Time Dependent Survivability against Flooding of Passenger Ships in Collision Damages

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ABSTRACT

The time dependency of the survivability of passenger ships in flooding accidents is shown to be confined within short times after flooding initiation. Both RoRo ferry and cruise type ships demonstrate such behaviour though as vessel types substantially differ with respect to the subdivision and the ship flooding process. The presented research is based on simulations for the probability to capsize and the flooding of ships in collision damages. The systematic fast character of capsize events is shown to be a consequence of large hull breaches. The IMO regulatory concept for *orderly abandonment* for damaged passenger ships, in addition to the *safe return to port* regulatory provisions, are discussed in view of the present results. The timely onboard damage identification and the enhancement of survivability requirements are suggested as rational measures for improved survivability and safety of people onboard passenger ships.

KEYWORDS: *Survivability; flooding; damage stability; time to capsize; passenger ships; orderly abandonment;*

1. TIME FOR ORDERLY ABANDONMENT

The IMO regulatory concept of *safe return to port* for flooding casualties became mandatory for passenger ships (of length 120 m and over) with the resolution *MSC.216(82)*, (2007), through the SOLAS Regulation II-1/8-1: *A passenger ship shall be designed so that specified systems remain operational when the ship is subject to flooding of any single watertight compartment.*

This regulation implements the first part of the guiding approach of IMO to passenger ship's survivability after flooding, according to which ships should be designed for *improved survivability* based on the concept that "*a ship is her own best lifeboat*". Depending on the casualty extent, passengers and crew should be able to either *stay safely on board* while the ship would always be able to proceed back to port at a minimum safe speed or, to *orderly evacuate and abandon* the ship, if this is deemed necessary. The two folds of the above regulatory approach are:

a. Safe return to port
b. Orderly evacuation and abandonment

The goal to enhance the safety of passenger ships was adopted in response to the concerns (of late '90ties) regarding the timely evacuation of the *large passenger ships* in emergency situations and in view of their growing size and the number of people on board, particularly for post panamax cruise ships, which have reached capacities of more than 8,500 people.

Crucial parameters of these developments are the assumed *casualty threshold* namely the damage extent, and the *time frame* namely the time the ship remains viable and operative after damage. As long as the damage extent does not exceed the specified threshold (of one watertight compartment according to the safe return to port provisions) then the passenger ships should survive infinitely and be able to proceed to a port, whereas when the threshold is exceeded (i.e. breach of two or more compartments) and abandonment becomes a possible event then *sufficient time* should be available to allow a safely and orderly evacuation and abandonment.

So far the *3 hours* survivability has been assumed as a *minimum* time criterion for the orderly abandonment, which includes the start time of the initiating event until all persons have abandoned the ship, *MSC 78/26*, (2004). This time duration is also assumed for the safe return to port provisions, *MSC.216(82)*, (2007). Meanwhile the general time requirement for the mustering, evacuation and abandonment is shorter and is set to 60 *min* for passenger ships, or 80 *min* for non-RoRo ships with more than three main vertical zones, *MSC.1/Circ.1238,* (2007).

So the time (either as *time to sink* or *to flood* or *to capsize*, or *survive time* and regardless of the particular differences) has become a crucial variable for the safety of damaged passenger ships and forms a major ship *design objective*, especially for larger passenger ships; namely the compliance of the ship design with the orderly abandonment by ensuring sufficiently slow sinking conditions in case of extended ship flooding.

While the *safe return to port* provisions (*MSC.1/Circ.1369*, 2010) are currently under the development of guidelines for implementation (*SLF 54/17*, 2012), the *orderly abandonment* is still an open challenge for passenger ships and is viewed as a long term objective, requiring further progress in the knowledge about the time-dependent survivability and particularly the relationship of the time with the design characteristics of ships, including the life saving appliances.

Nevertheless from the early days of these developments there were concerns about the usefulness of time to flood analyses (*SLF 48/6/2,* 2005). While in *Spanos and Papanikolaou* (2007, 2012) it was pointed out that orderly abandonment of RoRo/passenger ships was not a workable objective either. Extending this research it is illustrated here that cruise ships demonstrate similar characteristics for the time-dependent survivability in flooding. Thereby the identification of some modified objective proves necessary for properly addressing the safety of passengers in flooding casualties.

2. PROBABILISTIC ANALYSIS

2.1 Probability Simulation

Historical data of ship accidents demonstrate that the time a ship takes to sink may be notably scattered. Though the time scatter is not yet well attributed, this variation mostly depends on the particulars of the incident and the extent of hull breach through which flooding occurs.

For specific accident the expected time variation can be quite limited as then most of the determining parameters are specific too. But when considering the survivability of a ship throughout her life, at the stage of ship design, then a generic random hazard environment that accounts for the *wide* range of probable hull damages should be assumed. This results to a much wider variance for the capsize time (compared to a specific accident). This variance is a characteristic of each damaged ship and is evaluated in this research for two vessels, one RoRo ferry and one cruise ship.

The *time to capsize* for given ship is assumed as a random variable depending on the random environmental conditions during a flooding casualty, the random shape and location of the hull breach, and the ship's loading and local details of the flooded spaces. Its statistical probability distribution (when capsize is a possible event) can be approached with a basic *Monte Carlo* MC simulation. The time to capsize is here sampled from a deterministic time domain simulation for the ship flooding and for a sufficiently large number of damage cases to meet statistical convergence of the results.

With this approach the domain of the possible damage cases is mapped to the sample space of the random variable of the time to capsize. Then the probability distribution can be statistically estimated over the sample space. The two-steps function f for the probability simulation is

$$f : D \xrightarrow{q} \Omega \xrightarrow{p} \Re$$

where	D	Domain of damage cases
	Ω	Sample space of Time to Capsize
	q	Mapping of domain
	p	Probability measure

2.2 Deterministic Flooding Simulation

For specific damage cases the time to capsize is deterministically estimated with a widely established first-principles numerical simulation approach for ship's flooding in the time domain. The ship flooding problem might be formulated at different level of detail, including even high analysis with CFD techniques for the local flow through openings. However such an approach would not be practical for the probabilistic framework here addressed. Alternatively, an efficient formulation for the flooding rates of the flooded compartments can be based on the modified *Bernoulli* equation, an approach which is widely adopted by researchers, by *Spanos and Papanikolaou* (2001) too. Nevertheless this simulation approach is still computationally demanding and results to marginal applicability for the probabilistic analysis, but for the present research purposes the computational efficiency remains of low significance.

In the deterministic simulation the governing process for the ship flooding and any possible progressive flooding of the connected spaces is the water flow through the assumed damage openings. The complex arrangement of the watertight compartments is modelled together with the interconnecting openings. Additional openings on the hull shell are assumed, namely the damage openings, through which the ship flooding occurs.

The floodwater mass inside each compartment is time variable and results from the sum of water flux through all the connected openings. The water flux across each opening is assumed to be described by the *Bernoulli* equation and modified with some linear discharge coefficient c_d which accounts for all deviations from the ideal flow. The elementary flux dq is

$$dq(t) = c_d sign(\Delta H)\sqrt{2g|\Delta H|}dA \qquad (1)$$

where ΔH is the difference of water heads in both sides of the assumed opening and dA the elementary area. Here, plane quadrilateral openings were considered and constant (=0.65) discharge coefficients.

The ship may also change her position due to the weight of the accumulated floodwater inside the rooms. The nonlinear motion of the ship under the action of the floodwater, and the flooding of the compartments were calculated in coupled way over the time domain. For each run, a capsize event was conventionally detected when heel angle exceeded 45 degrees.

3. STUDY CASE PASSENGER SHIPS

Two passenger ships are discussed in the present investigation, one *RoRo ferry* (which corresponds to *MV Estonia*, sunk on 1994) and one medium size *Cruise* ship (a design concept introduced in the FLOODSTAND 2009-12 research project). The *RoRo* complies with former stability requirements (SOLAS'74) and is characterized by a single, undivided car deck of maximum exploitable area. The *cruise* is developed in compliance with the latest regulations (SOLAS'09). The main dimensions of the ships are given in Table 1.

Table 1: Main dimensions of the study case passenger ships.

Dimension	RoRo ferry	Cruise
Lpp (m)	137.4	216.8
B (m)	24.2	32.2
T (m)	5.4	7.2
D_{DECK} (m)	9.1	9.8
Displ. (tn)	12300	35000

As demonstrated in Figure 1 and Figure 2 both vessels have longitudinal subdivision arrangement comprising of fifteen watertight compartments abaft the collision bulkhead. The bulkhead deck is that of the vehicle deck for *RoRo ferry* and that of No 3 (blue line) for the cruise ship.

For the *RoRo ferry* the modelling of superstructures extended up to one deck over the car deck. The car deck space is assumed watertight and the lower compartments are connected to the upper spaces through the central casings located on the car deck. For the modelling of the cruise ship all decks up to No 7 (three decks above the bulkhead deck) were taken into account. Thereby, with the present modelling (of decks) each watertight compartment (as defined with the transverse bulkheads) is further subdivided vertically into rooms which are interconnected with openings that correspond to doors, stairways and lift wells, whereas all the watertight doors on the transverse watertight bulkheads were assumed always closed as appropriate.

The rooms were treated as unrestricted spaces with homogeneous permeability. Inner boundaries (like A-class) were not modelled, though such boundaries might slow down the flooding in function of the strength (in deformation and collapse) of the non-watertight doors and openings on these boundaries, with evident effect in lower depths of floodwater. Since the collision damages are assumed to extend along the full draught the particular impact of inner boundaries on the time to flood should be limited to the later stages of flooding.

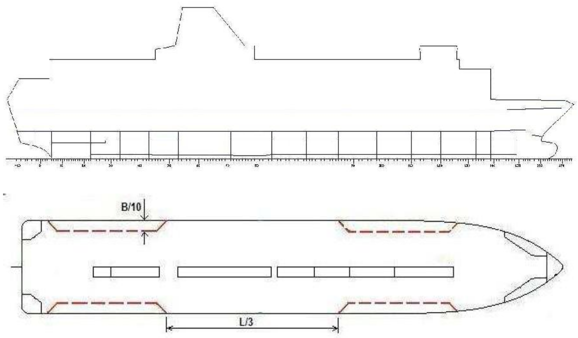

Figure 1: Subdivision layout of RoRo ferry.

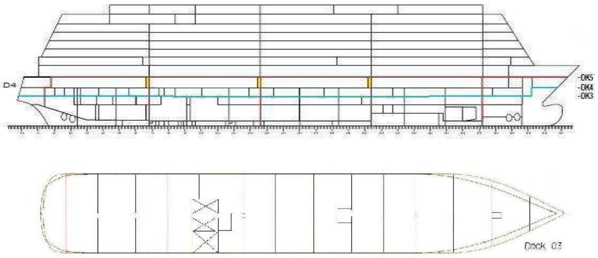

Figure 2: Subdivision of the cruise vessel.

Some basic modifications of the original subdivision layouts were also considered, which were applied above the bulkhead deck and may affect the later stages of the ship flooding too. In this way, four watert1ight side casings were developed on the car deck of the *RoRo ferry* (dashed lines in Figure 1). For the cruise ship, three transverse bulkheads on deck No 5 could extend upwards the main vertical zones by two decks above the original bulkhead deck (double line on deck No 4 of Figure 2).

4. DOMAIN OF COLLISION DAMAGE CASES

Damage cases that result to ship flooding are determined by the assumed damage openings on the hull shell, the ship's loading condition and the sea waves prevailing during ship flooding incidents. All these parameters were assumed as random variables. The assigned probability models for the opening dimensions and the significant wave height correspond to collision damages as updated by the HARDER (2000-2003) research project and which form the background of current SOLAS'09 damage stability regulations.

According to the assumed probability model for the significant wave height in collision damages and for *any* ship type, the significant wave height is distributed up to 4.0 m, while a notable percentage of *40%* of collision accidents regards collisions in *calm water*. If consider also the small wave conditions (i.e. < 1.0 m) the percentage remarkably raises up to 70%.

The probability for the damage length was that of Figure 3, a piecewise linear function, with some probability (8%) for lengths between 0.15-0.30 of the ship length. Distribution regards the *dimensionless* damage length and the *average* damage equals 6.6% of the ship length. SOLAS'09 assumes this distribution too, however truncated for larger lengths above 60 m, which affects ships of length over 200 m. The here considered cruise ship of length 216 m is marginally affected from such truncation.

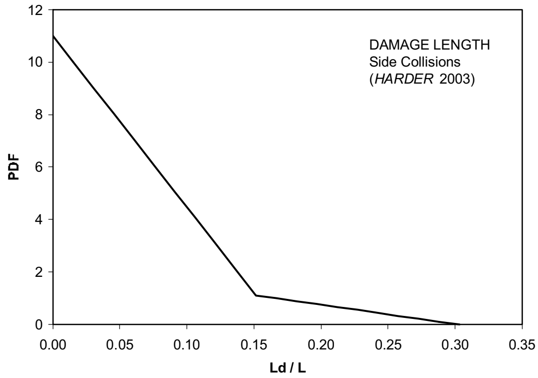

Figure 3: The assumed probability of *damage lengths.*

The probability of ship's displacement (loading conditions) was distributed between three discrete conditions and in line with the SOLAS 2009 regulation, namely 40% for each of the full and the partial draughts and 20% for the light draught condition. The initial stability (metacentric height) for the intact ships was empirically distributed as shown with Figure 4. The range of *GM* may represent some wider operational conditions, besides minimizes the probability of testing for particular conditions.

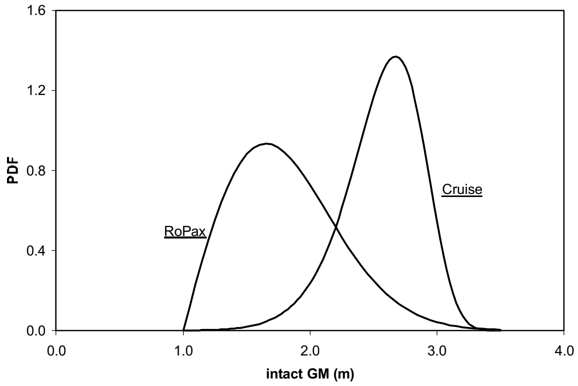

Figure 4: The assumed probabilities for *GM* of the intact ships.

5. PROBABILITY OF TIME TO CAPSIZE

The probability distribution of the time to capsize for the two tested ships and the subdivision modifications was estimated with the probability simulation method and are shown in Figure 5 and Figure 6.

These distributions correspond to ship capsize conditions, whereas for the survive conditions the time is infinite. The probability to capsize within 3 *hours* from the collision incident converges to 4.9±0.5% and 2.4±0.3% for *RoRo ferry* and cruise vessel respectively (were the 10% uncertainty is associated with Monte Carlo simulation).

According to these results, the capsize events for both ships were limited within 15 *min* from the assumed damage incident. Such time is rather short and is notably shorter than the set threshold of 3 *hours*, which is the assumed objective for the orderly abandonment of the passenger ships in case of flooding, and still less than 1 *hour* which is the evacuation requirement.

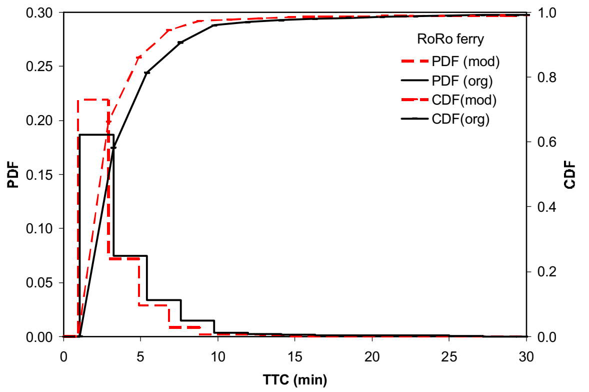

Figure 5: Probability of the *Time to Capsize* for the damaged *RoRo ferry* capsizing in calm water.

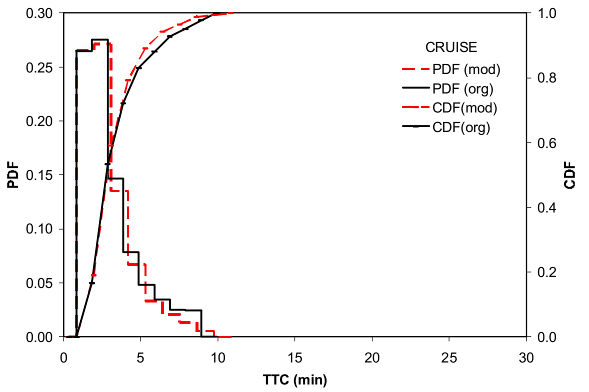

Figure 6: Probability of *Time to Capsize* for the damaged *Cruise* ship capsizing in calm water.

Insignificant effect from the assumed subdivision modifications was recorded too (red dashed lines of Figure 5 and Figure 6). The particular design modifications are mainly effective in later stages of ship flooding, and since here the capsize events occurred in short times this effect was eventually limited.

Capsize events for the *RoRo ferry* occur strictly only when the car deck gets damaged. When the hull breach is limited to below this deck, thus the car deck space remains intact, then this large intact volume contributes with large buoyancy and restoring that the ship capsize is not feasible any more. Note that up-flooding might happen here only through the central casings (Figure 1).

The time to capsize is distributed within ranges of the same width for both ships, though the cruise ship is three times larger than the *RoRo*. This is related to the size of the damage opening, which is proportional to the ship length and then to the flooding rates. For the *RoRo ferry* the actual damage sizes are 36% lower than the damages assumed for the cruise ship. Nevertheless, because the capsize times result short enough, even if equal damage sizes would be assumed for both ships, e.g. those of *RoRo*, then the range of the time to capsize for the cruise ship would result wider however still short and lower than 20 *min*.

The corresponding distribution of the damage length for the capsize events is plotted in Figure 7 and Figure 8, which may well explain the short capsize times as recorded for both ships. There the capsize cases are obviously related to large damage openings only. The average damage length converges to 0.19L and 0.18L for each vessel (while the incident damage length averages to 0.066L, whereas 8% exceeds 0.15L as commented in Figure 3). Such large lengths correspond to multiple damaged watertight compartments, namely three or more. Thereby, ships capsize for the large openings only, and then flooding is trivially fast (large damage areas) and the recorded times are short accordingly.

In earlier investigation, *Spanos and Papanikolaou* (2007, 2012), the fast capsize was shown to be the characteristic behaviour of the damaged *RoRo ferries* in waves too. These ships are vulnerable to the flooding of the car deck which can take place only in the presence of waves exceeding some critical wave height. As long as this critical wave height is exceeded, then the time to capsize rapidly shortens. And then the time-dependent survivability in waves is limited in short times similarly to the present results.

Cruise ships, differently to *RoRo ferries*, usually do not have large undivided spaces near the sea surface, like the car deck of *RoRo*, and the significance of waves for the distribution of the time to capsize is expected to be limited. The flooding process for well subdivided ships follows a sequential flooding of rooms in a cascade mode. The sea waves may not alter the qualitative characteristics of the distribution of Figure 6. This argument is further supported by the low probability of collision in larger waves, as discussed in the previous section for the passenger ships.

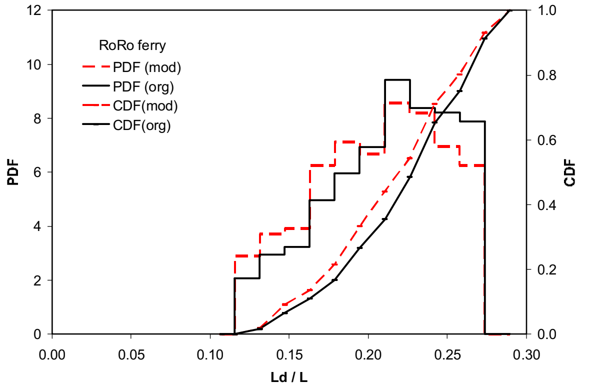

Figure 7: Estimated probability of the *damage length* for *RoRo ferry* capsizing in calm water.

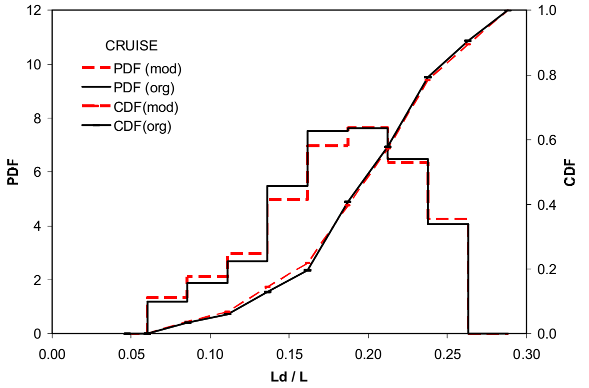

Figure 8: Estimated probability of the *damage length* for *Cruise* ship capsizing in calm water

Capsize in calm water was trivially correlated with zero or very low residual stability, as detailed with Figure 9 and Figure 10. Approximately 80% of cases were fully unstable (zero stability) while for the rest cases the GZ_{max} was low and below 0.10 m. This limit is straightly comparable to the current limit of 0.05 m used by SOLAS 2009 (Ch. II-1, Part A, Reg. 7.2) to define the fully survive capabilities for intermediate stages of flooding. The present results indicate that the current regulation may fail by 10% (i.e. to the probability to exceed 0.05 m). Thus some refinement of the current s-factor would make sense.

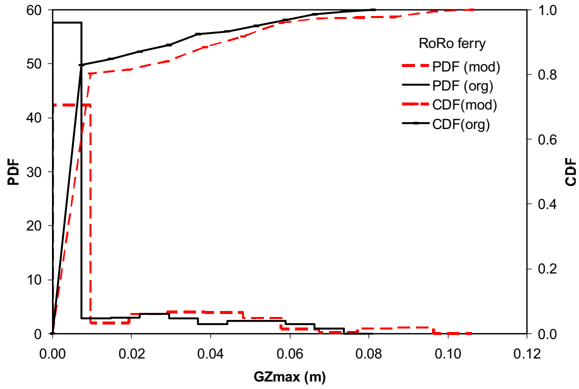

Figure 9: Probability of GZ_{max} for *RoRo ferry* capsizing in calm water.

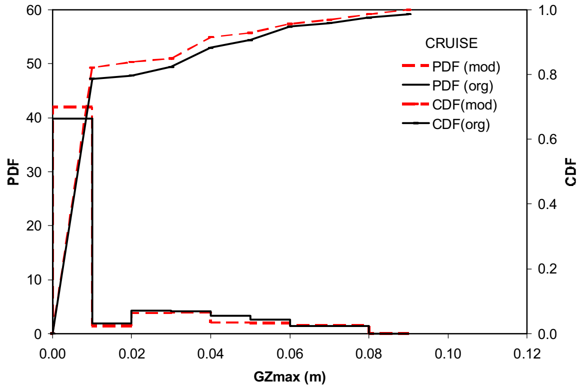

Figure 10: Probability of GZ_{max} for *Cruise* ship capsizing in calm water.

6. DISCUSSION AND FUTURE RESEARCH

The collected results (Figure 5, Figure 6) suggest that when capsize is a likely event for a passenger ship, then the ship should be abandoned as faster as possible. Capsize occurs in remarkably shorter times than it would be needed for an orderly abandonment. The *3 hours* objective or even the *1 hour* requirement for evacuation (*MSC.1/Circ.1238,* 2007) which is closer to the actual evacuation times, are both much longer times than actually required in case of accident. Thus unconditionally, the *orderly abandonment* appears infeasible, while optimistically, it might be only partially accomplished.

The objective for orderly abandonment concerns damages which exceed the current threshold of *one* compartment for the *safe return to port*. The present research points out that loss of passenger ships is fast event and it is connected to three or more compartments damages. While for two compartment damages ships do not capsize and then abandonment is unnecessary in principle.

Therefore, the *timely identification* of the damage case, namely whether it encompasses two or three compartments, proves to be crucial for the onboard safety assessment. The timely identification of survive conditions would allow to keep people on board as much and as long it is assumed safe, instead of ordering the abandonment of the ships and sending people unnecessarily to the sea.

However when considering actual damage incidents then any onboard assessment remains today a challenge, as the onboard and timely identification of actual damage and survivability still suffer by remarkable uncertainty. To the extent this uncertainty can be minimized then the estimated ship's survive time converges to either too long (survive conditions) or short time (capsize conditions). Independently of the identification and assessment capabilities the situation appears practically binary.

The difficulties of the identification are even more stressed if one takes into account that the survivability of the damaged ships is assumed within a probabilistic framework, like the current SOLAS regulations, where deterministic casualty thresholds are not applied (namely full survivability for two or three watertight compartments). And if such deterministic thresholds would be applied then the probabilistic principles and all related advantages would be practically abandoned.

The design of ships with time-dependent survivability and capsize times longer than the present time requirements appears an ineffectual objective. Instead, the *improvement* of survivability might be always reasonably achieved via shifting present safe boundaries to higher levels, namely by enhancing the typical survivability of the damaged ship through increased survivability requirements.

It is noted that the presented research regards side collision damages, and similar analysis should be extended to different damages, like groundings, for completeness and further strengthening of the findings. Nonetheless because of the fact that ships' capsize occurs trivially for large damages, which are connected with large flooding rates, it could be early inferred that capsize due to grounding damages will be accordingly of short time.

7. CONCLUSIONS

The presented investigation explored the general probability distribution of the time to capsize for two passenger ships of different type in collision damages and was concerned with the detection of possible conditions related to slow ship capsize.

The results demonstrated, however, that sinking and capsize of passenger ships occur systematically in *short times* after the damage incident, as a consequence that ship's loss is trivially connected with large sizes of damage. The estimated times are far less than the current regulatory objective for orderly evacuation and abandonment, and make this objective appearing not workable (at least for the subdivision arrangements tested).

The survivability of damaged ships results practically to be time-independent, while measures for improved survivability seem not sufficient to control the capsize time. Thereby the timely *onboard identification* of the actual damages and survivability proves the most important function, and measure, towards an improved safety of people on passenger ships.

Taking into account the current difficulties for reliable onboard damage identification, an alternative and reasonable objective is always to seek for *higher survivability* requirements (subdivision required index) as counter-measure to the risk of fast capsize.

Closing this article it is recalled that the present analysis concerns the collision hazard as it is defined through the damage statistics assumed from the current stability regulations (SOLAS'09). Other hazards, like groundings, should be also investigated to complete the research for the *time* characteristics of the sinking passenger ships due to flooding.

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