SUB-COMMITTEE ON STABILITY AND
LOAD LINES AND ON FISHING VESSELS
SAFETY
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Agenda item 5

REVISION OF THE INTACT STABILITY CODE

Proposal of a probabilistic intact stability criterion

Submitted by Germany

SUMMARY

Executive summary: This document proposes a probabilistic intact stability criterion for parametric rolling and pure loss phenomena. It is suggested that this proposal is discussed as a first step towards (several) dynamic stability criteria

Action to be taken: Paragraph 36

Related documents: SLF 48/4/7, SLF 48/21 and SLF 49/5

INTRODUCTION

1 One of the major reasons for this initiative of a revision of the IS Code (resolution A.749(18), as amended) was the increase of numbers of ships at risk observing severe rolling which mainly resulted in damages to the ships and its cargo in recent years and, fortunately, in few occasions only injuries to persons. It is recognized that ship hull forms of certain ship types have undergone rapid developments. It was mainly governed by the demand of an ever increasing carrying capacity (passengers and cargoes) and other economic demands such as higher speeds at optimized fuel consumptions. This vivid change in characteristics was not matched by a due consideration of the dynamic behaviour in seemingly moderate sea states (e.g. pure loss or parametric roll).

2 In order to back up the longer term work tasks, Germany (SLF 48/4/7) supported the implementation of at least some preliminary description of these phenomena and the need for them to be addressed as “dynamic stability criteria” within Part A, chapter 2 of the actual IS Code presented in the Correspondence Group report. This was to be supported by the inclusion of a sub-section on ‘Criteria addressing stability in waves’ describing phenomena, possible operational alertness and a need for future implementation of a set of criteria /simulation process.
The Capsizing Index

3 The concept presented previously to judge upon dynamic stability in waves was based on a simple empirical formula which tried to correlate the alterations of righting levers in head or following seas to the results of the direct numerical determination of capsizing frequencies. The capsizing index has been determined by the following procedure:

.1 Based on nonlinear sea-keeping simulations in irregular waves in time domain (ROLLS), a limiting significant wave height for a given significant wave length was determined in such a way that for a given course and speed the following criterion was met:

\[ E_R - 3s \geq 0 \]

.2 There, \( E_R \) means the residual area under the still water righting lever curve from the maximum angle obtained during one simulation to the point of vanishing stability and \( s \) means the standard deviation of that area obtained from several simulations. This criterion which was developed by Blume, HSVA was used due to the fact that it was found to be able to clearly distinguish between safe and unsafe. This is the reason why we call the capsizing probability actually a capsizing index, because the failure criterion distinguishes between safe (related capsizing probability is 0) or unsafe (related capsizing probability is 1) only. According to the detailed calculations, this concept is conservative from safety point of view, which means that the actual failure probability is slightly overestimated. In cases where the still water vanishing point of stability takes very large values (e.g. 80 Degrees), the criterion would most probably prevent a capsize, but the ship might be lost due to other reasons. In such cases, 50 Degree roll angle is also treated as a formal capsizing event.

.3 During the simulations, the irregular sea state is generated by a JONSWAP-spectrum with different random numbers for each simulation.

.4 As a result from many simulations, for each significant wave length a limiting envelope of wave heights (limiting area) are determined for a set of courses and ship speeds. This limiting area distinguishes between unsafe (all wave heights above this limiting area are considered as unsafe, capsizing contribution is 1) and safe (all wave heights below this limiting area are considered as safe, capsizing contribution is 0). For each situation resulting in a capsizing contribution given by the variables:

.1 significant wave length;
.2 significant wave height;
.3 course; and
.4 speed,

the total probability of occurrence of this particular situation is then determined. This total probability is represented by the product of the following probabilities:

- probability of occurrence of the sea state represented by a significant wave length and height;
- probability of occurrence of the course travelled; and
- probability of occurrence of the ship speed.

.5 As no better information was available, the course distribution was assumed equal for all courses. Regarding the speed distribution, it was roughly estimated which speeds could be travelled at a given sea state and then, the speed distribution in each interval was also assumed to be equal.

.6 If all these contributions were summed up for different significant wave lengths, a capsizing probability can thus be determined. Due to the fact that the actual capsize contributes only by distinguishing between safe (0) and unsafe (1), and also due to the fact that some basic probability distributions are vaguely known only, we call the result capsizing index instead of capsizing probability, but the meaning is practically the same.

.7 The capsizing index can only be correct in absolute terms, if all basic probability distributions are known with sufficient accuracy, and this clearly holds for the speed and course probabilities. In this context, the question whether the simulations shall distinguish between safe and unsafe or deliver a direct capsizing probability is marginal, as long as the criterion to distinguish between safe and unsafe is good enough, which is definitely the case.

4 In conclusion, it can be stated that the actual capsizing index based on numerical simulations is a good tool to compare ships on a qualitative level. If this is quantitatively to be improved, more detailed information on course and speed distributions needs to be known.

**Stability- Criterion suggested previously**

5 Based on the evaluation of about 150 vessels, a criterion was established that took into account the alterations of the righting lever areas in crest and trough conditions. It was assumed that the stability should be related to the specific crest and trough alterations, the larger the latter are, the more stability should be provided. This criterion was suggested as only one of a set of criteria which should together with these other criteria (e.g. dead ship condition, wind, etc.) create an envelope curve for the limiting stability values to ensure a sufficient safety level. The criterion presented was developed to cover the combined phenomena parametric roll and pure loss of stability on a wave crest. As in parallel, direct calculations were also considered as an appropriate tool to evaluate dynamic stability; the limiting values have been suggested in a conservative manner (the same basic procedure as for the suggestion of the revised wind criterion).

6 The dynamic stability criterion covering parametric roll and pure loss was determined in such a way that simple variables which could be derived from righting lever alterations were studied with respect to their sensitivity regarding the capsizing index. The more sensitive the capsizing reacted on a small alteration of such a variable, the more this variable was found useful to represent a simplified criterion. Further it was considered that the scatter in data at a constant capsizing index with respect to that variable should be small.

7 Therefore, the following principle criteria have been suggested to ensure a sufficient intact stability in heavy weather:

\[ h_{\text{max,still}} = k_H (h_{\text{max,trough}} - h_{\text{max,crest}}) \]
where $h_{max}$ is the maximum righting lever at still water condition up to the angle of incidence. The indices trough or crest denote the maximum righting lever at trough or crest condition, and:

$$a_{xx,\text{still}} = k_d(a_{xx,\text{trough}} - a_{xx,\text{crest}})$$

where $a_{xx}$ is the integral under the righting lever curve up to an angle of $xx$ degrees (including all negative contributions).

8 Most promising seemed to be an approach where the area alterations at 15 Degree were considered. This was presented to the correspondence group prior to the SLF 48 meeting. The concept was to relate the stability to be attained to the alterations of crest and trough righting levers.

9 In the mean time, the proposed concept was thoroughly discussed and some deficiencies were identified, namely:

.1 The scatter in the absolute safety level was considered to be too large;
.2 Especially container vessels with large form stability and substantial alterations of initial GM are not represented correctly; and
.3 The safety level represented by the criterion is not directly obvious.

10 Based on these deficiencies, some improvements were suggested, namely:

.1 To minimize the impact of beam sea capsize on this criterion by more realistic course distributions;
.2 To improve the speed distributions to eliminate capsizing contributions in following seas at unrealistically low ship speeds; and
.3 To improve the criterion to further reduce the scatter.

The following sections deal with the results of the investigation concerning these issues.

**Beam Sea Problem**

11 The criterion was formulated to cope with large rolling motions in head or following seas only. Beam sea cases are not covered by the criterion (and this was also not intended) due to the fact that beam sea capsizing can not be related to alterations of the righting levers as such. This is due to the fact that the failure mechanism in beam seas differs from that in head/following seas.

12 If a vessel experiences large rolling motions in head or following seas, the following boundary conditions must be fulfilled:

.1 The significant wave length (together with the related significant wave height) must lead to significant alterations of the righting levers in crest and trough condition;
.2 The encounter frequency must meet roughly the 1:1 or 2:1 resonance; (or)
.3 The ship suffers from significant stability loss at the wave crest.
13 How large the rolling angles then actually become, depends on the specific characteristics of the vessel, such as hull form, load case, weight distribution etc. The investigations have clearly shown that there is a large number of vessels where the above mentioned situations are not met. This generally holds if the stability of the ship takes such a large value:

1. that possible resonances occur in the range of wave lengths that do not lead to significant alterations of the righting levers;

2. due to the large stability the related loss on the crest leaves sufficient residual stability.

In both cases ships are sufficiently safe in head or following seas against capsizing.

14 In case the stability takes large values, the possibility of a capsize in beam seas may occur. This may happen if half the wave length takes roughly the value of the beam of the vessel (this results in the largest rolling moments the ship is exposed to) and if at the same time the encounter frequency meets the natural rolling frequency.

15 For larger vessels, this is not likely to occur simply due to the fact that the resulting GM values which fulfil the a.m. boundary conditions have to take extremely large values. Or the critical waves do not take sufficient wave height to endanger the vessel. For the larger ships, only for some Stockholm Agreement Conversions with very high initial GM values a beam sea problem could be identified.

16 But smaller vessels may experience situations where the a.m. boundary conditions are fulfilled if they are operated at quite substantial GM values, either from operating conditions or due the limiting stability requirements from the rules. Fig. 1, left, shows such a case of a small passenger vessel, length about 60 m, GM equaling to approx. 1.60 m.

![Fig. 1: Polar Diagrams for a typical case dominated by beam sea failures (left) and by head/following seas (right). The vessel is the same in both cases, but the left case has significantly more GM compared to the right case. The failure mechanism is different in both cases, which is shown by the polar diagrams.](image)

17 It can clearly be seen that the characteristics of the left polar diagram are different from the right one, which expresses failures due to head/following seas. An increase of metacentric height would result in reduced safety in rough weather if the following/head sea scenarios would remain quite unaffected, but if the beam sea resonance cases would be more pronounced. In this respect, the fact has to be taken into account that the theory over predicts the beam sea failures due to the fact that especially the sway motion is treated linearly. Nevertheless, qualitatively the effects are predicted correctly.
18 If now the vessel would be operated with significantly lower GM-values, e.g. 80 cm, the scenarios where the ship is endangered in head or following seas become more dominating, refer to Fig. 1, right, but the beam sea problem still can be seen.

19 This example illustrates the fact that a complete evaluation of a capsizing risk as performed by this simulation can not clearly distinguish between head/following sea failures and beam sea problems, because this simulation contains both effects at the same time. This is shown also by the comparison between the simplified criteria (which do take into account head/following sea effects only) and the results of the direct computations. This makes the evaluation of any simplified criterion more complex and shows that each case has to be judged upon individually. Therefore, a large number of ships and calculations are required to get a reliable answer.

20 In this context, the role of the existing stability criteria is extremely important to better understand the general behaviour of a ship, especially the weather criterion. If any statement on the existing fleet shall be put forward, it is important to take into account the actual limiting stability values, because they form different clusters the ships may be grouped into.

21 Due to the interaction of the weather criterion with the damage stability limit curve there is a large number of ships which do not have problems in following/head seas simply due to the relatively large initial GM they obtain from these requirements, but these ships may suffer in beam seas. If these ships would be operated with lower GM-values (which is at present not possible due the a.m. restrictions), they would be significantly more endangered in following or head seas, but beam sea problems would be reduced. Concluded, the following statement can be put forward:

22 A simplified dynamic criterion for minimum GM-values in head/following seas must take into account the relevant effects in these scenarios, but not of other ones. The possible failure in these scenarios becomes more dominant if the stability values become smaller. With larger the stability values, the risk of failures decreases. In this case, the beam sea failures may become more dominant. The actual failure mode of the vessel is strongly influenced by the existing (static) stability criteria.

Insufficiencies of the criteria suggested

23 The most severe problem with the criteria suggested is related to the in-transparency of the actual safety level and the still large scatter. In this context, several investigations have been carried out to clarify the discussion, with the following results:

1. The actual scatter is most influenced by the fact how actually the reference wave for the determination of the relevant alterations of the righting levers was determined. This affects the ratio wave length/height and also the actual crest and trough position. Variations of these input assumptions have shown quite significant influence on the scatter and therefore on the resulting minimum GM-values. Concluded, it can be stated that the resulting minimum GM should not depend on one specific design wave, but on a couple of waves.

2. The righting lever area alterations up to 15 Degree have been identified as the strongest variable in the sense of a simplified criterion due to the fact that the capsizing index reacts very sensitive to any changes in this variable. This was taken as a proof that the best variable has been identified, but recent investigations have shown that this is not fully correct. If a dynamic criterion in head/following
seas shall lead to minimum GM values, then the criterion shall prevent large rolling amplitudes. The investigation has shown that whenever large rolling amplitudes have occurred, the ratio of righting lever area alterations trough/crest up to 15 Degree took critical values. On the other hand, not all scenarios where this ratio took critical values actually resulted in large amplitude rolling. Therefore this variable can be taken as criterion if large amplitude rolling may occur, but it does not really quantify the resulting rolling amplitudes. For vessels which have negative form stability (where the righting lever curve is clearly below the GM - line), the variable results in the correct judgement, because in all cases studied large rolling amplitudes actually occurred. But for vessels with significant form stability (the righting lever curve is above the GM -line), large amplitude rolling did not occur in many cases although the a15 criterion took critical values. The a15- variable therefore is a sensitive variable to express the risk of large amplitude rolling in head/following seas because a critical a15 alteration is always necessary to initiate rolling motions, also in mixed failure mode cases (capsizing in bow/stern quartering cases). If a criterion shall be suitable to actually predict large amplitude rolling, it seems more realistic to use the area alterations up to larger angles, because they can be better associated to large amplitudes of roll. In this context, also the comparison of the alterations of maximum righting levers in crest and trough condition was found to be useful.

24 Concluded, it was found that an improved dynamic criterion for following/ head seas should treat more waves than one specific design wave and should make use of variables that can be better related to the actual occurrence of large amplitude roll motions.

Proposal of a dynamic criterion in head or following seas

25 The new criterion is now suggested as a probabilistic one, and it has the basis in the simplified determination of a capsizing index which may then be quantitatively judged upon. The simplified criterion is based on the evaluation of all possible sea states expressed by a significant wave length and height, reference area North Atlantic, e.g. Soeding, Global Seaway Statistics. The simplified capsizing index \( a_k \) is then calculated by the formula:

\[
a_k = \sum_{i=1}^{N_{\lambda_{1/3}}} \sum_{j=1}^{N_{H_{1/3}}} p_{i,j}(\lambda_{1/3}, H_{1/3}) \cdot a_{i,j}(\lambda_{1/3}, H_{1/3})
\]

Here, \( p_{i,j}(\lambda_{1/3}, H_{1/3}) \) denotes the probability of occurrence of a sea state given by the significant wave length \( \lambda_{1/3} \) and height \( H_{1/3} \) and \( a_{i,j}(\lambda_{1/3}, H_{1/3}) \) denotes the probability of capsize of the vessel in this sea state. Based on the previous investigations, the determination of capsizing probability of the vessel is suggested as follows:

\[
a_{i,j} = 1 - \sqrt{s40_{i,j} \cdot shmax_{i,j}}
\]
Here, \( s_{40_{i,j}} \) denotes the probability that the ship may survive the sea state \( i,j \) expressed by a simple energy criterion, and \( sh_{\text{max}_{i,j}} \) denotes the probability that the ship may survive the sea state \( i,j \) expressed by the alterations of the maximum righting moments. \( s_{40_{i,j}} \) and \( sh_{\text{max}_{i,j}} \) shall be calculated as follows:

\[
\begin{align*}
s_{40_{i,j}} &= \frac{(a_40/a_{40_{\text{diff}}})}{k_1} \\
sh_{\text{max}_{i,j}} &= \frac{(h_{\text{max}}/h_{\text{max}_{\text{diff}}})}{k_2}
\end{align*}
\]

In the a.m. formula, no larger values for \( a_{40}/a_{40_{\text{diff}}} \) than \( k_1 \) must be used and no value smaller than 0.

Again, no larger values for \( h_{\text{max}}/h_{\text{max}_{\text{diff}}} \) than \( k_2 \) and no smaller value than 0. These formulae take into account that if the crest- trough differences are smaller than a limiting minimum value, the ship is regarded as safe. This also holds if these alterations become 0. In the formulae, \( a_{40} \) denotes the still water righting lever area up to 40 Degree, \( a_{40_{\text{diff}}} \) denotes the difference trough- crest at the significant wave length \( \lambda_{1/3} \) and wave height \( H_{1/3} \), \( h_{\text{max}} \) denotes the maximum righting lever in range up to 40 Degree, \( h_{\text{max}_{\text{diff}}} \) the trough crest difference of that righting lever for the given wave. \( k_1 \) and \( k_2 \) are factors which may be fitted to the results of the direct computations. Based on this comparison to the directly computed capsizing index, the following values are suggested:

\[ k_1 = k_2 = 0.7 \]

26 This combination resulted in good agreement of the simplified and directly computed capsizing index and may be taken as first guess.

**Evaluation**

27 The criterion suggested above was evaluated for all ships in the data base. Only the so called intact cases have been considered, which means that each vessel is analyzed according to the minimum GM- required values of the intact criteria. Any larger GM due to other criteria (e.g. damage stability) is not taken into account. In the following diagrams, each vessel is represented by a marker. The abscissa shows the capsizing probability determined by the simulations, and the ordinate shows the results of the simplified capsizing index obtained by the a.m. criterion. If the simplified criterion did not indicate failures, the value was set to 1E-6 for reasons of presentation. If the simplified criterion represents the capsizing phenomena well enough, the results should be located at a 45 Degree straight line. As the simplified capsizing index now represents a safety level, too, further discussions are required about the level of acceptance.
All ships of the database under consideration:

![Comparison of the simplified to the directly calculated capsizing index, all ships, intact cases only](image)

28 The evaluation for all ships shows that the existing fleet may be distinguished in two groups: At the left side, all vessels are located that are not affected by the dynamic criterion. All these vessels either have low righting lever alterations or sufficiently large GM values, so that a capsizing may occur due to beam sea effects only. These ships not affected by the suggested criterion are not covered due to the fact that they are not endangered in following/ head seas, either because the initial stability is sufficient or the righting lever alterations are small.

29 All other ships are quite close to a 45 Degree straight line, where the scatter becomes smaller the larger values the capsizing index takes. This is exactly the case when the vessel is endangered in head/following seas and large rolling angles result. In total, the scatter seems to be acceptable, and in contrary to the results published earlier, the ships are not that significantly clustered by ship types. Therefore it can be concluded that the newly suggested criterion is a definitive improvement.
Following the discussions of the previously suggested deterministic criterion, the container vessels have been studied more in detail. This was due to the fact that for this type of ship, the \(a_{15}\) criterion seemed to disregard the large form stability of these vessels. The new concept better takes into account the actual occurrence of large amplitude roll motions, and the vessels benefit from their pronounced form stability. Both the directly computed and the simplified capsizing index show that the dominating failure mode is large amplitude roll in head/following seas. The behaviour of these vessels is well represented by a 45 Degree straight line. Especially those vessels which are limited by larger values than 0.15 m minimum GM show a significant increase in safety.
RoRo- Vessels

Fig. 4: Comparison of the simplified to the directly calculated capsizing index, RoRo- vessels, intact cases only

31 The trend is generally the same as for container vessels, but on a significantly lower safety level. The failure mode is the same, but despite the larger GM-values the safety level is drastically smaller due to the fact that the ships do not have positive form stability. The large Length/draft ratio makes these vessels vulnerable for righting lever alterations. A better fit of the data may be achieved by other selections of k1 and k2.
RoPax- Vessels

Fig. 5: Comparison of the simplified to the directly calculated capsizing index, RoPax vessels, intact cases only

32 The RoPax vessels follow the same trends as identified for Container- and RoRo- vessels, but the vessels clearly split into two groups: At the left side, those vessels are located which are operated by quite large GM- values due to design boundary conditions (damage stability plus weather criterion). In this group, for example, all Stockholm Conversion cases can be found and most of the RoPax vessels with lower hold. Due to the a.m. reasons, these vessels are not covered by the criterion. For the other vessels, the same trend as for the RoRo- vessels can be observed, due to the same reasons. Active roll damping devices usually fitted to this type of ship were not taken into account in the analysis, this results in the relatively large capsizing indices.
Passenger Vessels

Fig. 6: Comparison of the simplified to the directly calculated capsizing index, passenger ships, intact cases only

33 The same trend as identified for the RoPax vessels can be found here. Some vessels, namely the smaller ones, are not affected by the criterion because they can be related more to beam sea problems. The other ones are located close to a 45 Degree straight line at somewhat larger capsizing indices. This may be related to the large rolling moments introduced into these types of ship and, as for the RoPax vessels, the fact that any active damping devices have not been considered.
These types of vessels show a small risk of capsize in the head/following sea scenarios (the diagram is scaled differently than the others). As the database consists of many different types of these vessels, also some smaller vessels with probably insufficient freeboard, the scatter is slightly larger. All the larger vessels of these types are practically not covered by the phenomenon. The same holds for the smaller vessels, provided they have sufficient freeboard (if the freeboard is too low, the freeboard deck becomes submerged in the crest cases, resulting in pure loss failures). The scatter in the initial GM-values is somewhat larger as for the other ships due to the fact that different criteria of the existing intact stability code govern the GMreq curve (e.g. max GZ at 25 Deg.) The general trend is represented sufficiently well at slightly larger scatter.

Conclusion

The concept suggested for a probabilistic approach to determine a simplified capsizing index shows a clear improvement with regards to the deterministic concept presented earlier. The newly suggested criterion for a minimum stability to cope with parametric rolling and pure loss in head or following seas clearly has identified the relevant physical phenomena. Compared with the directly computed capsizing index by numerical simulations, the scatter seems to be acceptable. The grouping of ships into specific clusters has been significantly reduced. Further developments will be the introduction of better speed profiles to obtain more realistic basic probabilities. This will result in a general shift of the capsizing index, which makes it necessary to determine the free coefficients k1 and k2 again.

Action requested of the Sub-Committee

The Sub-Committee is invited to consider the proposal of a relevant probabilistic draft criterion for inclusion in the IS Code in the longer term and take action as appropriate.