STAB'2000, Seventh International Conference
on Stability of Ships and Ocean Structures,
Launcheston, Tasmania, 2000.

Reprinted: 05-12-2000
Website: www.shipmotions.nl

Report 1220-P, February 2000,
Delft University of Technology,
Ship Hydromechanics Laboratory,
Mekelweg 2, 2628 CD Delft,
The Netherlands.

The Effect of Crashworthiness and Solid Buoyancy on Survivability of Damaged and Flooded Ro-Ro Ships

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Abstract

The SOLAS conventions on survivability of partially flooded ships mention two aspects that are usually not seen as design parameters in the sense that they can be influenced significantly by the naval architect. These parameters are permeability of flooded compartments and crashworthiness of the ship's hull. This paper shows the huge potential, with respect to damage survivability, of decreasing the permeability of void spaces and increasing the crashworthiness of the ship side structure. Decreasing permeability can be realised by stowing light weight foam blocks. An increase of the crash resistance of the side can be achieved by applying foam in void spaces as crash barrier. Investigations involving hydrostatics, ship motions, including progressive flooding (water ingress), and crash behaviour are reported. Other important issues such as fire safety, including toxic fumes, and access for surveys are addressed. Results are shown for an existing Ro-Ro ferry, ready for her midlife refit.

1 Introduction

The ability to survive damage to the hull with respect to sinking and capsizing has always been of great interest to ship owners and shipbuilders. Improving damage stability survivability starts with understanding what actually happens during and after a collision. Achieving such an understanding proves to be very difficult. This problem also occurs when an analysis is carried out of the flooding, sinking and capsize mechanisms occurring during an accidental event. For example, still there is a lot of discussion on which mechanisms were active during the loss of the Estonia, see Naval Architect (1998-1999). Developments in analysis tools over the last decade have enabled designers and researchers to simulate hull crashing, see Kitamura et. al. (1998), and consequential flooding, see Vermeer, Vredeveldt and Journée (1994) and Journée (1997). Crash simulations could be validated against full scale collision and grounding tests, flooding and capsize simulations have been validated against model experiments only, see Vermeer, Vredeveldt and Journée (1994) and Vassalos and Turan (1994).

More or less conventional design measures to improve damage survivability of ships up to now are: increased subdivision of the hull, reduction of operational $\overline{KG}$'s and increased width. The non-conventional measures of stowing Expanded PolyStyrene foam (EPS) blocks in void spaces, has been mentioned only once in literature, see Sen and Wimalsiri (1991). Initiated by mr. Ernst Vossnack, former head of Nedlloyd's design department, extensive investigations have been carried out to establish the potential benefits and risks of applying foam blocks.

The Dutch ferry SIER (80 m), launched in 1994 and owned by Wagenborg Passenger Services, features EPS in her voids.

Recently an investigation has been carried out in the Netherlands on applying foam blocks in a 165 m ROPAX vessel.

Both investigations were based on a 'first principle approach' rather than on 'complying with the rules'. The results of the investigations and the experience so far are reported in this paper.

2 Qualitative Description of Collision Accident

Apart from flooding due to faulty valves, piping and shell doors, there are two main causes for water ingress. These are collision and grounding. Flooding, due to grounding damage is usually restricted by applying a double bottom. At the moment flooding due to collision damage is assumed to be impossible to prevent. Therefore flooding scenarios must be identified and assessed. When, for example a ROPAX ferry is hit by a vessel with a bulbous bow, damage will occur to the side shell of the struck vessel. This damage, may look similar to an 'excla-mation mark' as observed when the Ro-Ro vessel EUROPEAN GATEWAY was struck by the Ro-Ro vessel SPEEDLINK VANGUARD. The side damage is showed in Figure 1.

The actual damage that will occur will depend on the shape and structural rigidity of the penetrating bow, the crash behaviour of the struck side structure, the striking location, the incident angle, inertia's of both vessels involved and their speeds at the moment of impact.

In general the structure of the struck ship will dent, buckle and tear while the bow of the striking ship may dent and buckle. Bulbous bows in general will prove to be rather rigid when compared with side structures.

Through the damage area, water will flow into the damaged compartment, spread over this compartment and may flow into connected compartments if any. Since the water will usually enter through the side, initially a heeling moment will be acting on the damaged ship. Therefore, the ship will respond in terms of roll, trim and sinking.

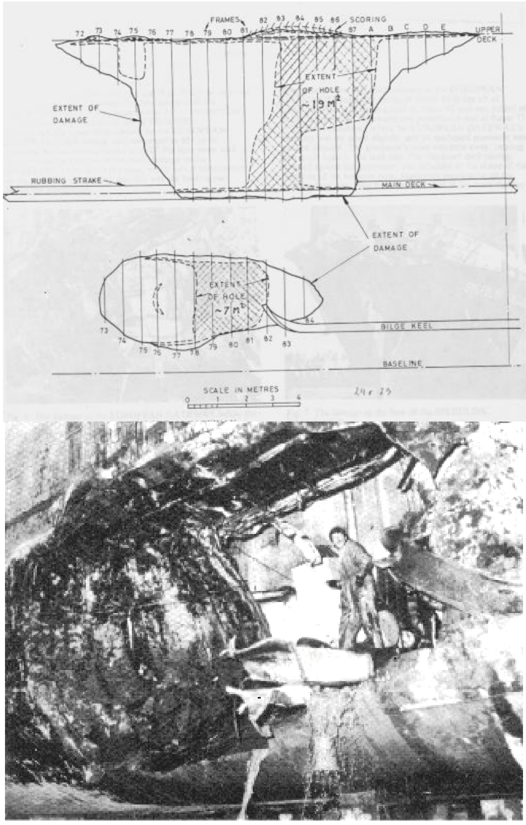


Figure 1 Side damage on EUROPEAN GATEWAY (top), damage below the water line (bottom).

It should be remarked here that neither the actual area of the ingress openings nor the shape of the damage can be determined from any damage statistics because only damage extent, i.e. damage length, damage penetration and damage height, are reported.

Another interesting remark is that in case of a collision it is worthwhile not to withdraw the striking ship from the struck ship. The striking ship's bow will act as a plug, so water ingress will be slow. Moreover the striking ship provides additional stability to the struck ship. No guidance or 'best practice' exists on this matter.

After some time a hydrostatic equilibrium may be found provided sufficient buoyancy remains present and provided no unstable situations occur during water ingress and flooding of the ship. The struck vessel will find a new draught, trim and heel. When the damaged vessel is in a sea state further water ingress may occur due to waves and ship motions. Especially water accumulation on a vehicle deck often proves to cause an unstable situation after some time of exposure to the waves. It is interesting to note that by manoeuvering the struck ship in a quartering seas course coming in from the intact side, may prove to be very effective in reducing or even preventing gradual water ingress into the ship and especially onto the vehicle deck. No guidelines are available in this respect nor are there any publications on such a measure.

3 Simulation Tools

Currently rather good simulation tools are available for both predicting damage due to collision and grounding, see Kitamura et. al. (1998), as well as for predicting the sinkage and the roll motion due to sudden water ingress and progressive flooding, see Vermeer, Vredeveldt and Journée (1994). At least one prediction tool is available on ship motions and water ingress of a damaged vessel while subjected to a sea state, see Vassalos and Turan (1994).

The damage prediction tools are based on explicit finite element method. In this method the governing partial differential equations of the discretized structure can be expressed as:

$$\ddot{x} = M^{-1} \cdot (F_{ex}^{(n)} - F_{\text{int}}^{(n)}) \qquad (1)$$

where M is the diagonal mass matrix, F_{ex} the applied load vector at time $t^{(n)}$, F_{int} the stress divergence or internal load vector at time $t^{(n)}$ and $\ddot{x}$ the vector of nodal accelerations in a global co-ordinate system. The load vectors

may depend on nodal displacements, nodal velocities or other internal variables.
Unlike 'conventional' FE methods, here no stiffness matrix inversion is required; instead a simple time integration scheme is used to update nodal velocities $\dot{x}$ and displacements x respectively. In this scheme the time step size is limited by numerical stability requirements. The stable time step size is typically 1.0 microsecond.

Ship motions due to sudden water ingress and waves can be described as:

$$\sum_{j=1}^{6}\{(M_{i,j}+A_{i,j})\cdot \ddot{x}_j(t)+\int_0^{\infty} B_{i,j}(t)\cdot \dot{x}_j(t-t)\cdot dt + C_{i,j}\cdot x_j(t)\}=X_i(t) \quad (2)$$

These equations are known as 'Cummins' equations. The index i runs from 1 to 6, referring to the six rigid body motions of the ship. $x_j(t)$ is the parameter for the translational and rotational displacement in direction j at time instant t. $M_{i,j}$ and $A_{i,j}$ describe the solid and hydrodynamic inertias respectively. $B_{i,j}$ describes the retardation functions and $C_{i,j}$ the spring coefficients. $X_i(t)$ describes the external loads in direction i at time t. These external loads may be wave loads but can also be inclining moments due to water influx trough damage openings. This water influx can be described by a Bernoulli differential equation using input data such as water levels inside and outside the ship, air pressures in tanks/compartments and flow areas representing damage openings, openings related to progressive flooding and air vents. These differential equations are also solved by numerical integration.

The numerical integration schemes, especially in case of equation (1), are rather demanding with respect to required computational power and memory. However the current generation of personal computers can cope quite well. The attractive feature of time integration is that geometrical and mechanical non-linearities can be dealt with without any trouble.

4 Validations

Both calculation schemes have been validated by comparison with data from experiments. The damage prediction calculation methods have been checked and, to a lesser extent, tuned against full-scale ship-collision-experiments, see Kitamura et. al. (1998) and Kulzep and Peschmann (1998). In the context of this paper it is worth mentioning a validation reported in Kulzep and Peschmann (1998) where large-scale penetration tests of a 3.5 tonnes drop hammer into a foam backed steel shell are simulated. Figure 2 shows the test set up, see TNO Report (B-92-0506).
Figure 3 shows the calculated energy dissipation versus penetration in comparison with the test results of Kulzep and Peschmann (1998).

Figure 2 Test set up foam backed side panel penetration test.

The upper line refers to the measurements, the lower three lines refer to simulations with various material failure models. It shows that the calculation 'under-predicts' the energy absorbing capacity by about 12%. For the purpose of safety assessment, such accuracy seems satisfactory.

With respect to ship motion response to sudden water ingress and wave loads, while the ship is damaged, various validations have been carried out, see Journée, Vermeer and Vredeveldt (1997). Unfortunately almost all experimental data is obtained from model experiments, usually at a scale of 1:40. For ship motions this may be acceptable however with respect to damping due free moving water in the hull and quasi static water flow still doubts exist, see Journée, Vermeer and Vredeveldt (1997) and Journée (1997).

5 Equivalence with Current IMO Regulations

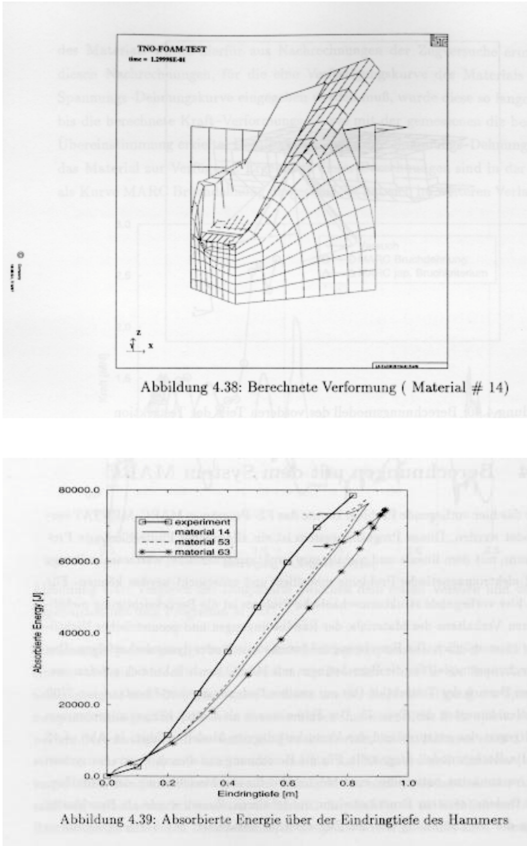


Figure 3 Calculated and measured results deformation (top) and energy versus penetration (bottom), see Kulzep and Peschmann (1998)

Including the effects of foam in the safety assessment of ships with respect to damage stability is not straightforward.

SOLAS conventions do not explicitly mention how to take the presence of foam into account. Implicitly however some parameters seem to present opportunities. The obvious parameter is permeability. When foam blocks are stowed in void spaces, these spaces are not likely to flood. So pending the stowage rate (V_{foam}/V_{void}) that can be attained, the permeability reduces accordingly. However when a foam filled compartment is damaged due to a collision or grounding the foam will show a dent. The volume associated with this dent does not contribute to any buoyancy. From the previous section it may be clear that calculating the damage to be expected is not a very difficult task. However choosing an adequate shape and size of the penetrating object as well as the energy to be absorbed by the struck ship does pose a substantial problem. The Explanatory Notes in IMO Resolution (A.684) on SOLAS regulations show that use is made of damage statistics from the past. However it is not possible to establish a link between these statistics and absorbed energy.

Obviously applying foam in wing voids reduces the risk of damage to adjacent compartments between wings and the CL. The foam acts as a crash barrier. However quantifying the risk reduction is not readily possible. Again the main problem is assuming an adequate shape and size of the penetrating object and energy to be absorbed.

6 165 m Ferry

This ferry is about 12 years old, and as of the 1st of January 1999, she must comply with SOLAS 90 requirements. A more or less conventional solution is fitting moveable flood control barriers on the vehicle deck. Five partitions are required for this vessel, so four barriers have to be fitted. These barriers will restrict any accumulation of water on the vehicle deck to approximately 1/3 of the deck area. With this measure the vessel is able to comply with both SOLAS 90 and Stockholm Agreement requirements. Unlike most Ro-Ro passenger ferries this vessel features $1/5\,B$ voids along its full length, also in way of the engine rooms. For this reason the option of reducing the permeability of the voids may be very effective since side damage will lead to hardly any influx of water in the voids. With a permeability of 15%, freeboard in the damaged condition has been calculated to be about 0.25 cm larger than in case of empty voids.

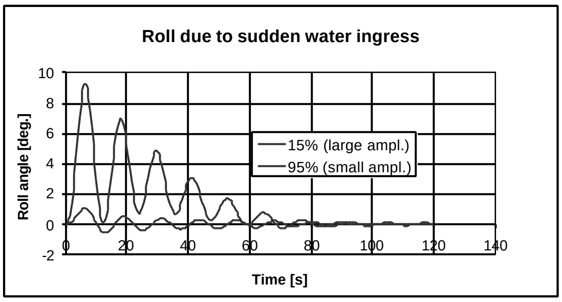


Figure 4 Effect of reduced permeability on (roll) lurch of a 165 m ferry, due to sudden water ingress

Due to this increased freeboard the accumulation of water on the vehicle deck, while damaged and in a seaway, has been calculated to decrease significantly. Moreover complying with SOLAS 90 requirements is less onerous. Preliminary assessments, based on hydrostatics calculations and ship motions simulations, show that compli-ance with both SOLAS 90 and Stockholm requirements can be achieved with only two flood barriers and two relatively small buoyancy tanks on the vehicle deck.

Another phenomenon is the lurch the vessel may make after a collision, due to sudden water ingress through the damage area. Current regulations ignore this mechanism.

The results of a simulation of this lurch, based on the method as described in the section on simulation tools, is shown in Figure 4. As can be seen the initial roll angle is reduced significantly in case of a permeability of 15%.

7 Other Aspects

Stowing foam in void spaces introduces some practical problems and a potential fire hazard. The most important practical problems are:

1) proper stowage of the foam,

2) the need to inspect void spaces at regular intervals on structural damage and corrosion,
3) water absorption,
4) chemical resistance of the foam and
5) chemical properties with respect to corrosion of the voids.

In 1994 the passenger ferry SIER, operating between the Dutch main land and the Isle of Ameland, was launched. Due to its shallow draft and high width to draught ratio this vessel has a high intact stability. She can also easily comply with any damage stability regulation. In spite of these superior stability properties the owner decided to fit foam blocks in her void spaces, basically to increase her collision resistance. For this purpose research was carried out with respect to energy absorbing capacity of various foams as well as fire behaviour of the foam in confined spaces. Figure 2 shows the test set up which was used for the energy absorption tests in TNO Report (B-92-0506). The conclusion is that Expanded Polystyrene foam proved to have the most favourable energy absorbing properties.

Classification societies usually inspect at five-year intervals. Therefore at least every five years the foam block have to be unloaded. Experience with the ferry SIER showed that no substantial problems occurred in the process of foam stowage and unloading. Figure 5 shows the foam block (top picture) after having been taken out of the void spaces (bottom picture).

Manufacturers of EPS issue product data sheets on various material properties. From these is can be found that water absorption for 20 kg/m^3 EPS is zero for short-term exposure (less than one day). At long term exposure (many years) absorption of 5% is found. Chemical resistance to fuel oil and lubrication oil is non-existing. The chemical properties of the foam are such that no corrosion occurs due to its presence in voids. Figure 5, bottom picture, shows one of the voids of the SIER after 5 years of EPS foam blocks stowage. No damage could be observed to the coating.

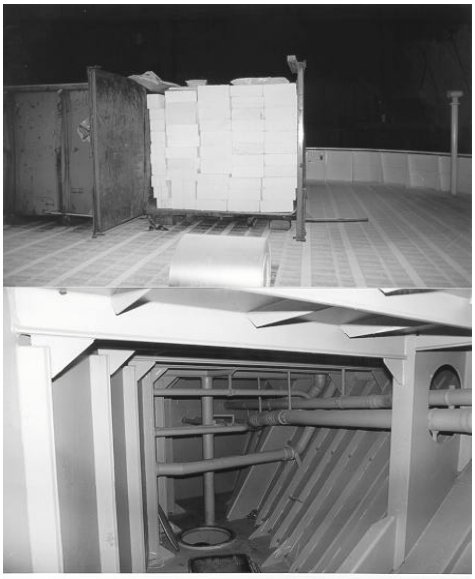
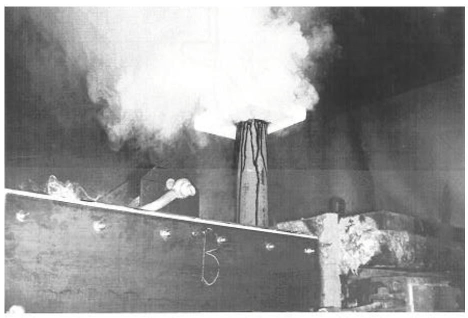


Figure 5 EPS foam blocks as used in ferry SIER (top), wing tank i.w.o. ER after 5 years of foam stowage (bottom).

Fire tests were carried out on various foams, see Figure 6. The blocks were stowed in a steel box, representing the void spaces as present in the SIER. The box was closed and sealed to be airtight.

One side of the box was subjected to a SOLAS engine room heat exposure. In all cases the foam started to deteriorate, Toxic fumes developed and escaped through the non-return air vent. Such fumes need to be discharged outside the ship, i.e. at weather deck level.



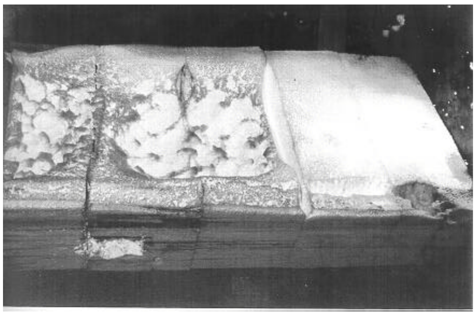


Figure 6 Fire test with foam in a void space, smoke development (top), melting/degradation of EPS (bottom).

However no fire occurred inside the box due to a lack of oxygen. When simple rock wool insulation was applied between foam and exposed steel wall, nothing happened. Because of the initial pentane emission right after production, EPS must be given time to cure (at least six weeks) before stowing it permanently in closed compartments.

8 Way Ahead

As may be clear from the previous sections adequate tools are available to assess the structural damage and ship motions during a collision and during subsequent water ingress. It may also be clear that extent of damage has a major impact on the survivability of Ro-Ro vessels. SOLAS 90 regulations and The Stockholm Agreement state damages to be assumed while assessing damage stability survivability. Unfortunately these damages can not be linked to any energy absorbed during a collision because they are intended for other purposes, i.e. determining which compartments will flood and which damage area will be available for water ingress into the ship. However assumptions are required with respect to size and shape of penetrating bow and the amount of collision energy to be absorbed by the struck ship if the effect of foam blocks on crashworthiness and buoyancy is to be assessed. Future efforts will be directed on solving this issue.

With some fantasy this roll response to sudden water ingress can be seen as a ‘step response’. In case of a linear system a step response fully describes the dynamic characteristics of the system. It may be worth while to investigate if the ‘step response’ can be used to assess the motion characteristics for the damaged ship in a sea state.

9 Conclusions

Stowing expanded polystyrene foam block in void spaces can be a very effective and relatively cheap measure for increasing the survivability of existing Ro-Ro passenger ships with respect to collision, because of its buoyancy, its light weight and its crushing energy absorbing capacity.

EPS foam can be safe from a fire risk point of view when applied in closed, air tight, spaces only.

When EPS is applied a curing time must be taken into account because of pentane escaping from ‘fresh’ material.

When foam blocks are stowed permanently in void spaces, air vents must be fitted with non-return valves extending to the weather deck.

Damage prediction calculations methods as well as ship motion calculations methods, including water ingress and progressive flooding, should be considered as valuable tools in the design stage of ships.

10 Acknowledgements

The authors acknowledge the permission of both ship owners Wagenborg Passenger

Services and P&O-NSF, to publish the research results as obtained for their vessels.

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