Damage Stability and Evacuation Performance Requirements of Passenger Ships

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ABSTRACT

This paper proposes a novel approach to establish rational functional requirements on the evacuation performance of passenger ships, based on a holistic, risk based consideration of relevant accident scenarios. In particular it is demonstrated that damage stability performance in collision and grounding scenarios will be dimensioning for the evacuation requirements although current regulations is dimensioned according to fire scenarios. Damage stability considerations would imply more stringent requirements on the escape arrangements. Hence, a rationale for revising the current evacuation performance regulations, considering damage stability in particular, is established.

Keywords: *Passenger ship safety, damage stability, risk analysis, evacuation analysis, collision and grounding, maritime safety, design for safety, operational and regulatory aspects*

1. INTRODUCTION

Modern passenger ships have the capacity of carrying an increasing number of people and the safety of such large passenger ships is thus an increasingly important issue. In an attempt to improve safety, current IMO regulations for ro-ro passenger ships require that escape routes shall be evaluated by an evacuation analysis early in the design process (IMO, 2002, 2004).

Even though much attention has been paid to the development of sophisticated evacuation models, less effort has been directed towards development of a structured and rational framework for including evacuation analyses in an overall risk assessment. The evacuation scenarios presented in this paper facilitate use of advanced evacuation models within a risk based framework, and the methodology for doing this will be further outlined in this paper. The scenarios are anchored in a basic understanding of the overall risk, and it is realized that damage stability is one of the most critical safety issues when it comes to passenger ships. This paper will present an assessment of the damage stability performance and the evacuation performance of passenger ships. It will then be discussed how these performances are interdependent and how the damage stability performance implies strict requirements on the evacuation performance and vice versa.

2. EVACUATION RISK ASSESSMENT

A study on evacuation from passenger ships has recently been carried out where three main causes were investigated, namely fire, collision and grounding (Vanem & Skjong, 2004a, 2004b). Although current evacuation requirements relate to fire safety, the study concludes that collision and grounding are much more critical, mostly due to the fact that capsizing and sinking might develop quite quickly.

The probability of emergency evacuations and the risk levels were estimated for a typical passenger ship with 3,000 people onboard. The results are reproduced in table 1 and it can be seen that even though evacuations due to fire are more frequent, the overall risk level is completely dominated by the collision scenario. (PLL = Potential Loss of Lives per shipyear).

Table 1. Probabilities and PLL.

Scenario	Evacuations per shipyear	PLL (N = 3,000)
Fire	2.6×10^{-3}	1.4×10^{-2}
Grounding	1.1×10^{-4}	1.5×10^{-1}
Collision	6.9×10^{-4}	1.3
Total	3.4×10^{-3}	1.5

Only in exceptional cases will fire result in sinking, and fire spread will normally be delayed by firewalls between fire zones. People will therefore generally have plenty of time to abandon the ship if this should become necessary. However, the time to escape the particular fire zone where the fire broke out will be critical for those occupying it. In a flooding scenario on the other hand, the time before the ship takes a list that impedes evacuation will be critical, and everyone need to abandon the ship faster than this to be safe. Thus, the damage stability characteristics will imply strict requirements on the evacuation performance.

The graphs in figure 1 illustrate expected available evacuation times for different scenarios, and it clearly indicates that evacuations due to collision and grounding are most time-critical. When evaluating the evacuation performance of a passenger ship therefore it is very important to consider scenarios corresponding to collision and grounding accidents as well as fire.

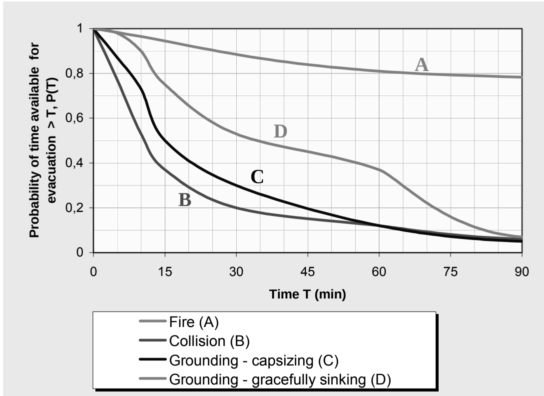

Figure 1 Time available for evacuation

3. EVACUATION PERFORMANCE REGULATIONS

A number of regulations related to evacuation of passenger ships are contained in i.a. the fire protection, detection and extinction part of SOLAS. New requirements that entered into force in 2002 states that an evacuation analysis shall be performed early in the design process for new ro-ro passenger ships that demonstrates that the total evacuation time do not exceed 60 minutes (80 minutes for ships with more than 3 main vertical zones). Such analyses are only mandatory for new ro-ro passenger vessels, but it is encouraged that they are conducted on a voluntary basis also for other types of passenger ships.

3.1 MSC Evacuation Analysis Guidelines

Interim guidelines for evacuation analyses (IMO, 2002), set forth how the total evacuation time should be calculated and also how simulation software should be validated and verified. In addition, passenger demographics and associated response times and walking speeds are specified and four benchmark scenarios are outlined. These scenarios are to be considered as a minimum for the required evacuation analyses.

The MSC benchmark scenarios are described by assigning response times and initial distributions of passengers and crew according to day or night, coupled with a primary or secondary evacuation case. The four scenarios are:

- Primary night case: Night case with full availability of all escape routes
- Primary day case: Day case with full availability of all escape routes
- Secondary night case: Night case with restricted escape route availability
- Secondary day case: Night case with restricted escape route availability

4. EVACUATION REQUIREMENTS IN CRITICAL ACCIDENT SCENARIOS

Studying the graphs in figure 1, it can readily be seen that whereas 80 minutes might seem a reasonable requirement in relation to fire, even 60 minutes is inadequate to account for collision and grounding scenarios. Thus, stricter evacuation performance requirements would result if they were developed with considerations of flooding scenarios and vessel behaviour in damaged condition.

There are fundamentally two types of evacuations, i.e. precautionary evacuations and emergency evacuations. A precautionary evacuation can be initiated in potentially dangerous situations even though there are no immediate threats to the people on board. Time will not be critical in such situations, and a typical scenario will be to first go ashore and abandon ship there. In an emergency evacuation on the other hand, the overall objective will be to evacuate as quickly as possible. Failure to evacuate in time will be fatal and the time spent during evacuation will therefore be of uttermost importance.

Precautionary evacuations are more or less covered by the primary MSC benchmark scenarios. The focus of the current study will hence be to construct novel evacuation scenarios describing emergency evacuations in different situations. The aim is to identify a few generic scenarios that account for a major part of the overall risk. This is assumed achieved by considering two types of accident scenarios, i.e. fire scenarios and scenarios related to flooding events and damage stability.

4.1 Fire and Explosion

Almost 70 % of all passenger ship fires have its origin in the machinery spaces (Vanem & Skjong, 2004a). Most of these will be confined and extinguished within the engine room. Other places where fires are likely to occur are accommodation areas, public spaces, galleys, car decks and laundry rooms. Fires in accommodation areas and public spaces are particularly relevant to evacuation and might have fatal consequences even if they are quickly confined within the fire zone of origin.

The presence of fire may influence evacuation performance in mainly two different ways, not considering psychological effects such as panic, shock or paralysis. First, it might cut off parts of the escape routes, so that alternative routes must be used. Secondly, smoke and poisonous gas produced in the fire might spread through the corridors and hinder evacuees and rescue workers.

In the event of fires in public spaces or accommodation areas, immediate escape from the fire will be very critical; more so than abandonment of the ship. Heat and smoke will be fatal within a few minutes and the time available for safe evacuations will be short. This situation should be accounted for by one evacuation scenario for use in evacuation analyses. Escalating fires that ultimately requires abandonment of the ship is another scenario. The maximum permitted evacuation time for this scenario may be quite long, and considerations of this scenario are not likely to imply additional requirements on evacuation from accommodation room fires. However, it will be relevant for e.g. engine room fires.

4.2 Damage Stability and Flooding Scenarios

Evacuation due to flooding and loss of damage stability are mostly associated with either collision or grounding (Vanem & Skjong, 2004b). Thus, collision and grounding are considered in order to evaluate how flooding scenarios relates to the evacuation performance.

A collision event will cause an emergency evacuation if there is a possibility that the ship will sink. It will generally be the struck ship that sinks since it receives the collision energy to its side, and one can assume that it will develop a list and capsize before it sinks. When the list exceeds a critical angel around 20°, it will no longer be possible to use the lifeboats, and people still remaining on board are likely to perish. Thus, a relevant scenario will be a passenger ship struck by another ship, resulting in flooding of more than two watertight compartments, gradually developing list and finally capsizing and sinking. Estimates of probabilities related to collision of passenger ships as well as estimates of time to sink presented in Vanem and Skjong (2004b) will be used for developing these scenarios.

A grounding event will trigger emergency evacuation if it is believed that the ship might sink. The manner in which the ship sinks will be important, and there are two fundamentally different ways of sinking, i.e. sinking gracefully and capsizing. If the ship sinks gracefully, meaning that it will sink in an upright position, there will generally be more time available for evacuation, and the decks of the ship will remain more or less horizontal. In a capsize scenario, however, the ship will sink much faster, and a list will develop as the ship heals over to one side. This scenario will resemble the collision scenario outlined above.

According to figure 1, adequate evacuation requirements for both flooding scenarios would need to be as strict as 10 – 15 minutes in order to be effective in reducing the risk.

5. DEVELOPMENT OF EVACUATION SCENARIOS

The accident scenarios discussed above cannot be utilized by an evacuation simulator directly; they must first be mapped into well-defined evacuation scenarios. Background information from two main sources will be exploited in order to do this mapping. The first is the recent evacuation risk assessment that was briefly discussed in chapter 2, and the second is the benchmark scenarios set forth in the MSC guidelines as reviewed in chapter 3.1.

In order to define evacuation scenarios, they must be unambiguously described by a set of parameters. These parameters can be grouped into four categories, i.e. geometrical, population, environmental and procedural which will be discussed further in the following. Two of these will be influenced by the accident types that are taken into account, i.e. the geometrical and the environmental parameters. This is illustrated in figure 2.

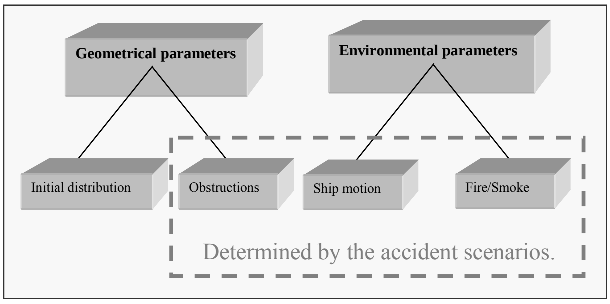

Figure 2 Parameters defining the evacuation scenarios.

The geometrical category includes the layout of escape routes, possible obstruction and partial unavailability and initial passenger and crew distribution. The layout of escape routes is normally the parameter one wants to test by the evacuation analysis, and simulations will be run over various design alternatives in order to identify the best solution. Obstructions and blocking of certain parts of the escape routes can be results of different types of accidents. The quantitative effects this will have on the evacuation performance should be incorporated into the evacuation scenarios. Reasonable initial distribution of passengers and crew will be an important part of the scenarios, and it is assumed that the proposals made by MSC will be appropriate.

The population category contains the different parameters related to the population demographics on board, i.e. parameters such as distribution of age, gender, physical conditions (e.g. disabilities), response time, family or group bindings etc. It will be important to map these parameters into quantitative effects on the evacuation simulations such as walking speed under different conditions etc. These issues have received some attention (e.g. UK, 2004; Yoshida et al., 2001; Gwynne et al., 1999), but for the purpose of this study, it is sufficient to assume a reasonable and realistic description of the population of the ship is available.

The environmental category describes static and dynamic conditions of the ship, e.g. caused by weather and sea or list caused by an accident. Possible presence of fire, smoke and toxic gas should also be included in this category and such effects should be identified for the different accidents and included in the scenario definition.

The last category of parameters is the procedural category. This covers the procedures for the crew members ready to assist in an emergency, as well as procedures for passenger responses. E.g. should they collect lifejackets in their cabins or should they proceed directly to the muster station and receive their life vests there? An evacuation analysis can be utilized to evaluate such procedural parameters. For the purpose of developing scenarios, no specific models for crew procedures are considered.

Only the geometrical and environmental factors are considered further in this paper. Reasonable parameterisation of the effects of selected accidents scenarios on these factors will be derived. This will be coupled with reasonable initial distribution of passengers and crew to define the final evacuation scenarios for use in the simulations. The distribution of passengers and crew as set forth by MSC contains two cases, i.e. day case and night case. Thus, for each evacuation scenario there will be two cases, as illustrated in figure 3.

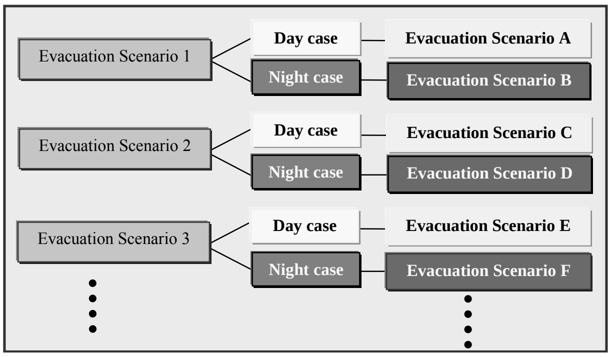

Figure 3 Coupling between scenarios and passenger distributions.

6. PROPOSED EVACUATION SCENARIOS

The following complete set of scenarios is proposed for use in evacuation analyses.

6.1 Precautionary Evacuation Scenarios

A precautionary evacuation would correspond to the primary evacuation cases proposed in the MSC benchmark scenarios. Such evacuation simulations will measure the evacuation performance associated with a proposed design under ideal conditions and cannot be mapped to any specific accident. The simulation results will solely be the time consumed before everyone is successfully evacuated and this time and can be compared to some maximum evacuation time. The outcome of such evacuation simulation will not consist of any number of fatalities and precautionary evacuations will thus not contribute to the estimated risk.

6.2 Emergency Evacuation Scenarios

Part of the scope of this paper is to present evacuation scenarios that correspond to realistic passenger ship accidents. In section 4, three types of accidents were discussed, i.e. fire, collision and grounding, and these can be mapped to evacuation scenarios as summarized in table 2.

Table 2. Evacuation scenarios and associated accident scenarios.

Accident scenario	Evacuation scenario
Fire scenario	Escape from fire zone (public space/accommodation area)
	Escalating fire, abandoning ship (i.a. engine room fires)
Collision scenario	Evacuating from ship that is capsizing/sinking
Grounding scenario	Evacuating from ship that is capsizing/sinking
	Evacuating from ship sinking gracefully

Thus, five generic evacuation scenarios are identified. However, two evacuation scenarios are similar and could be merged into one: Evacuation from a sinking ship that is capsizing and sinking. Each of the four remaining evacuation scenarios is associated with a probability of occurrence, which will be derived in the following (in terms of evacuations per shipyear).

The first evacuation scenario, escaping from a fire zone, is associated with fires starting in a public space or accommodation area. This was investigated by Vanem and Skjong, (2004a), and approximately 20% of the fires were found to start in such areas. The probability associated with this scenario will thus be: $P_{\text{Scenario 1}} = 2.4 \times 10^{-3}$.

The second scenario covers escalating fires that lead to abandonment of the ship at sea. Fires starting anywhere onboard the ship contributes to this scenario, and according to the event trees presented by Vanem and Skjong (2004a), about 15% of the fires escalates and causes an emergency evacuation at sea. This gives the following probability associated with this evacuation scenario: $P_{\text{Scenario 2}} = 1.8 \times 10^{-3}$.

The third evacuation scenario has contributions from two different accident scenarios, i.e. collision and grounding. The probabilities associated with this scenario can be derived from the results presented by Vanem and Skjong (2004b). The contributions from collision and grounding to this evacuation scenario add up to: $P_{\text{Scenario 3}} = 6.7 \times 10^{-4}$.

Table 3. Time to sink probability distribution associated with evacuation scenario 3.

Time (min)	Probability
< 5	0.18
5 – 10	0.19
10 – 15	0.20
15 – 30	0.18
30 – 60	0.13
60 – 90	0.07
> 90	0.05

This scenario is really a composite of various scenarios with different times to sink. How rapidly the ship will sink is determined by the received damage extent and is associated with a probability distribution. The distribution presented by Vanem and Skjong (2004b) are utilized in order to find a probability distribution for the time to sink for use in this study. This is presented in table 3.

The fourth and last evacuation scenario corresponds to evacuation from a ship that sinks gracefully. This scenario corresponds to a grounding incident and is associated the following probability: $P_{\text{Scenario 4}} = 5.8 \times 10^{-5}$. A probability distribution for the time to sink in this scenario is presented in table 4 (based on results by Vanem and Skjong, 2004b).

Accidents can occur either at daytime or night time. Assuming the probability of an accident is uniformly distributed over the hours, probability factors of ⅔ (day case) and ⅓ (night case) can be used. Table 5 contains the final probabilities (per shipyear) associated with the proposed evacuation scenarios. A total of eight evacuation scenarios, in addition to the precautionary evacuation scenario, are thus proposed for use in evacuation simulations. These will be described further by defining the four main evacuation scenarios.

Table 4. Time to sink probability distribution associated with evacuation scenario 4.

Time (min)	Probability
< 5	0.02
5 – 10	0.08
10 – 15	0.15
15 – 30	0.22
30 – 60	0.16
60 – 90	0.30
> 90	0.07

Table 5. Complete set of generic evacuation scenarios.

Main evacuation scenario	Case	Resulting evacuation scenario	Probability
Escaping from a fire zone	Day	Escaping from a fire zone at daytime	1.6 x 10-3
	Night	Escaping from a fire zone at night	8.0 x 10-4
Abandoning ship on fire	Day	Abandoning ship on fire at daytime	1.2 x 10-3
	Night	Abandoning ship on fire at night	6.0 x 10-4
Evacuating from ship capsizing and sinking	Day	Evacuation, capsizing and sinking at daytime	4.5 x 10-4
	Night	Evacuation, capsizing and sinking at night	2.2 x 10-4
Evacuation from ship sinking gracefully	Day	Evacuation, ship sinking gracefully at daytime	3.9 x 10-5
	Night	Evacuation, ship sinking gracefully at night	1.9 x 10-5
Precautionary evacuation	Day	Precautionary evacuation at daytime	N/A
	Night	Precautionary evacuation at night	

7. DESCRIPTION OF MAIN EVACUATION SCENARIOS

7.1 Scenario 1 – Escape from Fire Zone

This evacuation scenario considers only one fire zone at a time. The simulations should be run separately for each fire zone containing passenger accommodation areas or public spaces. The simulation will start with the mustering alarm and end when the evacuees exit the fire zone. The required input for this scenario is an overview of total ship layout, detailed layout of relevant fire zones, reasonable starting points of fire for each fire zone and initial distribution of passengers and crew. The expected output is, for each fire zone, the average, maximum, and minimum evacuation time and the number of fatalities.

7.2 Scenario 2 – Evacuating Ship on Fire

Simulations based on this evacuation scenario consider the entire vessel's layout and model a complete evacuation process until everyone has either safely abandoned the ship or perished. Each simulation run will result in a set of evacuation times for the passengers as well as number of fatalities, and one will obtain mean values of the average, maximum and minimum evacuation times as well as number of fatalities from a set of simulations. The time available for evacuation is expected to be quite long in this scenario and fatalities are expected to occur due to exposure to smoke and heat.

7.3 Scenario 3 – Capsizing/Sinking Ship

The third scenario describes a ship gradually listing until it capsizes and sinks. For simplicity, it can be assumed that the list is increasing constantly with time. Each time to sink is associated with a probability (table 3) and it is assumed that using a relatively slow sinking will be appropriate within this context, e.g. a cut-off time of around 60 minutes can be assumed. The consequences can be found from investigating how many people were not safely evacuated by the different times to sink.

The entire vessel layout must be available for this scenario and the initial distribution of passengers and crew must be specified. In addition, the direction of list should be defined, e.g. to port or starboard, and the maximum angle of list that still renders evacuation possible should be entered. 20º can be used as a default value as this corresponds to the requirements for launching of survival craft (IMO, 2004).

The fatalities in this scenario will be the ones not successfully evacuated by the time the ship sinks. The output from the simulations should therefore be number of people successfully evacuated as a function of the evacuation time. Coupled with the probabilities of different time to sink in table 3, the risk associated with this scenario can be estimated.

7.4 Scenario 4 – Gracefully Sinking Ship

This evacuation scenario will resemble main scenario 3 apart from not developing list. Prior to running the simulations, the layout of the vessel and the initial distribution of passengers must be known. The simulations should result in a distribution describing how many people have successfully been evacuated as a function time. This can be coupled with the probabilities of sinking within a certain time presented in table 4 to estimate the total risk associated with this scenario.

8. RISK BASED APPLICATION OF EVACUATION SCENARIOS

The total risk associated with different types of evacuations for a particular ship can be found from the simulation results. Thus, the evacuation scenarios can be utilized in a structured way in order to estimate the overall risk associated with a particular passenger ship.

The first two main scenarios consider fires and simulations will provide estimates of the expected number of lives lost in typical fires. These fatality rates can be multiplied with the probabilities associated with the scenarios to estimate the risk contribution in terms of fatalities per year for that particular ship.

Contributions to the risk from the third and fourth main scenarios will be people trapped inside the ship, i.e. people not able to evacuate in time. The expected number of fatalities can be calculated from the simulation output and the time to sink probabilities given in tables 3 and 4. An example of this has been provided in Vanem & Skjong (2006). However, the time to sink distributions in tables 3 and 4 are generic estimates and these should be replaced with the actual survival capability and time to sink characteristics of the particular ship design subject to the evacuation analysis.

When the risks for all scenarios have been successfully calculated, the total risk associated with the design alternative will be:

$$Risk = \sum_{\substack{i=Day,Night \\ j=1-4}} Risk_{i,Scenario\_j} \tag{1}$$

This risk estimate is directly linked to the input of the evacuation analyses and the main contributors to the overall risk can easily be identified.

8.1 Evacuation Analyses and Safety Regulations

When the design of a new ship is to be examined, it is suggested that evacuation simulations are carried out in two steps. First, the precautionary evacuation scenarios can be used to reveal potential bottlenecks along the escape routes and estimate the maximum time consumed by the evacuation process. This can be compared to prevailing requirements regarding maximum permitted evacuation time. This step is equivalent to present safety regulations, where approval of the design will be granted if these requirements are met, although stricter requirements is suggested in order to account for flooding scenarios.

The next step would be a more comprehensive study of the overall risk associated with evacuation of the ship. For this, the complete set of eight evacuation scenarios as proposed in this paper should be used. Different design options will give different overall risks and the alternatives associated with the lowest risk can easily be identified.

In a truly risk-based regulatory regime, approval based on a fundamental understanding of the overall risk level is suggested. In such a regime, it would not be sufficient to meet certain performance criteria, e.g. on damage stability, without knowing the impact this has on the total risk. It would be more important to meet fundamental risk criteria. In order to facilitate such a risk-based regulatory regime, there is a need for an unambiguous way to link performance criteria to the overall risk, such as the proposed set of evacuation scenarios.

Hence, approval can be based on the following requirements, where the risk is calculated from equation (1) and appropriate probabilistic risk acceptance criteria are established based on a sound rationale (Norway, 2000, Skjong & Vanem, 2004):

$$\text{Risk} \leq \text{Risk criteria} \tag{2}$$

With this approach, the risk based criteria will dictate restrictions on the acceptable safety performance of the system as a whole, and thereby also on its different parts. For instance, if it is found that damage stability issues are critical, and that the risk criteria cannot be met by improving the evacuation performance alone, the criteria will imply improvements on the damage stability characteristics.

8.2 Damage Stability and Evacuation Performance Requirements

The recently performed risk assessment on evacuation from passenger ships identified collision and grounding scenarios as the main contributors to the overall risk. Both these scenarios are related to damage stability of passenger ships. The main reason that damage stability turned out to be so crucial, is that there is a mismatch between the current evacuation performance requirements and the general characteristics of a typical flooding scenario. Whereas evacuation requirements are based on the assumptions that 60 minutes will be available for evacuation, much less time are expected to be available in a flooding scenario.

In order to remedy this situation, two obvious routes of action exist. The first will be to improve the evacuation performance so that the fatality rate in flooding scenarios will decrease considerably. The required maximum evacuation time will depend on the damage stability characteristics of the ship, but would typically need to be in the order of 10 – 15 minutes in order to be effective in flooding scenarios. The other alternative is to improve damage stability so that current requirements on evacuation performance will be sufficient to keep the fatality rate low. Especially, passenger ships should be designed to facilitate graceful sinking and extended time to sink.

In both cases, it will be important to take a holistic view on all safety issues and in particular to consider the interdependence of evacuation and damage stability requirements. The proposed methodology and the set of evacuation scenarios will be an important component in any safety study of passenger ships. E.g., the approach could easily be incorporated into the study on collision damage stability presented by Vanem et al (2006).

9. CONCLUSIONS

Based on the benchmark scenarios described in MSC/Circ. 1033 and a recent risk assessment of passenger ships, this paper proposes a novel set of evacuation scenarios to be used in evacuation simulations. The development of the scenarios has been presented as well as the coupling between the evacuation scenarios and critical accident scenarios. The link between the evacuation scenarios and the overall risk level associated with the ship has also been explored. In particular, damage stability in collision and grounding incidents has been identified as dimensioning for evacuation performance requirements and it is indicated that prevailing evacuation requirements are too lenient.

Finally, possible future developments of the maritime safety regulations have been discussed, i.e. it has been demonstrated how the proposed set of scenarios will facilitate the emergence of truly risk based, probabilistic safety regulations.

10. ACKNOWLEDGMENTS

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