The Impact of the Inflow Momentum on the Transient Roll Response of a Damaged Ship

Teemu Manderbacka, *Aalto University, School of Engineering, Department of Applied Mechanics*

teemu.manderbacka@aalto.fi

Pekka Ruponen, *Napa Ltd* pekka.ruponen@napa.fi

ABSTRACT

Dynamics of an abrupt flooding case are studied by comparing fully dynamic and quasi-static flooding simulation methods. Transient asymmetric flooding is traditionally modelled by dividing the compartment into smaller parts with bulkheads representing different obstructions in the flooded compartment. The implications of this assumption are studied by varying the size of the opening on the dividing bulkhead. The importance of the inflooding jet to the response is shown. The jet i.e. the inflooding momentum flux is modelled as force acting on the lumped mass. When the flooded compartment does not have significant obstructions it is important to account for the inflooding momentum flux.

Keywords: *damage stability; dynamic simulation; transient flooding*

1. INTRODUCTION

Collision or grounding can cause a large opening on the ship hull. An abrupt flooding may lead to ship capsize at the intermediate stages of flooding *(Spouge, 1985)*. The roll response to an abrupt flooding is a complex problem. The geometry of the flooded compartment and the damage affect the flooding. The flooding process consists of the inflow, floodwater motions and its progression *(Khaddaj-Mallat et al., 2011)*. These, in turn, are all affected by the ship motions. The ship response and the flooding process are coupled.

The inflow phenomenon is governed by the inflooding jet. The obstructions in the flooded compartment affect the propagation floodwater and the ship response *(de Kat and van't Veer, 2001; Ikeda et al., 2003)*. As shown for example in the experiments of *Manderbacka et al., (2015b)*. In the beginning of the flooding a dam-breaking type jet ingress the damaged compartment. When the opening is relatively large, the jet can push floodwater to the opposite side of the opening. As the jet meets the opposite wall in the compartment a water run-up on the wall takes place. This run-up creates a breaking wave on the wall. The jet is partly reflected from the wall and can create a reflected wave propagating back towards the opening side. As a consequence, the sloshing of the floodwater is created.

The inflow jet had been observed to play an important role in case of an undivided compartment. The ship can roll to the opposite side of the damage. In this case, the opening can be lifted above the sea surface and the inflow can be stopped *(Ikeda and Ma, 2000; Ikeda and Kamo, 2001)*. The inflooding jet can be slowed down in case of a compartment with obstructions. In these cases, a quasi-static modelling of the flooding may be sufficient. The transient asymmetric flooding of symmetrical compartments has traditionally been modelled by dividing the compartment into smaller parts with bulkheads representing different obstructions e.g. the main engines in the flooded compartment, *Santos et al. (2002)* and *Ruponen et al. (2009)*. If the size of the connecting opening between the parts is large, the dynamics of the floodwater may still be significant. In this paper the implications of this assumption are studied by varying the size of the opening on the dividing bulkhead.

This work aims to study the impact of the inflow momentum on the roll response for different damaged compartment layouts. Here a calculation method described in *Manderbacka et al., (2015a)* based on the lumped mass motions is applied *(Spanos and Papanikolaou, 2001; Jasionowski, 2001; Valanto, 2008)* The ship and flooded water motions are fully coupled and simulated in the time domain. The rate of change of the momentum due to the inflooding water (inflow momentum) is accounted for.

The impact of the inflow momentum is studied for different damaged compartment layouts for an abrupt large flooding. The response to transient flooding is simulated for undivided and divided compartments. The divided compartments have non-watertight divisions allowing but limiting the cross-flooding. A systematic variation of flooded space arrangements is realized. Size of the damage and internal opening in the divided compartment are varied. The limits of the flooded compartment geometry (size and divisions) where the inflow momentum should be accounted for and where the quasi-static simulation is sufficient are studied.

2. METHODS

Ship motions are modelled as a rigid 6 d.o.f motions. Hydrostatic forces acting on the ship hull are integrated over the actual wetted surface. Hull surface is presented with triangular panels.

Radiation forces are divided on the added mass and potential damping parts. The added mass and damping matrices are assumed to be constant, they are pre-calculated for the ship with the potential theory based strip method code *(Frank 1967)*.

All the equations of motion are written in the ship fixed coordinate system **xyz**, which is fixed to the intact ship center of gravity *cog*. Ship angular position is expressed in modified Euler angles. The inertial **XYZ** and ship fixed coordinate system and its orientation is shown in Figure 1.

Flooded water is modelled in each flooded room as a lumped mass concentrated on its center of gravity. The floodwater surface is assumed to stay plane but is free to move *(Jasionowski, 2001; Spanos and Papanikolaou, 2001; Valanto, 2008)*. Position of the lumped mass in ship fixed coordinate system $\mathbf{r}_i$ is a function of the lumped mass m_i and the angle of the free surface ϕ_i Figure 2. The flow through the opening is modelled with the hydraulic model based on Bernoulli equation *(Dillingham, 1981; Ruponen, 2007)*. In/outflow jet i.e. the inflow momentum flux is accounted for as a force acting on the lumped mass *(Manderbacka2015a)*. Energy dissipation in the motion of the floodwater due to the viscous effects is modelled as a friction force acting on the lumped mass *(Manderbacka et al., 2014)*.

Equations of motion for the ship and the lumped mass are combined into one system with 6 + *n* d.o.f, where *n* is number of flooded rooms. Position of the ship and floodwater are solved time integration applying fourth order Runge-Kutta scheme. Simulations performed with the presented method are denoted as **sim**. The impact of the inflow momentum on the roll response was studied by simulating the cases also without accounting for it. The simulations where the inflow momentum flux is eliminated are denoted as **sim no fdm**.

In order to compare different methods of predicting the ship response to an abrupt flooding quasi-static flooding simulation was also performed. In addition to the dynamic

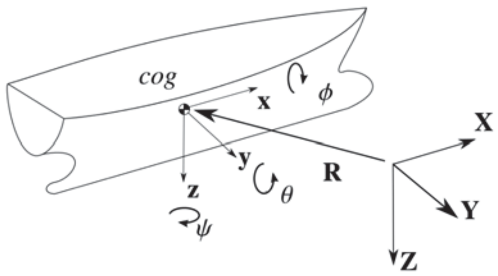

Figure 1. Ship coordinate system.

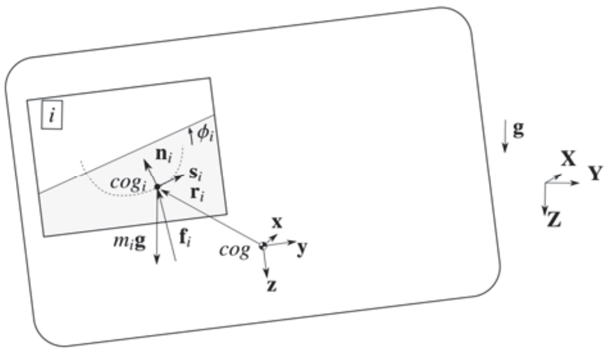

Figure 2. Model for the motions of the lumped mass with a moving free surface (Manderbacka et al., 2015a).

simulation described above (where the flooded water sloshing is simulated by a lumped mass with a moving free surface method) the ship response was simulated with NAPA software quasi-static flooding simulation *(Ruponen et al., 2007)*. Quasi-static NAPA simulations are denoted as **NAPAsta**. One degree of freedom model, where the roll motion is modelled is added to NAPA quasi-static flooding simulation. This model is denoted as **NAPAdyn**, where the linear equation of roll motion is solved. Linear roll damping is applied. Draft and trim are treated as quasi-static.

2.1 Validation

The lumped mass with a free moving surface method was validated against the measurement data *(Manderbacka et al., 2015a)*. Transient flooding of the Box shaped barge model was measured by *(Manderbacka et al., 2015b)*. The same model was used for the ITTC benchmark study on the progressive flooding *(van Walree and Papanikolaou, 2007)*. Load case and damage opening was modified compared to the progressive flooding tests. Two different compartments were flooded separately, undivided and divided compartment Figure 3. Both compartments were of same size. The divided compartment had two longitudinal bulkheads with narrow and tall openings (20 mm wide and 200 mm high). The breach on the starboard side was 200 mm x 200 mm square opening. In the measurements for the undivided compartment, the model experiences largest roll on the opposite side of the breach, on portside, while for the divided compartment flooding the

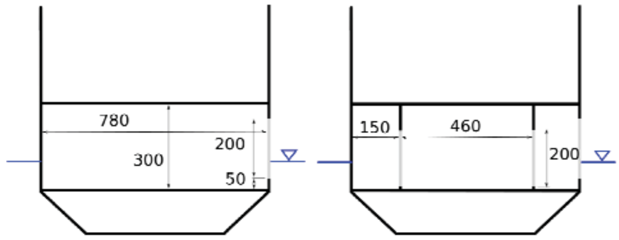

Figure 3. Box shape barge flooded undivided compartment (on left) and divided compartment (on right).

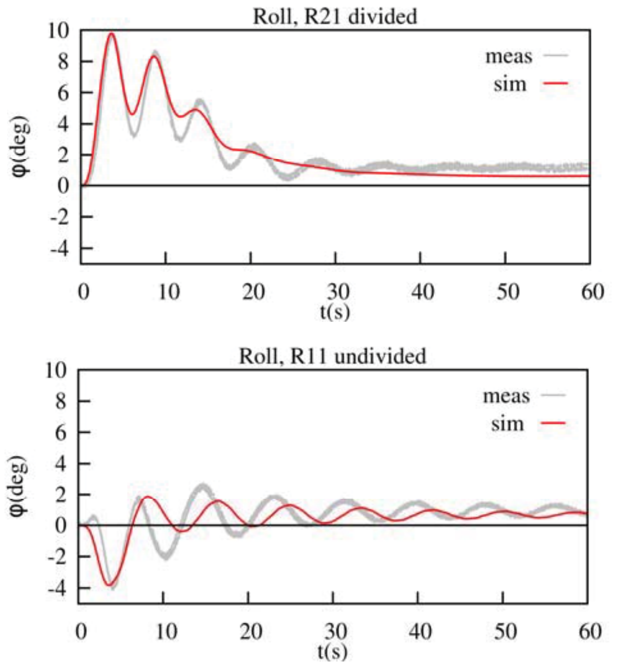

Figure 4. Measured and simulated roll response to abrupt flooding of Box shaped barge. Undivided compartment (above) and divided compartment (below) *(Manderbacka et al., 2015a)*.

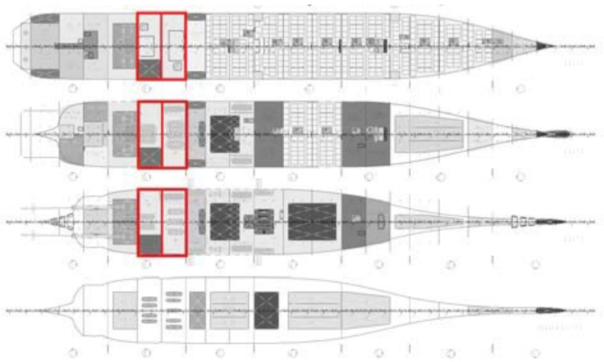

Figure 5. Ship general arrangement and engine room compartments.

model rolled on the breach side, on starboard. The maximum roll angles are well predicted by the presented simulation method Figure 4.

3. CASE STUDY

Case study was performed on the Floodstand Concept Ship A. The ship is a Post Panamax cruise ship with size of 125 000 GT. It is designed for world-wide cruises with capacity of total 5600 persons on board. The design of the vessel shall fulfil relevant international rules and regulations *(Kujanpää and Routi, 2009)*. Main particulars of intact Concept Ship A are presented in Table 1. In this flooding case study engine rooms 1 and 2 are flooded, Figure 5. Hull is presented by 6508 triangular panels, Figure 6. Water density in the simulations was 1025.0 kg/m^3 and gravitational acceleration 9.807 m/s^2.

Table 1: Ship main particulars.

Length *Loa*	327.0	m
Length *Lpp*	300.7	m
Breadth *B*	37.4	m
Draft *T*	8.1	m
Displacement Δ	63823	t
Initial stability GM0	1.9	m
Height of *CoG* KG	19.2	m
Roll radius of gyration *kxx (= 0.42B)*	15.708	m
Pitch and yaw radii of gyration *kyy = kzz (= 0.26Lpp)*	78.182	m
Roll natural period T_ϕ	26.2	s
Roll damping factor ξ	0.027	

3.1 Damage Case

The layout of the damaged compartments is simplified. Compartments are prismatic tanks with permeability of 1.0 each. The locations of the center of the compartment bottom and compartment dimensions are listed in Table 2. The engine blocks are not included in the compartments in the simulations. Instead the obstructing effect of the engine blocks is modelled by a non-watertight longitudinal bulkhead in the middle.

External hull breach height ranged over the height of the compartment. Four different breach widths L_B are introduced. The breach width for the biggest breach is equal to the compartment length $L_B=L_R$. Then the breach width is reduced to half $L_B=L_R/2$, then $L_B=L_R/4$ and finally smallest breach width $L_B=L_R/8$ is used. The breach is located on the starboard side. The simulation is performed in calm water. Initially ship is at even keel. The hull breach is introduced in the beginning of the simulation. Hull breach is presented as a line opening shown in Figure 6.

The undivided compartment cases were simulated with above mentioned four different breach widths. In addition to the undivided cases, simulations were performed for divided engine room compartments, Figure 7. The engine room compartments were divided by a non-watertight longitudinal bulkhead. The opening height on the longitudinal bulkhead was equal to the compartment height. The opening width L_O was varied. Four different opening widths were used; largest opening width was equal to the compartment length $L_O=L_R$, then $L_O=L_R/2$, $L_O=L_R/4$ and the smallest opening width was $L_O=L_R/8$ of the compartment length. Largest opening on the bulkhead corresponds to the undivided compartment case. The difference in the simulation in comparison to the undivided case is that the engine room compartment is divided into two spaces with an opening between the starboard and portside space ranging over the entire compartment height and length.

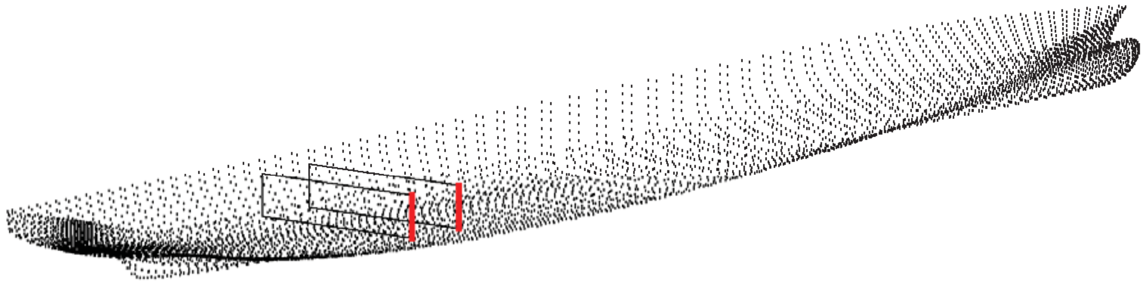

Figure 6. Hull panels. 6508 triangular panels and a 2D representation of the flooded engine room compartments with breach on starboard side.

Altogether 16 different configurations of the flooded compartments with four different breach and four different opening widths were simulated Figure 7. Breach and the opening had discharge coefficient C_d=0.6. The case L_O=L_R, where the divided compartment had the largest opening, was also simulated with the discharge coefficient value C_d=1.0.

Table 2. Flooded compartments.

compartment 1, engine room closer to aft		
x1, from aft PP	70.115	m
y1, from CL	0.0	m
z1, bottom height from keel	3.2	m
room 1 length	13.65	m
room 1 breadth	37.4	m
room 1 height	8.4	m
compartment 2, engine room closer to bow		
x2, from aft PP	83.89	m
y2, from CL	0.0	m
z2, bottom height from keel	3.2	m
room 2 lenght	13.9	m
room 2 breadth	37.4	m
room 2 height	8.4	m

Table 3. Damage opening.

breach to room 1	
discharge coeff. C_d	0.6
opening height	8.4 m
breach to room 2	
discharge coeff. C_d	0.6
opening height	8.4 m

4. RESULTS

4.1 Undivided Compartment

Total floodwater volume in the undivided compartments is calculated with simulation where the inflow is taken into account, **sim** in Figure 8. and without taking the inflow momentum into account with presented simulation method and with NAPA quasi-static flooding simulation, **sim no fdm** and **NAPAsta** in Figure 8. The compartment is symmetrical and the ship initial metacentric height stays positive in flooded case so no roll motion occurs when in-flooding momentum is not taken into account. Total floodwater volume is simulated with NAPA until the equilibrium stage is reached.

With simulations accounting for the inflow momentum, the ship experiences roll on the portside i.e. the opposite side of the damage. At biggest opening, the ship experiences smallest transient roll (approx. 6 degrees) The transient roll is increased when the opening size is reduced to half (approx. 8 degrees). Highest transient roll (approx. 9 degrees) is experienced at the opening width 1/4 of room length, Figure 9.

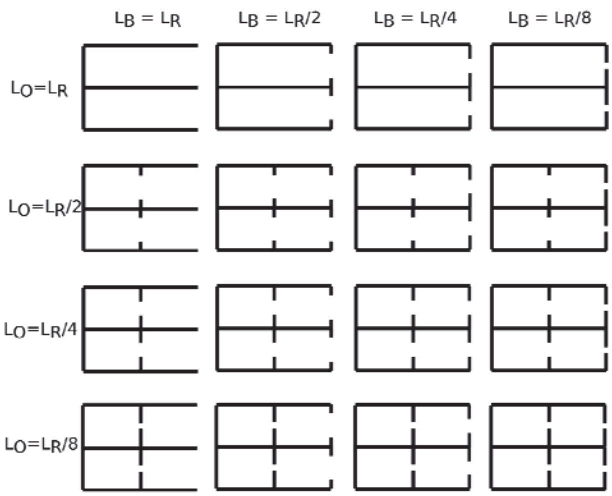

Figure 7. Configurations of flooded compartments (viewed from above) at different breach L_B and opening L_O widths. Breach is on the starboard side.

The maximum floodwater volume is attained fastest with the biggest opening, around 15 seconds after the damage. The time to attain the maximum floodwater volume is roughly doubled always when the opening size is halved.

The transversal *y* position (positive towards starboard) of the floodwater center of gravity is shown in Figure 10. With the biggest opening the motion of the floodwater center of gravity is more limited due to bigger volume than in case of smaller openings.

4.2 Divided Compartment

The biggest roll in case of the undivided compartment flooding was reached when the breach width was one fourth of the compartment length. Here both engine compartments are divided in the middle by the longitudinal non-watertight bulkhead. Four different opening widths were introduced to the dividing longitudinal bulkhead in the center line. Opening width was varied from compartment length to one eight of the compartment length. The biggest opening corresponds to a situation where the whole longitudinal bulkhead is open i.e. the division into two rooms in this case is virtual. This case is simulated with two different discharge coefficient values, one for no pressure loss C_d*=1.0* and the other with same discharge coefficient as in the breach C_d*=0.6*. Other opening widths were simulated with the discharge coefficient C_d *=0.6*, the same value

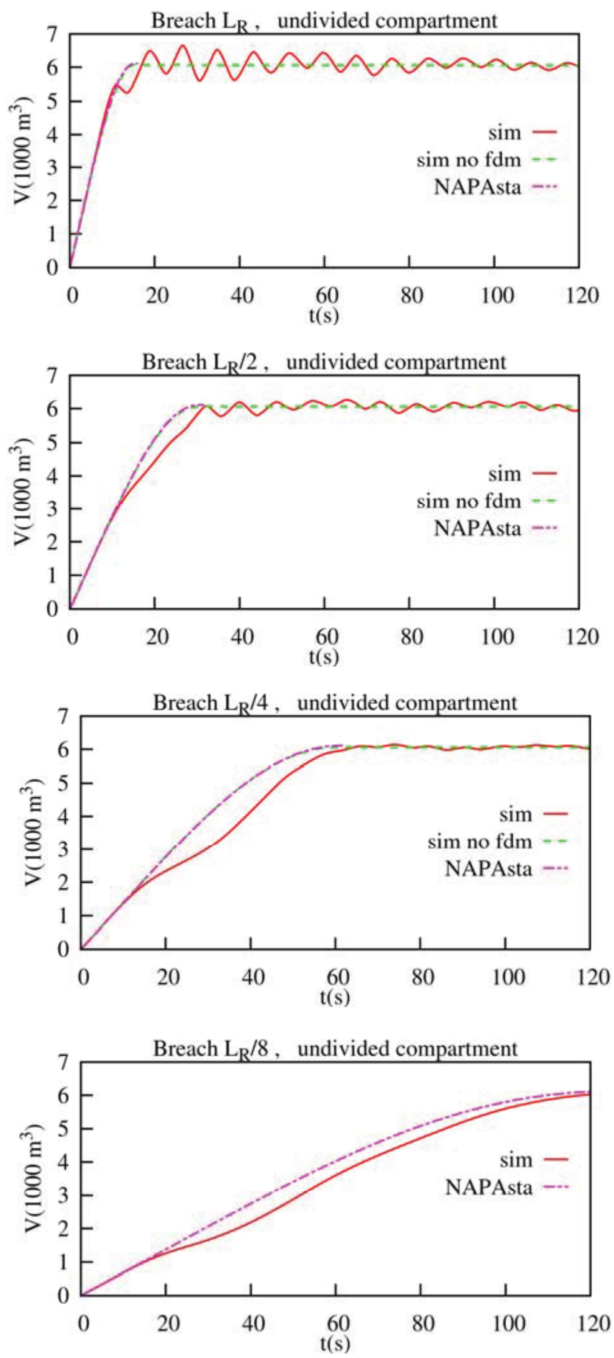

Figure 8. Total floodwater volume. Undivided compartment flooding case at four different breach widths.

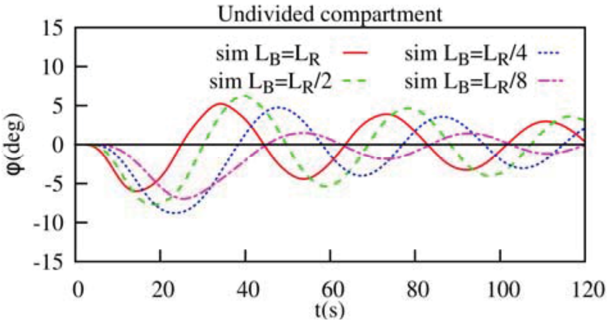

Figure 9. Roll in the undivided compartment flooding case at four different breach widths.

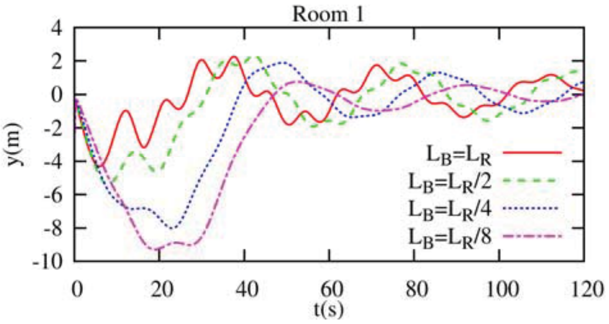

Figure 10. Transversal position of the floodwater center of gravity wih different breach widths.

was used for the breach. These cases with breach width $L_B=L_R/4$ were simulated with presented simulation method including **sim** the inflow momentum flux, without the impact of the inflow momentum flux **sim no fdm** and with NAPA quasi-static and dynamic roll motion models, **NAPAsta** and **NAPAdyn**, respectively. The total floodwater volume for these cases is shown in Figure 11 and roll response in Figure 12. When the opening width of the dividing bulkhead is biggest the results between the methods vary the most. At biggest opening $L_O=L_R$ with the discharge coefficient $C_d=1.0$ the result of the simulation with undivided compartment is also shown in the figures of volume and roll time histories. In this case the presented simulation method with inflow momentum flux predicts approximately 5 degree roll on the opposite side of the damage. The simulation with undivided compartment predicts even bigger roll angle. The flooding is also slower with **sim** calculation due to the roll on the opposite side of the damage.

When the opening width is reduced the presented simulation method predicts the first roll on the damage side. Reducing the opening width increases the roll angle on the damage side with all the simulation methods. When the opening width is smallest $L_O=L_R/8$ the results between different methods correspond quite well to each other. Results of the fully quasi-static simulation **NAPAsta** differ the most from the other methods.

4.3 First Maximum Roll Angle

A summary of the first maximum roll angle for four different breach widths is shown as a function of the opening width in Figure 13. The opening width L_O is made proportional to the breach width L_B. In most of the cases ship experiences the first roll angle on the damage side. In fact the quasi-static simulations and the simulations where the inflow momentum flux is not accounted for predict the first roll on the damage side in all cases. The dynamic simulation for divided compartments with the inflow momentum flux accounted for predict first maximum roll on the opposite side or close to zero when the opening is four times wider than the breach. When the opening width is reduced, the first roll on the damage side increases and its value predicted by all the methods gets closer.

The case where the opening reached over the whole compartment was calculated as one undivided compartment. The simulations with undivided compartment predict the first roll on the opposite side of the damage at all breach widths Figure 9. When the breach side is reduced the simulation **sim** with divided compartment gets closer to the results of the undivided compartment simulations Figure 13.

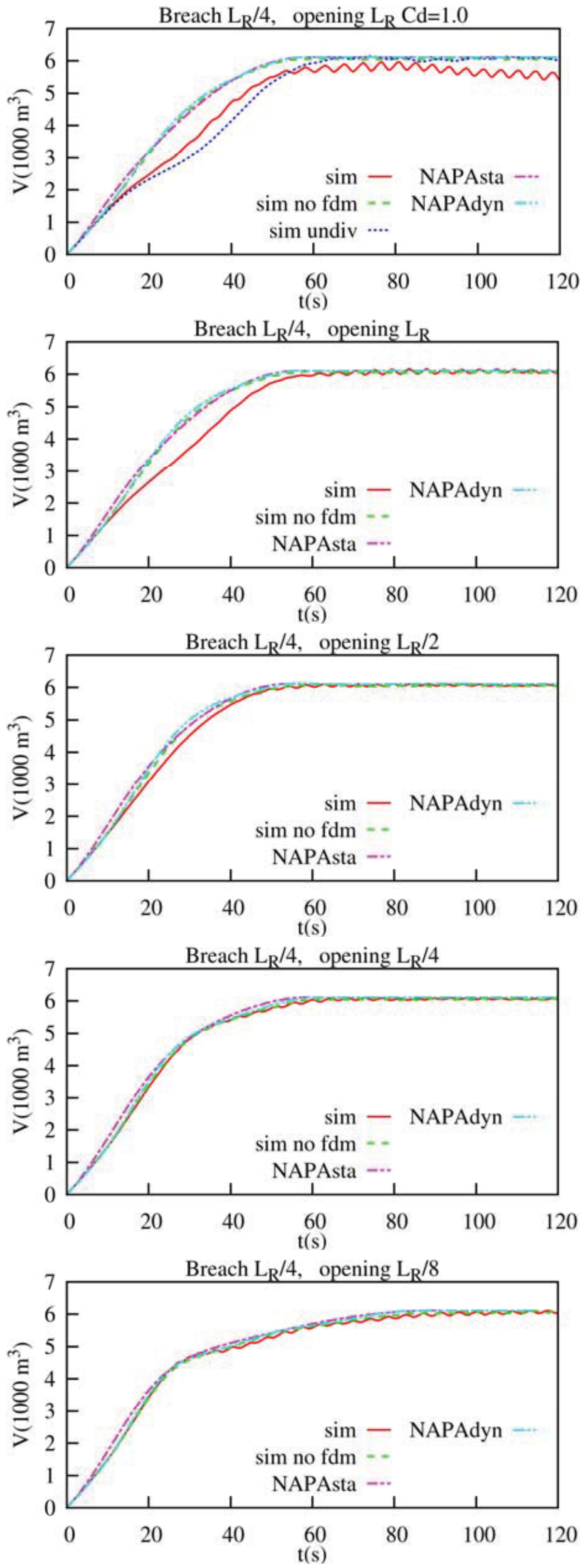

Figure 11. Total floodwater volume. Divided compartment with five different bulkhead openings. . Breach width is $L_R/4$.

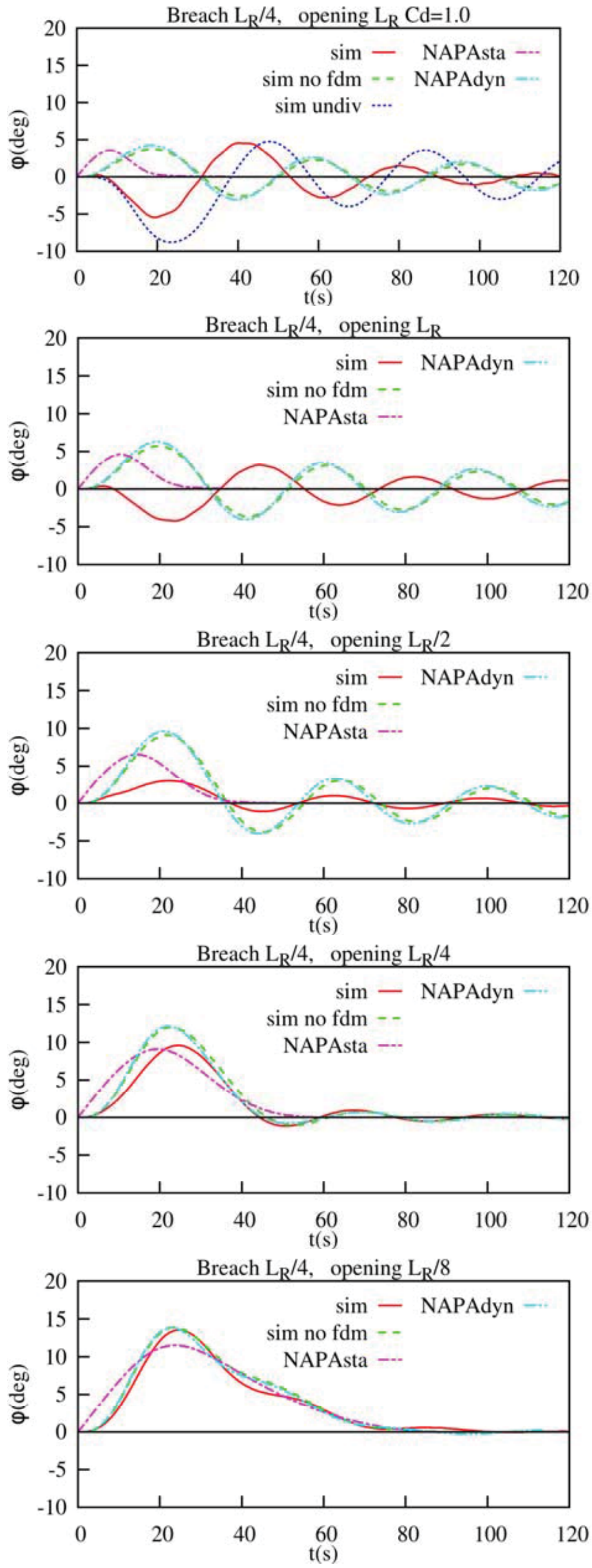

Figure 12. Roll motion. Divided compartment with five different bulkhead openings. Breach width is $L_R/4$.

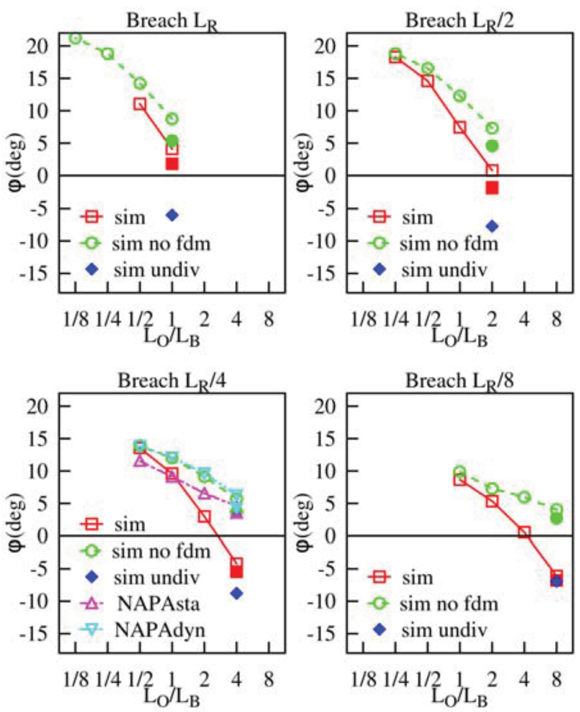

Figure 13. First roll angle for different breach widths as a function of opening width per breach width. Filled red square and filled green circle are **sim** and **sim no fdm** with opening C_d=1.0.

5. DISCUSSION

For divided compartments, where the opening on the dividing wall is small, all the methods give quite similar results. The flooding is asymmetric and the cross flooding is slow. The water motion inside the smaller compartment does not affect the roll response and it is sufficient to simulate the flooding with a quasi-static simulation method. When the width of the opening on the dividing longitudinal bulkhead is increased, the results between the methods start to deviate from each other. Different methods do not even agree on the direction of the initial roll angle. The inflooding water can be pushed fast on the opposite side of the breach when the compartment is undivided or the opening on the dividing bulkhead is sufficiently wide. In this case the quasi-static methods or calculation, which do not account for the inflooding momentum flux and thus are not modelling the inflooding jet, cannot predict the initial roll on the opposite side.

6. CONCLUSIONS

Abrupt flooding cases to an undivided compartment with four different breach sizes and flooding cases to divided compartment at one breach size were simulated with four different methods; Dynamic flooding simulation with lumped mass method with a moving free surface with and without the inflow momentum flux and a totally quasi-static simulation and quasi-static simulation with one degree of freedom were applied.

Presented case and simulations give insight to the significance of the assumptions when predicting the transient flooding response. The importance of the inflooding jet to the response is shown. When the opening on the dividing bulkhead is small compared to the breach, i.e. the obstructions in the compartment are significant, the assumption of quasi-static simulation is sufficient. Conversely, the bigger the opening is on the bulkhead compared to the breach i.e. there are not significant obstructions in the compartment, accounting for the inflow momentum flux becomes more important.

7. ACKNOWLEDMENTS

Aalto University, School of Engineering and City of Turku, MERIDIEM Maritime Innovation Hub are greatly appreciated for the financial support.

8. REFERENCES

de Kat, J. O., van't Veer, R., 2001.Mechanisms and physics leading to the capsize of damaged ships. In: Proceedings of the 5th International Ship Stability Workshop. Trieste, Italy.

Dillingham, J., 1981. Motion studies of a vessel with water on deck. Marine Technology 18 (1), 38–50.

Frank, W., 1967. Oscillation of cylinders in or below the free surface of deep fluids. Tech. Rep. 2375, Naval Ship Research and Development Center, Washington, DC.

Ikeda, Y., Kamo, T., 2001. Effects of transient motion in intermediate stages of flooding on the final condition of a damaged PCC. In: Proceedings of the 5th International Ship Stability Workshop. Trieste, Italy.

Ikeda, Y., Ma, Y., 2000. An experimental study on large roll motion in intermediate stage of flooding due to sudden ingress water. In: Proceedings of the 7th International Conference on Stability of Ships and Ocean Vehicles. Launceston, Australia, 270–285.

Ikeda, Y., Shimoda, S., Takeuchi, Y., 2003. Experimental studies on transient motion and time to sink of a damaged large passenger ship. In: Proceedings of the 8th International Conference on Stability of Ships and Ocean Vehicles. Madrid, Spain, pp. 243–252.

Jasionowski, A., 2001. An integrated approach to damage ship survivability assessment. Ph.D. thesis, University of Strathclyde.

Khaddaj-Mallat, C., Rousset, J.-M., Ferrant, P., 2011. The transient and progressive flooding stages of damaged ro-ro vessels: A systematic review of entailed factors. Journal of Offshore Mechanics and Arctic Engineering, 133 (3).

Kujanpää, J., Routi, A.-L., 2009. WP1: Concept Ship Design A. Tech. Rep. Deliverable 1.1a, STX Europe, Finland, FLOODSTAND, EU FP7.

Manderbacka, T., Mikkola, T., Ruponen, P.,Matusiak, J. E., 2015a. Transient response of a ship to an abrupt flooding accounting for the momentum flux. Accepted for publication in J. of Fluids and Structures, June 2, 2015.

Manderbacka, T., Ruponen, P., Kulovesi, J., Matusiak, J. E., 2015b. Model experiments of the transient response to flooding of the box shaped barge. Accepted for publication in J. of Fluids and Structures, June 2, 2015.

Manderbacka, T. L., Jacob, V., Carriot, T., Mikkola, T., Matusiak, J. E., 2014. Sloshing forces on a tank with two compartments, application of the pendulum model and CFD. In: Proceedings of the ASME 2014 33nd International Conference on Ocean, Offshore and Arctic Engineering. San Francisco, California, USA.

Ruponen, P., 2007. Progressive flooding of a damaged passenger ship. Ph.D. thesis, Helsinki University of Technology, Ship Laboratory.

Ruponen, P., Metsä, A., Ridgewell, C., Mustonen, P., 2009. Flooding Simulation as a Practical Design Tool, Schifstechnik – Ship Technology Research, Vol. 56, 3-12.

Ruponen, P., Sundell, T., Larmela, M., 2007. Validation of a simulation method for progressive flooding. International Shipbuilding Progress 54 (4), 305–321.

Santos, T. A., Winkle, I. E., Guedes Soares, C., 2002. Time domain modelling of the transient asymmetric flooding of ro-ro ships. Ocean Engineering 29 (6), 667–688.

Spanos, D., Papanikolaou, A., 2001. On the stability of fishing vessels with trapped water on deck. Ship Technology Research-Schiffstechnik 48, 124–133.

Spouge, J. R., 1985. The Technical Investigation of the Sinking of the Ro-Ro Ferry European Gateway. Transactions of RINA 127, 49–72.

Valanto, P., 2008. Research study on the sinking sequence and evacuation of the MV Estonia - final report. Tech. Rep. 1663, HSVA, Hamburg, Germany.

This page is intentionally left blank