Holistic and Risk Based Approach to Collision Damage Stability of Passenger Ships

Rolf Skjong, *DNV Research*

Erik Vanem, *DNV Research, Det Norske Veritas*

Sigmund Rusås, *DNV Maritime Technology and Production Centre*

Odd Olufsen, *DNV Maritime Technology and Production Centre*

ABSTRACT

This paper presents a risk based approach for viewing damage stability of passenger ships in a holistic way. It is recommended that such an approach is adopted in the design of new ships in order to control the risk associated with collision scenarios. In addition, the methodology presented can be applied on segments of the existing fleet of passenger ships in order to gain a better understanding of the risk. Within a risk based framework, the methodology can be utilized in order to establish reasonable performance criteria for damage stability in a consistent and rational way.

Keywords: *Damage stability, passenger ship safety, risk analysis, collision, maritime safety, design for safety, risk based design*

1. INTRODUCTION AND BACKGROUND

At the MSC 80, amendments to SOLAS Chapter II-1 were adopted by resolution 194(80) (MSC, 2005), replacing the existing text of parts A, B and B-1 regarding subdivision and stability. The new harmonized regulations for damage stability are probabilistic, requiring A ≥ R; the attained subdivision index A, should not be less than a required index R, calculated according to the new regulations. However, it is not immediately clear exactly how this index influence the overall risk level of the ship. This relationship is believed to be particularly important for passenger ships. Thus, this paper presents a holistic approach for linking the overall risk associated with passenger ships to the methods applied when calculating the attained subdivision index, A.

The paper introduces an overall risk model comprising of five sub-models, i.e. a collision frequency model, a flooding frequency model, a survivability model, a time to sink model and an evacuation model. All of these sub-models will be described in greater detail, with different techniques and calculation methods proposed as the best approach within each. Furthermore, it will be explained how the various sub-models can be combined in order to provide for an understanding of the overall risk associated with collision.

The proposed approach can be used to assess the risk levels associated with passenger ships. In addition, it can be used to evaluate directly the effect of improvements in damage stability on the risk level. It is believed that such an approach would be crucial in a future risk based regulatory regime.

2. OVERALL RISK MODEL

The overall risk model for collision damage stability of passenger ships can be illustrated as in Figure 1, where the different sub-models will determine the various probabilities that influence the total risk. The last element in this model, i.e. the evacuation model, will determine the expected consequences for different scenarios corresponding to different times to sink. The model is similar to overall risk models used in previous studies, e.g. in Rusås and Skjong (2004) and in Olufsen et al. (2003).

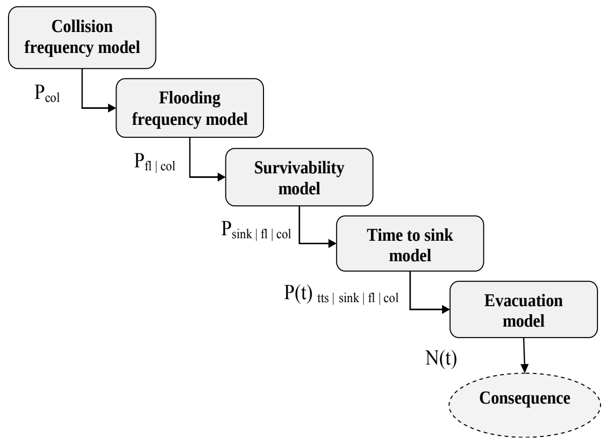

Figure 1 Overview of the collision damage stability risk model.

The risk related to collision damage stability according to this risk model can be expressed as follows: Risk = $P_{collision} \times P_{flooding} \times P_{sink} \times \sum_t \{P(t)_{time\ to\ sink} \times N(t)\}$.

2.1 Collision and Flooding Frequency Sub-models

For the collision frequency and the flooding frequency sub-models, it is believed that reasonable estimates can be obtained from accident statistics. For the purpose of this study, estimates from a previous FSA on generic cruise ships, embracing data from the period 1990 – 2003, can be utilized (Kjellstrøm & Johansen, 2004). However, the estimates are slightly adjusted in order to account for recent improvements in navigational safety, e.g. some of the risk control options outlined in Norway (2005) have been implemented during the last fifteen years. The following estimates are then arrived at:

- $P_{collision} \approx 3.0 \times 10^{-2}$ per ship year
- $P_{water\ ingress\ given\ collision} \approx 6.5 \times 10^{-2}$

These numbers are somewhat different from what was used by Vanem & Skjong (2004), but their product, although a little lower, is within the same order of magnitude. This is reasonable in light of the adjustments made due to recent improvements in navigational safety.

Survivability Sub-model

An estimate of the conditional probability of sinking can be obtained from the probabilistic method for calculating damage stability as set forth by MSC 194(80). This method is based on the principle of employing an attained subdivision index A, i.e.:

$$A = \sum (p \times v \times s) \qquad (1)$$

The attained subdivision index, A, reflects the ship's ability to survive a collision damage that leads to flooding and is calculated from three probability distributions *p*, *v* and *s*. *p* reflects the probability for location, length and penetration of the damage, *v* represents the probability distribution for the vertical extent of the damage and *s* represents the probability of the ship to survive the given damage.

Through the process within IMO it is assumed that the factors *p* and *v* represent a robust model for the probability of the size and location of the damage. However, the *s*-factor cannot be used directly in a risk model. This is because it contains some design parameters that could give *s* = 0 even though the ship would remain afloat, when calculated in accordance with MSC 194(80). On the other hand, the studies carried out showed that a parameter such as the distance from the equilibrium waterplane to any unprotected openings, such as stair cases and corridors is a crucial parameter which should be included.

Hence, although not entirely accurate, the conditional probability of sinking is given by the complement probability of the attained subdivision index A:

$$P\ sink = 1 - A \quad (2)$$

The attained index A should in this context be calculated based on the *s*-values reflecting the maximum angle of heel that renders evacuation still possible, the characteristics of the GZ-curve and the distance to unprotected openings (corridors, staircases, etc.).

2.2 Time to Sink Sub-model

The risk level of a passenger ship will be closely related to the time to sink and to whether it capsizes or sinks. The time to sink or capsize will result from different damage cases. This will again result in different fatality rates. The time to sink sub-model is therefore a very important component of the overall risk model. The desired output from such a time to sink sub-model will be a probability distribution of different time to sink for all damage cases the ship *does not survive*. It should be noted that time to sink in this context should mean the minimum of time to sink, time to capsize or time to reach a degree of heel that renders further evacuation futile.

Van ‘t Veer et al. (2004) present time-to-flood simulations of a passenger ship in different sea states for one particular damage case. According to their simulations, the time to reach the flooding criteria decreased from more than 10 hours in sea state with significant wave height H_s = 5.5 m to 38 minutes in sea states with H_s = 9.5 m. The damage case used in this study was 8.0 meters in length, 9.5 meters in vertical extent and B/5 deep. This is a damage the ship is expected to survive, and thus not the most interesting damage case to study for the purpose of a risk analysis. Valanto (2002) reports another set of computations for two-compartment damages. Time to flood simulations for a four compartment damage was reported in US (2003) where the flooding criteria were reached within a few minutes.

The studies referred to above use advanced computer programs to simulate the time to sink. Utilization of such programs would be the preferred solution for the time to sink sub-model, but the damage cases that would be most interesting would be those the ship does not survive. An estimated time to sink should be calculated for selected damage case that the ship might not survive, i.e. where $s < 1$. These damages could then be grouped into generic damage categories, corresponding to two-compartment damages, three-compartment damages and four or more-compartment damages. For each of these categories, a probability distribution function P(t) can then be extracted for the time to sink estimates for use in the overall risk model.

Without sophisticated time to sink software, a simplified, static approach can be adopted. For the purpose of this exercise, a simple macro was developed in NAPA[1] in order to determine how and at what time the ship will sink for damage cases where s < 1. The leakage pressures and collapse pressure height for the different types of openings were derived from studies presented in Finland (2004). Dynamic effects are not directly calculated, but a factor describing the relative motion due to waves has been included. An example showing the typical envelope from the time simulations of a damaged case is presented in figure 2. This example has been calculated with reasonable good initial figures for the GZ-height and the range of the GZ-curve. A relative motion of 0.5 m, corresponding to a wave height of 1 m has been used.

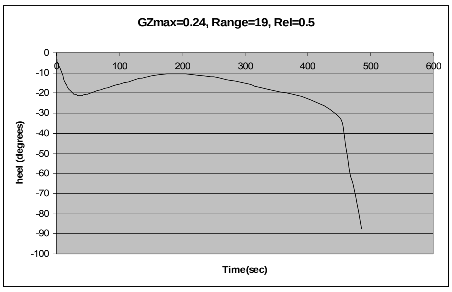

Figure 2 Typical envelope from the time simulations of a damage case.

[1] The Naval Architecture Package, a CAE-system for ship design. http://www.napa.fi/Napa.htm

The outlined approach was used on a generic passenger ship of two-compartment standard to arrive at the probability distribution for time to sink presented in table 1. As can be seen, the results obtained from this approach indicate that the ship is not likely to survive for more than 30 minutes regardless of damage category (only cases it does not survive were investigated).

Table 1. Time to sink probability distribution.

Time to sink (min)	**Probability distributions**		
	2 comp. damages	*3 comp. damages*	*≥ 4 comp. damages*
< 5	0.16	0.73	0.88
5 – 10	0.24	0.17	0.05
10 – 30	0.60	0.10	0.06
30 – 60	0	0	0
> 60	0	0	0

2.3 Evacuation Sub-model

There are a number of software packages commercially available that can simulate the evacuation process on a ship in great detail. Some of these have included the effects of ship heel and trim. However, it is recognized that such software can not support evacuation scenarios where the ship heels suddenly to a very large angle. Because of this, expert judgement was deemed the best way of obtaining fatality rate estimates for different times to sink, and this was elicited in a Delphi session with a group of experts.

The outcome of the evacuation model will be connected to the time to sink model, and this was reflected in a questionnaire where fatality rates were estimated for a number of different time to sink cases. A scenario following the collision where this ship will sink in two steps was assumed: a) the ship inclines to one side and reaches a large angel of heel in a rather short time and b) it stays afloat in this position of heel until it sinks after a time T.

The fatality rate would also be expected to depend on various environmental factors such as sea and weather condition, time of day, water temperature and geographical location of accident. It was hence distinguished between two separate cases:

- Case A: friendly summer-like environment
    - Temperate waters, calm seas
- Case B: harsh winter-like environment
    - Cold waters, rough seas

The majority of cruise vessels operate in areas associated with environments resembling case A, and an 80/20 weighed combination of the two cases was assumed as an overall average. The results from the Delphi session are reproduced in table 2 below (the average of the experts' estimates after two iterations).

Table 2. Expert judgement on evacuation.

Time to sink (min)	**Case A**	**Case B**	**Overall fatality rate**
T = 10	0.81	0.95	0.84
T = 15	0.77	0.93	0.80
T = 20	0.68	0.88	0.72
T = 25	0.56	0.80	0.61
T = 35	0.47	0.66	0.51
T = 65	0.38	0.53	0.41
T = 95	0.32	0.44	0.34
T > 95	0.28	0.40	0.30

For the purpose of the current study, it is adequate to consider average fatality rates for the time intervals in table 1, as given in table 3.

Table 3. Fatality rates used in the overall risk model.

TTS (min)	**Average expected fatality rate**
< 5	0.92
5 – 10	0.82
10 – 30	0.65
30 – 60	0.45
> 60	0.35

3. RISK ACCEPTANCE CRITERIA

When the approach outlined above has been performed on a particular ship, the achieved risk level should be compared to established risk acceptance criteria in order to assess whether the design corresponds to an acceptable risk level. Currently, no commonly agreed set of risk acceptance criteria are established, but a methodology for doing this is set forth by Norway (2000) that can be regarded as state of the art. Adopting this approach, the risk acceptance criteria in figure 3 can be derived for passenger ships based on the following assumptions:

- Passenger ship with 2,500 passengers
- Average revenue of USD 190 – 230 per passenger day
- Occupancy rate of 100%
- 273 days of operation per year
- New-building cost of approximately USD 190,000 per passenger berth
- Economic lifetime of the ship of 30 years
- Interest rate of 10% (quite high)

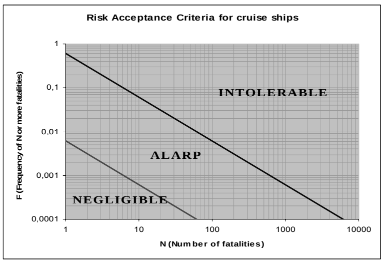

Figure 3 Risk acceptance criteria for cruise ships.

4. VALIDATION AND EVALUATION OF THE APPROACH

The methodology for assessing collision risk for passenger ships as outlined above use different techniques for the various elements within the overall risk model. Some of the techniques are based on assumptions and are undeniably somewhat subjective and uncertain. Thus, an evaluation and an attempt to validate the various sub-models would be appropriate. In the following, such an evaluation of the approach will be presented.

4.1 Collision and Flooding Frequencies

The first two sub-models, the collision and flooding frequency estimates, are based on accident statistics investigated in a previous FSA study on cruise ships. Entries in the LRFP[2] database from 1990 to 2003 were examined to establish the actual collision frequencies in this period. The basis for the statistics was an exposure of nearly 3,500 ship years and this is assumed sufficient in order to arrive at reasonable robust estimates.

The historic collision frequency was also adjusted down by 16% in order to reflect recent improvements in navigational safety since 1990 (e.g. due to implementation of some of the RCOs proposed by Norway (2005)). The navigational developments that were considered are presented in table 4 together with the associated adjustment to the collision frequency. This is believed to result in estimates that better represent the collision frequency of the current fleet. At any rate, historic accident data are deemed the most reliable source of information to estimate collision and flooding frequencies and it is not believed that this needs any further validation.

Table 4. Adjustments made to the collision frequency due to navigational developments.

Developments	Adjustment
Two officers on the bridge	5 %
AIS integration with radar	3 %
Improved bridge design	5 %
Improved navigator training	2 %
BRM guidelines	2 %
Total cumulative adjustment	16 %

4.2 Validity of Survivability Estimates

Although commonly regarded as being the most reliable method for estimating the damage stability of a vessel, the attained subdivision index as calculated by the method adopted by IMO in MSC 194(80) is not necessarily identical to the actual survivability of a ship. In addition, the method cannot easily be used in

[2] Lloyd’s Register Fairplay is commonly regarded as the most extensive maritime accident database in the world.

an overall risk model because no considerations of the time to sink are included.

Hence, a somewhat modified approach was used in this study. The *p*-factors from the IMO proposals where kept, but the *s*-factors were calculated in a slightly different way. Some of the design factors that would give $s = 0$ even if the ship survives were removed, and the *s*-factors were calculated based on the GZ height and range parameters.

The *p*-factors adopted by IMO were based on analysing an extensive set of data and were subject to serious discussions and thorough review before they were finally decided. They should therefore be regarded as robust. However, when it comes to large ships in particular, it is noted that there were very few data points, and the uncertainty is therefore higher for large ships. Nevertheless, the *p*-factors are believed to constitute the best available estimates and it is argued that the approach does not need any further validation.

4.3 Time to Sink from Actual Accident Experience

The time to sink estimates were obtained using a simplified approach, and it may thus be suspected that the results contain uncertainties. Therefore, the results will be compared to historic accident experience in order to see whether there are strong disagreements. It is noted that according to the time to sink estimates in table 1, the maximum time was found to be 30 minutes. This was conditioned on a collision damage case the ship did not survive.

Information on time to sink due to collision is available for three cruise ships with which comparison is reasonable. These are presented in table 5.

Table 5. Historic cruise ship collisions.

Ship name	Year	TTS (min)	Fatality rate
Admiral Nakhimov	1986	8	0.34
Jupiter	1988	40	0.007
Royal Pacific	1992	15	0.017

Although three accidents are not sufficient statistics to draw any conclusions, the available material suggests that the estimates, which indicated maximum 30 minutes, might be somewhat conservative. However, the estimates represent the minimum value of time to sink, time to capsize and time to reach a certain degree of heel and this does not necessarily conflict with the Jupiter scenario. Indeed, in Hooke (1997) it was reported that there were no time for Jupiter to lower the lifeboats as the ship quickly listed heavily and began to sink. Therefore, no immediate disagreement between the estimates and historic experience can be identified. At any rate, the available statistics is too sparse to either validate or invalidate the time to sink estimates.

Even though there are uncertainties related to the time to sink estimates, it is realized that the overall risk estimates would not be very sensitive to variations in the individual time to sink calculations for each damage case. E.g. adopting an uncertainty factor of 2 would correspond to an uncertainty of less than 1% in the overall risk. This is explained by the very rapid sinking for most cases with $s = 0$. Even a doubling of the time to sink will not reduce the number of fatalities considerably in these cases. This does not mean that the time to sink is not critical, but improvements beyond a factor of two would be needed in order to significantly reduce the expected fatality rate associated with the most rapid sinking scenarios.

4.4 Validating Evacuation Model Against Accident Experience

The problem of assessing the ratio of

successfully evacuated persons for different time to sink is a difficult one and it is believed that the Delphi technique is a good alternative to address this. However, it is commonly recognized that experts are never entirely objective and that certain biases may be introduced (Skjong and Wentworth, 2001). In order to evaluate the results based on the experts' judgement, they are evaluated against actual accident experience.

Table 5 contains information about three collision accidents that resulted in sinking of a cruise vessel. Additional information is available for incidents involving ro-ro passenger vessels, and four of these are presented in table 6. It should be noted that none of these are collision accidents, but all vessels capsized and sank within a short time. The scenarios are therefore believed to be relevant when it comes to evacuation. In figure 4, the fatality rate estimates from the evacuation model is plotted as a function of time to sink for the summertime and wintertime case as well as the weighed overall average. These graphs are then compared to the experience from the actual sinking accidents presented in table 5 and 6.

Table 6. Actual RoPax sinking accidents.

Ship name	Year	TTS (min)	Fatality rate
Heraklion	1966	10	0.82
Dona Josephina	1986	15	0.48
Salem Express	1991	20	0.71
Estonia	1994	20	0.87

Compared to the three cruise ship accidents, figure 4 seem to suggest that the evacuation model is conservative. On the other hand, the experience from MV Estonia suggests that the results are optimistic. The experience from the three remaining ro-ro passenger vessels corresponds well with the estimates from the evacuation model. It is realized that all major accidents are unique and have its own peculiar set of characteristics and it is not possible to identify any representative evacuation scenario from such a small number of accidents. However, acknowledging a notable degree of uncertainty, it can be argued that the overall results from the evacuation model are in general agreement with historic experience.

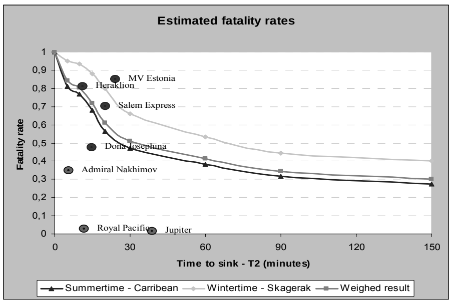

Figure 4 Comparing evacuation model with accident experience.

Recently, the tragic sinking of the al-Salam Boccaccio '98 off Egypt resulted in a fatality rate of 0.73, but since reliable information of time to sink is not yet available for this accident, it has not been included in the study.

Another approach to validate the evacuation model could be to create a complete model of a sample ship within an evacuation simulation package and simulate the time to evacuate under various conditions, e.g. along the lines described in Vanem and Skjong (2006a, c). However, it is doubtful that current evacuation software are able to accurately support accident scenarios involving very large angels of heel, and the value of such an exercise is believed to be limited. Yet, this might change in the near future with the continuous developments and improvements of sophisticated evacuation simulation tools. Nevertheless, for the time being, the results obtained from the Delphi session are believed to constitute the best available estimates to this problem, and further validation is not deemed to be feasible.

5. RECOMMENDATIONS FOR FURTHER WORK

5.1 Areas of Improvements

The presented methodology for evaluation of risks related to collision damage stability is based on a simple, yet structured and holistic approach. The risk model that was developed is modular in nature, and each module or sub-model can be treated independently. For each sub-model, what is deemed as the best and most practical method currently available was suggested. However, there are notable potential for improvements and refinements within the various sub-models. Given the modular nature of the approach, further developments within simulation tools and calculation methods can easily be incorporated into the model and this would contribute to reduced uncertainties.

In particular, further studies and improvements related to the following areas would be welcomed:

- Collision simulation and probability distributions of collision damage extent
- Flooding and time to sink simulations
- Evacuation simulations during severe conditions, e.g. under large angles of heel

5.2 Risk Acceptance Criteria

The risk acceptance criteria suggested in this study was developed according to the method set forth by Norway (2000), e.g. by considering the economic value of the activity. Although this method is based on a sound rationale it does not unambiguously describe a set of acceptance criteria. In practice, application of this approach is sensitive to a number of assumptions related to earnings, costs, interest rates, vessel life time etc. and a range of different criteria can result. Thus, even with a commonly accepted methodology for establishing criteria, there are still considerable uncertainties related to the risk acceptance criteria themselves.

In order to facilitate a more coherent assessment of risk, a set of commonly accepted risk acceptance criteria would be beneficial. In a truly risk based regulatory regime, such risk acceptance criteria could be set forth by the regulator, i.e. it would be recommended that IMO establish risk acceptance criteria for all major ship types. These would need to be periodically revised and updated e.g. every five years. This would eliminate the uncertainties associated with the criteria, and the evaluation of results from different risk analyses would be without bias. Remaining uncertainties would be related to the actual risk analyses, and the risk analysts could focus on minimizing these.

5.3 Risk Based Performance Criteria

The probabilistic rules adopted by IMO is an important step forward, since it promotes a more effective subdivision of the ship compared to the deterministic approach. However, for stake holders wishing to investigate the risk level of a design or the effect of introducing risk control options, a more comprehensive approach as proposed herein will be required.

The approach outlined in this paper links the required subdivision index R directly to the overall risk associated with passenger ships. In other words, the maximum permitted sinking probability is given by (3).

$$\text{Max}(P\ \text{sink}) = 1 - R \tag{3}$$

The collision risk is a product of this sinking probability, and thus of the required index, and the remaining sub-models (4 and 5).

$$\text{Risk} = P\ \text{sink} \times \Pi\ \text{remaining}\ (P \times N) \tag{4}$$

$$\text{Risk} \leq (1 - R) \times \Pi\ \text{remaining}\ (P \times N) \tag{5}$$

Currently, the required index for passenger ships is a function of the ship length, the number of people it is permitted to carry and the lifeboat capacity:

$$R = 1 - \frac{5000}{L_s + 2.5N + 15225} \tag{6}$$

In a risk based regulatory regime, performance criteria for damage stability could be established based on overall risk criteria. I.e. from a high-level criterion for collision risk, Risk ≤ Risk criterion, a required subdivision index could be derived to replace the definition in (6). Hence, the proposed approach would facilitate risk based performance criteria for damage stability. These would be a function of the risk criterion and on the performance of the remaining components in the risk model (7).

$$R \geq 1 - \frac{Risk\_criterion}{\prod_{remaining} P \times N} \qquad (7)$$

5.4 Contributions from Non-collision Scenarios

This paper only focuses on collision scenarios. This is believed to be the biggest contributor to the risk associated with passenger ships (Vanem and Skjong, 2004), but a comprehensive risk analysis should also consider other risk contributions. In particular, all relevant scenarios should be included before comparing the risk with risk acceptance criteria. It is hence recommended that similar risk models are developed for the following accident categories: Grounding, contact, foundering, fire and explosion and hull/machinery/equipment.

5.5 Investigate Possible RCOs

Even though this study does not explicitly quantify the risk level, it is acknowledged that damage stability of passenger ships is a critical issue, and the associated risks are far from being negligible. It is therefore recommended that the tasks of identifying, evaluating and implementing cost effective risk control options related to collision are initiated.

Risk control options related to navigation, damage stability and evacuation are all believed to be promising candidates. However, risk control options aimed at enhancing damage stability and in particular those aiming at prolonging the time to sink or capsize are believed to be most crucial. Recommendations on a set of risk control options related to navigational safety of large passenger ships have already been submitted to IMO where several cost effective options were proposed (Norway, 2005). Furthermore, a recent study on risk control options related to evacuation of passenger ships concluded that it is difficult to find cost effective options directly related to evacuation (Vanem and skjong, 2006b).

Based on the above arguments, it is recommended that further studies are initiated with the aim to identify, prioritize, evaluate and possibly recommend various risk control options related to damage stability of passenger ships.

6. CONCLUSIONS

This paper has outlined and proposed a holistic and risk based approach for assessing the collision damage stability of passenger ships. In particular, it has been demonstrated how the attained subdivision index A, as calculated according to the new probabilistic damage stability regulations, is directly related to the overall risk associated with passenger ships. Furthermore, it was demonstrated how the required subdivision index R is related to the overall risk. This relationship can be exploited in order to evaluate the appropriateness of the required index and possibly to establish a new required index, truly based on risk considerations.

In order to develop safer ships, it is recommended that future designs of new passenger ships are subject to a risk evaluation similar to the proposed approach. This would help control the risk related to collision accidents and ensure that the damage stability characteristics of the ship are adequate. Furthermore, it is recommended that prospective risk control measures related to damage stability are investigated, and the outlined approach can be useful in the evaluation of prospective options.

7. DISCLAIMER

The opinions expressed are those of the authors and should not be construed to represent the views of DNV.

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