confirmed from the plots of deformed configurations shown in Figure 11. The coarse mesh can not capture all the local buckles that develop, while the deformation pattern is reasonably similar for the two other mesh configurations.

It is concluded that mesh sizing of intermediate fineness is required in order to obtain reliable results for webs in girders and floors.

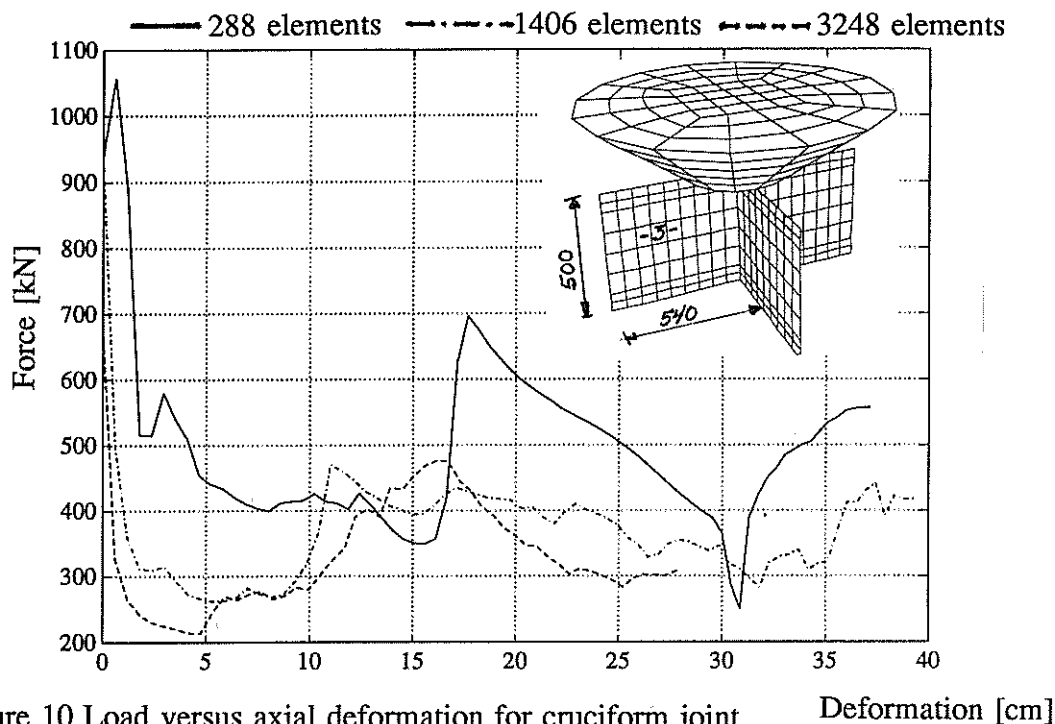


Figure 10 Load versus axial deformation for cruciform joint

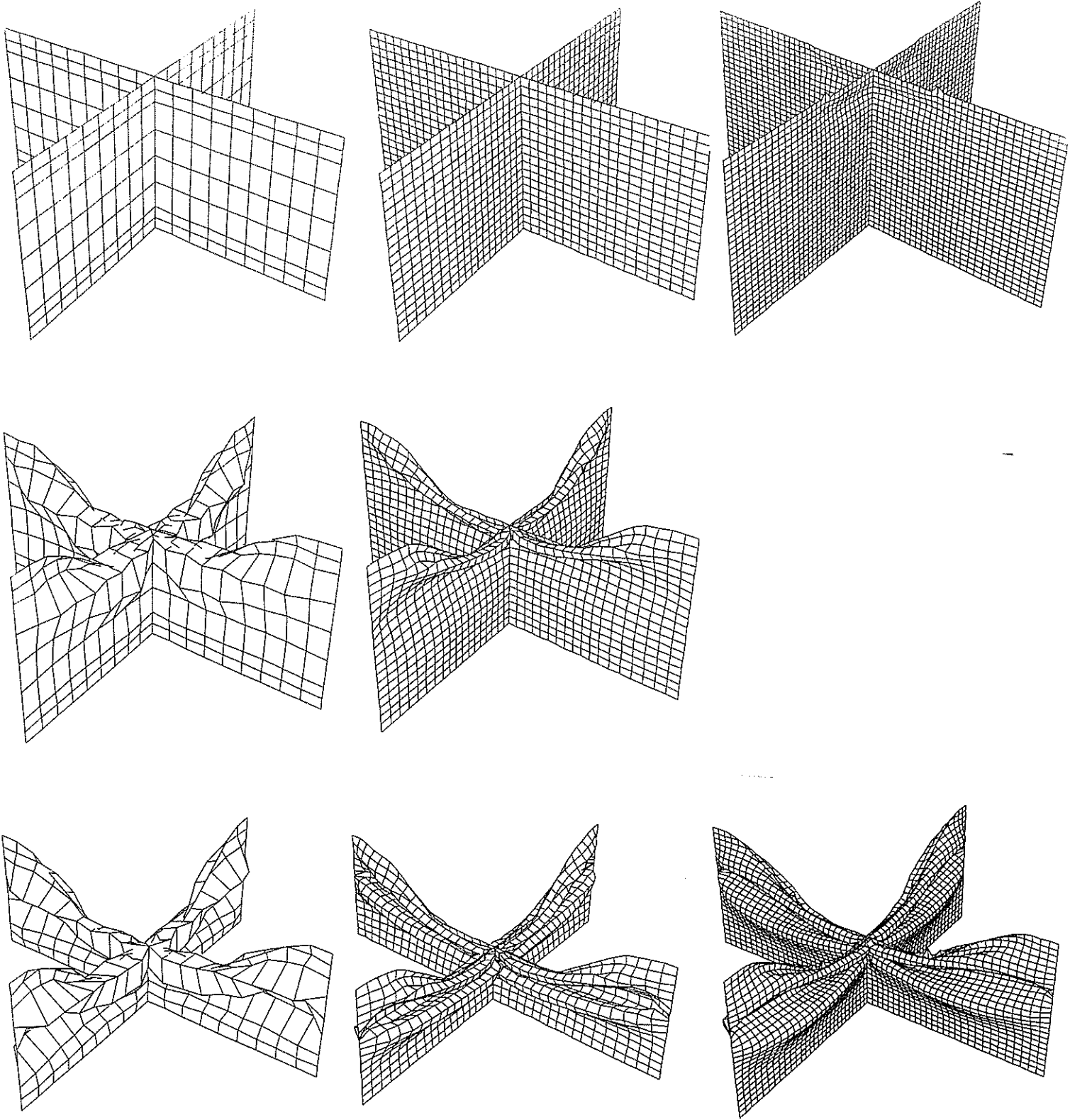


Figure 11 Axial deformation of cruciform with three different mesh sizing

The next study concerns the speed of the indenter. This is important because the number of time increments is inversely proportional to the impact speed. The primary dynamic effect in these simulations are inertia forces, which in general influences the buckling pattern. Strain rate effects are not taken into account in the analyses, which are based upon the model with 288 elements.

Figure 12 shows that the peak load associated with initial buckling is rather sensitive to impact speed, but also the post collapse behaviour is influenced. Although the true "static" response can not be deduced from these results, dynamic effects are considered to be moderate for impact speed up to  $\sim 6$  m/s.

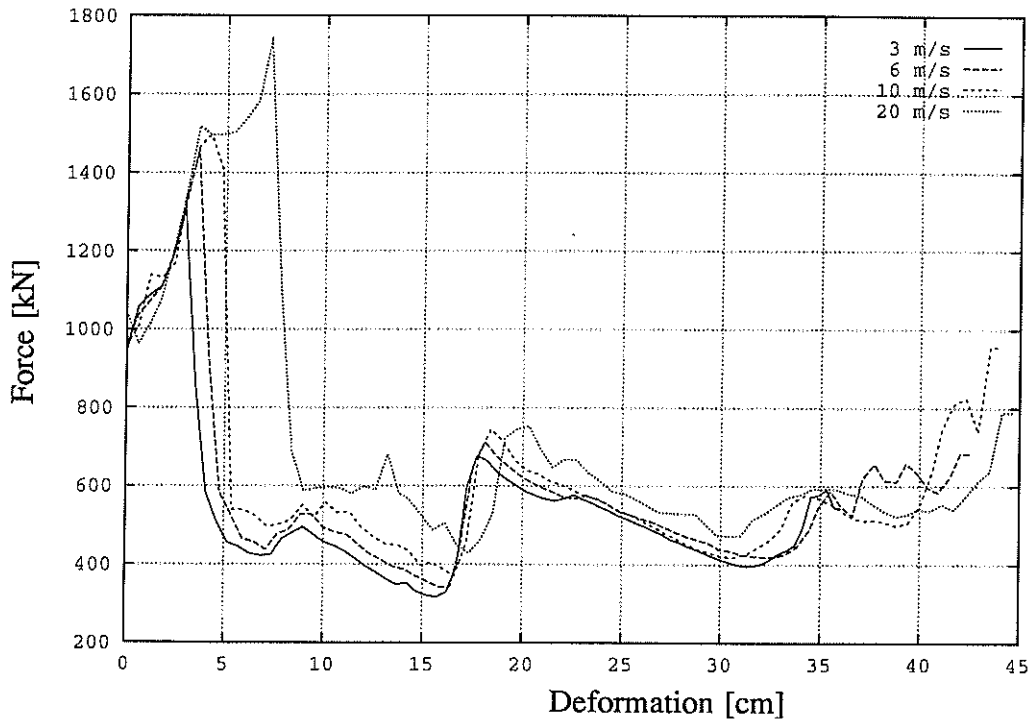


Figure 12 Load versus lateral indentation for various impact speed.

Figures 13 and 14 show the finite element mesh of double bottom models 1 and 2. It consists of 7500 - and 5200 elements, respectively. The speed of the indenter is 3 m/s.

Load - lateral indentation relationships found by simulation are compared with tests results in Figures 15 and 16. Taking into account the complexity of the problem the agreement is not bad. The initial peak load is overestimated. This is to be expected because the models have geometry imperfections and residual stresses. Furthermore, the element mesh is probably too coarse to pick up local buckling properly.

Fracture in the outer plating takes place a little late on model 1, but approximately correct for model 2. In the large displacement range the resistance is overestimated by DYNA3D, especially for model 2. A major reason for that is probably the way fracture is simulated. The element loses stiffness in both directions whereas significant load carrying capacity may remain along cracks.

The plots of the deformed model at the end of the simulation in Figures 17 and 18 show that the mode of deformation in both cases is very local in the sense that only the part of the structure being in direct contact with the indenter is significantly distorted. This is in correspondence with test observations.

Strain gauge locations in outer and inner bottom plating for model 2 is shown in Figure 19. Recorded strains are compared with simulated strains in Figures 20-23. It should be noted that measured strains are total strains whereas the numerical values are effective plastic strains. The figures shows that the theoretical predictions follow the test results quite well although a phase lag is apparent.

The maximum strain measured in the inner bottom at the end of the test (when fracture occurred) is 3.5%. This shows that rupture in the inner bottom as experienced in the tests is a very local phenomenon which may difficult to capture by simulation. For model 1 the maximum strain in the inner bottom at the point of fracture is 4%.

## Simulation of actual tanker double bottom

Figure 24 shows the finite element model of the double bottom of a 280,000 dwt tanker. The height of the double bottom is 4 m. The center tank and wing tank are modelled. An intermediate transverse bulkhead in the wing tank is neglected. Symmetry is assumed in longitudinal direction so that the analysis is carried out with half of the model shown. All longitudinal stiffeners and most of the secondary stiffeners have been modelled. The floors and girders are assumed fully clamped at the tank boundaries. Material properties are identical to the ones used for double bottom test model 1. The sea floor is assumed to have the same shape as the one used in the test and is scaled up by a factor of 5. The speed of the indenter is 1.5 m/s.

Lateral load versus indentation is depicted in Figure 23. The simulations stopped after 2 m of deformation due to disk space problems. The curve resembles the ones obtained in the simulation of laboratory tests. The first peak is attained once the center longitudinal girder undergoes web buckling. Fracture occurs in the outer bottom plating at point 2 and in the center girder-floor connection at point 3.

The deformed configuration at the end of simulation is illustrated in Figure 25. It appears that the deformation are very local with little effect on the structure outside the direct contact area.

The model consists of 16000 shell elements. The CPU consumption on HP 785 work station is 185 hours. This indicates that the present model is too big for practical large scale analysis. A reduction in computer time will be aimed for taking greater advantage of symmetry and using higher impact speed.

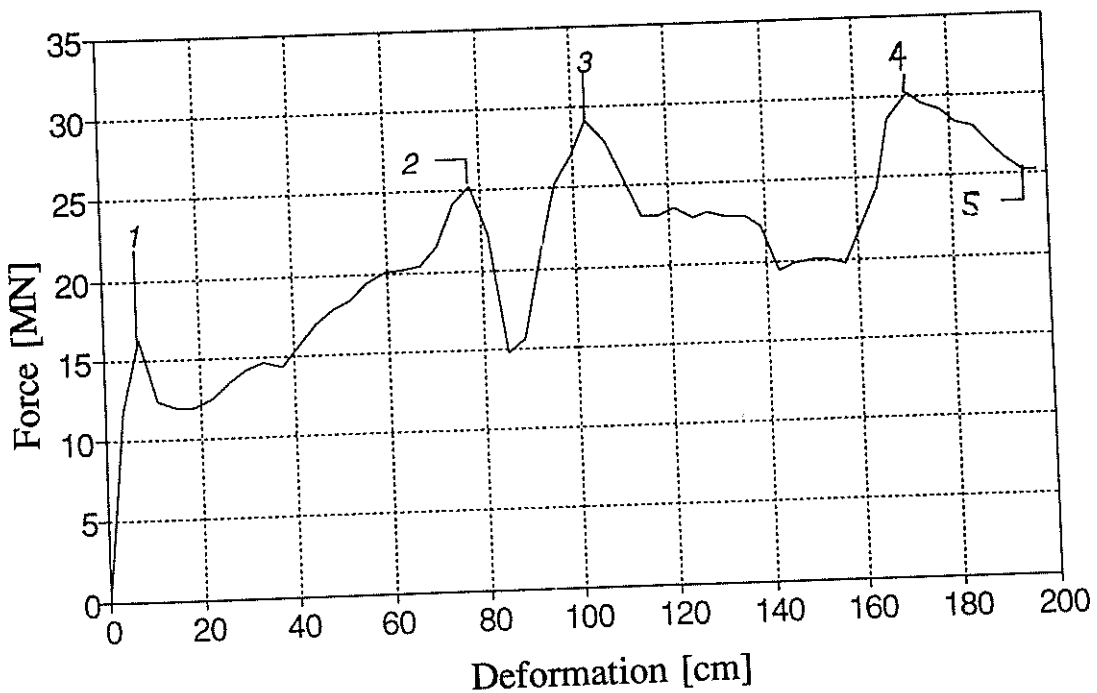


Figure 23 Load versus lateral indentation for 280,000 dwt tanker double bottom

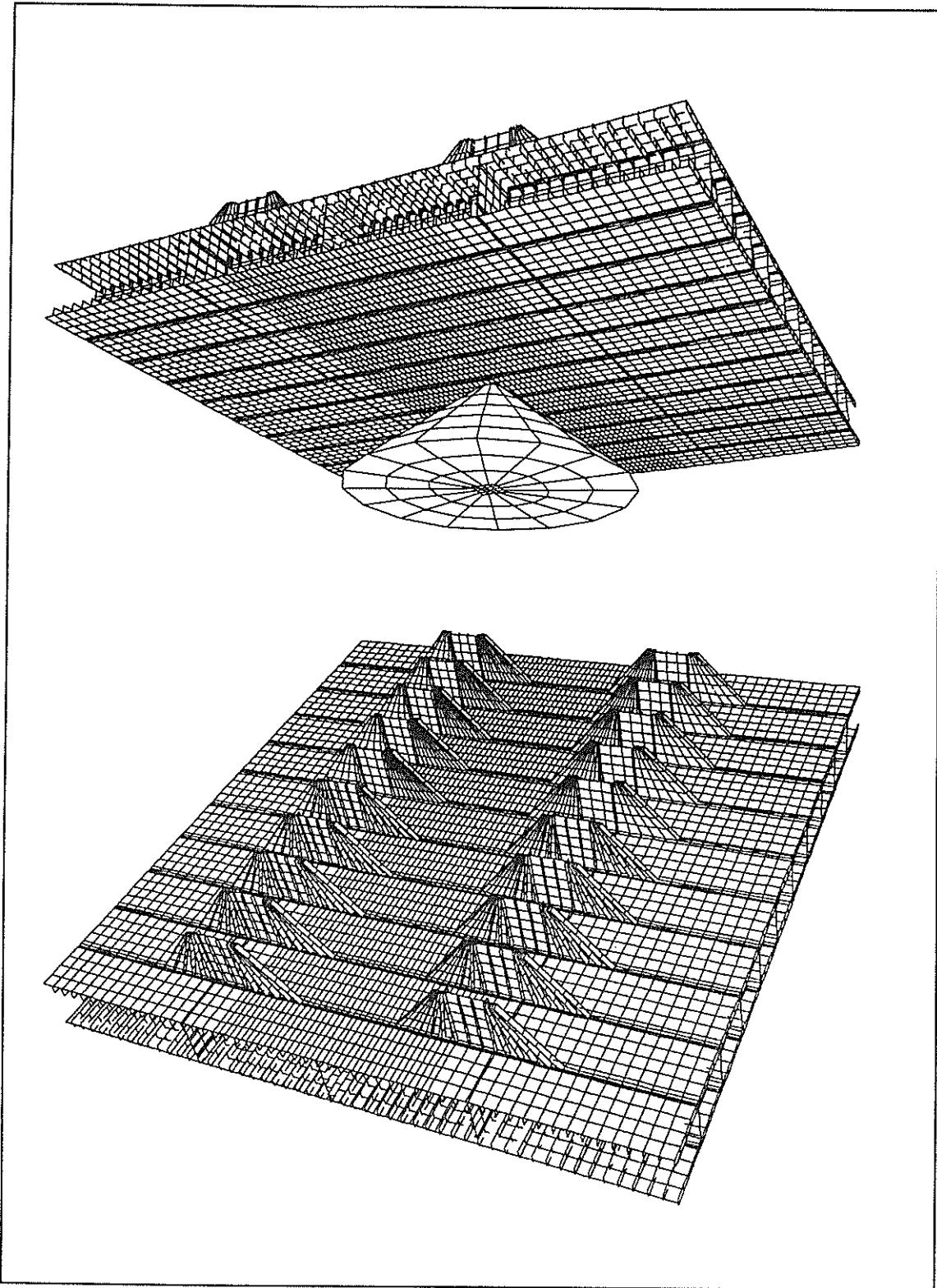


Figure 24 Finite element model of 280.000 dwt tanker double bottom.

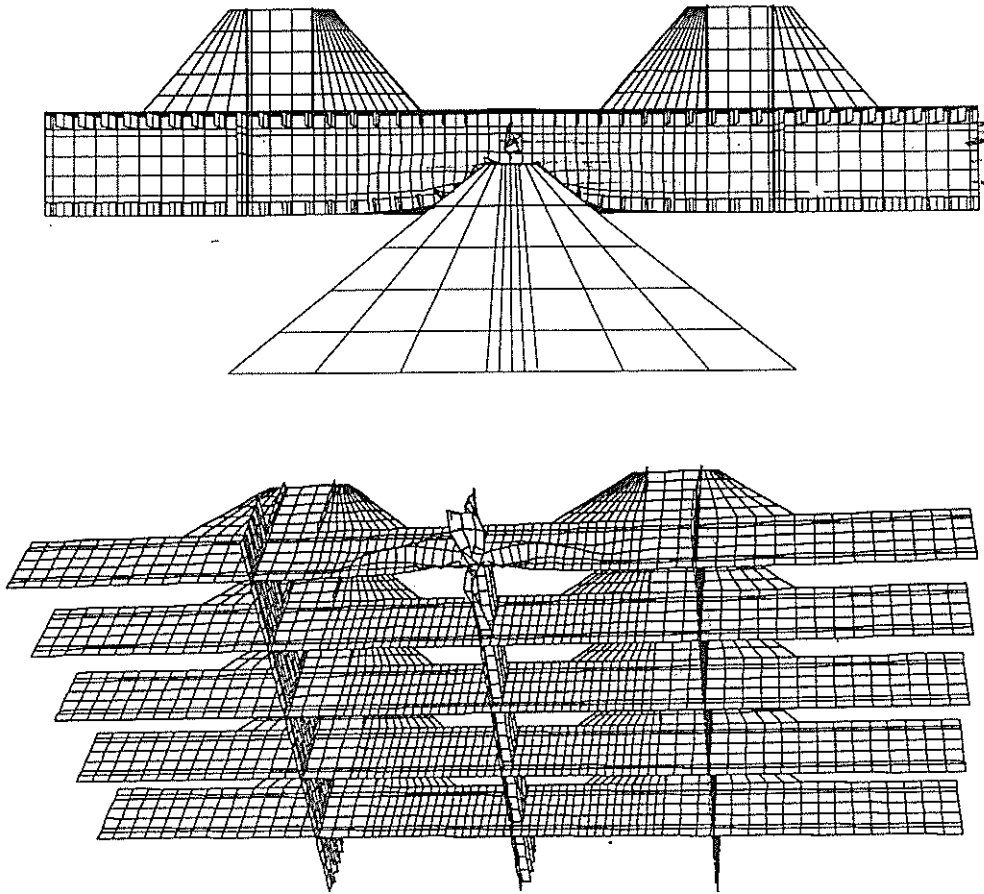


Figure 25 Double bottom at the end of simulation.

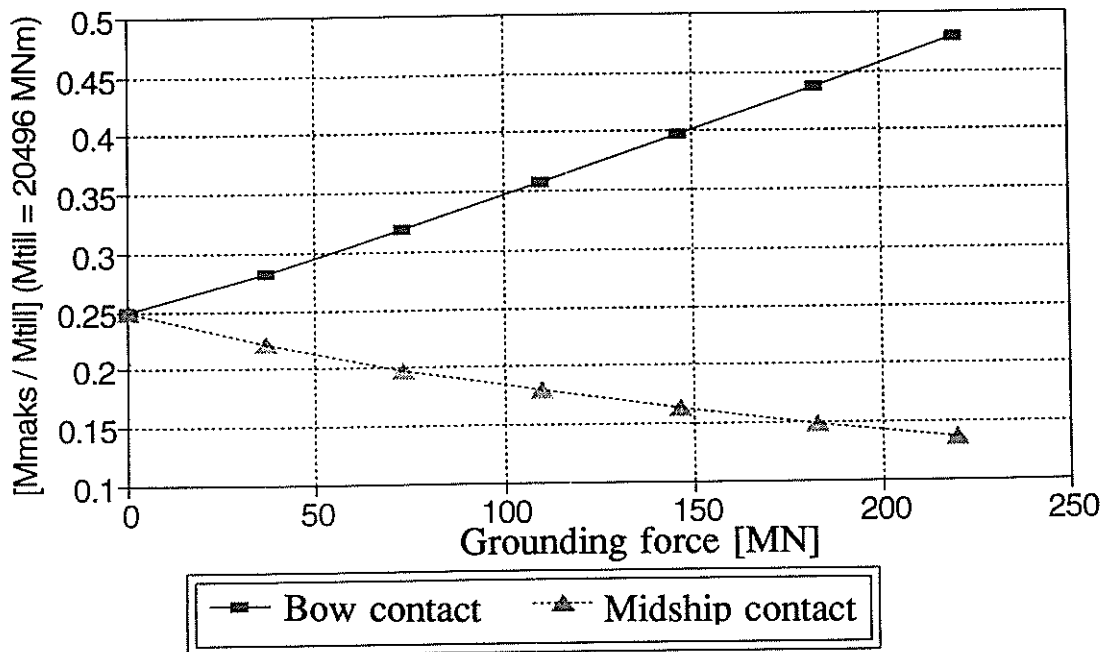


Figure 26 Maximum hull girder moment as a function of lateral grounding force for contact midship and at the foremost tank

Figure 26 shows the hull girder bending moment as a function of the grounding force as determined by VESIM. The ship is assumed to be fully loaded yielding a sagging moment midships. Comparing with Figure 23 it is seen the contact force is much too small to endanger the overall integrity of the hull girder.

### **Conclusions**

With present super computers detailed nonlinear finite element analysis of a complete tanker compartment has become feasible. This enables a better understanding of how different configurations perform in grounding and collision. Comparison with test results are encouraging with respect to the credibility of the theoretical predictions. Further tests with different double bottom configurations should, however, be carried out.

The use of nonlinear finite element analysis should be confined for research purposes. Ordinary design and more extensive studies of different accident scenarios should preferably be based upon approximate and less costly methods.

### **Acknowledgements**

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