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TRANSIENT FLOODING ON LARGE PASSENGER SHIPS

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SUMMARY

This paper summarises research into effects of transient stages of flooding on stability of modern large passenger ships (LPS). The sample study-case configuration exhibits high vulnerability to attaining excessive angles of heels due to inrush of water, possibly leading to immediate capsizing even for small damages. The underlying physical mechanism derives from effects of multiple free surfaces, which cannot be analysed in traditional manner and must be simulated in the time domain. Though typical numerical model for such time domain simulations is capable of pinpointing the potential problems, it displays ambiguity in relation to (a) modelling of roll motion energy-dissipating rate when subject to damage and (b) modelling of water flow by simplified Bernoulli equation.

1 INTRODUCTION

Recent progress[1] in development of the new harmonised probabilistic method for damaged ship stability assessment have necessitated thorough verification of scientific foundations underlying the new rules proposed in [5].

Such verification studies have specifically been addressed by extended efforts deployed[2] within the scope of an on-going EUREKA project SAFENVSHIP. The overall aim of this collaborative project, involving 11 participants from six European countries, has been to develop, evaluate and validate methodologies and tools for design of the next generation cruise and ferry ships with aspects of safety (fire protection, structural reliability, stability, evacuation) and environment (clean sea and air) catered for inherently.

The specific verification studies undertaken entail a series of stability calculations within the probabilistic method, numerical simulations and physical model tests on a selected sample of passenger vessels, aiming at testing consistency and correspondence of the new regulations with the actual survivability levels of these ships. The results of this work are to be presented to the respective national delegations at the relevant SLF sessions.

This paper discusses some of the research results derived to date, in the context of (a) current rules as well as (b) other research with similar objectives conducted elsewhere.

1.1 Related research

The other research projects addressing the issue of survival criteria of LPS are described in documents [1] to [4]. The following quotes derived from these two projects and public comments, relevant for the discussion of this paper, are presented below for easy reference.

Study A

[1, Annex page 51] “A large two-compartment SOLAS damage including unlimited flooding on deck 4, is survivable in small waves up to 1.5 m. If the splashtight doors (STD) were assumed to be closed, the ship would be able to survive very much longer – perhaps indefinitely. …”

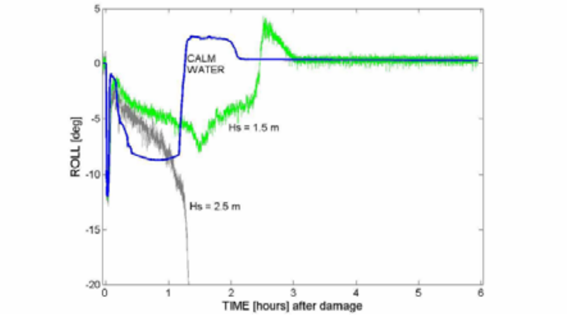

Figure 1 Results of numerical simulation obtained in [1, Annex page 31]. Roll motions in calm water, in Hs=1.5m and in Hs=2.5m, with side downflooding points. Collapsing doors on Deck 2. *Splashtight doors assumed open*: if closed, roll motions would tend to follow that of the calm water case.

[3, page 2, §4] “The MARIN study only evaluated the time-to-flood for a single unbuilt passenger ship design. Nevertheless, with proper and effective damage control

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[1] IMO, SLF 46 meeting held in London on the 8-12 September 2003 and SLF 47, September 2004

[2] Since November 17th/18th 2003, actions ratified by the SAFENVSHIP Consortium, 3rd Steering Committee Meeting, Glasgow, UK

procedures, the results showed that this design has a very high degree of survivability in calm as well as in moderate sea conditions - including a case involving four compartment raking damage. Time-to-flood analyses of other passenger ships are necessary in order to develop a broad assessment of the present levels of survivability applicable to existing large passenger ships (SLF 45/14, subparagraph 8.14.6). The group believes that similar conclusions about the high degree of survivability will be reached about other existing large passenger ships, also based on effective damage control and door closures. Time domain flooding analysis can be used to study the effectiveness of damage control procedures. The ship will provide a long-duration lifeboat for the passengers. Evacuation would not be necessary."

[3, page 3, §13] "The group has a number of issues to be pointed out for these simulations. In general the group agrees with the magnitude of floodwater in this and the two-compartment collision damage simulation runs. We cannot agree with the rate of ingress. We believe that with the proper SLF 46/8 - 4 - modeling of the internal spaces and doors, the rate would be much slower. Therefore, the initial heel angle after damage would not increase to 12 degrees immediately but probably to less than 10 degrees within 10 minutes after collision damage. The group further concludes that the presence of closed splashtight doors would reduce the equilibrium heel as reported: final heel would be well under 10 degrees. Some initial simulation runs in Phase 1 resulted in equilibrium angles in the range of 5 to 9 degrees."

[3, page 4, §20] "The group concludes that the design modeled will survive in 4.5 m or greater sea conditions."

[3, page 6, §27] "Another (different) design ---- Seek the co-operation of another designer/owner to get a different ship design model, or rearrange the current model's internal arrangements to generate another ship. The need is to ensure that the Sub-Committee has studied enough variations of internal arrangements in time-domain so conclusions can be drawn. Greater credibility would be gained if the simulation runs on the different ship design were performed on an alternate time-domain computer code or model tests."

Study B

[4, page 1, §3] "The experimental results show that a large passenger ship can make large roll motion in the intermediate stages of flooding and that multiple decks in a damaged compartment of her, play an important role in the transient roll motion and time to the final flooded condition."

[4, Annex page 1] "Survivable probability of the damaged large passenger ship used in the present study is confirmed to be completely different from the assessed ones at the final condition in static assumption."

[4, Annex page 3] "These results suggest that water on the middle deck can cause capsizing of the ship during the intermediate stages of flooding although the ship is stable in the final condition after flooding."

The above statements lead to two main observations:

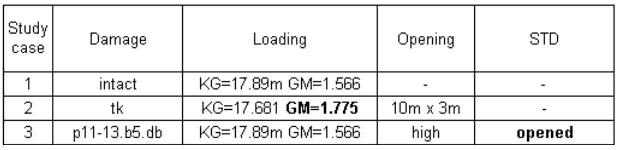
- On one hand, it is concluded based on the FREDYN time-domain numerical simulations that the study case LPS is highly survivable in sea states of up to 4.5m, although call for study extended to different scenarios/arrangements and by alternative numerical codes is made.
- But on the other hand, it is concluded based on an experimental study that ship with multiple decks arrangements, such as LPS, are highly vulnerable during transient and intermediate stages of flooding.

These two observations shall be the background subject of discussion offered in this paper.

2 THE STUDY VESSEL

This paper reports on a limited number of tests, as summarised in Table 1, carried out for an un-built large passenger ship, nicknamed C1, representative of modern designs. The pertinent details assumed, are given in Table 2, and Figure 2 to Figure 7, below.

Table 1 Test matrix



Study case	Damage	Loading	Opening	STD
1	intact	KG=17.89m GM=1.566	-	-
2	tk	KG=17.681 **GM=1.775**	10m x 3m	-
3	p11-13.b5.db	KG=17.89m GM=1.566	high	**opened**

Table 2 Particulars of the LPS C1 vessel

Lpp	242	m
Breadth, B	36	m
Draught	8.4	m
Displacement Δ	53,179	t
KMT	19.456	m
KG	17.89	m
GM	1.566	m
k_{xx} , … $\frac{1}{B}\cdot\sqrt{\frac{I_{xx}}{\Delta}}$	0.46	-

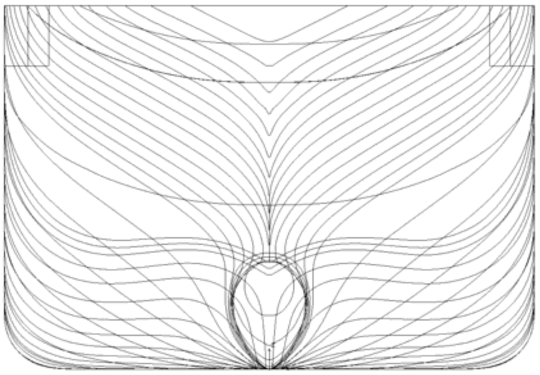


Figure 2 Body-lines used by PROTEUS-3 software

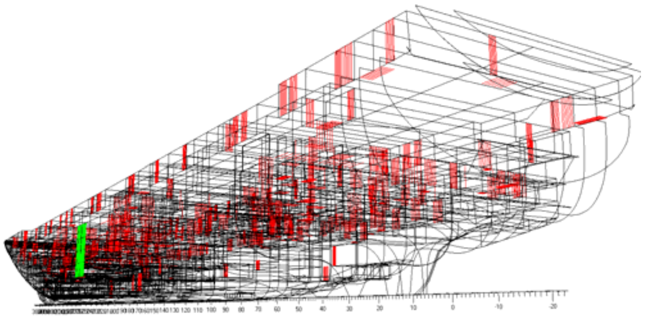


Figure 3 Aft view of Proteus-3 model of the ship

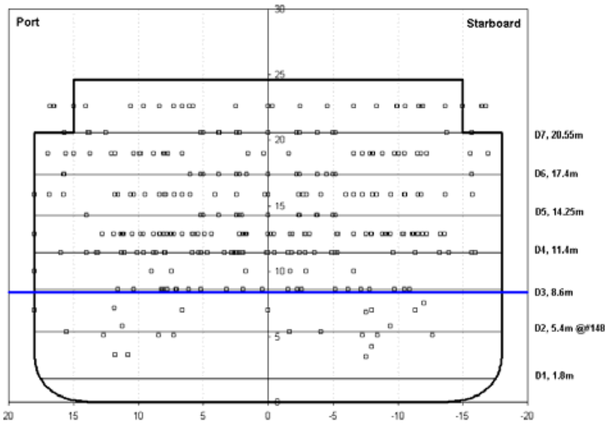


Figure 4 Outline of the distribution of all the openings on the ship considered in numerical simulations, draught marked 8.4m.

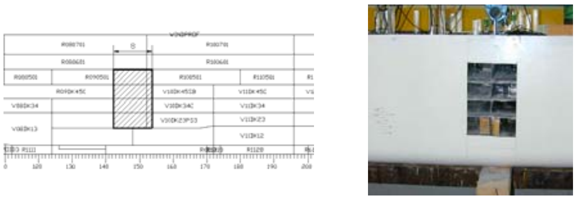


Figure 5 Definition of the "high" damage opening, penetration assumes only external hull damage, with decks remaining intact.

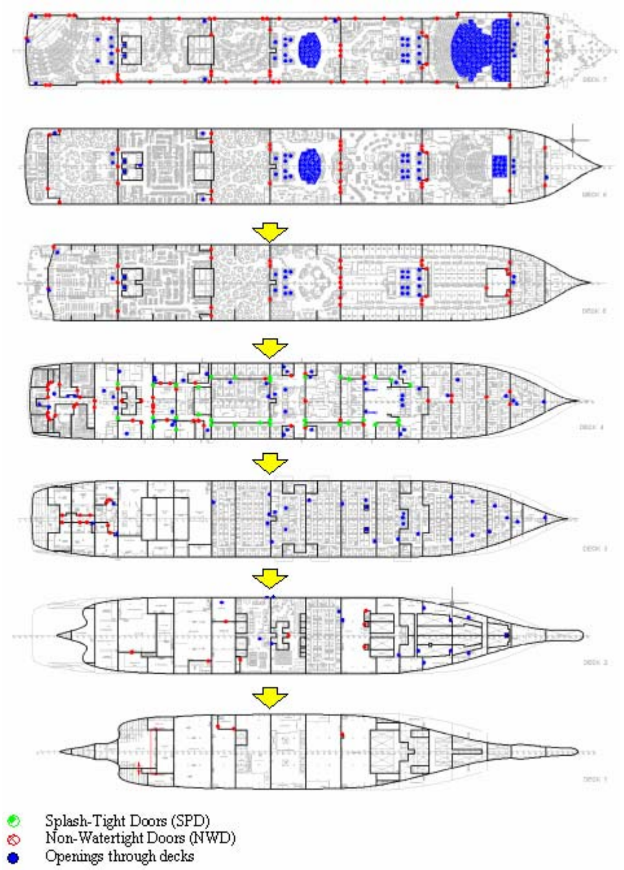


Figure 6 Arrangement of watertight boundaries and connecting openings. Proteus-3 model entails all details up to and inclusive of Deck 7, the assumed damage location at frame 148 is marked by the arrow.

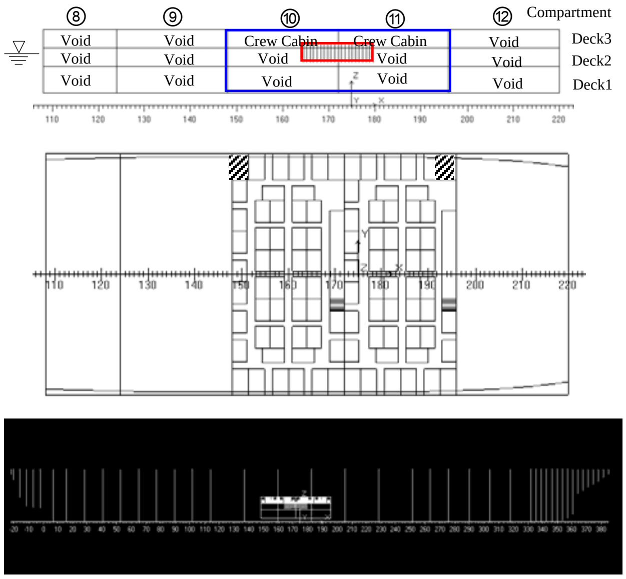


Figure 7a Definition of damage case "tk", size of the starboard side opening is 10.5m x 3m.

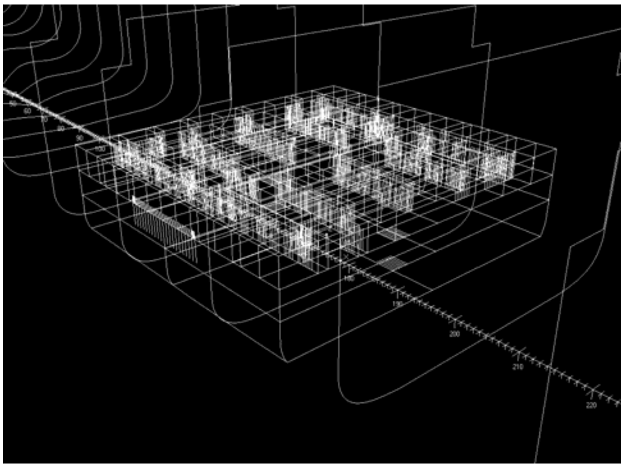


Figure 7b Definition of damage case “tk” – perspective view, size of the starboard side opening is 10.5m x 3m.

3 DISCUSSION OF RESULTS

This chapter discusses various issues pertaining to survivability of large passenger ship as well as means of assessing it, based on analyses of the few study cases summarised in Table 1.

3.1 Study case 1

This study case is the fundamental “roll decay” simulation to verify modelling consistency of all the details of intact ship, such as loading, hull geometry and appendages. As can be seen from Figure 8, an agreement between numerical and experimental models demonstrates sufficient engineering accuracy.

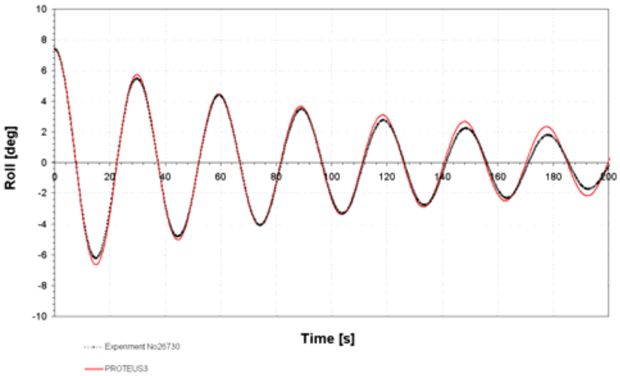


Figure 8 Decay test, draught 8.4m, KG=17.89m (GM=1.566m).

3.2 Study case 2

This study case addresses modelling of ship behaviour in transient flooding stages. A 2D model of mid-body of the vessel described in Figure 2 was used for experimental study underlying publication [10]. Although it was 2D geometry, the basic hydrostatic properties were very similar to the 3D case for heel angles of up to some 20 degrees. The internal geometry was created as shown in Figure 7, spanning 2 compartments longitudinally, and three decks vertically, with the Deck3 containing cabins. Experimental and numerical results for a chosen study case are shown in Figure 9. During the experiment, the model, initially in intact condition, is heeled to about 2 degrees to the starboard side and the doors are removed manually to allow flooding. As a result of this water ingress the vessel heels to about 17 degrees within approximately 2 minutes and then slowly regains its equilibrium attitude at an angle of approximately 2 deg to starboard side. This final condition appears to result from asymmetric arrangement of cabins on the Deck 3, some of which remain impermeable, see Figure 7.

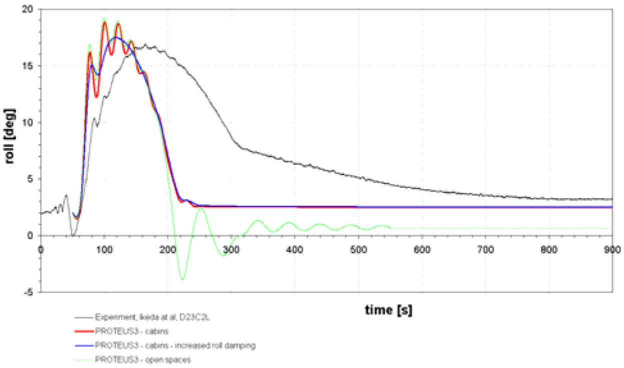


Figure 9 Comparison between experimental and numerical simulations of ship response during transient flooding.

There are three sensitivity studies involving the numerical simulations related to this experiment, as shown in Figure 9. Firstly a case indicated by “PROTEUS-3 – cabins” represents simulations where the space in Deck 3 is modelled in details involving cabins as seen in Figure 7. Also no correction for damping effects to accommodate for reported earlier, [8], inabilities of numerical models to represent motion-energy-dissipating effects of flooding are included in this instance.

As can be seen, the character of the transient response can be simulated to some extent only. The main disagreements relate to the predicted time it takes to flood the spaces, in that the flooding rates simulated based on Bernoulli equation with correction coefficient of 0.6, are twice as high as they appear to be obtained during the experiment. Secondly, the roll response derived experimentally seems to display lesser oscillation than predicted numerically, implying higher levels of damping due to roll motion.

Some ad-hoc study was undertaken in an attempt to attain feeling on the sensitivity of the PROTEUS-3 model to the underlying assumptions and thus understand possible sources of these discrepancies, assuming it was numerical modelling that was inaccurate.

Inclusion of the correction for damping does subdue the oscillation, see the curve marked “PROTEUS3 – cabins – increased damping”. However the mean process of rolling response in the transient stages is the same as obtained in the first simulation, i.e. the rates of flooding are not affected noticeably by some small change in the roll response.

Some study on sensitivity of the flooding model to variations of correction coefficient was performed, as shown in Figure 10, where it was found that reducing it to 0.35 would lead to match between simulations and the experiment. Such quantitative discrepancies prompt for further investigation of the procedures applied during the experiments, as much as of the details of the numerical models. For instance, some suggestion arises whether the scale effects in representing openings in the experiment would not lead to this level of differences.

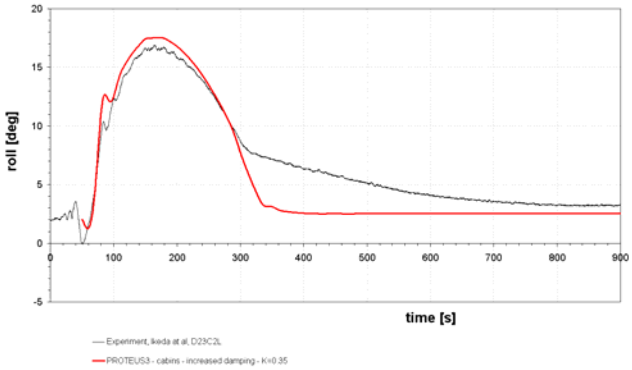


Figure 10 Comparison between experimental and numerical simulations of ship response during transient flooding, effect of decreasing flooding rates.

Coming back to Figure 9, the last curve “PROTUES3 – open spaces” relate to modelling of the Deck 3 without cabins, allowing the water to propagate across the deck unobstructed. The final equilibrium is zero in this case as no asymmetry was included on the Deck 3. A conclusion can be drawn, at first instance, that modelling of spaces without considering of details of internal arrangements, such as cabins and corridors, is accurate enough, and that the predicted response would not be affected even though some differences in water propagation in Deck 3 can be seen in sample Figure 11. However, this conclusion might be too hasty based on only one sample calculation, simply because the Deck 3 contributes very little to the buoyancy and ultimate response of the ship. The response is driven by flooding on decks 1 and 2, hence detailed modelling of spaces on these decks could have greater effect on the simulated response, as was for instance reported in recent work [9].

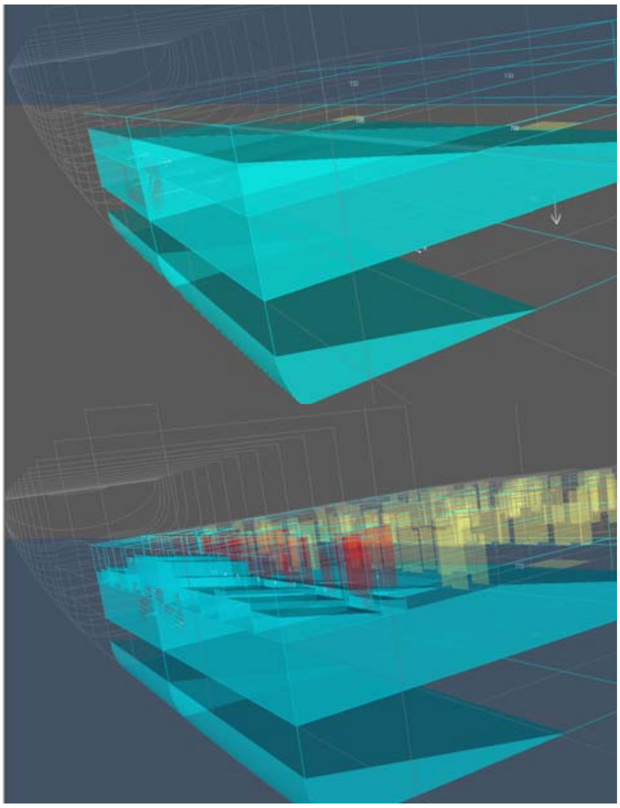


Figure 11 Damage case “tk”, comparison between option of modelling damage geometry without cabins (upper picture) and including cabins (lower picture)

3.3 Study case 3

This case addressed time-domain simulation of the response of the vessel during transient stages of flooding. In essence, this study can be considered as the response to the call of SLF-46 Sub-Committee [3, page 6, §27] mentioned in §1.1, on confirmation of the study [1] by independent party.

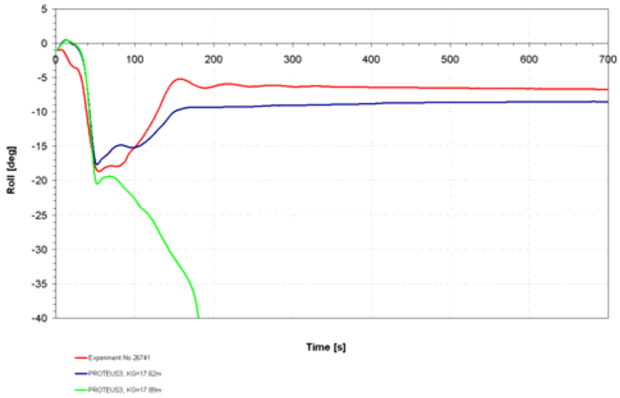


Figure 12 Transient flooding, comparison between experiment and time-domain simulations with PROTEUS-3 tool

The above Figure 12 summarises three tests to this effect. Firstly a record from model experiments, see Figure 13 and Figure 14, demonstrates that the vessel heels to some 18deg during transient stages of flooding, and regains an equilibrium heel of about 7deg, all taking place within some 2 minutes in real scale. This is essentially the experiment to be used as verification base for study discussed in §1.1 and shown in Figure 1. Neither the large heel angle, nor the final equilibrium seems to be represented by the model underlying the work [1]. Furthermore, other experiments resulted in the vessel capsize[3], exacerbating on one hand the differences of conclusions on stability and survivability of such large passenger ships, between this study and the study reported in [1], but on the other hand confirming findings of research [4].

Figure 13 The C1 vessel in the workshop, view towards her port side, "high" damage opening visible.

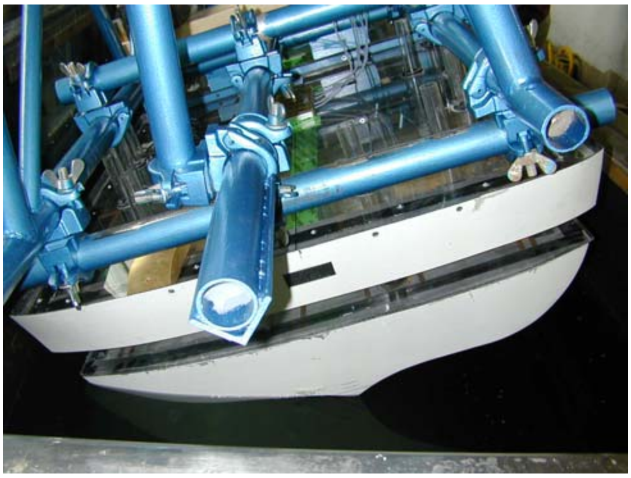


Figure 14 The C1 vessel in heeled condition, some 18deg heel to port side.

The mentioned elements of randomness in outcome of experiment, e.g. capsizing or non-capsizing due to transient flooding, remains subject of an ongoing research. For instance, although considerable care was taken in building the internals of this highly complex case, some clear discrepancies[4] seem to have occurred in modelled characteristics of static stability in damaged conditions, as shown in Figure 21. Since the vessel seems to be so vulnerable to capsizing and violent response due to transient flooding, any such error must be addressed.

Notwithstanding some minor doubts remaining to be resolved, several inferences on mechanisms driving the survivability of LPS, can be drawn, as discussed next.

Firstly it can be seen from Figure 12, that the employed numerical model PROTEUS-3, predicts capsizing of the C1 vessel at its KG=17.89 during transient stages of flooding when subject to "high" damage case, as used in [1] and shown in Figure 5. A sequence of the simulated flooding propagation through the vessel is depicted in the Figure 15.

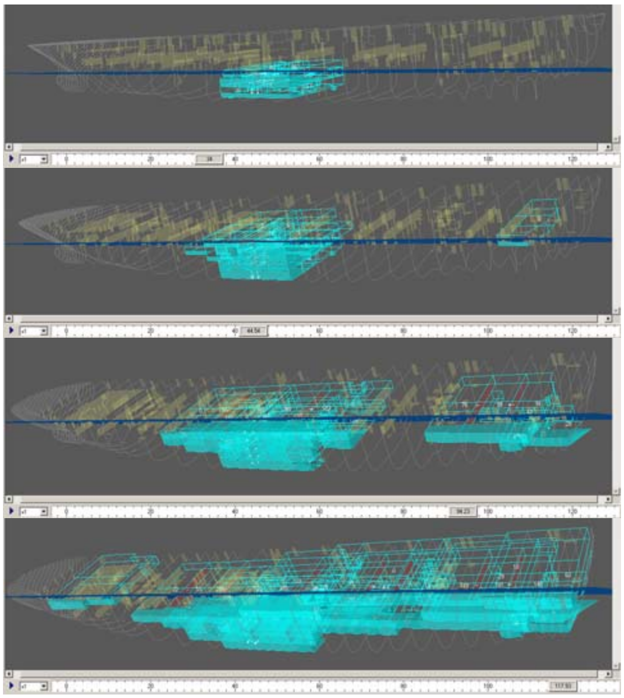


Figure 15 Proteus-3 simulations.

Since the vessel attains large angles of heel, the water reaches upper decks, whether via the main damage opening or other openings, such as doors O250 located aft-port-on deck5, and then spreads instantly through these spaces. Clearly, the amount of accumulated water will depend on the roll angle, and vice versa, the roll angle will depend on the flooding propagation. Perhaps it is because of this complex interrelation that predictions of the ensuing dynamics, whether by numerical

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[3] unfortunately no digital records of responses were derived in these particular experiments

[4] note that the stability of the physical model in this damage is significantly higher than predicted, hence any experimental result is expected to be non-conservative

simulations or by model experiments, is so susceptible to any deviations in the input.

For instance, an ad-hoc variation to the loading of the vessel was made in the numerical input to accommodate somewhat for the inaccuracies of the physical model. Though, no level of confidence that the set conditions are representative of the conditions created during experiment, can be attained at present, some general behavioural characteristics can be observed. In particular, it can be seen that relatively small variation in the stiffness of the ship will prevent the capsizing of the vessel in calm water, as simulated by curve “PROTEUS-3, KG=17.62“ in Figure 12. Furthermore, unlike in Case 2, described in §3.2 above, the numerically predicted flooding rates seem to match, or indeed be slightly lower than those observed during experiments.

Though it is appreciated that precision of the input information and solution technique in either experiment or numerical simulations is of vital importance to derive results reflecting reality accurately, especially in such cases, a very meaningful conclusion can be derived already based on the above exercises.

Namely, it appears that Large Passenger Ships are vulnerable to extremely large angels of heel during transient stages of flooding, potentially leading to instant capsize. The mechanism responsible for this weakness, not addressed at present by regulations, is demonstrated visually in Figure 16 and discussed in the next chapter.

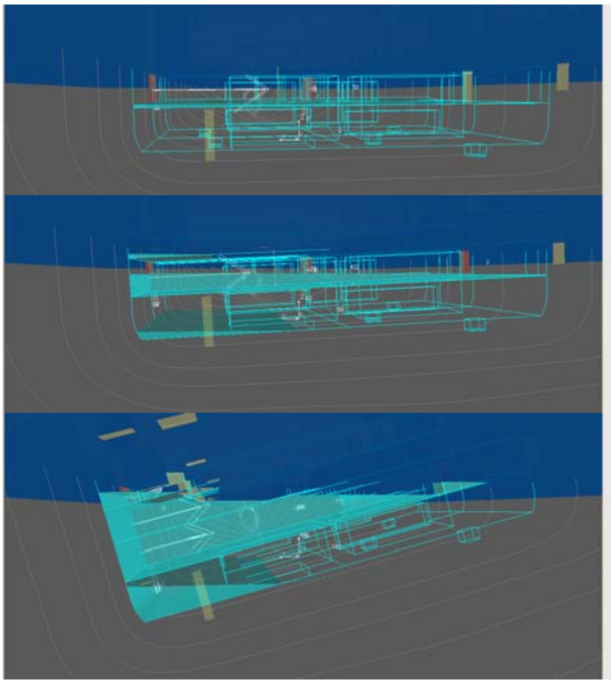

Figure 16 Intermediate stages of flooding to compartments at frame 148, damage p11-13-b5-db, typical process of heeling/capsizing takes some 2-3 minutes from the instant of hull breach.

3.4 Static Stability Characteristics

This chapter discusses a number of observations derived from analyses of stability and survivability of the C1 large passenger ship, carried out in support of the aforementioned studies.

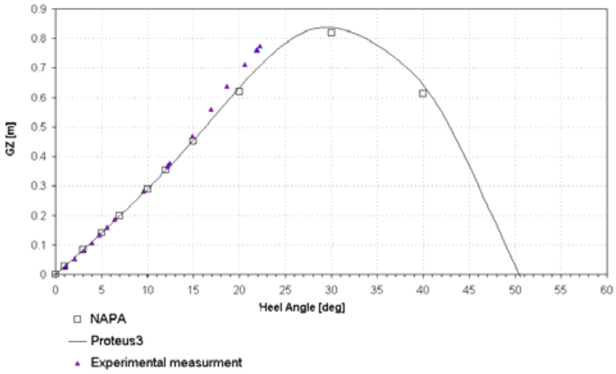

Figure 17 Righting lever for an intact ship, verification of accuracy of physical modelling, comparison between NAPA and Protues3 numerical models, hull defined up to 24.6m.

As can be seen from Figure 17, the accuracy of physical modelling of the vessel’s external geometry appears satisfactory, though some level of discrepancy can be noticed for heel angles exceeding 10 degrees. No plausible explanation has been identified as yet, however, it is clear that this will lead to non-conservative results.

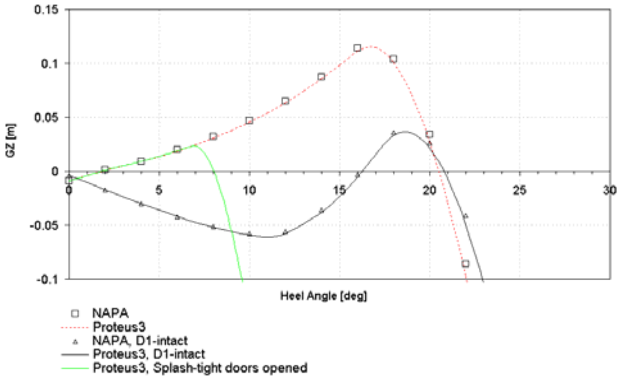

Figure 18 Righting lever for a damaged ship, comparison between NAPA and Protues3 numerical models. Effect of intact compartments on Deck 1.

The next of note is Figure 18 where three basic stability curves are shown. Firstly, static stability curve for damage p11-13-b5-db is shown as derived by PROTEUS-3 (red dashed) and NAPA (squares) codes, for purposes of verification of proper mapping of data between different numerical packages. These curves were derived on the bases of assumption that all the

Splash Tight Doors (STD) on Deck 4 are closed. The second curve (green continuous, Proteus3) pertains to the same damage case, however, derived on the bases of an assumption that all STD are opened. One can see immediately the magnitude of stability that relies on these doors remaining closed in case of damage.

Lastly, GZ curves were derived by both Proteus3 (black continuous) and NAPA (triangles) packages, for a hypothetical case, whereby compartments in the lowest Deck 1 remained intact. The purpose of this curve is to demonstrate substantial difference in the final equilibrium that can be expected if the lower spaces do not flood instantaneously, but rather undergo transient phases of flooding.

This phenomenon of transient flooding is unpredictable by basic static stability unless exact sequence of flooding into the interior of the ship is known a priori, otherwise only various hypothetical scenarios can be analysed, as is exemplified by Figure 19.

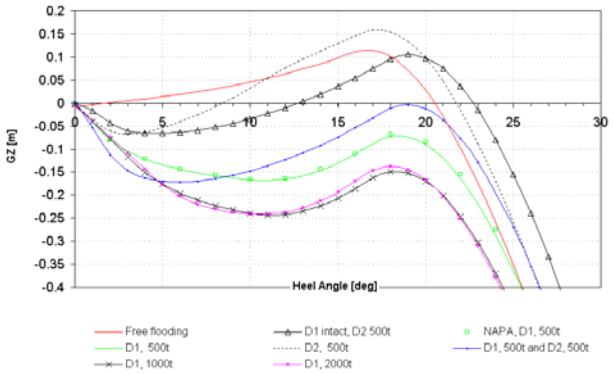

Figure 19 Righting levers for a damaged ship, case p11-13-b5-db. Effects of various stages of transient flooding on Decks 1 and 2.

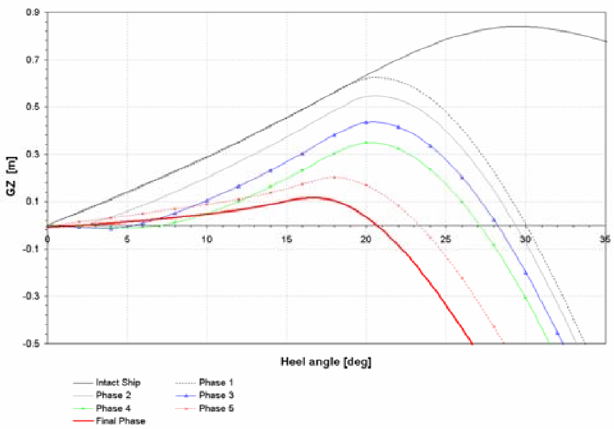

Figure 20 Predictions of GZ curves by NAPA for various transient flooding stages, p11-13-b5-db.

As mentioned earlier on, the survivability is a result of instantaneous interaction between floodwater ingress and vessel's response. Hence, the only viable technique other than model experiments and capable of accounting for this highly dynamic situation is to perform time-domain numerical simulations, where at every instant of time floodwater progression through the ship is assessed, vessel mass properties updated, ensuing dynamics accounted for and its response predicted. Typical static stability will always assume water to reach the lowest floodable compartments immediately, and hence effects of transients are not properly accounted for, see Figure 20 for a sample of typical statically-based predictions demonstrating negligent transient effects in this case, contradicting model experiments or numerical time-domain simulations.

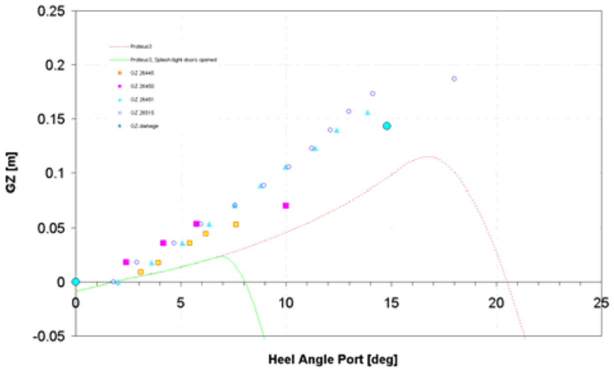

Figure 21 Righting levers for a damaged ship, case p11-13-b5-db, comparisons of measurements with calculations. See also Figure 18.

Last but not least comment offered is that regarding peculiarities of attaining equilibrium attitude.

It is intuitively expected that the final equilibrium state is that predicted by traditional static stability calculations. However, the study cases discussed in this paper, demonstrate time and again, that this attitude can be quite an unlikely condition the vessel will find itself in when damaged. A realistic floodwater progression will be affected by the location and shape of the opening, internal architecture, and vessel dynamic properties, all of which will have an effect on what the final equilibrium condition can be.

A good example of this statement, in addition to discussions offered in the foregoing, is the case of damage p11-13-b5-db where it can be seen that the compartment D3C10-2 on Deck 3, see Figure 22, floods from Deck 4 unless damaged directly, thus leading to different equilibrium (~0deg heel) in calm water than predicted by static stability (~2 deg port heel).

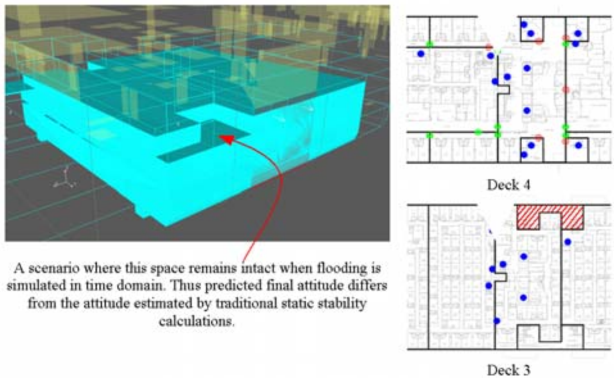

Figure 22 The final equilibrium simulated in time-domain or modelled experimentally, will not always correspond to the statically predicted attitude. The compartment on Deck 3 (marked above-right) floods from the Deck 4 unless damaged directly.

4 CONCLUSIONS

This paper discussed a number of aspects pertaining to assessment of survivability of large passenger ship.

Firstly it is shown that the problem of effects of flooding on the ship motion energy-dissipating rate is reoccurring and needs to be addressed by purposeful experimental studies, for tuning numerical tools. Also, it seems that approximation of the process of water ingress-egress by Bernoulli model must be addressed.

Secondly, it was shown that the transient stages of flooding can have substantial impact on vessel stability, and that current techniques based on GZ curves do not account for this properly. The underlying physical mechanism deriving from effects of multiple free surfaces must be simulated in time domain, as it is a process o instantaneous interaction between dynamics of floodwater and the vessel.

In this respect the study does not concur with conclusions of either [1] or [3], as quoted above.

5 ACKNOWLEDGEMENTS

This research has been funded in part by EUREKA collaborative project SAFENVSHIP, which support is gratefully acknowledged.

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