ON FACTORS AFFECTING THE TRANSIENT AND PROGRESSIVE FLOODING STAGES OF DAMAGED RO-RO VESSELS

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ABSTRACT

Roll-On/Roll-Off vessels are extremely vulnerable with regard to their hydrostatic stability when damaged.

This paper aims at contributing to enhance knowledge of the flooding physics. It sheds light on the transient and progressive flooding stages, focuses on relevant factors, and comments on some points which remain hard to take into consideration, whatever the adopted methodology is. Furthermore, it proposes recommendations for a more reliable assessment of the flooding process.

This review shows that the intermediate flooding phase depends upon many factors and recommends carrying out a wide range parametric investigation into these factors which takes their interdependency into consideration.

Keywords: *Ro-Ro ships, intermediate, flooding, survivability, experimental, investigation, recommendations*

1. INTRODUCTION

Reducing or preventing the occurrence of water flooding is becoming a significant issue for the safety and operability of ships. Compact masses of water entering and flowing inside the ship seriously menace both advancing and moored vessels, and might lead to their physical or conventional loss, despite compliance with all international regulations in force. Particularly, Ro-Ro vessels proved to be extremely vulnerable regarding their hydrostatic stability when damaged (Boltwood, 1988, Dand, 1989, and Spouge, 1986). For those ships, the intermediate stages of flooding can be more severe than the final condition due to large free surface effects as well as inertia effects with regard to the roll motion. These effects, reinforced by an abrupt ingress of water right after the damage creation, can induce large heeling angles during the early stages of flooding, rendering the intermediate phases of flooding potentially dangerous and their examination requisite since the ship may capsize well before the final stage is reached.

After much research has been devoted to investigate, on a first hand, the damage survivability of Ro-Ro Passenger Ferries (Dand, 1994, Ishida and Murashige, 1997, Molyneux et al., 1997, Pucill and Velschou, 1990, van't Veer and de Kat, 2000, Vassalos and Turan, 1994, and Winkle, 1996) and, on a second hand, some maritime accidents, namely the European Gateway (1982), reported by Spouge (1986), the MS Herald of Free Enterprise (1987), reported by Dand (1989), and the MV Estonia (1994), recently reported in SSPA Research Report No. 134 (2008), the early 2000s marked an intensive research concerning the dynamic behaviour associated with transient and progressive flooding of Ro-Ro ferries (de Kat et al., 2000, Santos and Guedes Soares, 2006, and Vassalos, 2000) as well as Large Passenger Ships LPS (refer to Ikeda et al., 2004, Ikeda et al., 2003, IMO SLF46/INF.14, 2003, Katayama et al., 2005b, van't Veer et al., 2004, and Vassalos et al., 2004, and also to the outcomes of the flooding simulations carried out by MARIN and reported in IMO SLF47/INF.6, 2004, van't Veer et al., 2002, and van't Veer and Serra, 2003). In spite of these studies, the damage stability analysis relied, until recently, on the knowledge of the hydrostatic properties, both in intact and final damaged conditions, while the intermediate stages of flooding were not taken into consideration.

One particular research project of the Hydrodynamics and Ocean Engineering Team of the Laboratory of Fluid Mechanics of the Ecole Centrale de Nantes in France is underway at the moment of writing this review, and concentrates on the dynamic behaviour and survivability in waves of damaged Ro-Ro passenger ferries subjected to flooding. Preliminary examinations supported by a rich state-of-the-art-research in this field demonstrate that a suitable basis of this project commencement is the investigation of the ship's motion behaviour and the associated stability characteristics during the intermediate stages of flooding in calm water at zero forward speed.

Ship motion and flooding are distinct but intrinsically interrelated and highly interacting processes, as pointed out by Vassalos and Letizia (1998). Actually, when an intact ship is subjected to a sudden breach of the hull at its side, it can experience a large transient roll angle during the initial stages of flooding. This is particularly true for Ro-Ro ships that usually have a centre of gravity above keel in the range 1.5-2.0 times full load draught. The peak roll angle can be significantly larger than the final equilibrium heel one depending mainly on the value of the metacentric height. Moreover, the motion of the ship in the transient and also progressive flooding stages seems to be complex, as being dependent on hosts of factors. The high non-linear character of the hydrostatics with respect to the floodwater and also the hydrodynamic effects contribute to complicating the ship behaviour, and render it more sensitive to a multitude of parameters determining the system. Furthermore, according to Santos et al. (2002), 'Very few attempts have been made to ascertain exactly what happens at the intermediate stages of flooding and its influence in the capacity of a damaged ship to survive under given environmental conditions'. Therefore, it remains of great importance to be able to answer the following query: Would the damaged ship capsize or sink before a steady state is reached, and consequently what factors could be involved?

The present paper is devoted to provide a piece of useful information to answer this inquiry. We purpose to enhance the knowledge of the flooding physics by treating the transient and intermediate flooding stages and some relevant important topics. We also focus on involved and evolved factors, and suggest combinations between factors strongly affecting the flooding before the steady state is reached. Furthermore, we discuss the effects of the transient flooding phase on the ship damage survivability, and comment on some points which remain hard to take into consideration either in a numerical or an experimental investigation, and propose, when found necessary, recommendations for a more reliable assessment of the flooding process. We conclude this paper by stressing on an actual need of carrying out a wide range parametric investigation into entailed factors which might take, as practically as possible, their interdependency into consideration. In order to optimise the outcome of such painstaking research, we advocate the use of a statistically-based experimental design methodology, namely, the DOE methodology.

Since probabilistic and statistical analyses of the occurrence of the flooding events are beyond the scope of this work, the present paper will be limited to the case of Ro-Ro vessels encountering a midship damage at zero forward speed. Hereinafter, the intermediate flooding refers to the flooding within both the transient and progressive stages.

2. THE INTERMEDIATE FLOODING STAGES

2.1 Description

Right after the damage creation, water starts to inflow through the damaged shell inside ship compartments. This water ingress initiates the first stage of the flooding process, i.e., the transient phase, and is actually a complex process since it depends upon a wide range of parameters describing the damage features, the vessel geometrical and hydrostatical characteristics, and the environmental conditions. If the damage occurs with sufficiently high energy, a rapidly increasing heeling moment generated by the weight of the floodwater could be induced by the water ingress, which generates a roll motion of the damaged vessel. At the resonance frequency, the floodwater can lead to greater amplitudes, whereas flooding water can act as an additional ‘damper’, reducing the roll amplitude, at other frequencies. Consequently, the ship would heel violently due to the fluid momentum and asymmetric flooding, and might capsize if other flooding consequences, e.g. cargo shift, make this heeling moment exceed the residual restoring one. Experimentally, it was demonstrated, by Vredeveldt and Journée (1991), that dynamic considerations are required while judging the damage stability of ships during water ingress. Moreover, it was emphasized, in Spanos and Papanikolaou (2001), that the transient flooding is characterized by strong non-linear effects related to the floodwater dynamics and the damage opening shape. Sometimes, the final stage during flooding will never be reached due to the dynamic effects of ingress water through large damage openings in intermediate stages of flooding, and the roll motion is dynamic in the stage even if no excitation forces act on the damaged hull, as pointed out by Ikeda and Ma (2000). According to Palazzi and de Kat (2002), this complicated character remains when also taking the air flow in the damaged compartments into account, despite the damping provided by the air flow which can significantly reduce the motion behaviour inside the compartment and limit the resonance.

After the transient phase, water will proceed to other compartments through internal openings. During this so-called progressive phase, the water behaviour is highly influenced by the internal ship arrangements, and also by other factors, such as the external pressure, velocities variation, ship motion, and behaviour of trapped air inside flooded compartments. It was also indicated, as within the EU HARDER Project (2000-2003), see IMO SLF46/INF.3, 2003, that progressive flooding can lead to capsizing, and the situation is very different between Ro-Ro ferries and LPS.

In fact, the procedure of accumulation of water inside flooded compartments mainly determines the ship behaviour. Besides, the amount of accumulated water in each compartment needs to be determined in order to assess the residual stability of a damaged ship. This procedure is related to the water ingress/egress through the outer shell damage and internal openings, the floodwater behaviour and its interaction with the ship, and also to the coupling between them. Other phenomena could play a significant role, such as the sloshing during the intermediate stages, as concluded in Journée et al. (1997).

2.2 The Entailed Factors

The above-demonstrated complexity of the intermediate stages of flooding is believed to be fostered by hosts of intervening factors.

Some of them are involved since the start of the flooding, and others, namely those intrinsically related to the flooding physics, e.g. air behaviour, could evolve. On the whole, they could be classified into three categories:

a) Category A is related to the event of damage creation: it consists of the circumstances, the process, and the results of the damage creation. Namely, it comprises the damage opening characteristics (shape, height, longitudinal extent, vertical location, penetration), and the time of damage creation,

b) Category B regards the ship hydrostatical and geometrical characteristics. The hydrostatic characteristics consist of the vertical mass distribution (and consequently the metacentric height) and the initial intact conditions (draught, trim and heel). The geometrical ones contain the layout of large compartments (dimension, permeability, transverse and longitudinal locations of inside obstructions), the internal openings, the cross-flooding arrangements (design, size), the air ventilation level, the strength of the non-watertight subdivisions in watertight compartments, and some features influencing the water spread between compartments, as doors, piping, and ventilation systems,

c) Category C is related to the environmental conditions, namely, the timing of the damage occurrence in waves, the tuning of the vessel and waves, sea state, relative wave direction, wind force and direction.

It is worth mentioning that for LPS, the category B, and namely the ship geometrical characteristics, significantly affects the ship behaviour in the intermediate flooding stages. Actually, multiple decks in the damaged compartments and the vertical location of the damage opening highly influence the large roll motion appearing in these stages. That’s why careful attention should be paid to prevent water spreading on the bulkhead deck, which plays an important role in the safety of LPS during these stages.

3. THE ASSESSMENT OF THE INTERMEDIATE FLOODING STAGES

3.1 The Adequacy of Calm Water Condition

Based on the findings of some past investigations devoted to assess the damage survivability, the authors noticed the adequacy of the calm water condition to assess a) the transient phase of flooding of Ro-Ro ships (Ro-Ro ferries and LPS), and b) the progressive flooding of LPS. Regarding the transient phase, and according to de Kat et al. (2000), a significant transient roll peak to the damaged side, not influenced by the presence of waves, can result during the first stages of water ingress, regardless of the damage speed and wave period. The time to reach this maximum roll peak was found dependent upon the metacentric height and the heeling moment impulse exerted by the floodwater. Furthermore, very similar roll response was obtained, by de Kat and van’t Veer (2001), while considering the transient flooding both in calm water and in waves. It was also noticed that roll motions in waves are small compared to the maximum roll angle due to the transient flooding. Concerning the progressive phase, Papanikolaou et al. (2003) found that in cases of highly compartmented internal arrangements, like those in LPS, and in absence of wide spaces, like the car deck, the progressive flooding is governed by the hydrostatic flooding in calm water, whereas the waves’ effect is limited, especially when the damage opening is limited too. Moreover, it was indicated, in IMO SLF46/INF.3, 2003, that a significant large roll angle towards the damage occurs due to intermediate flooding situations of a LPS with complex internal arrangements and that this roll angle was almost not influenced by the sea state in which the damage is created.

On the basis of these results, it is reasonable to assume that the waves do have a significant effect neither on the transient flooding phase in a Ro-Ro vessel, nor on the progressive stage in a LPS, nor on the ship motions within these stages. This assumption will decrease the complexity of both experimental and numerical studies, and assist in identifying the flooding due to hydrostatic head difference at the damage opening, and that due to waves and ship motion.

In addition, when examining the entailed parameters, their extent in influencing the intermediate flooding phases, and the successive stages of the evolution of some of them, namely the air behaviour, the authors noticed that some of these parameters could, to a certain limit, have similar tendencies whether assessed in calm water or not. Furthermore, it is so clear that the evaluation of such parameters is easier far from the noise of waves and perturbation it can produce, and could provide more reliable results because of being more practically controllable. Thus, the identification of such factors seems challenging and might be significantly important in the assessment of the intermediate flooding stages, and still requires further investigation.

3.2 Recommendations to More Reliable Assessments

The interdependency between the response of the damaged ship and strong non-linear dynamic effects developed within the intermediate stages of flooding and related to both external wave motions and internal floodwater behaviour complicates the situation. The resulted high degree of complexity renders these problems difficult to simulate by means of mathematical modelling. As well, these same dynamic effects make heavy demands on the model construction and test techniques in physical model experiments. Consequently, some points seems delicate and, sometimes, impossible or at least hard to be correctly taken into account either in a theoretical or an experimental investigation.

This section of the paper highlights some difficulties encountered in past investigations of the intermediate phases of flooding, and suggests, where found necessary, some recommendations to more credible and reliable assessments.

1) Being a fluid flow phenomenon in essence, the flooding should, when investigated experimentally, be assessed by use of large model scales in order to minimise scale effects, by properly accounting for viscous effects and turbulence. Taking such flow characteristics into account and improving the scaling level of water ingress enable a better reproduction of some phenomena, e.g. the TAF as reported by Santos et al. (2002), and, as a result, a quantitative reproduction of the phenomenon could be better predicted.

2) Due to structural reasons as maintaining sufficient model rigidity, it is clear that it is so difficult to ensure a detailed geometrical similarity between real and model ships, and consequently the ‘global permeability’ of the ship is altered. Furthermore, the ‘symmetry of the permeability’ may not remain after real collision damage. It should be noted that the asymmetry of permeability due to the notch in the deck plates is larger in model scale since the plates are thicker than predicted by the scale. This is a subject that needs more investigations to be better understood. Therefore, it is important to verify that the damaged compartments are modelled as accurately and practically as possible to ensure that the correct volume of floodwater is represented. Experimentally and in addition to the ship shell, all manufactured decks and bulkheads plates have to be as thin as possible and consistent with adequate strength, in attempt to correctly scale the buoyancy arising from deck and shell thicknesses. This relative low thickness would cause the deformation of the model in torsion and longitudinal (sag and hog) modes. However, in order to remediate

the hull thickness issue, a correction for the differences in stability curves as a result of the model hull thickness, can be performed. By doing this, the scaling of the damaged GM (model) to ship will improve the assessment accuracy.

3) In flooding simulations, the proper discharge coefficients for all openings, namely that of the damage hole, need to be determined, as they are related to the inflow velocity, which affects the dynamic behaviour of the damaged vessel before the steady state is reached. Apparently, it is still hard to find out these coefficients, as mentioned in Ruponen et al. (2009). The effect of the scale on the discharge coefficient for a rectangular sharp-crested opening was studied in Katayama and Ikeda (2005), by testing two openings with the same shape but different scale. The opening discharge coefficient was found to be dependent on the model size, the air compression in the watertight compartment, as well as the flooding condition, i.e., the relative water level inside the flooded compartment with respect to the initial draught. They also found that the smaller scale results in larger values of the discharge coefficient. Therefore, the application of model tests with relatively large scales with the aim of determining these values for full scale simulations is strongly recommended. Conspicuously, more studies on the quantification of discharge coefficients used for through-flow through openings are still needed. In particular, the identification of water flow characteristics through typical openings in ships is indeed required in order to improve the reliability of the flooding simulations.

4) This section deals with the progressive flooding phase and suggests some subjects that require further investigations. Actually, after the damage creation, the floodwater has to pass several compartments and internal openings, e.g. doors, before down flooding points are reached. These internal openings are not completely watertight, and thus, despite being closed, water may leak. Furthermore, some incidents that could alter the characteristics of the flooding process during the progressive phase might be encountered, such as the collapsing of a closed door when a certain pressure has built up and the turning direction of a door which depends on the flow direction. As well, the pressure losses in the air pipes and valves are not constant and increase when possible bends occur. In practice, for a straight pipe, the frictional losses depend on the length and the diameter of the pipe along with the surface roughness. Thus, it is really hard to attain a high degree of accuracy in modelling internal subdivisions, such as correctly copying drains, ventilation ducts, electrical conduits and so forth, that would make internal compartments more porous. The simulations, presented in van't Veer et al. (2004), show that the applied critical pressure head for collapsing of a closed door to a staircase can have a significant effect on the roll motion and time-to-flood. Therefore, it is essential that the simulation method can also handle leaking and collapsing structures. Nevertheless, there is insufficient experimental data on the critical pressure heads for typical non-watertight structures. Some values were presented in IMO SLF47/INF.6, 2004 but in general, these are mainly assumptions. Moreover, there is a need for systematic tests of various types of doors to give a more detailed input into the process of time-domain flooding simulations. Therefore, further experimental investigations are needed concerning this item. According to IMO SLF46/INF.3, 2003, an accurate assessment of the flooding process requires an accurate modelling of internal compartments and the openings between them, e.g. doors, windows, piping and ventilation systems, electrical cable penetrations, etc. More investigations are needed in the future about progressive flooding on the bulkhead deck through semi-watertight bulkheads and further downwards through any staircase or escape trunk. Furthermore, more tests of different types of windows are also needed to establish the leakage and collapse pressure thresholds.

Moreover, the following points are believed to require further investigation:

- The quantification of the strength and collapse behaviour of interior rigid sub-division, doors, and windows,
- The effect of the time of splash tight door closing on the vessel survivability,
- The active damage control, such as closing the splash tight doors or other measures that would be expected to be performed by the crew. Therefore, the modelling of the flooding process should take account of active damage control which affects the ship's survivability,
- The effects of down-flooding and up-flooding through stairwells and other openings.

5) Within the assessment of the damaged ship's behaviours in intermediate stages of flooding, carried out by Katayama et al. (2005a), it was noticed that the non-dimensionalised time to reach the maximum heel angle after flooding is dependent upon the model scale, and was larger for the large model than it is for the small one. It was confirmed that this outcome is caused by the difference of the flooding velocity from the damaged opening affected by the size of the opening and air compression in the damaged watertight compartments. Therefore, the authors believe that the non-dimensionalised time to reach the maximum heel angle after flooding could not serve as a parameter of interest within either an experimental or a theoretical assessment of the intermediate stages of flooding, as it does not follow, at least, Froude's similarity. Nonetheless, the magnitude of the maximum heel angle should be considered as it is affected by a multitude of factors, such as the metacentric height GM, the heeling moment impulse exerted by the floodwater, the flooding velocity through the damage opening, the size of the damage opening, as well as the air ventilation level. Furthermore, carrying out such experiments for various scales could be a convenient alternative to evaluate the importance of scale effect.

6) The intermediate phases of flooding are highly influenced by what actually happens during and after the damage occurrence, whose understanding proved to be not easy to achieve. Past investigations devoted to assess the flooding phenomenon and, consequently, the vessel's survivability have demonstrated an extreme difficulty in copying all aspects of a collision event. Consequently, modelling the contact force, the damage penetration, and possible effect of growing damage in time are currently not taken into account, when assessing the flooding process. This is because qualitative data about forces and phenomena evolved within the striking vessel accidents are still unknown, despite the large amount of collision studies performed experimentally in recent years (Määttänen, 2005, Tabri et al., 2004, 2008, and Wevers and Vredevelt, 1999). Actually, the damage that will occur due to a collision will depend on a multitude of factors, such as the shape and structural rigidity of the penetrating bow, the crash behaviour of the struck side structure, the striking location and angle, the inertia of both involved vessels and their speeds at the moment of impact. In general, the structure of the struck ship will dent, buckle, and tear which may increase or reduce the transient heeling. However, the striking ship might reduce the stability of the struck one, as the former one would obtain some pitching induced by complex wave patterns during the collision which also affect the rolling of the latter one. Therefore, before the transient flooding even starts, the struck ship might already have some rolling motion. The energy transfer between the implicated vessels that might alter their stability is still ignored by current relevant regulations. Unfortunately, damage statistics only report damage extent (length, height, and penetration) which is not sufficient to determine either the damage shape or the actual area of the ingress opening. Furthermore, according to Vassalos and Jasionowski (2007), the probabilistic concept of ship subdivision in SOLAS 2009

regulations, mandatory since January 2009, disregards the cause of the breach and the collision event with all the circumstances leading to its occurrence, and, consequently, the interest focuses on the conditional probability of the stability loss. In view of the above, it is the authors' opinion that a trustworthy assessment of the intermediate phases of flooding should consider the whole physical aspects causing the damage. Hence, we advocate, while comprehending the difficulty it has, the performance of physical experiments mixing collision experiments and survivability ones. Past studies mentioned in this survey on each of the two experiments establish a threshold for carrying out such experiments.

4. CONCLUSIONS

The risk of flooding due to maritime accidents can be reduced either by minimizing the probability of accidents' occurrence or by reducing the consequences. However, the reduction of the consequences requires a good understanding of the physical phenomena. To minimize the risks associated with collision and grounding accidents, we should improve ship operations to reduce the likelihood of accidents and design stronger ships to minimize losses should an accident occur; whereas improved internal vessel arrangements, structural crashworthiness which is an aspect of the ships' structural design, and stabilized damage reduce the consequences.

In this paper, we treated the transient and progressive flooding stages and found them complicated as depending upon several factors. These factors are potentially related to the ship stability and geometrical characteristics, the environmental conditions, as well as the accident circumstances, causes and peculiarities. We also found them highly affecting the floodwater behaviour and the water inflow/outflow process (and hence the water accumulation in damaged compartments) and consequently the damage survivability on the whole. As hosts of factors are implicated into the intermediate phase, a probabilistic analysis seems of significant importance before a deterministic one is performed. Joined analyses are believed to conveniently encompass the problem and make progress towards framing of new stability regulations.

On the other hand, we demonstrate the adequacy of the calm water condition to assess the transient flooding phase of Ro-Ro ships (Ro-Ro ferries and LPS), and the progressive flooding of LPS. Furthermore, we advocate carrying out a wide range parametric investigation into the entailed factors which could take, as practically as possible, their interdependency into consideration, and encouraged the application of the DOE methodology. At last and not least, we advocate such study and would indicate that the principle of carrying out experiments which are a compromise between time, budget and predetermined degree of delving into investigation, should never restrict the whole investigation goal neither by eliminating nor by reducing the degree of representation of parameters, especially those that appear insignificant at the beginning but prove to be of paramount importance after a hard work is accomplished.

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