MECHANISMS AND PHYSICS LEADING TO THE CAPSIZE OF DAMAGED SHIPS

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SUMMARY

This paper focuses on the characteristics of flooding and capsizing of different types of ships. For ro-ro ferries the paper discusses transient flooding in calm water and in waves, including the influence of cross flooding arrangements. Furthermore the progressive flooding and capsizing in waves due to accumulation of water on the car deck are considered and how this may be influenced by the initial conditions at the time of damage occurrence. The paper dwells in some detail on fluid dynamics relevant to flooded compartments that are subjected to oscillatory motions. The capsizing process of a frigate-type ship with a high degree of subdivision is shown to differ from a damaged ro-ro ferry in waves.

1. INTRODUCTION

Over the past decade a significant amount of experience has been gained associated with predicting the capsize behavior of intact and damaged ferries and naval vessels. Experiments and numerical simulations have contributed greatly to an ever-increasing body of knowledge in this field.

The objective of this paper is to provide insights into different physical aspects relevant to the flooding and capsizing of damaged ships in waves. The information presented here is derived from internal research at MARIN, research sponsored by the CRNAV consortium, and from participation in EU projects under the Safer Euroro Thematic Network.

For ro-ro ferries transient flooding is considered in calm water and in waves, including the influence of cross flooding arrangements. Concerning the progressive flooding and capsizing due to deck edge submergence and accumulation of water on the car deck, it is shown that the initial conditions and wave group properties at the time of damage occurrence may have a significant influence on the ship's behavior.

Techniques are discussed for predicting the fluid forces exerted on flooded compartments undergoing oscillatory motions. The paper highlights differences between capsize mechanics of ro-ro ferries and those associated with a frigate-type ship that has a high degree of subdivision.

2. DYNAMICS OF DAMAGED RO-RO FERRY

A significant amount of research involving damaged ro-ro ferries has focused on capsizing associated with the accumulation of water on deck, while drifting in beam seas. Typically model tests are carried out with the vessel starting in the flooded equilibrium condition after damage; this procedure avoids transient effects associated with the initial and intermediate stages of flooding. While subjected to waves, the model will gradually settle in a new equilibrium position, or it will eventually capsize once a critical amount of water has accumulated on the main car deck. An experimental run where the model reaches and remains in a safe equilibrium condition is shown in figure 1.

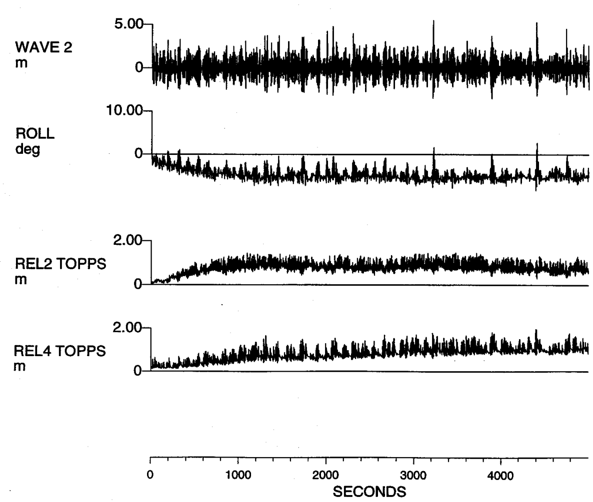


Figure 1 Behaviour of damaged ro-ro vessel while drifting in beam seas (Hs = 4 m)

To investigate the damage behavior of a modern ro-ro ferry with extensive lower hold, Deltamarin designed a vessel for model testing at MARIN. As can be seen in figure 2, the ship has longitudinal bulkheads on the main cargo deck, wing tanks extending from the keel upwards where port and starboard tanks are cross-connected. Part of the research aimed at investigating damage scenarios with the lower hold intact and damaged [1]. Since transient flooding after damage can lead to capsizing (as in the case of the *European Gateway* in the 1980s), this aspect was included in the investigations.

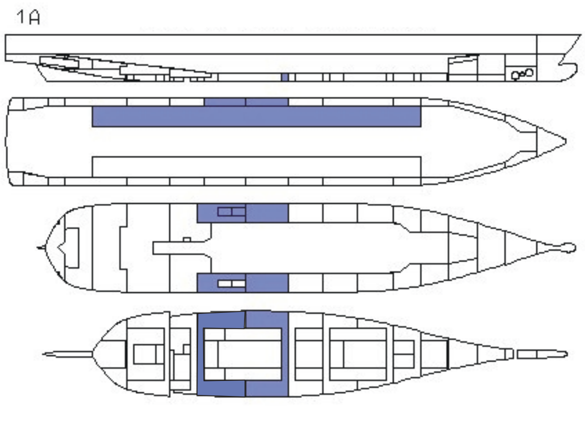


Figure 2 Damage scenario for modern ro-ro ferry

This so-called "ARD" model has been tested in the scenario of figure 2. Figure 3 shows the transient roll response of the ship with an intact GM value of 2.20 m in calm water and in waves following the occurrence of damage. For these tests the vessel started in the intact condition with sealed damage opening (corresponding to standard SOLAS damage). At some point in time, sliding a door created the damage in about 16 seconds prototype. This flooded the model, filled the wing tank on the damage side and flooded the opposite wing tanks through the cross-ducts.

Figure 2 demonstrates that the effects of flooding in calm water and in irregular seas can result in very similar roll response. Furthermore, the roll motions in waves are small compared with the maximum roll angle due to the transient flooding. For this particular configuration the total time of damage creation is of importance -- a long duration damage creation (in the order of one or two minutes) will result in quasi-static flooding without significant transient roll peaks. In this case at the roll peak of about 16 degrees the edge of the car deck was submerged briefly; most of the water captured flowed out of the opening after the maximum roll angle was reached and no critical accumulation of flood water took place.

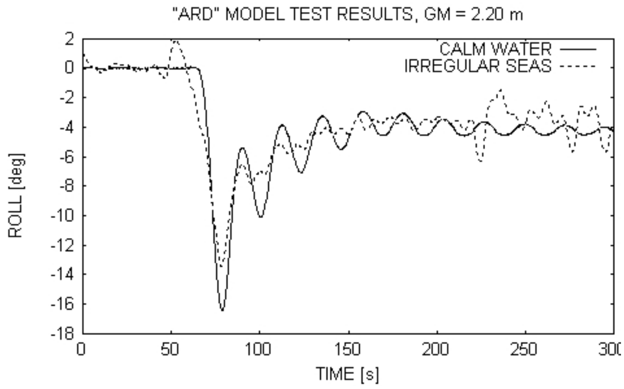


Figure 3 Transient roll response following damage occurrence in calm water and in waves

This transient flooding and motion behavior of the ARD model has been simulated numerically, and good correlation was found. This suggests that the initial water ingress can be modeled assuming a hydraulic flow model. Water ingress experiments with various ship configurations showed that such a flow model describes the physics of flooding and resulting forces adequately [2]. Sloshing effects are not important in this phase of flooding. An example of simulated and experimental roll response is shown in figure 4. The flooding scenario is given in figure 2. Different flooding scenarios and initial GM values gave similar comparisons.

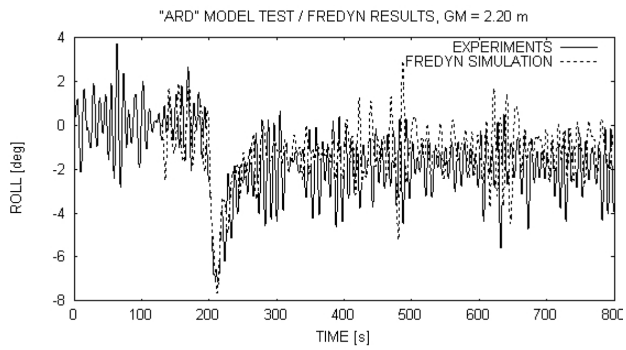


Figure 4 Simulated and experimental roll response following damage occurrence in waves

Cross flooding

The incorporation of cross-flooding arrangements is very effective in reducing final heeling angle in the case of an asymmetric damage scenario. To reduce maximum transient roll peaks during initial flooding of wing tanks, however, such arrangements are largely ineffective. Figure 5 demonstrates this for the ARD model, where the same scenario applies as in figure 2. It shows the measured roll motion and water elevation at the following locations of the damaged compartments underneath the main ro-ro deck (measured close to the cross duct openings): aft port and starboard side compartments (REL4) and forward port and starboard side compartments (REL6). It takes less than 10 s for the first water quantities to flow through the cross ducts and reach the intact SB compartments, but it takes between 50 and 100 s before cross flooding is completed.

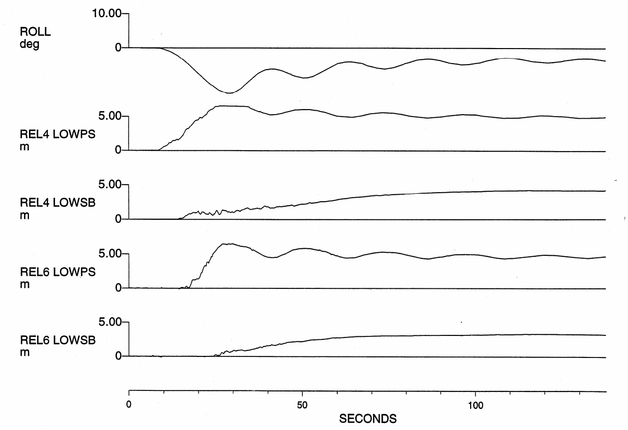


Figure 5 Roll motion and water levels in damaged (PS) tanks and intact (SB) tanks

GM and the heeling moment impulse exerted by the floodwater govern the time it takes for the ship to reach a certain maximum roll peak. The cross-flooding rate determines the time for the ship to reach its static equilibrium. Cross flooding into the intact SB compartments is quasi-static: the oscillatory roll motions do not seem to affect the flooding rate. Complete cross flooding within one roll cycle is not possible for the vessel in this damage scenario.

Influence of initial conditions and wave groups

The behavior of a damaged ro-ro ship in waves depends on the compartment layout below the main deck. This is illustrated by results obtained recently in a model test series conducted at MARIN for the European HARDER project. For this vessel the double bottom area was not connected with a wing tank and no side casings were present. This meant that damage to the side shell would flood the compartment (engine room) and the double bottom below immediately. Part of the double bottom consisted of a cross-duct arrangement between a port and starboard tank.

In the example given in figure 6, the model capsized eventually after the occurrence of damage, but the maximum transient heel angle towards damage (positive) after damage creation is small. There is even a negative roll angle away from the damage. This is due to the large inflow in the engine room, which acts like a "jet" on the side shell of the ship, despite the presence of several large blocks in the E.R. to model the correct permeability and large flow obstructions. The lack of wing tanks results in relatively small transient roll peaks.

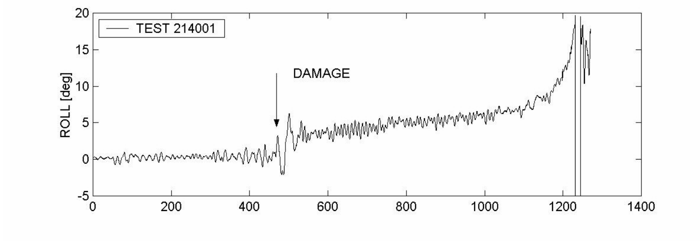


Figure 6 Capsize of ro-ro ferry in waves following occurrence of damage (Hs = 2.5 m, Tp = 9.5 s)

Figure 6 shows also a typical ro-ro vessel capsize. The roll motions in damaged condition are small, and due to the accumulation of water on deck the roll angle increases steadily. The floodwater increases damping (by means of the water mass and increased draught) of the ship and typically the natural roll period increases as well. For a certain time period the roll angle can be more or less steady or slowly increasing until a critical amount of floodwater is reached. The passage of one high wave group may then trigger the final capsize. This capsize point can be clearly seen in the experiments.

Figure 7 shows two capsize events in the same sea state and for the same damage scenario for the HARDER ro-ro ferry discussed above. The difference between the two runs stems from different wave realizations, among others. In the first run the damage opening is created at t = 718 s and the ship remains safe for a long period of time. Large roll angles are found, for example after 1500 seconds in damage condition, but the ship was able to survive those waves and capsizes at a much later stage. In the second run damage occurs at t = 677 s and the ship capsizes within the next 1000 seconds.

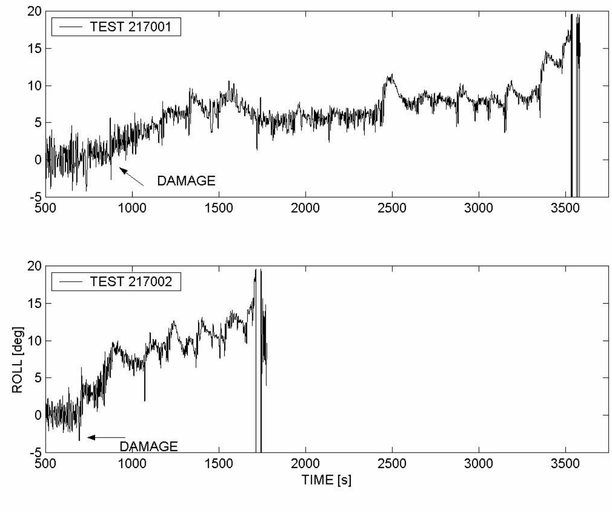


Figure 7 Roll response of ro-ro ferry in capsize conditions (sea state: Hs = 3.5 m, T = 8.0 s)

Analysis of the results in figure 7 suggests that the timing of damage occurrence is important: when damage occurs within a relatively low wave group, no significant flooding takes place at that time, which will delay the possibility of capsize. Alternatively, when damage occurs during the passage of a high wave group, the likelihood of significant water ingress is much higher.

Figure 8 shows for both capsize events the absolute wave elevation measured in-line with the drifting vessel and the relative wave elevation at the deck edge (positive value indicates submergence) determined from the measurements. Figure 9 shows the same information for the first 300 seconds after damage occurrence. For the first run it appears that the damage is created in a group with low waves and the deck edge is hardly submerged during the first 100 seconds. In the second run, however, the damage occurs in somewhat higher waves, immediately followed by the passage of a group with high waves. This changes the flooding process drastically -- in almost every subsequent wave the deck edge submerges, thereby forcing water to accumulate on the car deck, causing an almost monotonically increasing list until the point of capsize is reached.

In this case, the slight trim aft exacerbates the process, as any accumulation of water is here governed by the encounter with critical wave groups and water cannot flow out of the damage opening easily. Thus wave group statistics and damage creation play an important role in the time it takes to capsize.

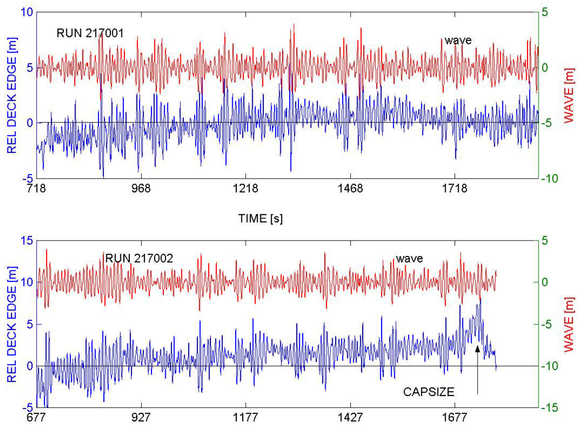


Figure 8 Absolute and relative (at deck edge) wave elevation for capsize events shown in figure 7

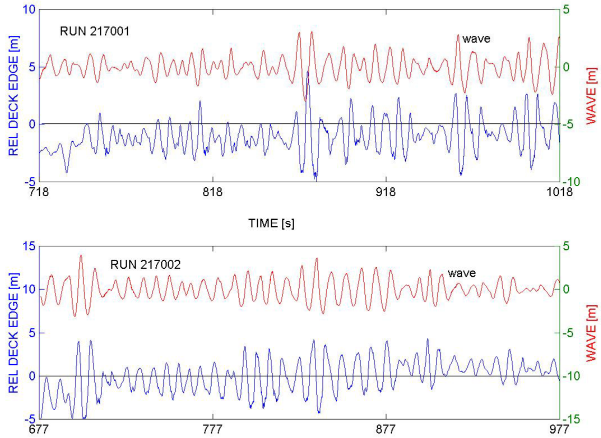


Figure 9 Absolute and relative (at deck edge) wave elevation for capsize events shown in figure 7

3. DYNAMICS OF DAMAGED FRIGATE

Whereas the capsizing process of a ro-ro ferry is governed by the heave response in wave groups and accumulation of water on deck, for a multi-compartment ship like a frigate the process is different. To study the dynamics of floodwater in a frigate-type ship, water ingress and forced oscillation tests have been carried out. Subsequently the capsize behavior in waves and wind has been studied. Results of the water ingress research have been presented in [2]. Additional results are discussed below.

Forced roll oscillations

For validation purposes for the numerical model (FREDYN) a series of forced oscillations were carried out with a schematic ship compartment layout as part of the CRNAV Dynamic Stability Project. A series of 12 small compartments were connected via doors with each other so that water flow was possible between the compartments. The space was filled with water to a certain depth, and then the whole set-up was oscillated in roll. Different frequencies and amplitudes were tested, consisting of sinusoidal motions around a fixed axis. Figure 10 gives an overview of the compartments and the connecting openings.

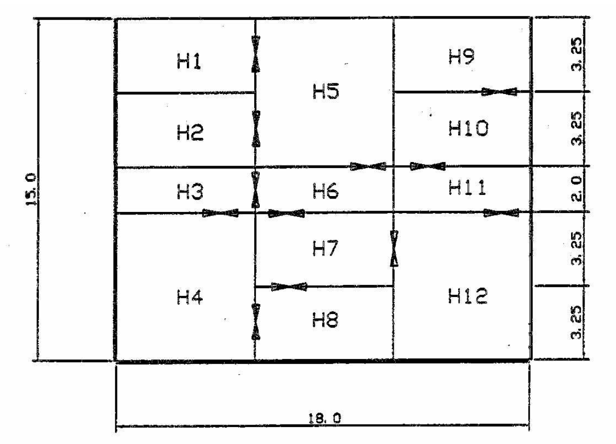
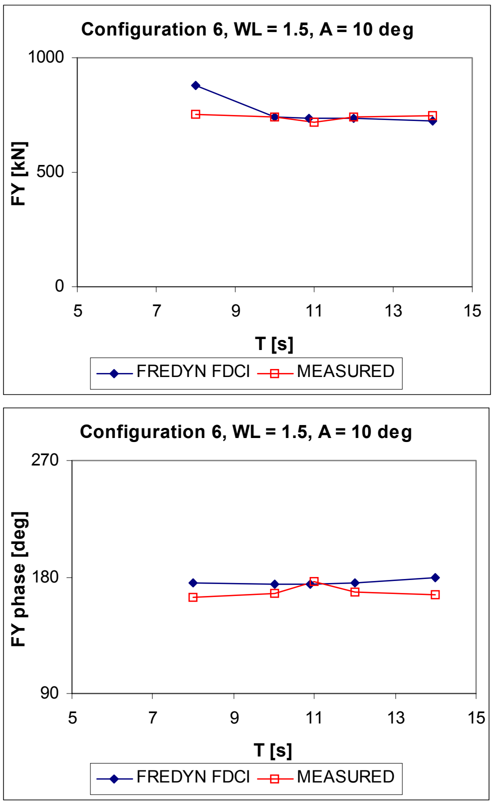


Figure 10 Accommodation space layout with openings for forced roll tests about center line axis through H3, H6 and H11

Figure 11 shows results for the transverse force (FY) and roll moment (MX) acting on the whole section. The sway force is very well predicted, and the roll moment tends to be somewhat overpredicted by FREDYN. This is a trend found in many calculation results. It suggests that the hydraulic model predicts more water flow between the compartments than is the case in the physical tests.



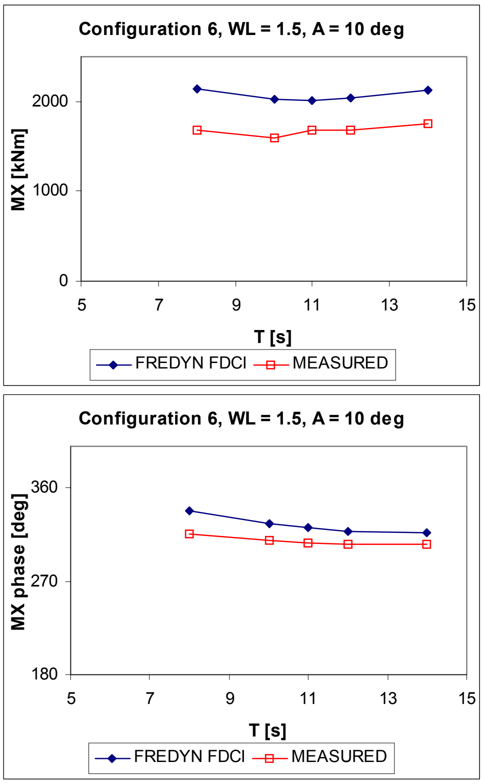


Figure 11 Sway force and roll moment acting on flooded accommodation space as a function of roll period (1.5 m flood level, 10 deg ampl.)

According to the hydraulic model water will immediately flow when there is a difference in water heights between openings; in the physical case there are delaying effects. It might also be due to 3D effects clearly visible in the compartments. The fluid motions were more chaotic than in the simulations in compartment corners and around the door openings. Overall, the comparison is reasonable.

Similar forced oscillation tests were carried out for a configuration where a wing tank on port and starboard side was connected via a cross-duct of diameter 0.3 m (prototype). The wing tanks were large compared to the cross-duct and in the analyses of the tests it appeared that the flow rate between the two compartments was almost nihil. This also indicates that after flooding of a wing tank after damage takes place the interaction between the two tanks diminishes. The water level should be earth-horizontal between the tanks, but with roll amplitudes of 10 degrees the difference in height is not very large. Figure 12 show an example; the correlation with FREDYN is good.

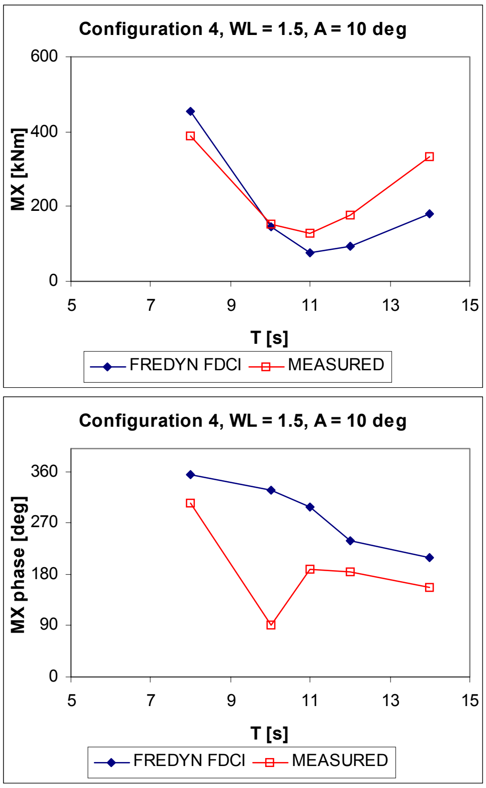


Figure 12 Forced oscillations of compartment with flooded wing tanks and connecting cross duct (measured and simulated roll moment)

For a U-tank compartment consisting of wing tanks and cross duct CFD (2D VoF) computations have been carried out with the program COMFLO. Figure 13 illustrates a vector plot of the fluid velocities for forced roll oscillations; figure 14 shows the associated dynamic pressure variations.

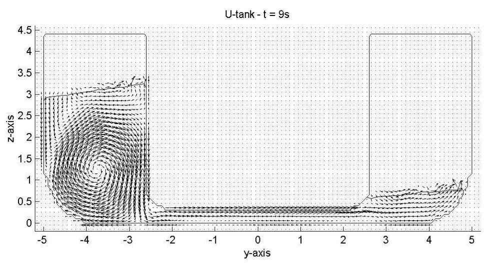


Figure 13 Velocity field in wing tanks and duct during forced roll oscillations

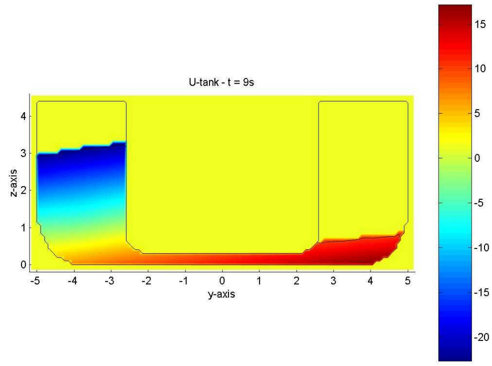


Figure 14 Pressure field in wing tanks and duct during forced roll oscillations

With the same CFD model 3D computations have been performed for a simplified engine room, similar to the one shown in figure 17. Figure 15 shows the predicted and measured roll moment as a function of the roll frequency for a roll amplitude of 10 degrees and 3 m fill level with floodwater. Figure 16 shows a time series of the water elevation at three locations in the compartment. The agreement between measurements and simulations is excellent, even when sloshing is present.

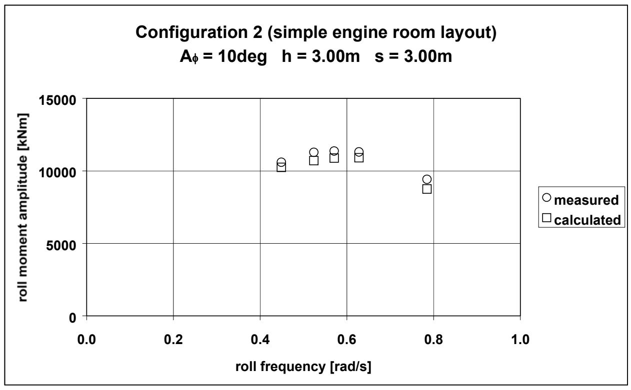


Figure 15 Roll moments acting on flooded engine room

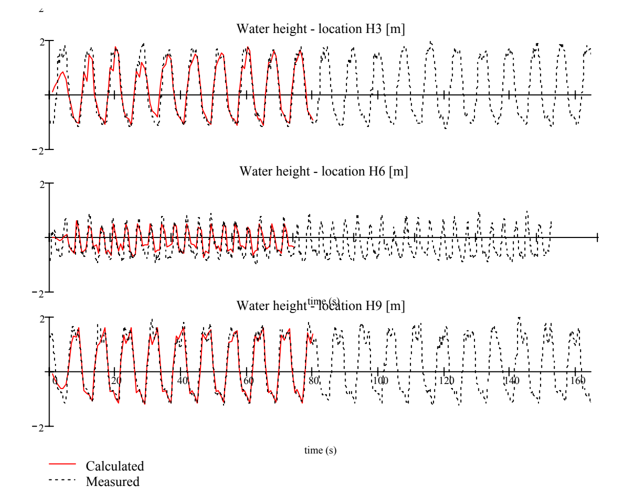


Figure 16 Water levels at three locations in flooded engine room (8 s roll period, 10 deg amplitude)

Capsizing in extreme wave conditions

To illustrate the capsize behavior in an extreme sea state, we consider a generic frigate with a length of around 110 m and displacement of about 3300 tonnes. For this vessel a parametric study has been carried out using numerical simulations, including the influence of compartment layout and damage scenario on capsize boundaries in terms of significant wave height.

It appears that when this vessel capsizes in a seaway under the various conditions considered, it is associated with the passage of a steep, high wave. This applies also to the frigate with a 5 x 4 m damage hole in just the engine room, the layout of which and righting arm (flooded) are shown in figures 17 and 18.

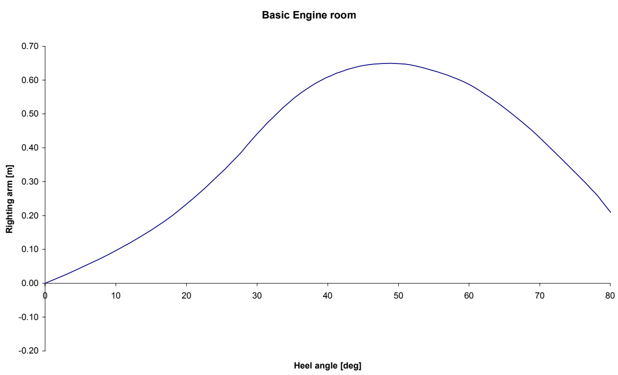


Figure 17 Righting arm curve of frigate with flooded engine room

Figure 19 shows the time series of the last 40 seconds of a typical capsize event; it shows the encountered wave elevation at the CoG (positive is downwards), wave slope at CoG, roll and yaw (90 deg is beam seas). The ship drifts freely at zero forward speed.

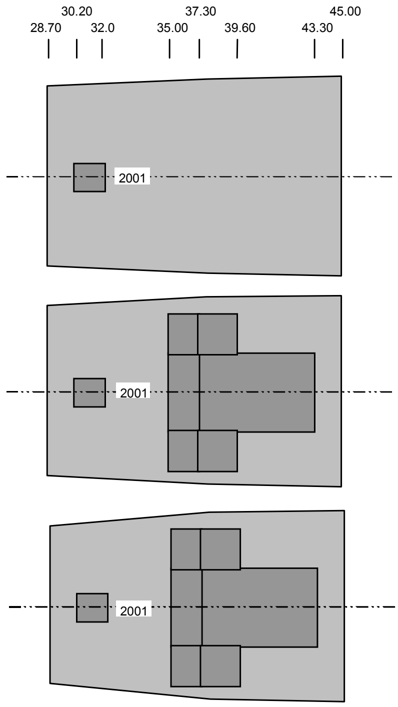


Figure 18 Layout of engine room (plan view)

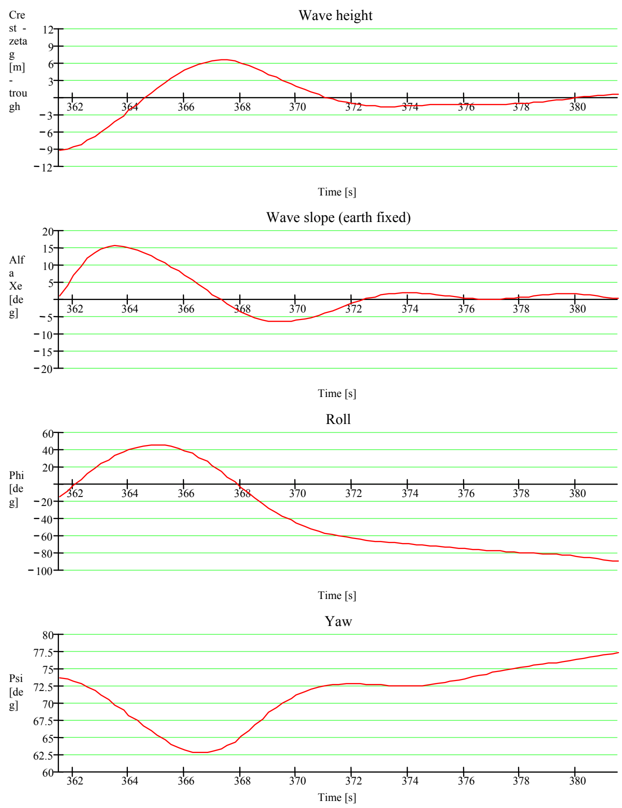


Figure 19 Motions of damaged frigate in extreme sea state (Hs = 11 m, Tp = 12.4 s)

As illustrated in figure 19, a high and steep wave passes the ship from the port side, the maximum slope is around 15 degrees, which causes the ship to undergo an extreme roll to leeward. The ship does not recover from this roll event and capsizes while rolling back; at he time of capsize the wave height is moderate. Figure 20 shows the spatial wave profiles over a length of 400 m as of the capsize inception point (t = 360 s); the zero point coincides with the CoG of the ship. Analysis of these waves suggests that the critical wave height initiating the capsize is around 15 m, and its spatial length is 240 m, i.e. the spatial wave steepness is $H/\lambda = 0.063$.

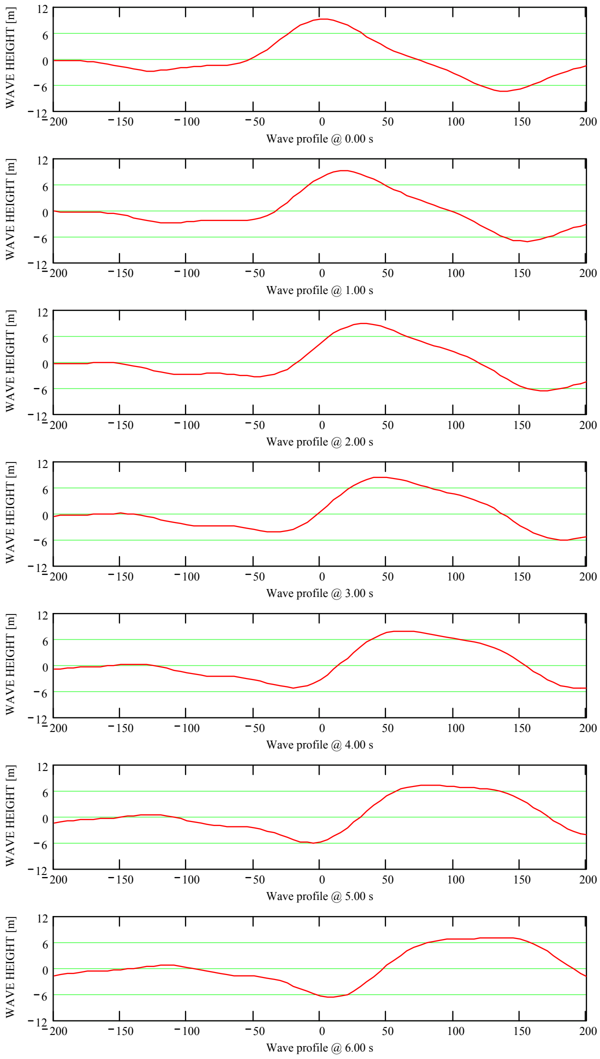


Figure 20 Spatial wave profiles shown every second from inception of capsize

It is possible to predict the occurrence of a wave with given period and height in a sea state when the joint probability density function (pdf) for period and height is known. From such a joint pdf we can derive the pdf of the spatial wavelength and steepness (H/λ), as shown in figure 21. This figure shows that the steepest waves ($H/\lambda = 0.1$) occur in the wavelength range of 50 to 200 m. A wave with $\lambda = 240$ m is very unlikely to have a steepness exceeding about 0.075. In this case its likelihood of occurrence is closely linked to the probability of capsize, where the duration of the sea state would have to be accounted for.

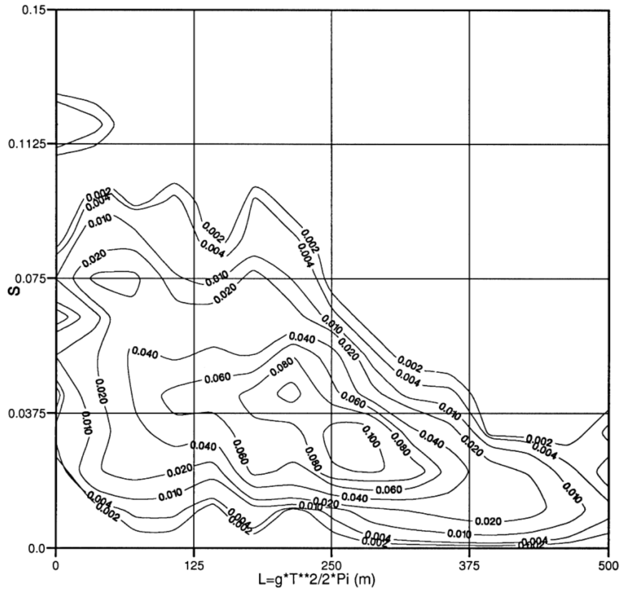


Figure 21 Joint probability density function of wavelength and spatial steepness (Hs = 11 m, Tp = 12.4 s)

5. CONCLUSIONS

The objective of this paper is to provide insights into different physical aspects relevant to the flooding and capsizing of damaged ships in waves.

For ro-ro ferries transient flooding following damage occurrence is discussed in calm water and in waves, including the influence of cross flooding arrangements. It is shown that the transient roll response characteristics are not influenced significantly by the presence of waves. A ship with wing tanks can experience transient roll peaks that are larger than the roll amplitudes in waves once flooded. It is shown that the initial conditions and wave group properties at the time of damage occurrence may have a significant influence on the ship's behavior; damage occurrence in a group of high waves can lead to a capsize within a short time frame.

Techniques are discussed for predicting the fluid forces exerted on flooded compartments undergoing oscillatory motions. The paper highlights differences between capsize mechanics of ro-ro ferries and those associated with a frigate-type ship that has a high degree of subdivision. The capsizing of a damaged frigate can be initiated by the passage of a steep, high wave. Properties of such waves are discussed.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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