Prediction of Survivability for Decision Support in Ship Flooding Emergency

Pekka Ruponen *NAPA Ltd* pekka.ruponen@napa.fi

Daniel Lindroth, *NAPA Ltd* daniel.lindroth@napa.fi

Petri Pennanen, *NAPA Ltd* petri.pennanen@napa.fi

ABSTRACT

Several recent flooding emergencies on passenger ships have pointed out the need to quickly get a better assessment of the survivability onboard a damaged ship. The development of time-domain flooding prediction methods has enabled advanced decision support tools. In this paper a method for assessment of the survivability of the people onboard a damaged ship is presented. The level sensor data is used to detect the breach and calculate progressive flooding in time-domain. The predictions are constantly updated to increase the reliability of the results. The method is tested with two realistic damage scenarios for a large cruise ship.

Keywords: *damage stability, flooding simulation, decision support*

1. INTRODUCTION

Several recent flooding emergencies concerning passenger ships, such as the Costa Concordia incident, have clearly pointed out the need to quickly get an accurate assessment of the survivability onboard a damaged ship. It is essential for the crew of the ship to know the extent of the damage and how the situation will develop. If the ship will survive the damage with sufficient reserve stability, the ship is likely the safest place for the passengers and the crew. On the other hand, if the ship is expected to capsize or sink, evacuation and abandonment of the ship should be started as soon as possible. Every minute counts when a large number of persons needs to be evacuated in a safe manner. In this context the term survivability is associated with the survivability of the people onboard the damaged ship, not the survivability of the ship itself, as it is in the damage stability calculations in ship design.

Several different methods have been presented for decision support for flooding emergencies onboard a damaged ship. *Ölcer and Majumder (2006)* presented a method based on pre-calculated damage cases. *Jasionowski (2011)* presented a method for assessing the safety level of an intact ship, based on increased vulnerability due to open watertight doors. A fast time-domain flooding prediction method was introduced by *Ruponen et al. (2012)*, and more recently, also *Varela et al. (2014)* have described a tool for decision support for damaged ships.

Recent developments in the time-domain prediction of progressive flooding now enable a new kind of decision support system that produces more detailed information on the damage case. The actual loading condition and flood level sensors can provide input data for predicting the progress of flooding. Yet the interpretation of the results is a challenge. One major question that remains is how to assess the survivability of the people onboard a damaged ship, even when the actual damage case is known with a fairly good accuracy.

Spanos and Papanikolaou (2014) have concluded that for actual damage incidents a reliable assessment onboard is still a technical challenge as the identification of the damage extent and related survivability suffers from uncertainty. This paper describes a new approach, where information from systems already available is utilized for fast time-domain flooding predictions. The results are continuously updated in an attempt to improve the accuracy. As the flooding progresses, more information is collected by the level sensors that can be used to update the breach definitions for the calculations. This approach will decrease the uncertainty in the results.

The key factors that affect the survivability are reviewed. These include the extent of flooding, stability and possibility for an orderly evacuation and abandonment. Based on these, a method for assessing the survivability on the basis of a time-domain flooding prediction is presented. Finally, the developed method is tested with a large passenger ship design and two realistic damage scenarios.

2. FLOODING PREDICTION

2.1 Progressive Flooding

Over the past two decades, several time-domain flooding simulation tools have been developed and successfully validated. Most of these are based on an application of Bernoulli's equation. However, for use onboard a damaged ship, the computational performance is of utmost importance. This combined with the fact that the available input data is never fully accurate, justifies the use of a more approximate and robust method with good computational performance.

In this study a time-domain simulation method, *Ruponen (2007)*, is used with a long time step of 30 s. The implicit time integration of the pressure-correction method ensures numerical stability, even with such a long time step. However, this means that the results are not as time-accurate, as they would be with a shorter time step. Consequently, the word "prediction" is used instead of "simulation". The applied method has been validated also against full-scale measurements, *Ruponen et al. (2010)*. Updating the flooding predictions at certain intervals will provide better information of the situation at hand. The actual measured floodwater is added to the initial condition. For rooms without level sensors, the volumes obtained from the previous prediction can be used as input for the updated prediction.

2.2 Ship Motions

Ship motions are considered to be quasi-static, so that at each time step a static floating position of the ship is calculated based on the distribution of floodwater inside the ship. It is also assumed that the sea is calm. This simplification allows for purely deterministic approach, based on the real flooding scenario. On the other hand, the increased flooding due to waves is disregarded. However, the HARDER statistics indicate that over 90% of the collision damages occur in a sea state, where the significant wave height is less than 2.0 m, *Tagg and Tuzcu (2003)*. For a large passenger ship with a dense internal subdivision, the effect of waves on the flooding process can be considered as minimal.

2.3 Ship Model

The flooding prediction requires a detailed 3D model of the rooms and openings. For non-watertight doors, additional parameters are needed for modelling leakage or collapsing due to floodwater pressure. Results from the FLOODSTAND, *IMO SLF54/INF.8/Rev.1*, can here be used as the best available approximation for this data.

The status of the watertight (WT) doors (open/closed) is obtained from the automation system. For most of the non-watertight doors this information may not be available. The cold room doors can be assumed as closed, while fire doors to staircases and along the service corridor may be open. In order to achieve some level of conservativeness, all fire doors are assumed to be open, unless the status is available from the automation system.

3. BREACH DETECTION

A breach in the hull of the ship is detected by the floodwater level sensors. Both the size and the location of the breach need to be estimated based on this sensor data. Thus every WT compartment should have sensors on all deck levels on both sides of the ship, *IMO SDC2 INF.6*. Problems related to breach detection has previously been studied by *Penttilä and Ruponen (2010)*.

The rooms, where floodwater is initially detected within the first 30…60 s, are considered to be breached. Based on the measured water level rate and the floating position of the ship, a rough approximation of the breach size is done. If the room is limited to the hull surface the breach is modelled on the side, Fig. 1. Otherwise the breach is placed on the bottom of the room.

The ship is assumed to heel towards the breached side, and the area of the breach is approximated based on Bernoulli's equation:

$$A \approx \frac{\mu S \dfrac{dH}{dt}}{C_d \sqrt{2g\left(T - H\right)}} \tag{1}$$

where H is floodwater level, S is the surface area of the room corresponding the level, μ is the permeability, g is gravitational acceleration, T is the draft of the ship and t is time. A constant discharge coefficient C_d = 0.6 can be used.

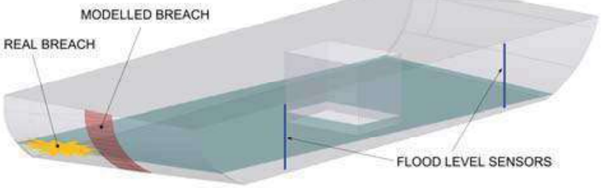

Figure 1: Approximated breach based on level sensor data

For an updated flooding prediction, the original breach is by default unchanged. Other flooded rooms are checked against the result of the previous prediction. If the room is not predicted to be flooded, the water may come from a previously undetected breach or through unknown progressive flooding (e.g. broken pipelines). For the updated prediction, these rooms are also modelled as breached in addition to the original breaches, Fig. 2.

The detected breaches and the door statuses from the automation system form the basis for the time-domain flooding prediction. The main challenge is to separate progressive flooding through the modelled openings from the flooding through breaches in the hull. This is essential since too many breaches will result in too fast flooding.

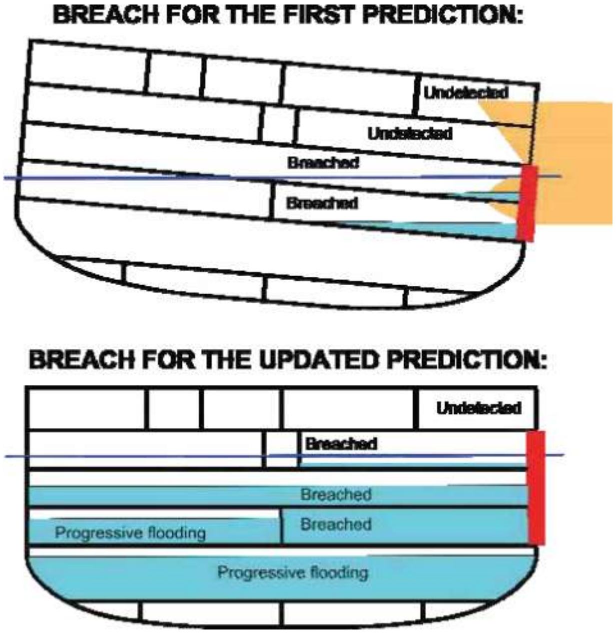

Figure 2: Update of breach for a new prediction

4. ASSESSMENT OF SURVIVABILITY

4.1 Methodology

In this study the survivability level is evaluated with the following equation:

$$F_{tot} = \min\left(F_{ext}, F_{stab}, F_{evac}\right) \tag{2}$$

The sub factors for flooding extent, stability and evacuation (F_{ext}, F_{stab} and F_{evac}) are presented in detail in the following sections. Each of them is a function of time, and the applied value is the minimum during a time window extending from the current time to the approximate maximum required evacuation time, see Fig. 3.

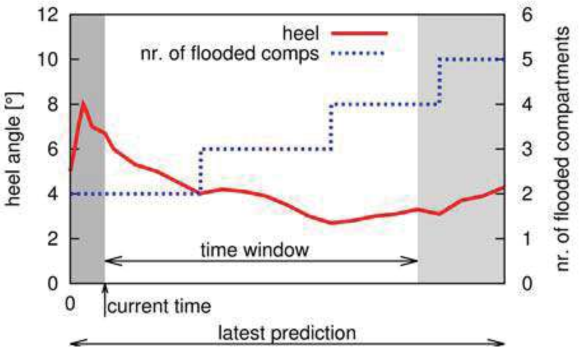

Figure 3: Time window for evaluation of the survivability level from the prediction results

4.2 Floating Position

Heel angle is considered to be the most important factor that affects the survivability level. At large heel angles launching of the lifeboats becomes impossible. Moreover, large heeling also increases the required evacuation time. Consequently, the predicted development of the heel is a primary information to the master for decision making. However, in the presented approach heel angle is only considered indirectly through its effects on stability and evacuation.

4.3 Damage Extent

The new probabilistic damage stability regulations do not set any specific requirements on how many watertight compartments can be flooded without a risk of sinking or capsizing. Despite of this, it is considered to be of the utmost importance to clearly identify how many WT compartments are flooded, since this is vital information for the decision making. If water is detected on the bulkhead deck, or at the time when floodwater is predicted to reach the bulkhead deck, the survivability level is significantly decreased. The reason for this is the increased risk of progressive flooding to undamaged WT compartments. In this study, the following approach is used:

$$\begin{aligned} F_{ext} &= 1.0 && \text{when } N_f \le N_1 \\ F_{ext} &= C \cdot \frac{N_0 - N_f}{N_0 - N_1} && \text{when } N_1 < N_f < N_0 \\ F_{ext} &= 0.0 && \text{when } N_f \ge N_0 \end{aligned} \tag{3}$$

where N_f is the number of flooded WT compartments during the time window (see Fig. 3), i.e. the flooding extent at the end of prediction. N_1 is the number of compartments that can be flooded without significant risk and N_0 is the number of flooded compartments when the survivability level is set to zero. The additional coefficient C is 0.5 if the bulkhead deck is flooded, otherwise 1.0. The function is illustrated in Fig. 4.

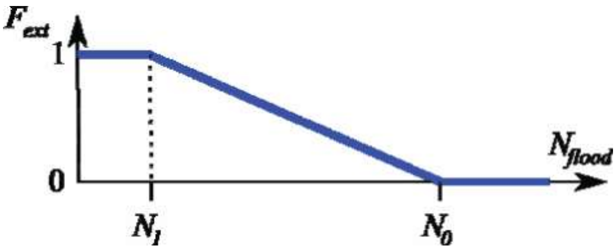

Figure 4: Flooding extent factor

In the present study $N_1 = 1$ and $N_0 = 6$ are used. However, N_0 should also be considered to depend on the size of the ship, i.e. the total number of WT compartments or the length of the ship. With $N_1 = 1$ it is ensured that $F_{tot} = 1.0$ only for one compartment flooding cases.

4.4 Stability

Even with a small heel angle the risk of capsizing can be significant if the stability of the ship is not good enough. The s-factor in SOLAS II-1 Part II-1 Regulation 7 is applied:

$$s_{final} = K \cdot \left(\frac{GZ_{\max}}{0.12} \cdot \frac{range}{16} \right)^{\frac{1}{4}} \qquad (4)$$

where GZ_{max} is limited to 0.12 m and *range* to 16°. The effect of the heel angle ϕ is accounted with the coefficient:

$$K = \sqrt{\frac{15° - \phi}{15° - 7°}} \qquad (5)$$

when the heeling angle is between 7° and 15°. If the heeling exceeds 15° the effective s-factor is taken as zero.

The *range* is limited to the angle where the first unprotected opening is immersed, Fig. 5. Only real unprotected openings above the bulkhead deck should be considered in order to avoid too conservative approach that limits the reserve buoyancy of the hull. On the other hand, if no limitation of the range is used, the results could be too optimistic. This approach also allows for a simple inclusion of the external heeling moments through the factor:

$$s_{mom} = \min\left(\frac{(GZ_{\max} - 0.04) \cdot \Delta}{M_{heel}}, 1.0 \right) \qquad (6)$$

where Δ is the intact displacement of the loading condition and M_{heel} is the maximum external heeling moment caused either by crowding of passengers, launching of survival craft or wind. In the present study the SOLAS wind pressure is applied.

The stability factor in the survivability assessment is taken as the smallest value during the time window t_{window} (see Fig. 3):

$$F_{stab} = \min\left(s_{final}(t_i) \cdot s_{mom}(t_i) \right), \ t_i \in t_{window} \qquad (7)$$

Although in SOLAS there is a separate, less stringent, s-factor formula for intermediate flooding stages, it is believed that the application of the s-final formula is more suitable for the assessment of damage stability onboard a damaged ship, since the flooding process can be slow.

For better computational performance, the s-factor does not need to be evaluated at every time step, but frequently enough, e.g. every 5 min. Still, for each intermediate time step without the stability curve calculated, the effect of the heeling angle can still be taken into account through the *K*-factor, eq. (5).

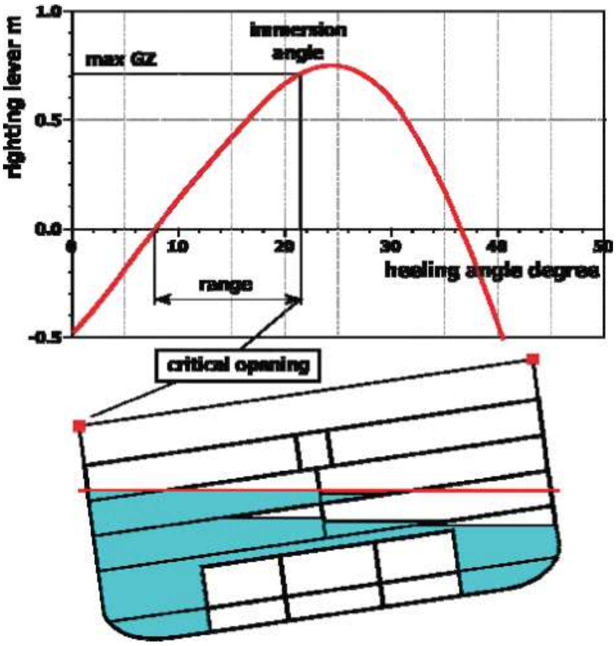

Figure 5: Effect of unprotected openings above the bulkhead deck on the GZ curve

For the survivability assessment onboard a damaged ship, the calculation of stability is somewhat different since the flooding process still continues. The traditional approach with the lost buoyancy method cannot be applied. Instead, the volumes of floodwater in the flooded rooms are kept constant for the calculation of the GZ curve. However, contrary to the added weight method, a constant displacement is used. With this approach also the so-called multiple free surface effect, see Fig. 5, is properly taken into account in the intermediate phases of flooding.

4.5 Evacuation Time

A key factor for evaluation of the survivability is the relation between the required evacuation time T_R and available evacuation time T_A. The following simple formula, providing some safety margin, is applied:

$$\begin{aligned} F_{evac} &= 1.0 && \text{when } T_R/T_A \le R_{evac} \\ F_{evac} &= \frac{\left(1-\dfrac{T_R}{T_A}\right)}{1-R_{evac}} && \text{when } R_{evac} < T_R/T_A < 1.0 \qquad (8) \\ F_{evac} &= 0.0 && \text{when } T_R/T_A \ge 1.0 \end{aligned}$$

This function is illustrated in Fig 6. The applied critical ratio of evacuation times was R_{evac} = 0.75. The available time is limited by maximum allowed heel of 15°.

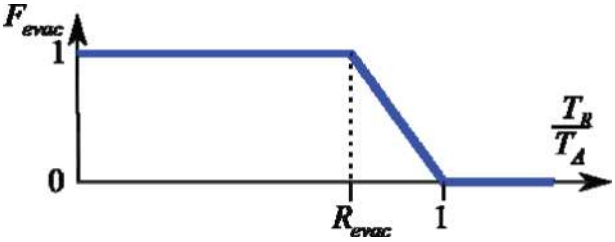

Figure 6: Evacuation time factor

The *IMO MSC.1/Circ.1238* gives the required evacuation time as 80 min for a passenger ship with more than three vertical fire zones. In the absence of more accurate data this value can be used as the best approximation.

Adverse conditions, such as extensive heel, will increase the required evacuation time. The simplest approach is to integrate over the predicted development of heel angle:

$$\int_0^{T_R} r\left(\left|\phi(\tau)\right|\right)d\tau = T_0 \qquad (9)$$

where $r(\phi)$ is the reduction factor due to the heel/trim angle and T_0 is the required evacuation time at zero heel and trim. The latter can also include the time of the day and other factors such as the number of passengers onboard. *Bles at al. (2002)* have concluded that the walking speed is linearly decreased with an increasing heel angle. In the presented calculations, it is assumed that the reduction factor is 0.5 at a heel angle of 20°. This is somewhat more conservative than in previous studies, *Meyer-König et al. (2005),* but even more radical decrease was initially presented by *Vassalos et al. (2002)*, Fig. 7.

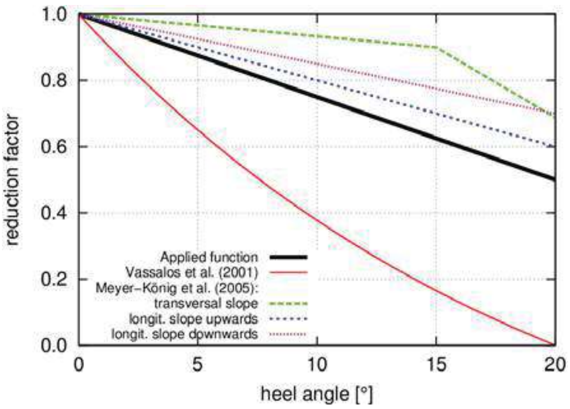

Figure 7: Reduction factor due to heel angle

4.6 Survivability Level

The vessel TRIAGE categorization[1] can be used to present the survivability level with color codes. This is very important in communication with the MRCC (Maritime Rescue Coordination Centre). A similar three-level categorization for stability of a damaged ship was presented by *Lee et al. (2005)*. The present approach is shown in Table 1. The limit between yellow and red was set on the basis of equation (5), corresponding to a heel angle of 10°. Also eq. (3) results in F_{ext} = 0.8 when flooding is limited to two compartments.

---

[1] http://www.raja.fi/vesseltriage

Table 1: Color coding for survivability level

Color	**Description**	***F***
green	- flooding is limited - ship is stable enough - orderly evacuation can be done	1.0
yellow	- ship is still safe but flooding is extensive - notable heeling can occur - orderly evacuation can be done	≥ 0.8 & < 1.0
red	- very extensive flooding - progressive flooding to undamaged WT compartments - very large heel angles - orderly evacuation may not be possible	< 0.8
black	- ship has capsized or sunk	-

5. TEST CASES

5.1 Testing Methodology

The 125 000 GT large cruise ship design, *Kujanpää and Routi (2009)*, developed in the FLOODSTAND project, is used. The actual breach geometry was first modelled, and the damage scenarios were calculated using an accurate time-domain flooding simulation, *Ruponen (2007)*, with a short time step of 2.0 s. The simulation results were then used to generate the level sensor data in the flooded rooms.

Total of 292 rooms, including the tanks, were modelled, as well as 313 internal openings, Fig. 8. A typical loading condition with GM_0 of 2.72 m, draft of 8.45 m and small bow trim of 0.05 m was used as an initial intact condition.

All cold room doors and WT doors were closed. 169 of the 227 fire doors were open. These open doors were located either in the passenger areas on Deck 5 or in locations where the crew frequently passes the door. Random variation, based on the Raleigh distribution, was applied to the leaking and collapsing parameters of the non-watertight doors in the accurate simulations of the reference data. In the flooding predictions the standard values were used.

The ship was considered to be equipped with 123 level sensors in the dry spaces, following the guidelines provided in *IMO SDC2/INF.6*. This represents 66 % of the rooms below the bulkhead deck and 50 % of the rooms on the bulkhead deck.

The first flooding prediction and analysis of the survivability level is done by using the sensor data from the first 60 s after the damage. The results are then updated by performing new predictions with a measured floodwater volumes as input for rooms with a level sensor. For the rooms without a sensor, the volumes of floodwater from the previous prediction were used as an initial condition. The predictions were repeated at the interval of 5…10 min. Calculation time for each prediction was about 2 min.

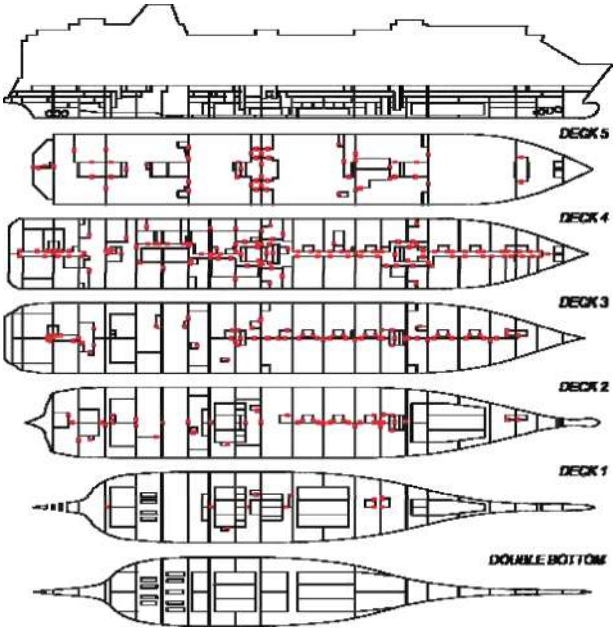

Figure 8: Modelled room arrangement and openings for the studied large passenger ship

5.2 Extensive Side Grounding Damage

This damage scenario is similar to the Costa Concordia accident. The grounding causes a 61 m long very narrow breach on the starboard side of the ship about 6 m below the sea level, Fig. 9. The damage extends over six WT compartments, including both engine rooms. Also part of the double bottom is breached.

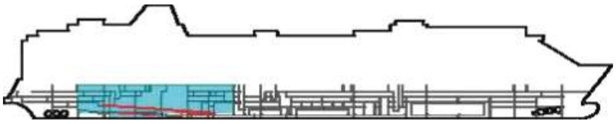

Figure 9: Damage case for extensive side grounding

The damage is so extensive that the bulkhead deck is flooded within 32 min, and water progresses also to undamaged WT compartments. In the reference simulation the ship capsizes after 3 h. The predictions indicate somewhat faster flooding, where the critical heel angle of 15° is achieved in about 2 h after the damage, Fig. 10. By this time there is already floodwater in nine WT compartments. The predictions assume that all A-class fire doors are open, whereas in reality the closed doors slow down the progress of floodwater, especially on the bulkhead deck. Thus also in the updated predictions the flooding rates are immediately somewhat faster than measured, Fig. 11. Consequently, the updated predictions indicate slightly faster time-to-capsize.

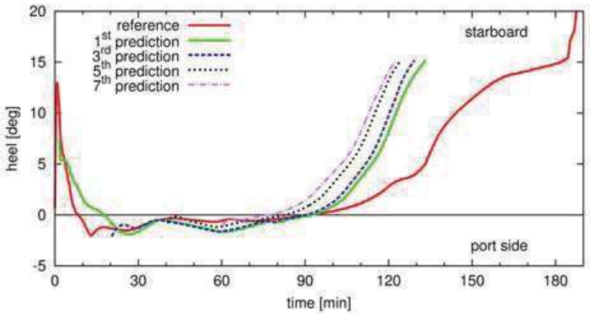

Figure 10: Comparison of heel angle for the initial and updated predictions against the simulated reference result

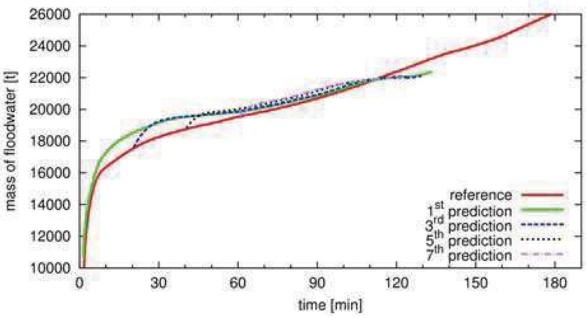

Figure 11: Comparison of the total mass of floodwater

Due to the very extensive damage, the survivability level is very poor. The color code is red (see Table 1) instantly since $F_{ext} = 0$. From the start, the prediction results provide important information to the crew that evacuation needs to be started immediately after the initial transient heeling has equalized. For a time frame of about 90 min the heeling is predicted to be less than 5°. And since the required evacuation time is about 85 min, there should be just enough time for orderly evacuation and abandonment before the ship is predicted to capsize.

5.3 Collision Damage

The second scenario is a typical collision damage, breaking two WT compartments. The breach extents above the waterline, but it is vertically limited so that the double bottom remains intact. Here however, one transverse bulkhead is not fully watertight, and also a third compartment is eventually flooded. This is accounted for in the reference simulation results by modelling a small additional internal opening in the bulkhead, Fig. 12.

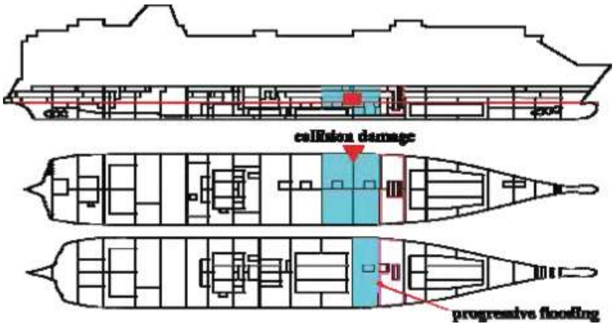

Figure 12: Collision damage case with progressive flooding

The first prediction that is started 60 s after the damage properly estimates the equalization of the initial heel towards the damaged side, Fig. 13. The predicted survivability level is fairly good with only the two damaged compartments rapidly filled up with water. The flooding extent factor is $F_{ext} = 0.8$, corresponding to a yellow color code, Table 1. Thus the initial result is too optimistic when compared to the reference simulation results for total amount of floodwater, Fig. 14.

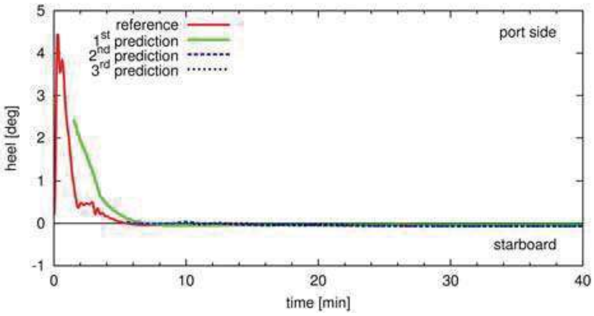

Figure 13: Comparison of initial and updated prediction against the simulated reference result

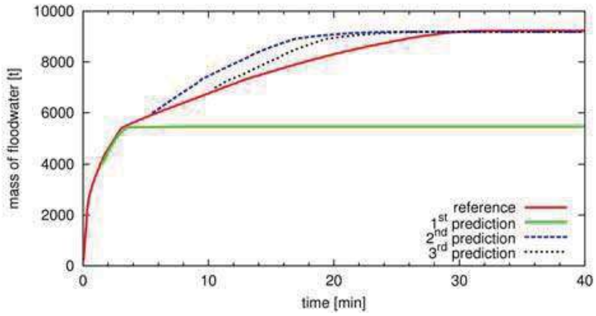

Figure 14: Comparison of the total mass of floodwater for collision damage

The updated prediction, starting 5 min later, accounts for the progressive flooding through the WT bulkhead and results in the same equilibrium as the reference result, Figs. 13 and 14. Now only the time-to-flood is somewhat shorter. The origin of the floodwater in the third compartment remains unknown, but an additional breach to one room is modelled, see Fig. 15.

The increased flooding extent results in $F_{ext} = 0.6$, and the color code changes to red. The ship is still very stable ($F_{stab} = 1.0$) and there is plenty of time for an orderly evacuation. Still, the fact that there is progressive flooding to a new undamaged WT compartment means that the situation could become more severe.

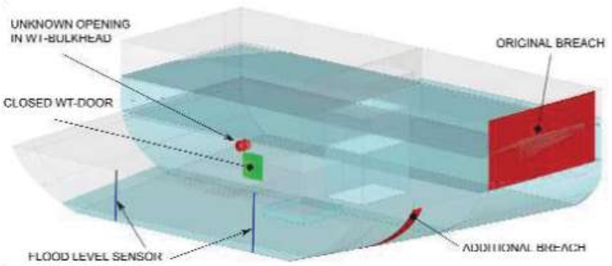

Figure 15: Additional breach in the hull to model detected flooding from an unknown source

6. CONCLUSIONS

A new approach has been developed for assessing the survivability of people onboard a damaged ship. Critical factors, such as stability of the ship and the evacuation time are accounted for. Data from level sensors is utilized and a fast time-domain flooding prediction method is used to assess the progressive flooding and the development of heel. Following the suggested principles for vessel TRIAGE, a color code representation for the severity of the situation can be determined based on the calculated factors for flooding extent, stability and available evacuation time.

The developed method has been tested with two realistic damage cases. The predicted time-to-capsize or time-to-flood is in general shorter than in the reference simulation due to the assumption that all A-class fire doors are open.

Thus the prediction results are normally somewhat more conservative. Fine-tuning of the presented criteria for the survivability level may still be needed, but the present approach forms a solid basis for further work.

It must be noted that a sufficient number of properly located flood level sensors is a prerequisite for a reliable assessment of the survivability. The combination of available measurement data from the sensors and the results from the previous prediction is a challenge. Based on the presented case studies the applied method seems to work well, but some improvements may still be needed.

Further studies are needed to ensure that the developed method works also in other damage scenarios. These cases could include also real accidents. In addition, the impact of inaccuracies in flood level sensor data needs to be further investigated.

The developed method for a fast analysis of the survivability onboard a damaged ship seems to work well in both tested scenarios. The results provide essential information on how the flooding will progress and how serious the situation is. The updated predictions can also account for additional breaches or unknown sources of flooding. This information is very useful and support the master in the decision making.

7. REFERENCES

Bles, W., Nooy, S., Boer, L.C. 2002 Influence of Ship Listing and Ship Motions on Walking Speed, Pedestrian and Evacuation Dynamics, Springer Verlag, pp. 437-452.

IMO MSC.1/Circ.1238 Guidelines for Evacuation Analysis for New and Existing Passenger Ships, 30 October 2007.

IMO SDC2/INF.6 Guidelines for Flood Sensor Placement and Technical Requirements, submitted by Finland, 2014.

IMO SLF/54/INF.8/Rev.1 Modelling of leaking and collapsing of closed non-watertight doors, submitted by Finland, 28 Oct. 2011.

Jasionowski, A. 2011. Decision Support for Ship Flooding Crisis Management, Ocean Engineering, Vol. 38, pp. 1568-1581.

Kujanpää, J. Routi, A-L. 2009. Concept Ship Design A, FLOODSTAND Deliverable D1.1a.

Lee, D., Lee, S-S., Park, B-J., Kim, S-Y. 2005. A Study on the Framework for Survivability Assessment System of Damaged Ships, Ocean Engineering, Vol. 32, pp. 1122-1132.

Meyer-König, T., Valanto, P., Povel, D. 2005. Implementing Ship Motion in AENEAS – Model Development and First Results, Pedestrian and Evacuation Dynamics 2005, pp. 429-441.

Ölcer, A. I., Majumder, J. 2006. A Case-Based Decision Support System for Flooding Crises Onboard Ships, Quality and Reliability Engineering International, Vol. 22, pp. 59-78.

Penttilä, P., Ruponen, P. 2010. Use of Level Sensors in Breach Estimation for Damaged Ship, Proceedings of the 5th International Conference on Collision and Grounding of Ships *ICCGS 2010*, Finland, pp. 80-87.

Ruponen, P. 2007. Progressive Flooding of a Damaged Passenger Ship, TKK Dissertations 94.

Ruponen, P., Kurvinen, P., Saisto, I., Harras, J. 2010. Experimental and numerical study on progressive flooding in full-scale, Transactions of the Royal Institute of Naval Architects, Vol. 152. pp., A197–A207.

Ruponen, P., Larmela, M., Pennanen, P. 2012. Flooding Prediction Onboard a Damaged Ship, *Proceedings of the 11h International* Conference on Stability of Ships and Ocean Vehicles STAB2012, Athens, Greece, pp. 391-400.

Spanos, D., Papanikolaou, A. 2014. On the time for the abandonment of flooded passenger ships due to collision damages, Journal of Marine Science and Technology, Vol. 19, pp. 327-337.

Tagg, R., Tuzcu, C. 2003. A Performance-Based Assessment of the Survival of Damaged Ships: Final Outcome of the EU Research Project HARDER, Marine Technology, Vol. 40, No. 4, pp.288-295.

Varela, J.M., Rodrigues, J.M., Guedes Soares, C. 2014. On-board Decision Support System for Ship Flooding Emergency Response, Procedia Computer Science, Vol. 29, pp. 1688-1700.

Vassalos, D., Kim, H., Christiansen, G., Majumder, J. 2002. A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance-Based Evaluation, Pedestrian and Evacuation Dynamics, Springer Verlag, pp. 437-452.

Vessel TRIAGE project: http://www.raja.fi/vesseltriage