DISCUSSION

EXPERIMENTAL AND NUMERICAL STUDY ON PROGRESSIVE FLOODING IN FULL-SCALE

P Ruponen, Napa Ltd, Finland
P Kurvinen, Aalto University, Finland
I Saisto, VTT, Finland
J Harras, Finnish Naval Research Institute, Finland

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COMMENT

P Corrignan, Bureau Veritas, France

Generally speaking, I think that the paper is of good quality. The work performed is clearly described and is original since I am not aware any other such experiments at full scale. Please find below some more detailed comments and questions to the authors:

- The summary and introduction should explicitly state that the paper concerns flooding in still water condition.
- Section 2.3 Measurements:
  - It would help to have a scheme presenting the air pipes and the locations of velocity measurements in the air pipes
  - "the flow velocity close to the pipe surface was measure...": this is not clear for me; a drawing would probably help
  - Could the water height measurement from pressure measurement be checked with direct water height measurement for some cases?
- Section 3.2(b): the legend of Figure.9 should be below the figure (not in the next column)
- Section 3.3, 4th paragraph: please add the definition of (critical) damping (ratio) x.
- Section 3.4: a drawing showing the coordinate system axes would be helpful
- Section 4.1
  - 1.2.1. first sentence of second paragraph: Air overpressure and water level should be put in opposite order.
  - 1.2.2. end of second paragraph: it is not clear for me why Figure12 shows a "too slow flooding" when using rough estimations of discharge coefficients since the curves show that the water level calculated using these coefficients is larger than the measured one during the first 80s.
  - 1.2.3. end of 4th paragraph: it is indicated that the stiffeners and brackets lead to a more rapide change of the water level at the sensor location, whereas Figure.12 shows a delay in the measured signal compared to the calculated ones.
  - 1.2.4. end of last paragraph: use of velocity measurements in the air pipe: the fact that the Pitot measured velocity in the centre of the pipe can be accounted for to derive average velocities which could then be compared to calculated velocities. By considering a turbulent flow in the air pipe, the velocity profile can be represented by $U/U_0 = (1-r/R)^{1/n}$, where n is about 7 for turbulent flow. Then the average velocity is related to the (measured) velocity in the centre of the pipe (U_0). Applying this, one founds Average velocity approximately $0.8U_0$, which seems to correspond to what is presented on Figure.15.
- Section 4.2: first paragraph: "...no notable air compression was observed...": how would a notable air compression be observed?
- Conclusion: the conclusion concerning the suitability of the simplified Bernoulli's equation for the modelling of progressive flooding seems to me a bit to fast, since the validation case here concerns the flooding in still water conditions. For the ship on waves, I would imagine that dynamic effects (e.g. sloshing in partially flooded compartments, variations in flooding conditions at the damage opening due to waves/interaction ship-waves), which do not seem to be modelled here, could play a role. It would be interesting that the author elaborate on the applicability of the software to a damaged ship on waves.

P Valanto, Hamburg Ship Model Basin HSVA, Germany

This is an interesting paper on a topic, which is not exactly new. After all, some of the issues in this paper have already been discussed by E. Torricelli around 1643. The authors, however, present full scale measurements, which are not often found in open literature and are in principle free of scale effects that may take place with measurements in reduced scale.

The theoretical modeling with the assumption of perfect gas and Bernoulli's theorem appear from the start as sufficient. The good correlation between the measured results and the simulations in the rather limited heeling range also confirm this.

This good correlation does not come as a surprise. The vessel floats in calm water inside the covered dock. Thus the ship is subject neither to wind nor to wave action. Two important openings are modeled as butterfly valves. Thus the situation is very much under control with quite accurate previous information of the discharge coefficients. The only exception to this is perhaps the valve between the side tank and the equipment room. Here the authors obtain discharge coefficient values between 0.41 and 0.7 for the one and same valve, depending on the height of the water levels on both sides of the valve. The discusser is not convinced about the correctness of this evaluation. Care has to be taken to choose correct values for h_A and h_B in Eq. (3), when calculating the discharge Q.

It would be of great interest to see the discharge coefficient C_d derived from the experimental data, as a function of time or as a function of the height difference between the water levels in the two tanks. The use of two separate values is of course a coarse simplification.

Any further analysis of the discharge through real openings in the ship structures is for modeling purposes of great relevance. Not much information is available on the discharge coefficients to be used when modeling the flow through e.g. a collision damage in the steel structure at the ship side, or through a typical grounding damage, which are not as idealized in shape as the man made openings inside the ship.

The true challenge in simulating or modeling the behavior of a damaged ship in seaway lays somewhere else than in the discharge coefficients. The authors' work in confirming generally used modeling assumptions is, however, a very welcome contribution is this field. The discusser hopes that the authors continue their work towards simulating more real cases, what comes to the openings in the ship and the behavior of the damaged ship in seaway.

K McTaggart, Defence R&D Canada – Atlantic, Canada

The authors have done excellent work, and the full-scale validation is a significant contribution to the field of damage stability.

The paper includes time series of heel angle for the damaged ship. Were any experiments conducted to examine the roll damping characteristics of the intact ship? Prediction of roll damping remains a significant challenge for seakeeping analysis of intact ships.

It is encouraging to see an efficient and robust method for computing flow within damaged vessels. Do the computations run faster than real-time? Have the computations been compared with other methods, such as Reynolds-averaged Navier-Stokes (RANS) approaches for computational fluid dynamics (CFD)?

The numerical approach assumes that no sloshing occurs, which is likely a valid assumption for naval and other vessels with small internal compartments. Have the authors considered how sloshing might be added to their numerical model while still maintaining efficiency and robustness?

A damage opening with a diameter of 250 mm was modelled. Have the authors had any experience with larger damage sizes, which could give more pronounced transient effects?

E Ypma, MARIN, Netherlands

Overall a very good paper, describing very interesting model tests. Herewith my (detailed) comments:

- Section 1 'intermediate phases' – If the phases are defined as transient, progressive and equilibrium then I think that all these phases can be addressed by time simulation tools.
- Section 2.3 What can you tell about the measurement accuracy? (levels, pressures, flow, vessel attitude) And could these influence the conclusions you have drawn?
- Section. 3.2(a) Discharge coefficients for the valve & pipe two values are used, one for fully submerged conditions, one for one side submergence. What about the intermediate stages? There must be some transition effect since the Cd value will not jump from 0.41 to 0.70.
- Section. 3.2(b) Permeabilities; What is included in the permeability values listed in table 3? Do these take into account all the machinery inside the compartments or was this compensated for before the permeability was determined (e.g. by subtracting the volume of 'large' equipment)?
- Section 3.3 Timestep & Level Criterion; How sensitive were the simulations for the size of the applied timestep and for the criterion of 0.01 mm? Did a larger timestep or criterion give significantly different results?
- Section.3.3 Simulated water level heights; The levels in the plots are presented wrt to the 'bottom' of each compartment – thus the local compartment-level (or it seems like that).
- Section.4.2 Air pressure peak; The measured peak is higher than the simulated peak. Effects that contribute to this difference are a faster rise of the level in the model tests and/or a slower escape of air. When I look at the measurements of the flow velocity of water (through the damage opening) than the measured velocity is higher than the simulated velocity, the same applies to the measured air velocity. The last might be a secondary effect caused by the higher pressure, the first might however be caused by Cd values which were too low for the inlet and too high for the outlet openings. The difference in flow velocity is not reflected in the level measurement. What is the influence of measurement (in)accuracy – especially on the flow measurements?
- Section. 4.1 The comparison between measured and simulated levels, heel and trim is excellent (almost scary). It seems that the mismatch in air pressure does not really influence this. What if the air compressibility is completely ignored in the simulations? How does that influence the comparison? – This applies only to the first case.

- Section 4.1 You mention that 'some difference' is found between simulated and measured levels (at the start of the flooding). I understand that this can be caused by the stiffeners (we have found some quite serious effects caused by these) but I cannot conclude that from the plots.
- Section 4.2 sudden increase of heel at t~900 sec I think this only applies to the 'rough' simulation. The other simulation result is quite good. If that is the case can it than be caused by the stiffeners? Or were these modeled in the ''detailed' simulation?
- Section. 4.3 What could be the reason for the better results for the heel angle when using the 'rough' coefficients? What were the approximate volumes of each compartment? This can give a better idea of the relative importance of a level difference in relation to the heel. The interesting thing is that at t~1500 sec the differences between the measured levels and the 'rough' and 'detailed' levels is approximately the same. Hence in the simulations the same weight (and location of cog) was predicted. Or does the difference relate to the 'chaotic' properties of the flooding process (small, initial differences can results in quite different outcomes).
- Section. 5 I think that it is difficult to draw the conclusion that the effect of a Cd mismatch with a small damage hole is larger than when a large damage hole is used. A large damage hole will, on the other hand, introduce all kinds of other phenomena that will not be captured by the (current) simulation tools.

Lots of questions which might not all be relevant for the paper. Nevertheless, I am interested in your comments.

M Schreuder, Chalmers University of Technology, Sweden

I would like to commend the authors on this conspicuous and bold project. It was a pleasure to read the paper from start to end and I learned that the experiments were also very thorough and ambitious.

In the simulation set up you used two different accuracies in modelling two parameters, the discharge coefficients and the permeabilities. I think the presentation of the corresponding simulation results are quite enlightening and could be used as a guide for similar simulations. However in the presentation of the results you do not separate the parameters. Do you have any comment on the relative impact on the results of these parameters in the "rough estimation" and "detailed analysis" respectively?

You have also in the results detected and to some extent quantified the influence of structural members, usually not accounted for in scale models. Even if this influence is not very surprising and also quite small in your test cases, I think your findings are quite unique and also principally important.

Since you already have a numerical representation of the geometry and other properties of the tested ship, I think it would be of interest to do simulations of a geometrically scaled model, in order to isolate the influence of Boyle's law. Maybe you have already done similar simulation comparisons, or have any other comments to this proposal?

D Spanos, National Technical University of Athens, Greece

Thank authors for their paper which provides background information to the software developments in the computing of intermediate stages of flooding of the damaged ships.

The power of computer simulation for the analysis of intermediate and progressive flooding was pointed out during the investigation of the sink accident [5] when the feasibility to simulate large complicate arrangements was proved. The simulation method enables to determine the likely flooding scenario and the final flooded ship condition that is connected to a specific damage opening.

The presently applied theoretical model deals specifically with quasi-static conditions, thereof the software is properly validated in calm water and slow flooding through the small damage opening.

In this framework the flooding problem may be well determined by the set of input parameters those of discharge coefficients and permeability of the flooded spaces. Any uncertainty on the data obviously affects the computed results. The presented results appear sensibly sensitive while still stable to the data variations. Nevertheless when higher accuracy is required, this can be achieved with special assessment of the parameters, like it was done in the course of the present validation work. Thereby using refined data a good correlation between the calculations and the experiments demonstrated.

In reference to the discharge coefficients for the second valve, which was located between the side tank and the equipment room, it remains unresolved whether the estimated large difference was due to discharging into water or air, or due to pressure head small or large, or due to both factors. To the degree that the pressure head contributes to this difference, this would rather be attributed to the theoretical flow model, which explicitly takes into account the pressure head, instead of attributing the full difference to the discharge coefficient.

It would be also clarifying to which extent the vertically variable permeability was applied in the validation tests and what were the improvements from such detailed description.

X Kong, GVA Consulting AB, Sweden

The authors' work focuses on the comparison of experimental and numerical investigation of a naval ship subject to progressive flooding. The significance of this kind of work is notable. Firstly, the complex geometry and/or interactions between to exterior and interior flow domains make CFD simulation impossible for practical time consumption. Besides, the flooding flow involves salient viscous effects, for instance flow separation. This can introduce additional error if one uses the Froude scaling to perform model test.

This study takes advantage of exterior domain in calm water condition and non-violent flow (therefore assuming quasi-steady) in the damaged compartments due to flooding-induced ship motions. However, it is still expected the ship can have two-time scale motions, with one caused by floodwater loads on the ship and with the other by the ship's own motions in 'calm' water (actually the ship motions and flooding will definitely excite waves). This may explain some inconsistence between the presented results. Fortunately, the tank's sloshing period (assuming length and depth are 8 and 4meters) is much lower than the ship's natural roll period. Otherwise, the nonlinear or interaction effect has to be considered.

A Scott, Maritime and Coastguard Agency, UK

This is an extremely interesting and valuable piece of research which will increase overall confidence in the use of numerical flooding simulation as a method of assessing real-time survivability. It is quite a rare opportunity to be able compare simulation results with a full-size ship rather than a model and the high degree of correlation is impressive. The variation of discharge coefficient between air and water is interesting and will be of help with future computer modelling and simulation work, as will be the effects of air pressure, permeability and local structure on the degree of correlation. It is encouraging to see that even the rough method gives quite good correlation indicating that the theoretical basis of this method is sound. I really have no negative comments and congratulate the authors on an excellent piece of work. The only question I have is whether any further confirmatory work on more complex flooding scenarios is planned?"

REFERENCES

5. Papanikolaou, D. Spanos, E. Boulougouris, E. Eliopoulou, A. Alissafaki, Investigation into the Sinking of the Ro-Ro Passenger Ferry Express Samina, Proc. of the 8th Inter. Conf. on Stability of Ships and Ocean Vehicles, Madrid, Sep., 2003, Journal of International Shipbuilding Progress, Vol.51, No.2-3, 2004

AUTHORS' RESPONSE

Firstly, we would like to thank all the discussers for their comments and interest in the paper. As noted by **Dr Corrignan** and **Dr Valanto**, the presented study was limited to still water condition due to practical reasons. Furthermore, due to the small size of the damage hole, it was rightfully assumed that there would not be large transient motions. Consequently, roll decay tests were not carried out either for the intact or damaged ship. The authors agree with **Dr McTaggart** that this remains a significant challenge for seakeeping analyses. Also, comparative CFD calculations for the flooding process were not performed. This would have been very interesting, but also very time-consuming and expensive.

Dr McTaggart asked also about the computing times. On a modern laptop the simulation of the most extensive flooding case takes about 12 min (i.e. 4 times faster than real time). For simpler flooding cases the relative computing speed is much better. Naturally, faster calculations can be achieved with a longer time step. **Mr Ypma** asked about the effects of applied time step and convergence criterion. These parameters were selected so that it was certain that they had no effect on the results. In practice, somewhat larger time step might be applied. Nevertheless, it is a good practice to try a shorter time step and a stricter convergence criterion in order to ensure that the iterations are fully converged and the numerical error does not accumulate.

The principal idea behind using the rough estimations was to test how accurately a typical flooding simulation, based on values in literature, corresponds to the measurements. After all, the ship designer or accident investigator can only do simulations that are based on simplifications and assumptions. The detailed analysis for discharge coefficients and permeabilities was performed in order to validate the applied simulation algorithm, using as accurate input data as possible.

Mr Schreuder asked about the relative impact of the parameters. The applied permeabilities had much smaller effect that is visible especially in the final condition. The discharge coefficient of the valve between the side tank and the equipment room had the most significant effect on the results. This opening was clearly a bottle neck that affected the flooding rate to many other compartments.

Dr Valanto, **Dr Spanos** and Mr Ypma brought up the discharge coefficient for the second valve, located between the side tank and the equipment room. Direct analysis of the effective discharge coefficient, based on the measured water heights, is not possible since the flow rate in this valve was not measured. That is the reason why experiments with the valve were carried out in the laboratory of the Water Engineering Group at Aalto University. The results of these tests are presented in Figure. 20. As the discussers noted, in reality the discharge coefficient is a function of the pressure height, especially when the valve is not fully submerged. The applied values for the simulation (detailed analysis) were selected from these measurements, based on the most long-term flow conditions during the flooding tests. This was based on the video footage from the flooded compartments.

Dr Spanos and Mr Ypma asked for a clarification on the modelling of permeability. All permeabilities were considered to be constant, although the applied software can deal with variable permeabilities. Only in the pump room the large tanks were modelled as separate (impermeable) rooms. Thus all machinery was included in the permeability.

Mr Ypma and Mr Schreuder noted the effect of stiffeners, especially in the two-compartment case. The stiffeners and the brackets were not included in the detailed model. In fact, the room geometries were exactly the same; the only difference between the rough estimation and the detailed analysis was in the applied permeabilities and discharge coefficients. Figure. 4a and Figure. 7 give an idea of the web frames and other stiffeners in the ship. These structures affect the details of the flooding process, especially when the water level in the flooded room is low. However, the authors believe that these details usually have only a minor effect on the stability of the ship and on the progress of flooding to the other compartments.

Regarding Dr Corrignan's comments on water level figures and conclusions in the text, the paper contains only examples of the water level measurements. The locations of all sensors are shown in Figure. 7. The presented observations and conclusions, e.g. on the effect of stiffeners, are however based on all measurement data and visual observations from the video footage.

Mr Ypma and **Dr Khaddaj-Mallat** also asked about measurement accuracies and uncertainty analysis. The accuracy of heel and trim angles is about 0.02°. The water heights were measured through hydrostatic pressure with an accuracy of about 1 % or better. The largest uncertainty is related to the correct modelling of the sensor location. Thus the maximum error is considered to be about 5.0 cm. Some measurements were also checked against the video recordings. All water levels are presented as vertical distance between the water level and the sensor. Full uncertainty analysis was not considered to be necessary for the purpose of the study.

Mr Ypma pointed out the difference between simulations of the two-compartment flooding case. The equal water levels do not directly indicate equal volumes since the heeling angle can be different. In this case the results are quite sensitive to the discharge coefficient of the second valve. Yet in general small changes in the input data did not have major effect on the output. The stiffeners in the bottom of the store room are considered to be the biggest reason for the unexpected result that the simulation with rough estimations has a better correlation to the measurements.

Regarding the comparison of flow velocity in the air pipe, both Dr Corrignan and Dr Khaddaj-Mallat rightfully pointed out that the flow regime changes during the flooding process. As described in the text, the presented air flow velocities in Figure. 15 are not fully comparable. Dr Corrignan noted that the power-law equation can be applied for velocity profile of turbulent flow. The Reynolds number at the maximum measured velocity is about 10^5. Thus the peak flow velocity is in fact quite well estimated with the Bernoulli's equation for compressible flow. However, as Dr Khaddaj-Mallat noted, the Reynolds number will decrease and eventually the flow regime will become laminar near the final condition. Dr Corrignan also asked about the decision to ignore air compression in the other compartments. These rooms were vented through large open hatches. In addition, no peaks were observed in the measurements of over-pressure in these rooms.

Dr Corrignan and Mr Ypma raised a question on the measurement of flow velocity in the damage opening. A paddle wheel transducer was used. The measurement point was not in the centre of the pipe, but close to the perimeter of the pipe, whereas the calculated flow velocities are averaged over the pipe area. Thus direct comparisons are not reasonable. As mentioned in the text, the reliability of the measurement with low velocities is questionable.

Mr Ypma also asked about the effect of air compression in the side tank flooding case. With full ventilation in the tank the time-to-flood is about 10 seconds shorter. Mr Schreuder made an interesting suggestion on studying the scale effects by numerical calculations in scale. Since scaling of the numerical ship model is a rather laborious task, it remains a future research subject.

Dr McTaggart asked about the size of the damage hole. It is believed that a larger opening could have caused larger transient heeling angle if the "damage creation" would have been rapid. Due to structural and practical reasons, the used damage hole was the largest possible. In response to Mr Ypma and Dr Valanto, the conclusion that discharge coefficient is less important for large damage openings is based on the fact that in that situation the damaged room is flooded rapidly and the smaller internal openings then become the "bottle necks" for the floodwater. Consequently, the authors believe that the evaluation of discharge coefficients for realistic damage openings might not be very feasible.

The authors agree with Dr Corrignan that the presented conclusions on the applicability of Bernoulli's theorem may not be directly extended to flooding cases with significant sloshing. However, as Dr Taggart noted, for this ship type the sloshing is likely not an important issue. Regarding the comment on wave excitation **by Dr Kong,** the authors believe that this was very minimal during the tests. However, drifting motion, mainly swaying, was observed.

Mr Scott asked about possible future tests. Unfortunately, this kind of full-scale flooding tests are very laborious and expensive. Thus at the time of writing, no further tests with more complex flooding scenarios are being planned. But we do hope that in long-term this could be possible. In the meantime, efforts can be put to further improvements of the numerical tools. The way to go is to build enhanced numerical tools on a solid, well validated, basis and not to try to solve all problems in damage stability at once.

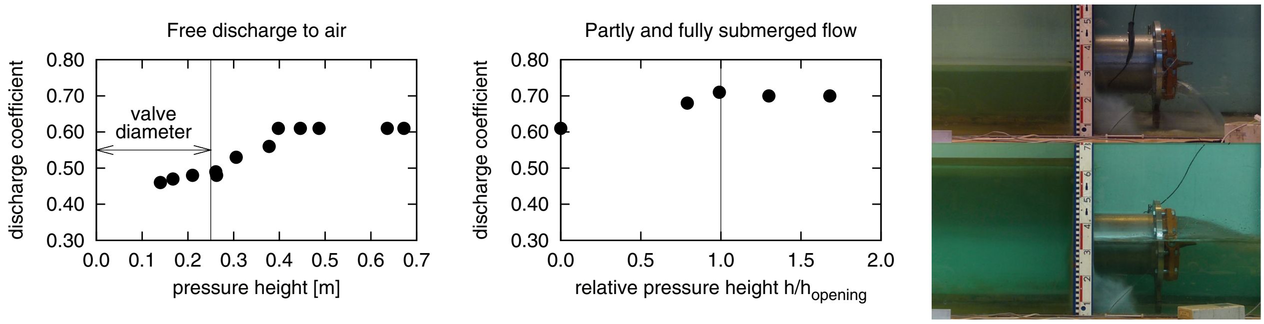

Figure 20: Discharge coefficients for the valve: free discharge to air (left) and partly and fully submerged flow (middle) with two photos from the flume tests (right), courtesy of Mikael Stening, Aalto University