Risk-based positioning of Flooding Sensors to reduce Prediction Uncertainty of Damage Survivability

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ABSTRACT

From the perspective of the design-stage evolution of damage stability, it is recognised that only certain combinations of damaged compartments will result in critical flooding cases with high risk of vessel loss. This knowledge may be utilised to identify optimised location of flooding sensors for the purpose of survivability prediction during actual flooding casualties. It is the aim of this paper to demonstrate the methodology for determining optimal sensor positions based on the identification of critical damage cases and associated flood-water propagation paths. The study confirms that a significant proportion of damage cases and relevant compartments are not critical, hence, focus should rather be placed on the critical, high-risk, areas to enable high accuracy prediction where it matters.

Keywords: *Flooding sensors, Damage stability, Prediction technique, Critical damage cases*

1. INTRODUCTION

The trend of increasing vessel size and complexity makes it challenging for the crew to accurately assess the extent of flooding casualty and to make fully informed decisions. The introduction of flooding sensors in compartments below the bulkhead deck as required by SOLAS Reg. II-1/22-1 (IMO, 2009) for passenger vessels aims at reducing this uncertainty and assisting the crew in decision making. The regulatory measures provide only minimum requirements for flooding detection systems with limited relevance for robust emergency management systems. Current research at the Maritime Safety Research Centre of the University of Strathclyde aims at adopting the concept of Dynamic Barrier Management (Astrup et al., 2016) through increased use of sensors and analytics for predicting the outcome of an actual flooding incident and to provide a decision support tool in emergencies (Karolius et al. 2017).

Recent research shows that predicting the evolution of flooding process purely based on flooding sensors is possible, but is highly dependent on sensor type, position and density (Ruponen et al. 2010, 2017a & 2017b). A high-density array of flooding sensors has shown to increase the accuracy of flooding assessment and compartment coverage but such dense network of sensors may be impractical or even not be feasible at all. On the other hand, the result of standard damage stability assessment demonstrates that only certain combinations of damaged compartments will result in critical high-risk cases leading to vessel loss. This knowledge may be utilised to identify locations for flooding sensors accounting for such high-risk cases enabling optimal position in terms of risk coverage and making sure the survivability assessment is delivered rapidly and with high accuracy. It is the aim of this paper to present the methodology for assessing the position of sensors by determining optimal locations based on the identification of critical damage cases and associated flood-water propagation paths.

The evaluation is carried out in two steps. Firstly, the initial assessment is performed to identify critical damages; it utilises probabilistic damage stability calculations in accordance with SOLAS Reg. II-1/6-8 (IMO, 2009) and the well-known p & s factors. As a first step, progressive flooding through openings is considered, resulting in a stepped GZ curve, an approach more realistic than is currently mandated by the regulations. As a second step, the identified critical damage cases are investigated in time-domain simulations to assess impact of dynamic factors, such as waves, on the flooding process and to identify a cut-off limit for high risk cases and flood-water propagation paths, which may be used for optimal risk-based positioning of sensors.

2. BACKGROUND

2.1 Current regulations and use of flooding sensors

Safety of passenger ships has traditionally attracted considerable attention because of their ever-increasing size, complex subdivision and large number of passengers carried. To account for this, a range of safety measures and safety systems have been implemented to improve safety and assist crew in decision making in high-risk incidents with inherent high uncertainty. In particular, the most recent developments resulted in significant (if not a step) change in the approach to damage stability and flooding response. Among the pivotal advancements are the IMO's regulations for Safe Return to Port (SRtP) (IMO, 2009). Although the regulations mainly focus on redundancy of on-board systems, they also provide guidance for what should be available for decision making post damage based on flooding extent and residual stability. As a result, on-board stability loading computers must be capable of providing operational information to the Master for safe return to port after a flooding incident as required by SOLAS Reg. II-1/8-1.3 (IMO, 2009). Moreover, flooding detection systems are incorporated with flooding sensors in watertight spaces below the bulkhead deck as required by SOLAS Reg. II-1/22-1 (IMO, 2009). However, a major shortcoming of the IMO requirements is that the SRtP flooding scenarios are deterministic and limited to single watertight compartments. In realistic scenarios and real flooding emergencies it is essential to determine the actual damage extent and produce a reliable estimate of the time available for safe evacuation and abandonment. Hence, the decision support tools for emergency flooding management systems must be far more robust than those required by the regulations.

2.2 Recent innovative use of flooding sensors

Recent, more advanced developments comprise flooding detection systems utilising flooding sensors for breach estimation in combination with time-domain simulations for real-time survivability assessment (Ruponen et al., 2010, 2012, 2015 & 2017a-b) and (Varela et al., 2007, 2011 & 2014). The latter studies do not account for sensor positioning in their developments, nor utilise sensors for detecting breach size; this is done by manual input. In the former studies, the authors utilise flooding sensors to estimate the breach size and have considered sensor positioning and its influence on detection accuracy. Their studies clearly highlight the need to use flood level sensors rather than limit switches for accurate breach estimation as well as sufficient sensor density for accurate and fast survivability assessment. Their involvement in the EU project FLOODSTAND (Jalonen et al., 2012) a few years earlier resulted in improved recommendations for positioning of flooding sensors (IMO, 2014). In brief, these guidelines recommend two flood sensors in each watertight compartment, one on each side of the ship to ensure fast detection.

The sensor layout required by the current IMO regulations as set out in guidance note MSC.1/Circ.1291 (IMO, 2008), focuses on compartments above a certain size limit, i.e. those that either have a volume in cubic metres larger than the ship's moulded displacement per centimetre immersion (at deepest subdivision draught), or have a volume in excess of 30 cubic metres.

2.3 Alternative take on sensor use: Pathway monitoring

Resistance to flooding and capsize is highly ship specific. Every vessel design has a unique subdivision and watertight integrity that will govern their survival capability in flooding incidents. Deciding on sensor layout purely based on compartment size alone will therefore be suboptimal, especially if the sensors are utilised for more advanced flooding prediction assessment as mentioned in 2.2. In general, larger compartments will accumulate more flood-water, which in many scenarios may lead to critical situations, but it is not always the case. Even if a damage resulted in flooding and deterioration of the vessel residual stability, the flooding may reach steady state and not necessarily cause loss of the ship. It is for cases not reaching steady state due to progressive flooding where high accuracy prediction is important as there will be a gradual deterioration over time, and possible capsize. More specifically, high accuracy prediction is needed to determine whether steady state will be reached and, if not, what is the likely time for the ship to sink/capsize? Smaller compartments on their own seldom result in high risk cases, but they may act as propagation paths to larger, critical, compartments initially not affected by the flooding casualty. Monitoring of these compartments would therefore be valuable for fast detection and accurate prediction, i.e. *pathway monitoring*.

Requiring sensors solely on compartment size, rather than on identified critical compartments and associated flood sequences in the progressive stages is certainly a flawed strategy. Investigating a specific vessel in the design stage, enables identification of combinations of damaged compartments, including progressively flooded compartments and their associated flood-water propagation paths that will result in vessel loss. The objective is to fit the high-risk compartments and associated flood paths with more sensors allowing for more efficient targeted positioning. Giving more focus to the actual cases likely to lead to vessel loss will achieve a higher risk coverage, faster detection and better accuracy.

3. CRITICALITY ASSESSMENT

As mentioned in the introduction, both a static and dynamic assessment have been applied for identification of critical damage cases, each described in the following sections. It is important to highlight that the models used for both assessments were identical in terms of compartmentation and openings.

3.1 Static damage assessment

Initially, a static assessment has been performed in the stability software NAPA using the probabilistic approach of SOLAS (2009) Reg. II-1/6-8. Generating all SOLAS damages for up to 7-zones, enabled calculation of the well-known p & s factors from the probabilistic framework. A detailed model was established with all openings represented as geometric objects rather than points. This enabled progressive flooding through the openings if submerged in the final stage utilising the calculation method WEPROGR2 (NAPA, 2018). Each damage was represented with an initial stage, i.e. initial damage extent, and a progressive stage, i.e. compartments progressively flooded as a result of submerged openings.

For every stage of equilibrium, new openings are checked and additional rooms added to the progressive flooding sequence. The approach accounted for all watertight doors closed and watertight, and all other doors as open and unprotected, enabling progressive flooding. In total, 661 openings were used. As all non-watertight openings were considered as progressive flooding points with relevant connections, weathertight points were added to the life-boat deck for assessment of the range criteria of the regulations. The model and internal openings are illustrated in figure 1.

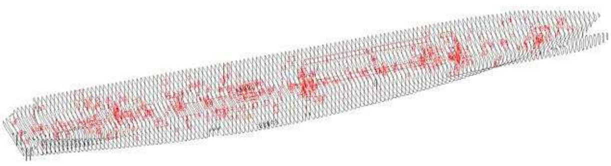

Figure 1 – NAPA model with internal openings

The inclusion of evacuation arrangements and control stations were further omitted as the requirement for including these are intended to assess the risk beyond damage stability and floatability, which is of interest in survival assessment. A flooding prediction system should give the status of the ship as a result of damage, providing assistance in decision making (i.e. to evacuate or stay onboard) and possible active measures to implement. In this study, the important aspect is therefore the identification of critical cases in terms of survivability and floatability only, and the effect on the vessel's ability to work as lifeboat as set out in SRtP requirements. Following probabilistic damage assessment, the s-factor could be used for categorising all cases into 3 categories as is illustrated in figure 2, using the relation (1 - s).

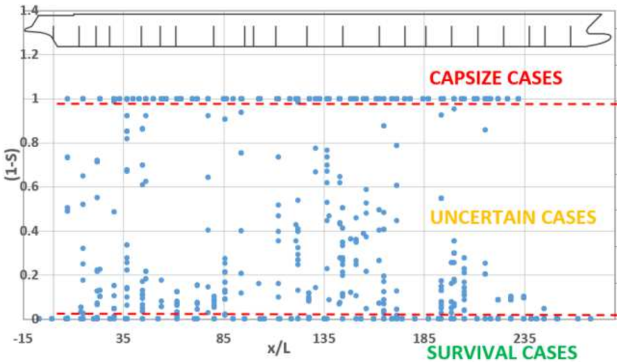

Figure 2 – Initial categorisation of static damage cases, (1-s) diagram

Cases with s = 0 were considered as capsize cases as they either capsize statically, or have insufficient residual stability margin and would not survive in waves. Cases with s = 1 were considered survival cases with sufficient residual stability margin for surviving in waves. The remaining cases with 0 < s < 1, uncertain in terms of survival in waves, were all checked in the dynamic damage assessment described in section 3.1 for identifying the cut-off limit for critical cases as is illustrated in figure 3.

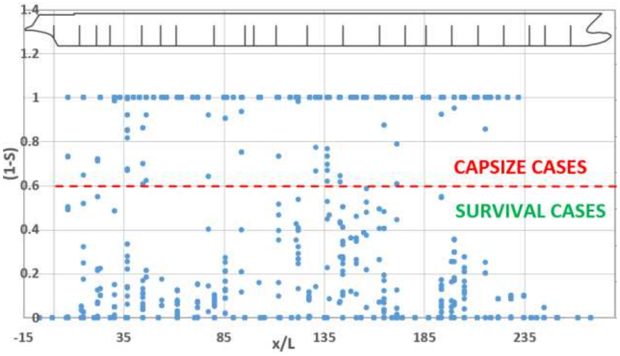

Figure 3 – Illustration of cut-off limit for critical loss scenarios

3.2 Dynamic damage stability assessment

As a vessel operates in a highly dynamic environment, such effects need to be accounted for when assessing its survival resistance to flooding incidents. In this study, time-domain simulation was conducted by the sea-keeping simulator PROTEUS3 (Jasionowski, 2001) for the cases where 0 < s < 1.

A conservative approach was followed with simulation runs in beam seas and random waves of 7 m significant wave height (H_S). Openings were given relevant collapse heads and discharge coefficients enabling a more realistic progressive flooding than was achieved in the static assessment. The model for the dynamic assessment is shown in figure 4.

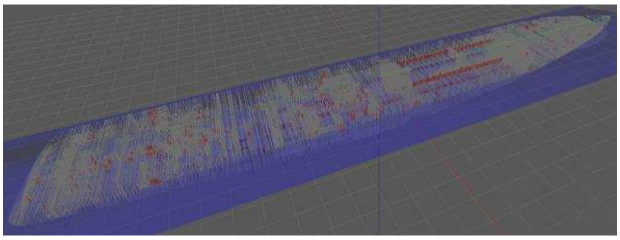

Figure 4 – Proteus3 model with internal openings

The capsize criteria followed the ITTC guidelines (ITTC, 2011), i.e.:

- instantaneous roll angle exceeds 30 degrees, or;
- the 3-minute average heel exceeds 20 degrees.

SOLAS damages in the stability software NAPA are generated using a zonal approach by applying a series of subdivision boundaries. Replication of the NAPA damages for the numerical simulations would involve generating large shell openings in the affected area leading to transient capsize in many cases. To overcome this, and to dampen the transient effect, only 1/3rd of the aft- and fore-most zones were included in the damage. The compartments missing out due to this reduction were added to the damage definition manually with the help of a compartment-connection table. An example for one specific deck is given in figure 5 for a 4-zone damage. As a result of only including 1/3rd of the aft- and fore-most zones, several smaller compartments as marked red in the figure are not included in the damage. Consequently, the damage case is not identical to the corresponding NAPA case.

As a solution, these rooms were accounted for by adding them in a connection table in the time-domain software tool.

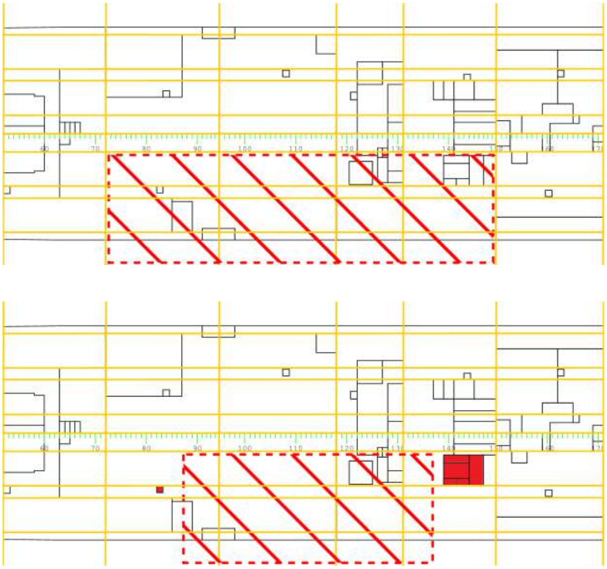

Figure 5 – Reduction in damage length to damp the effects of transient flooding

3.3 Sample vessel

The vessel used in the assessment is a large modern cruise vessel of 100,000 GT, currently in operation. The vessel main particulars are presented in table 1, including loading condition, D_S, used in the calculations.

Table 1. Vessel and loading particulars.

Parameter	Value [des.]
Length between perp., L_{BP}	273.00 [m]
Breadth, B	36.00 [m]
Depth (height of main deck), D	21.00 [m]
Gross tonnes, GT	100000 [tonnes]
Displacement, Δ	52565 [tonnes]
Draught, T	8.30 [m]
Trim, Tr	0.00 [m]
Metacentric height, GM	2.60 [m]
Vertical centre of gravity, KG	18.00 [m]

The vessel WT arrangement and current sensor layout in accordance to MSC.1/Circ.1291 is presented in Figure 6. A total of 52, and 94 sensors are fitted in dry spaces and tanks respectively.

Figure 6 – Arrangement of flooding sensors according to IMO guideline.

4. COMPARTMENT RATING

An initial approach was to use the well-known p(1-s) diagram as seen in figure 7 to identify critical cases and areas of the ship. This proved not to be detailed enough for the purpose of this study as the diagram may provide false criticality for certain cases comprising high number of zones.

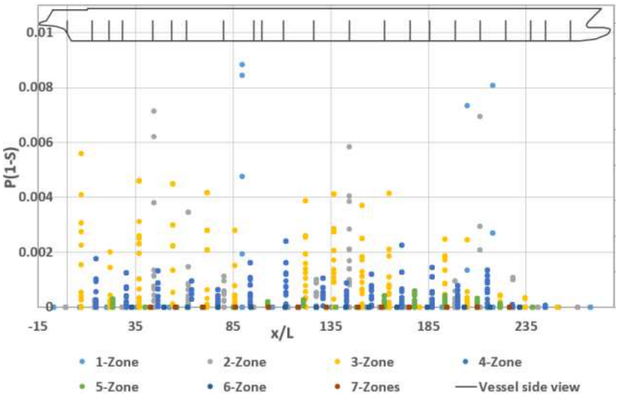

Figure 7 – P1S diagram illustrating damage cases in terms of risk along ship length

It is noteworthy that as each damage case is graphically represented using the mid position of the damage length, hence the marker position does not necessarily match the location of the critical compartments.

This can be illustrated with the help of a 4-zone damage centred at midship. This damage may be shown to be highly critical due to its inclusion of the engine room. The engine room, however, is located further aft than the x-coordinate from the p(1-s) diagram, and as such, the criticality position is deceptively presented at midship, while in reality, the critical compartment (the engine room) lies further aft. For a more detailed representation of critical areas, each compartment has been assigned a criticality metric as described in the following. Firstly, it is recognised that all the capsize cases have a survival index s = 0. This enables representing the risk from flooding by the p-factor alone, as in (1):

$$Risk = p(1-s) \rightarrow Risk = p \tag{1}$$

Each compartment can be given a risk rating based on all critical damage cases it is taking part in, by summing up relevant p-factors as in (2):

$$Risk_{Comp_k} = \sum_i^n p_{dam_i} \tag{2}$$

Were, n = number of damage cases i, resulting in flooding of compartment k.

5. METHODOLOGY SUMMARY

The following summarises the methodology applied for identification of critical cases, and subsequent compartment rating.

1. Assessment of static cases from NAPA:
    a. Remove all cases with $s = 1$ (these cases have sufficient residual stability margin to survive in waves.)
    b. Disregard all cases $s = 0$ (many of these cases capsize or sink in still water, and the remaining are assumed to capsize in waves due to insufficient residual stability margin)
2. For all cases with $0 < s < 1$, use time-domain simulations (PROTEUS3) to assess survivability in waves. This will identify a cut-off limit for critical dynamic capsize cases.
3. Compartment criticality rating:
    c. Calculate the criticality rating for individual rooms (by summing p-factors of the relevant damage cases) and rank the rooms accordingly.
    d. Screen all capsize cases and identify critical flood pathways. Identify common or partly-common flood pathways.
    e. Recommend sensor positioning.

6. RESULTS

6.1 Identification of critical capsize cases

The static calculations up to 7-zone damages resulted a total of 5564 different damage cases. The assessment was carried out at single loading condition (the summer load-line loading condition D_S). This is recognised as the worst damage stability loading condition of SOLAS. It is further shown that passenger ships normally operate around this condition most of the time (eSafe, 2017). Of all the damage cases, a total of 1568 cases resulted in $s = 1$, indicating survival, and 3450 cases resulted in $s = 0$, indicating capsize. This left 546 cases with marginal survival factor, i.e. $0 < s < 1$. The results have already been presented graphically in figure 2 in section 3.1.

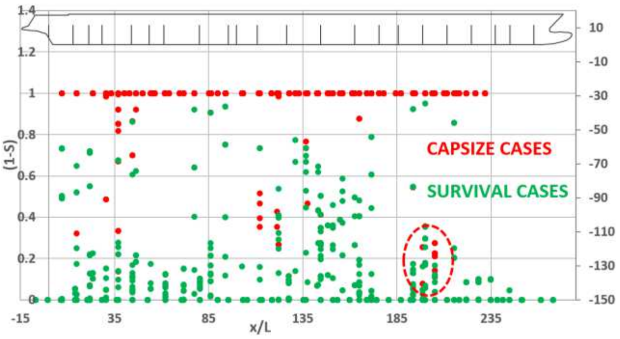

Figure 8 – Identified capsize cases in the uncertain region of the (1-P) diagram.

Due to the stochastic nature of the wave environment, the situation is not as black and white as presented in figure 3. Instead of a clear cut-off limit, there is a transition area for which neither capsize nor survival is definitive. This transition area, as shown in figure 8, may be related to the so-called capsize band (Vassalos et al. 1998), where the same flooding case may result in either capsize or survival if simulated a number of times. There will also be differences between a static and dynamic approach due to the dynamic effects incorporated in the time-domain simulations. This is particularly true in the transient stage, which is not covered by the static assessment method. Several of the capsize cases marked in red in the lower right corner of figure 8 are transient capsize cases.

Of the 546 identified cases with $0 < s < 1$, 108 cases have been identified as capsize cases following the dynamic assessment. In total, there were 3558 capsize cases which can be used in the compartment risk rating (including the initial $s = 0$ cases). It is noteworthy that the large number of capsize cases is mainly due to the extensive damage extents considered in the calculations. Of the total amount of capsize cases, 1690 are located on port side, while 1868 are located on starboard side. This difference is due to asymmetries in the vessel internal subdivision and openings arrangement.

6.2 Compartment rating

Having identified all capsize cases, these where then used in the compartment rating. Rating of the compartments (by means of relation (2)) is presented in the bar chart presented in figure 9. The rating can further be separated between initial and progressive stages as shown in figures 10 and 11, respectively. Due to the high number of compartments, the compartment names are not presented in the figures.

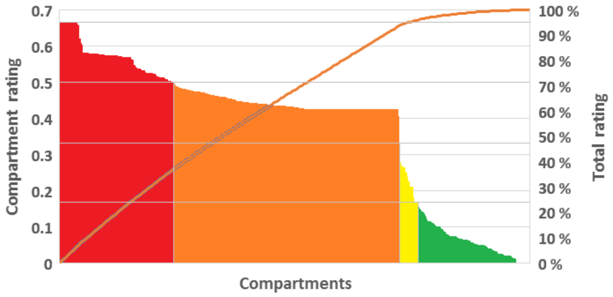

Figure 9 – Compartment risk rating: All stages

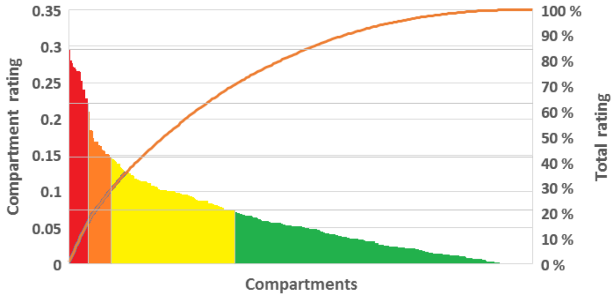

Figure 10 – Compartment risk rating: Initial stages

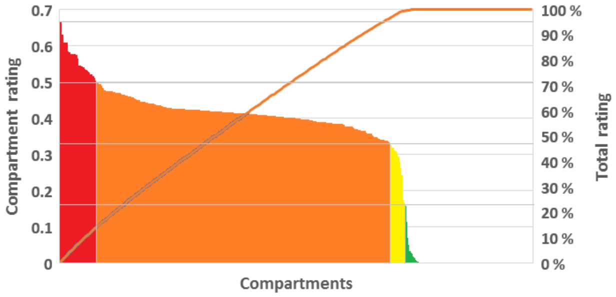

Figure 11 – Compartment risk rating: Progressive stages

The compartment have been represented graphically with colour coding corresponding to criticality. Table 2 shows the scales for criticality and corresponding colour coding. Figures 12 and 13 show the results for initial and progressive stages plotted on the deck layout.

Table 2. Colour coding for compartment criticality.

Risk/Criticality	Range	Colour
Very high	75% < Risk < 100%	Red 🟥
High	50% < Risk < 75%	Orange 🟧
Low	25% < Risk < 50%	Yellow 🟨
Very low	0% < Risk < 25%	Green 🟩

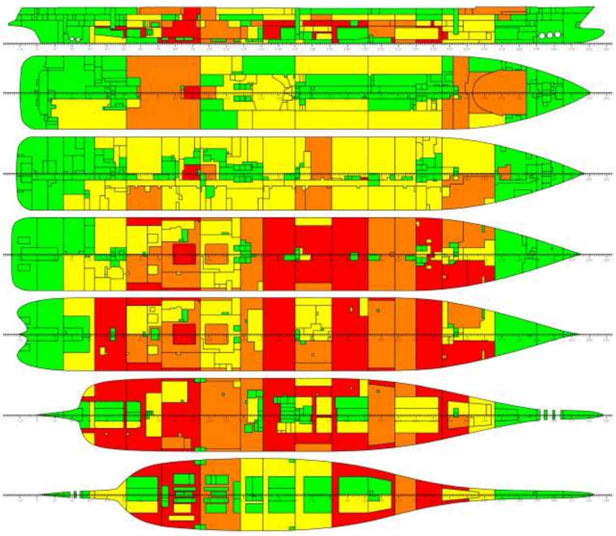

Figure 12 – Graphical representation of the compartment risk rating: Initial stage

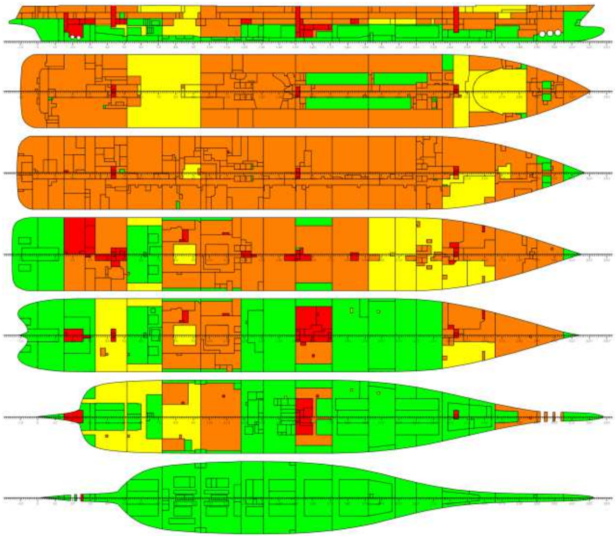

Figure 13 – Graphical representation of the compartment risk rating: Progressive stage

Figures 12 and 13 show the clear distinction between compartment criticality in the initial and progressive stages of flooding. In the initial stage, many of the critical compartments lie in the mid region of the vessel around the waterline. They also tend to be larger compartments in line with the IMO guidelines. In case of progressive stages of flooding (Figure 13), there are several smaller compartments (specifically stairwells, elevator shafts, and vertical escape shafts) that are given the highest risk rating. Interestingly, the large, upper, compartments are shown to be of secondary criticality despite being a direct cause (due to their size) for capsize when flooded. This is because the larger compartment in the upper decks are flooded in the progressive stages through the smaller compartments, acting as flood-water pathways. The smaller compartments are therefore taking part in a higher number of critical cases.

6.3 Optimised flooding sensor position

The results of compartment rating show clearly that the criticality information can be utilised in optimised positioning of the flooding sensors. In the case of compartments for which IMO requires installation of the sensors, their number and location can be analysed in detail in order to increase accuracy of flooding detection. Furthermore, additional sensors could be installed inside the compartments not covered by the IMO requirements but scoring high in the criticality rating. This should enable controlling of critical spaces and flooding pathways not only for flooding detection but also for monitoring of the flooding progress during actual casualties. Finally, openings belonging to the critical flooding pathways should also be monitored in order to allow for better assessment of the extent of the progressive flooding.

7. CONCLUDING REMARKS

The study presented here outlines the methodology for risk-based positioning of flooding sensors aiming at reducing uncertainty in the assessment of survivability of damaged ships. The study confirms that the extent of a damage case or geometrical properties of the compartments alone are insufficient criteria for the positioning of the flooding sensors for the accurate estimate of survivability during flooding casualties. The regulatory requirements should be also complemented by the systematic, risk-based rating to determine critical spaces and flooding pathways. This should lead to targeted and efficient sensor positioning.

The results also show that the same compartment may have different criticality rating in the initial and progressive stages of flooding. For this reason, these stages should be ranked separately as smaller compartments may form critical flooding paths to larger rooms (through up- and cross-flooding) and should also be fitted with sensors for early warning of capsize. Separating initial stage, and progressive stage may also help identifying sensor type and position. Specifically, the following can be taken into account:

- Initially damaged compartments below waterline: Flooding sensors for initial estimate of the damage extent, i.e. breach detection.

- Initially damaged compartments above waterline: Alternative sensor types for vertical breach detection.

- Progressively flooded compartments: Pathway monitoring for assessing survivability and watertight integrity.

- Openings: Status of the openings forming the critical flooding pathways should be closely monitored (e.g. open/close status, leaking, hydrostatic head build-up).

8. FUTURE DEVELOPMENTS

Similar approach for compartment rating should be implemented with survivability assessment by time-domain simulations. Random non-zonal damage cases can be sampled using Monte Carlo sampling directly from damage accident statistics. Sufficiently large damage sample (5000-10000) should ensure convergence to the zonal model (i.e. as used in static simulations). In this approach the criticality would also reflect random sizes of the openings and impact of environment on the progressive flooding. Time-domain simulations are particularly important for the inherently stochastic problem of detecting and monitoring critical flooding pathways.

Further work is also needed to verify if the proposed approach (i.e. criticality-driven sensor positioning) provides higher risk coverage and more robust survivability prediction.

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