Validation of a Simulation Method for Progressive Flooding

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ABSTRACT

A new simulation method for progressive flooding has been developed. The method is based on the pressure-correction technique and it is capable of dealing with coupled water and airflows. The iterative structure ensures time-accurate simulations with complex systems of flooded compartments. The principles of the simulation method are briefly described with the main emphasis on the simulation of the performed model tests and on the validation of the method. Furthermore, the simulation method is tested with a case study in order to research the effects of the level of the modeling details and ventilation.

Keywords: *progressive flooding, simulation method, model test, validation, case study*

1. INTRODUCTION

The flooding of a modern large passenger vessel is a very complex phenomenon. In case a vessel in operation suffers a damage that results in flooding, there is an evident need for both shipboard and shore-based personnel to assess the outcome of the events as reliably as possible. The results presented in this paper are a part of a research project that aims at producing tools and methods for such an assessment.

Transient effects at very early stages of flooding are not relevant in this type of emergency calculation. Similarly, the effects of seaway on the motions of the ship are neglected as most of the damages occur in calm or moderate seaway (the significant wave height is less than 2.0 m in 90% of the collisions, Tuzca et al. 2002). Based on this fact, the motions of the flooded ship are likely to be moderate and the waves are likely to have only a small effect on the flooding of the ship.

Because of the lack of public well-documented model tests, a series of tests was performed in order to facilitate the validation of the calculations.

2. SIMULATION METHOD

2.1 Background

The simulation of the progressive flooding and internal airflows is based on the pressure-correction technique. A more detailed description of the developed method is given by Ruponen (2006a). Only the principles of the method are briefly described in the following sections.

The flooding process is mainly dictated by the distribution of floodwater and air pressures inside the damaged ship. Therefore, it is practical to deal with hydrostatic pressures, i.e. water heights, instead of volumes of water. The compartments and openings of a ship can be considered as a staggered grid, where pressures are solved in the cell centers (compartments) and velocities in the cell faces (openings).

2.2 Assumptions

It is assumed that sea is calm and that the floodwater settles down instantaneously with a flat surface, parallel to the sea level. All dynamic effects of the floodwater are ignored.

In the presented simulations, the areas of free surfaces are assumed to be constant during each time step. This assumption somewhat limits the feasible time step but it also provides simple and practical pressure-correction equations.

The flow velocity in the center of a compartment (far from the openings) is assumed to be zero. This allows the application of Bernoulli's equation.

The original method (Ruponen 2006a) is extended to handle freely floating ships. The floating position is evaluated quasi-stationary on the basis of the solved distribution of floodwater inside the damaged ship at the end of each time step. In the studied cases, this assumption is reasonable since the changes of heel, trim and draft are relatively slow.

In the present version of the simulation method, all openings are modelled as one-dimensional points with a given area and discharge coefficient. Therefore, the large openings have to be modelled with several points.

2.3 Governing Equations

The flooding process can be described by two governing equations: the conservation of mass (equation of continuity) and the conservation of momentum (Bernoulli's equation).

The equation of continuity in integral form is, Paterson (1997):

$$\int_{\Omega} \frac{\partial \rho}{\partial t} d\Omega = -\int_{S} \rho \mathbf{v} \cdot d\mathbf{S} \tag{1}$$

where ρ is density, $\mathbf{v}$ is velocity and Ω is the control volume, bounded by the surface S. The normal vector points outwards of the control volume. Hence, inflow is defined to be negative.

The mass balance for water, i.e. the residual of the equation of continuity, can be expressed as:

$$\Delta \dot{m}_{w,i} = \rho_w S_{fs,i} \frac{dH_{w,i}}{dt} + \rho_w \sum_k Q_{w,k} \tag{2}$$

where S_{fs} is the area of free surface in the compartment (assumed to be constant during the time step), H_w is the water height and Q_w is the volumetric water flow through an opening in the compartment. The index k refers to an opening in the compartment i.

Similarly, the mass balance for air is, Ruponen (2006a):

$$\Delta \dot{m}_{a,i} = V_{a,i} \frac{\rho_0}{p_0} \frac{dp_i}{dt} + \frac{\rho_0}{p_0} p_i \sum_k Q_{w,k} + \sum_k \dot{m}_{a,k} \tag{3}$$

where V_a is the volume of air and $\dot{m}_a$ is the mass flow of air. The density of air is assumed to be linearly dependent on the air pressure p (Boyle's law); ρ_0 is the density of air in the atmospheric pressure p_0.

Bernoulli's equation for a streamline from a point A to a point B is, Paterson (1997):

$$\int_A^B \frac{dp}{\rho} + \frac{1}{2}\left(u_B^2 - u_A^2\right) + g\left(h_B - h_A\right) = 0 \tag{4}$$

where p is air pressure, u is flow velocity and h is water height. The point B is in the opening and the point A is far from it in the upstream. It is assumed that the flow velocity far from the opening (in the center of the compartment) is zero ($u_A = 0$).

The total pressure difference for an opening k that connects the compartments i and j is:

$$\left(P_i - P_j\right)_k = p_i - p_j + \rho_w g \cdot \left[\max\left(H_{w,i} - H_{o,k}, 0\right) - \max\left(H_{w,j} - H_{o,k}, 0\right)\right] \quad (5)$$

where H_w is the height of the water level and H_o is the height of the opening, measured from the same horizontal reference level, and p is the air pressure. It is also possible to deal with openings that can be formed when structures (e.g. closed doors or down-flooding hatches) collapse under the pressure of the floodwater.

The flow velocity in the opening is the volumetric flow divided by the effective area of the opening. The pressure losses in the opening are taken into account with a semi-empirical discharge coefficient C_d. This coefficient is assumed to be independent of the Reynolds number.

Bernoulli's equation for water flow through the opening k that connects the compartments i and j (positive flow from i to j) can be written in a form of a pressure loss:

$$\frac{1}{2} K'_k \dot{m}_{w,k} \left|\dot{m}_{w,k}\right| = P_i - P_j \quad (6)$$

where $\dot{m}_w$ is the mass flow of water and the absolute value is used to define the direction of the flow. The dimensional pressure loss coefficient is defined as:

$$K'_k = \frac{1}{\rho \cdot {C_{d,k}}^2 \cdot A_k^2} \quad (7)$$

where A is the area of the opening.

2.4 Iteration

The pressure-correction method is iterative. The pressures from the previous time step are used as an initial guess (H_w^* and p^*), and mass flows through each opening are evaluated with Bernoulli's equation (6), on the basis of these values. Furthermore, mass balances, (2) and (3), are calculated for each compartment. Bernoulli's equation (6) is linearised to form the pressure-correction equations for both the water height and the air pressure corrections, Ruponen (2006a). This set of linear equations can be solved easily and the new pressures are obtained by adding the corrections (H'_w and p') to the temporary guess values:

$$\begin{aligned} p_i &= p_i^* + \alpha \cdot p'_i \\ H_{w,i} &= H_{w,i}^* + \alpha \cdot H'_{w,i} \end{aligned} \quad (8)$$

The coefficient α is the under-relaxation factor. The performed simulations have shown that some under-relaxation, i.e. $\alpha < 1$, is essential, especially when the time derivatives of the pressures are small.

The corrected values are used as the guess values for the next iteration round. The iteration is continued until both equations of continuity are satisfied with a reasonable accuracy, i.e. all mass balances are less than the applied convergence criterion.

The volume of floodwater in each compartment is calculated on the basis of the iterated water height and the floating position of the ship (heel and trim).

It is also possible to model some compartments as fully vented, in which case the air pressure is considered to be constant during the flooding, i.e. the air pressure correction is always zero.

3. EXPERIMENTS

Model tests were performed in the towing tank of Helsinki University of Technology (HUT) – Ship Laboratory in January 2006. A detailed description of the model and the results are presented by Ruponen (2006b).

The model was basically a box-shaped barge with a plexiglass block containing eight compartments that were connected by internal openings. The principal dimensions of the model are given in Table 1. A photo of the model is presented in Figure 1 and the flooded compartments and the openings are shown in Figure 2. The damage opening was relatively small when compared to the size of the model. Furthermore, the model had a large initial metacentric height. As a result, the motions of the model were small and slow.

Contrary to the standard practice in the flooding tests, the compartments were not equipped with large ventilation ducts, as the aim of the study was to validate also the calculation of air compression and airflows. Therefore, the lowest compartments in the double bottom were equipped with air pressure sensors.

Water height was measured in every flooded compartment of the model. Furthermore, the floating position (heel, trim and draft) was measured.

Table 1 Principal dimensions of the model

Length:	4.000 m
Breadth:	0.800 m
Draft (intact):	0.500 m
Freeboard (intact):	0.300 m
Compartment length:	0.335 m
Volume of buoyancy:	1.450 m^3
Vertical center of gravity:	0.278 m
Metacentric height:	0.110 m

Figure 1 The model for the flooding tests

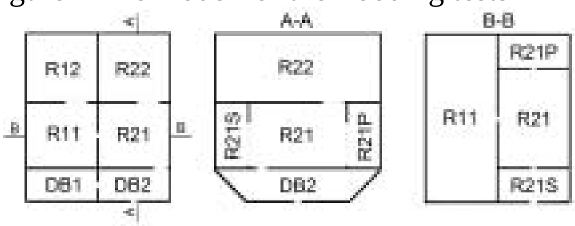

Figure 2 Compartments of the model and their identification

The sizes of the internal openings correspond to the scale 1:10. All openings are sharp-crested. The rectangular-shaped openings represent fully or partly open doors, manholes and staircase openings, while the circular-shaped openings represent broken pipes.

4. VALIDATION

4.1 Simulation Parameters

The tested cases were simulated with the developed method in the model scale and the results were compared to the experimental data. Because of the small scale, a relatively short time step (0.05 s) had to be applied in order to ensure convergence. The applied convergence criterion corresponds a water height difference of 0.01 mm as it was discovered that a stricter criterion does not affect the results.

The double bottom compartments DB1 and DB2 and the side compartments R21S and R21P (see Figure 2 for the identification) were modelled to have a restricted ventilation. All other compartments were considered as fully vented. A ventilation duct was modelled to the rooms R21S and R21P with the inlet on top of the room.

The size of the damage opening was 40 mm × 60 mm. The large internal openings were modelled with several points, while the small openings were modelled as single points.

The applied discharge coefficients were evaluated experimentally, by draining water separately through each opening. The area of the free surface above the opening was constant during the test, and therefore, the average discharge coefficient could be derived from the measured initial and final water height and the elapsed draining time. The results are given in Table 2. It is assumed that the discharge coefficient is independent of the Reynolds number. For airflows, it is assumed that there are no pressure losses in the openings or ventilation ducts.

Table 2 Evaluated discharge coefficients for the openings

Opening:	C_d:
∅20 mm	0.80
40 mm × 60 mm	0.78
20 mm × 200 mm	0.75
100 mm × 100 mm	0.72

4.2 Bottom Damage

The damage opening is located in the bottom of the room DB1 (see Figure 2). All internal openings are initially open. A large air pocket is formed in the damaged room. The flooding process is rather slow due to the long chain of flooded compartments.

Measured and calculated time histories for the trim angle and the vertical sinkage of the model are presented in Figure 3 and Figure 4, respectively. The flooding is symmetrical along the centreline, and hence, the model does not heel during the test.

The measured and calculated water heights are presented in Figure 5 – Figure 8, and the air pressure in DB1 is presented in Figure 9.

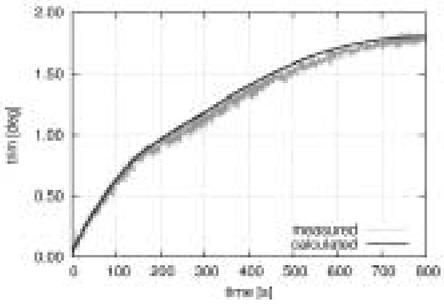

Figure 3 Trim angle for the bottom damage case

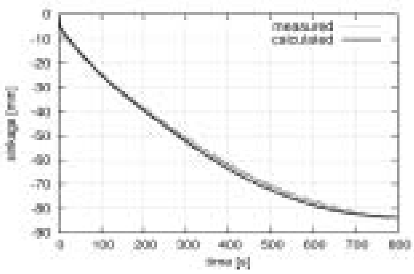

Figure 4 Vertical sinkage of the model for the bottom damage case

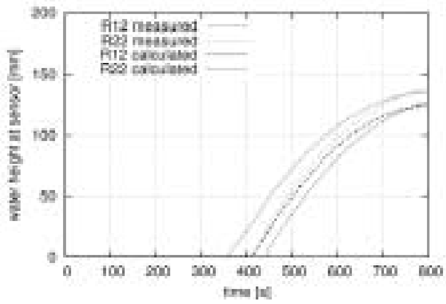

Figure 5 Measured and calculated water heights on the upper deck for the bottom damage case

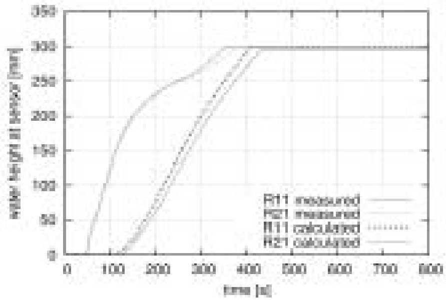

Figure 6 Measured and calculated water heights on the lower deck for the bottom damage case

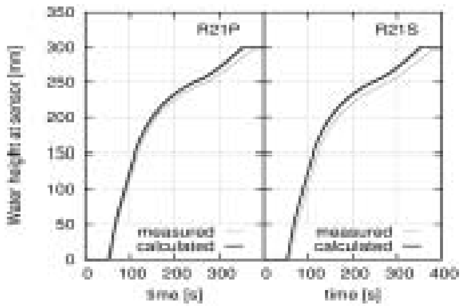

Figure 7 Measured and calculated water heights in the side compartments for the bottom damage case

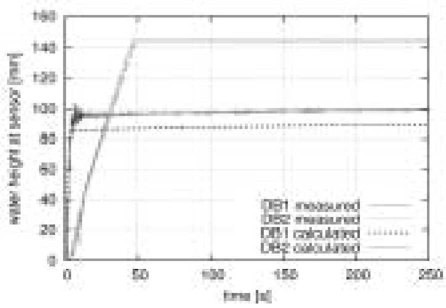

Figure 8 Measured and calculated water heights in the double bottom for the bottom damage case

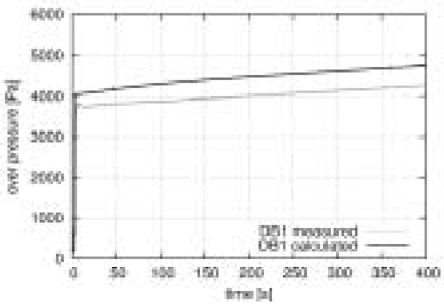

Figure 9 Overpressure in DB1 in the bottom damage case

The floating position is estimated with good accuracy (Figure 3 and Figure 4). The small differences are explained by the slightly underestimated water height in DB1. The calculated water height in the damaged room DB1 is slightly smaller than the measured height (Figure 8) while the calculated air pressure is correspondingly larger than the measured air pressure (Figure 9). This is very likely explained by the waves in the damaged room due to the fast flooding; see Figure 8. The waves allow more air to escape through the opening to the room DB2.

The flooding to R11 is slightly overestimated by the simulation method (Figure 6). This might be explained by a small inaccuracy in the applied discharge coefficient. Similarly, the flooding to the side compartments (R21S and R21P) is slightly overestimated (Figure 7). As a result, the flooding to the upper deck is predicted to start too early (Figure 5). In this test, the flooded rooms form a long chain, and therefore, a small inaccuracy in each applied discharge coefficient can accumulate to the observed difference between the measured and the calculated results.

4.3 Side Damage

The damage opening is located on the side of the room R21S, and the center of the damage is 185 mm below the sea level in intact condition. The manhole from R21 to DB2 is closed by a plate in order to keep the double bottom (DB1 and DB2) dry. The model is very stable, and therefore, the heeling is very minimal even in the first phases of flooding (max. measured angle was 0.6°). The comparisons between the measured and the calculated results for the floating position and the water heights are presented in Figure 10 – Figure 14.

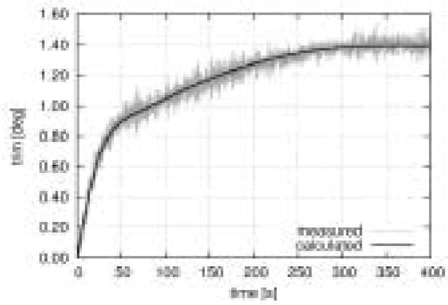

Figure 10 Trim angle for the side damage case

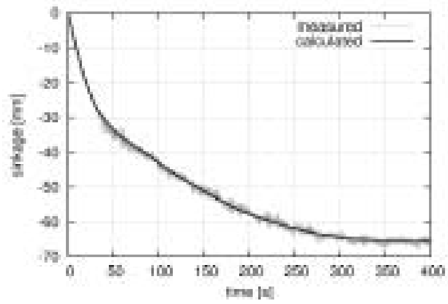

Figure 11 Vertical sinkage of the model for the side damage case

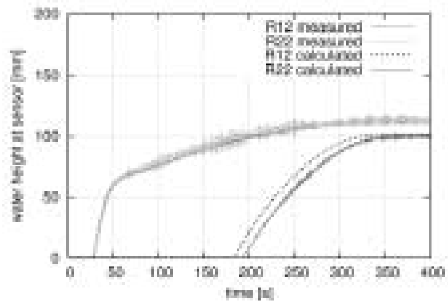

Figure 12 Water heights on the upper deck in the side damage case

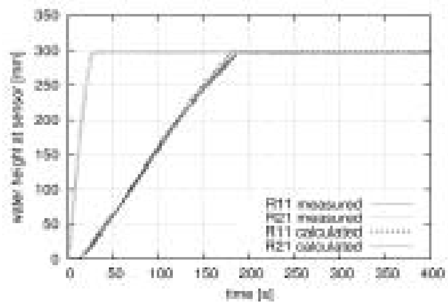

Figure 13 Water heights on the lower deck in the side damage case

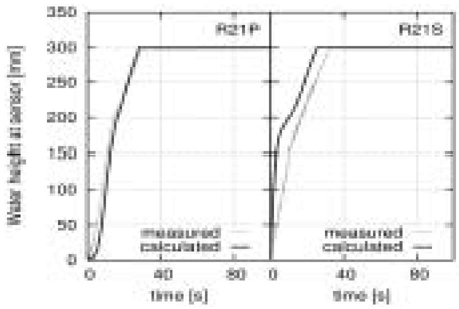

Figure 14 Water heights in the side compartments, damage opening is in R21S

The floating position is estimated very accurately (Figure 10 and Figure 11). The general correspondence between the measured and the calculated water heights is also good. The slight differences in the flooding to the room R12 (Figure 12) are likely caused by a small inaccuracy in the applied discharge coefficient, possibly due to the increased flow resistance when water is present on both sides of the opening between R21 and R11. In fact, the error seems to increase after the water level in R11 has risen above the opening from R21 (

Figure 13). Furthermore, it is likely that the discharge coefficient is actually, at least slightly, dependent on the Reynolds number.

The damage hole is in line with the opening from R21S to R21. Hence, the room R21 and also R21P were flooded slightly faster than predicted by the simulation (Figure 14).

5. CASE STUDY

The applicability of the simulation method for real ship geometries was tested with an unbuilt large passenger ship. Two watertight compartments on two decks were modelled with a typical layout, consisting of stores and crew cabins. Three different levels of modelling, i.e. detail levels, were tested. The layouts of the decks are presented in Figure 15.

In the detail level I, basically only the watertight bulkheads and decks are modelled. The level II is more detailed and contains all major steel bulkheads. The level III is the most detailed level and contains also the groups of crew cabins and cabin corridors.

For the cause of simplicity, all openings are modelled as single points with a given area and discharge coefficient (a constant value of 0.60 is used). The doors are modelled with multiple points in order to increase the accuracy. All internal doors are assumed to be closed in the beginning of the flooding. The applied thresholds for leaking H_l and collapsing H_c, and the leaking area vs. the collapsed area are given in Table 3; the values suggested by van't Veer et al (2004) are used. A constant permeability of 0.60 is used for the stores and 0.95 for the crew cabins and corridors.

Table 3 Applied parameters for the doors

Door type:	H_l **[m]**	H_c **[m]**	A_l/A_c
A class fire doors	0.0	2.0	0.1
B class joiner doors	0.0	1.5	0.2

The tested damage case is a relatively small opening of 4.0 m^2 in the side of the lower deck, 2.1 m below the initial sea level (see Figure 15). The damage extends symmetrically to both watertight compartments and there is no flooding to the other compartments or decks.

Figure 15 Tested levels of internal modelling; the grey squares mark B-class joiner doors, the black squares mark A-class fire doors and blank squares are connections that are initially open

The applied time step is 1.0 s and the convergence criterion corresponds to a water height difference of 0.1 mm. It was checked that a shorter time step or a stricter convergence criterion does not affect the results.

The time histories of the calculated floating position and the total volume of floodwater with the tested detail levels are presented in Figure 16 – Figure 19.

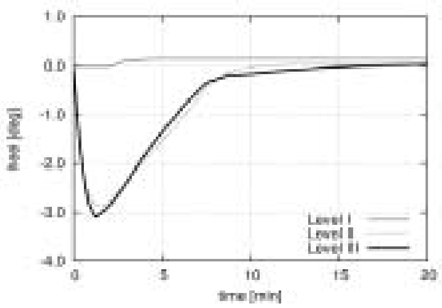

Figure 16 Heel angle with different detail levels

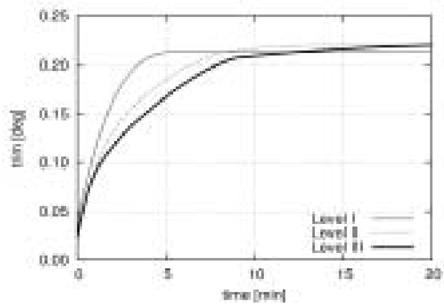

Figure 17 Trim angle with different detail levels

In the equilibrium condition, the ship heels slightly to the undamaged side due to the asymmetric distribution of permeability. The different equilibrium conditions between the detail levels are also caused by the different values of average permeability in the modelled compartments.

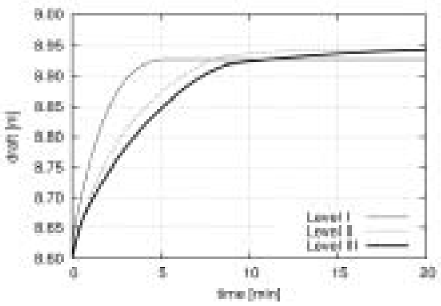

Figure 18 Draft with different detail levels

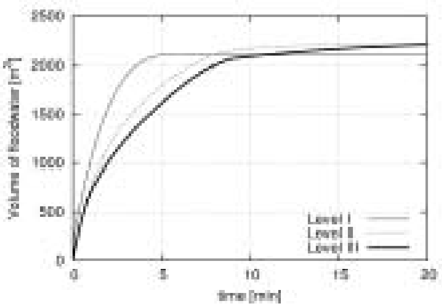

Figure 19 Total volume of floodwater with different detail levels

The detail level I is not dense enough, since the ship does not heel to the damaged side and the time-to-flood is much shorter than with the more detailed models. In this particular case, the levels II and III predict the heeling very similarly. The level II is conservative when compared to the level III since the estimated time-to-flood is shorter.

The effects of air were studied by modelling the ventilation ducts in the stores in the level III. The inlet of the duct is 0.2 m below the ceiling. The volume of floodwater in the damaged store on the lower deck with various levels of ventilation is presented in Figure 20. Obviously, the level of ventilation affects the flooding process, at least locally. It is noticed that the modelling of ventilation ducts is a complex task that needs to be studied further.

6. CONCLUSIONS

The general correspondence between the measured and the calculated results is very good. The simulation method can predict accurately both the floating position and the water heights in the compartments, provided

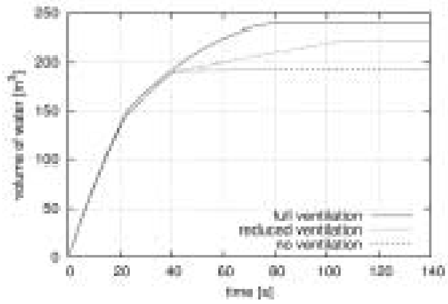

Figure 20 Volume of water in the damaged store (level III) with various ventilation levels

that the discharge coefficients are known and that all the assumptions of the method are valid. The results indicate that the effective discharge coefficient depends on whether water is present on one side only, or on both sides of the opening. Furthermore, there could be some dependency on the Reynolds number but this was not studied in detail.

The case study has shown that the simulation method can easily handle complex systems of compartments and openings. All the simulations of the case study were performed faster than real time. It was noticed that the detail level has a significant effect on the results. Also ventilation level affects the results, at least locally.

Simulation in model scale was found to be more demanding and time consuming than in full-scale since the pressure changes and dimensions are so small. However, increased under-relaxation and a shorter time step ensured convergence. Yet, the required number of iterations was quite large. Similar problems were not encountered in full-scale simulations.

The simulation method is still in a development phase, and new features shall be implemented. It is also recognised that when used in design work, there is a need to simulate also transient heeling during the initial stages of flooding. Furthermore, the quasi-stationary calculation of the heel angle can be sensitive to small local transient phenomena, such as a collapse of a large door. Therefore, the possibility of solving the differential equation for roll motion along with the progressive flooding shall be studied.

7. ACKNOWLEDGEMENTS

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