INVESTIGATION OF THE 2ND GENERATION OF INTACT STABILITY CRITERIA FOR SHIPS VULNERABLE TO PARAMETRIC ROLLING IN FOLLOWING SEAS

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ABSTRACT

The existing IMO intact stability criteria (IS-Code 2008) do not generally provide sufficient safety against dynamic stability failures such as parametric rolling for modern ships. Therefore, new stability criteria have been developed by IMO / SLF. These so-called Second Generation Stability Criteria shall ensure sufficient dynamic stability. The criteria are structured in a three level approach, where the first level consists of quite simple formulae. If a ship does not pass the first level, it is assumed that the ship is vulnerable to the phenomenon addressed, and the second level of criteria shall then be applied. This level consists of computations which are a little more complex, but they still treat the problems addressed in a strongly simplified manner. If now the ship does not pass the second level, a third level shall be applied to ensure that the ship can be designed and operated safely. This third level consists of direct calculation methods which shall be applied, however no criteria or procedures have yet been developed for this third level. We have applied the level 1 and level 2 criteria to a reference ship where a direct stability assessment has been performed during the design. The results showed extremely large scatter in the required GM-values of the criteria, and none of the criteria showed GM values roughly comparable to the direct assessment. The paper shows why the application of the criteria is challenging for the design of RoRo-ships and why a third level (direct assessment) is urgently required before the first two levels are put into force. Some conclusions are also drawn for the possible treatment of the new criteria in a stability booklet.

INTRODUCTION

When the International Code on Intact Stability was made mandatory by the IMO in 2008, it was widely recognized that the stability criteria of the code were not sufficient for all types of possible stability failures. Especially the motions of some ship types in a complex real seaway was seen as a problem the existing stability criteria could not cope with. Therefore, in the preamble of that code it was mentioned that further research is necessary to come to stability criteria which do explicitly take these phenomena into account. Therefore, new stability criteria have been developed by the IMO which shall better take into account the following phenomena in rough weather:
Several criteria have been proposed for these failure modes, and test applications shall be run to check whether these criteria provide a consistent and sufficient level of safety. The criteria are structured into three levels: The first level is intended to check if a ship is vulnerable concerning a certain failure mode. This first level consists of simple formulae which are easy to apply. If the ship is found to be vulnerable for a certain failure mode by the first level, the second level of criteria shall be applied to the ship. These criteria consist of more complex formulae and computations and they shall be therefore less conservative. The more detailed computations may then show that the ship does not have the problem the first level has suspected. In this case, the ship may be approved. It may also happen that the second level does show that the ship is in fact vulnerable to that phenomenon. In this case, a third level is foreseen which is a direct computation of the problem by appropriate methods. At present, there are proposals for the first two levels of criteria, but there exists no proposal for the direct computations in level 3. Is is also not fully clear how the different levels will be handled during the approval of a stability booklet, where typically $GM_{\text{Required}}$ or $KG_{\text{max}}$ curves are approved. Therefore, it is a useful task to test these stability criteria intensively with different ship types.

One useful test case are several RoRo-ship designs of the Schiffbau-Gesellschaft (FSG). These ships are in so far quite interesting as they have been intensively investigated during several research projects. During these investigations it was found that the existing stability criteria were not sufficient for some RoRo-ship designs and computations showed that some designs would capsize if operated at the existing stability limit. During the investigation of these ships, intense model tests in tailored wave sequences were conducted and it was indeed found that the ships could capsize if they were operated at the stability limit of the existing criteria. Interesting enough, the stability limit for one of these designs was in fact governed by the intact stability criteria and not by the damage stability criteria which underlined the fact that the existing stability criteria were not sufficient for some ship types. During the research project, a direct stability assessment - comparable to a level 3 approach of the new criteria - was performed by the shipyard to investigate the level of stability which was to put on top of the existing criteria to ensure a safe operation.

In summary, existing criteria fail to assess the stability of the reference ship and the amount of sufficient stability is known soundly. Hence, the stability assessment of this ship by means of new improved criteria is not only relevant but also verifiable. This combination turns the reference ship into an ideal benchmark for new criteria. This paper describes the key aspects of this criteria benchmark in the following order. First, the reference ship is presented and the inability of existing criteria to assess the stability is shown. Second, the new second generation of stability criteria are applied to the reference ship. Third, the process of deriving the amount of sufficient stability from a direct assessment, which is crucial for this benchmark, is presented. For the purpose of deriving the required stability from a direct assessment, the method of the Insufficient Stability Event Index by Kluwe [1] is used and described briefly.

THE REFERENCE SHIP

![Image](https://via.placeholder.com/150)


We have selected one of the ships investigated during the research program as reference ship for the application of the second level of stability criteria. The ship has four cargo decks intended for road trailers. The main dimensions of the ships are: Length over all 200m, length between perpendiculars 190m, moulded breadth about 26m, draft about 7m. The hullform was quite slender, including a wide transom over the full ship’s beam. As RoRo-vessels have comparable hull forms to container vessels, but a smaller draft, a wave of a given height leads to more pronounced righting lever alterations in waves compared to container vessels (see fig. 1), and consequently, RoRo-ships are in principle sensitive to any phenomenon that is connected to righting lever alterations in head or following seas [2]. Therefore, this ship design is a typical RoRo-freight ferry design and was (among others) chosen as reference ships for the German BMWi\(^2\) funded research program SinSee [3], where RoRo ships were intensively tested in so called tailored irregular wave sequences. The aim of the research project was to develop methods and design procedures for the design of safer ships on one hand

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1 We have always pointed out in the past that from a practical point of view, the intact stability criteria are not relevant anyway due to the fact that most ships are operated at the damage stability limit.

2 Federal Ministry of Economics and Technology
as well as the validation of numerical seakeeping codes for the prediction of large roll amplitudes [4]. It became obvious during the research program that the stability limit of RoRo ship designs according to the existing stability criteria is not sufficient, and the ship could capsize when operated the prescribed stability limit due to a combination of parametric rolling and pure loss on the wave crest (see fig. 3). In total, about 50 different runs with the model of the selected reference ship were performed, mainly in irregular seas. The following experiences were made during the experiments:  

- The ship did never capsize if operated with the stability limit obtained from the direct assessment. All dangerous situations took place if the stability was according to the existing regulations. 
- The ship capsized only in irregular following seas. Head sea scenarios lead to roll angles of about 20 degree, but the ship did never capsize. 
- The ship did also never capsize in regular seas. 
- The ship was endangered in irregular seas where the significant period \( T_1 \) was close to the so-called 2:1 resonance (2 pitch cycles per roll cycle). In following seas, this 2:1 resonance could not be explained with the still water roll period. 
- The righting lever curve was strongly non linear, which means that the natural roll period varied with the roll amplitude. As a result, there were alterations of the roll resonance. 
- The crest righting lever curve had a negative initial GM and differed therefore in shape significantly from the trough curve. As a consequence, the natural roll period of the ship depended on the time dependent wave elevation at midships and varied significantly. 

One result of the test series was that the stability represented by the existing regulations was not sufficient and should be increased. Typically the damage stability limit is responsible for the resulting \( GM_{req} \)-curve, and for most of the RoRo-vessels this damage stability limit implicitly provides sufficient safety also for the intact conditions. But for these ships the damage stability limit was below the intact criteria in the draft range of interest (see fig. 2). According to the existing stability criteria, \( GM_c \) value of about 1 m (at FS draft) and this is not sufficient. As a matter of fact, the ships ship design included a roll damping tank to avoid large roll angles. Due to the existing stability regime, such a tank - even if it provides a positive contribution to the ship’s safety - has a free surface which has to be subtracted from the solid GM. The free surface correction for this tank was about 0.4 m, which resulted in the situation that the design - with anti roll tank filled - needed about 1.4 m of GM to achieve the 1 m GM limiting value. Due to the fact that the effective stability of the ships was higher than the limiting value (1.4 m instead of 1 m) and due to the fact that the Interring Tank is actually damping the roll motion of the ship, there was no real stability problem. But according to the existing stability regime it would have been possible to operate the ship with emptied tank and heavy trailers on the top deck at 1 m GM, which is then not preferable. Therefore, a stability value was determined by a direct stability assessment, and this minimum stability value required was about 1.40 m. During the investigation, this stability was also tested and no dangerous situations were found.  

![FIGURE 2. GM-REQUIRED CURVES OF THE REFERENCE SHIP INCLUDING THE LIMITING CURVE OF THE DIRECT ASSESSMENT](image)

**THE SECOND GENERATION OF INTACT STABILITY CRITERIA**

This section describes the second generation of stability criteria which are applied to the reference ship in the subsequent section.

**General**

The criteria for failure modes parametric roll and pure loss of stability are investigated. For both failure modes, the criteria are divided into two levels. Level 1 consists of simple calculations based on information available in standard hydrostatic tables. If a ship fails to comply with level 1, level 2 needs to be applied. This level requires the calculation of hydrostatics in waves and more complex numerical procedures than level 1. If a ship is considered vulnerable by level 2, a direct assessment by state-of-the-art roll simulations is required.

The criteria are applied to the test ship according to the latest definition within the IMO SLF proposal 54/19 [5]. According to

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3Similar experiences were made with other ships tested during the program.

4Today, all ships designed and built by FSG have this voluntary stability standard, which is called the ISEI-standard (Insufficient Stability Event Index).
the latest definition, some limits of criteria, so-called standards, and wave specifications are still under discussion. Thus, there exist different proposals or slightly different versions of the same criteria. Therefore, this section covers not only a brief description of the criteria but a selection of the wave options and standards as well. Furthermore, it is noteworthy that for level 1 the least restrictive formulation among all proposals is chosen.

**Parametric Rolling**

**Level 1:** According to the level 1 criterion, a ship is considered vulnerable to parametric rolling if the ratio of GM alteration due waves to the GM in calm water exceeds a certain standard. The permissible standard of the ratio of the GM alteration amplitude to the calm water GM is 0.5. Particularly with regard to our results, it is important to note that this standard is the least conservative one used in previous sample calculations and definitions [5–8].

The GM alterations are calculated for the ship in longitudinal sinusoidal waves. Wave length \( \lambda_i \) and height \( H_i \) of these sinusoidal waves are specified within three different SLF proposals summarized in [5]. In this study, we use the wave option with a wavelength of ship length \( \lambda_i = L_{pp} \) and steepness of \( H_i / \lambda_i = 0.0167 \). Compared to the other proposals, this option has proven to produce the least conservative results for our test ship.

To avoid extensive hydrostatic calculations for level 1, the procedure to calculate GM variations in waves is simplified in the following manner. First, the variation of KB is neglected and only BM variations due to the difference of the waterline moments of inertia in crest and trough condition at midships are considered. In a second simplification, the waterline moments of inertia in crest and trough condition are approximated by the calm waterline moment of inertia at two different drafts. For unusual hullforms like tumblehome hulls the criterion does not allow simplifications. For these hullforms, GM variations have to be calculated with the true waterline of the sinusoidal wave at ten equally distributed longitudinal positions. Moreover, different steepnesses up to the maximum wave steepness are used with balanced trim and sinkage.

**Level 2:** The level 2 criterion is subdivided into two checks. If the first check considers the ship as vulnerable to parametric rolling, the second check must be conducted.

The first check requires calculation of the average and the variation of GM in a series of longitudinal sinusoidal waves. Two different wave series proposals are available in the current draft of level 2 [5]. In this study we implemented and evaluated a wave option which consists of 16 waves within a wave length range from 22 m to 631 m. For this wave option, both GM variation and average are calculated with the true sinusoidal waterline at different wave positions and balanced trim and sinkage. Each particular wave condition of a wave series is assessed by two criteria based on average and variation of GM. After assessing each particular wave case, a weighted average according to the probability of the wave cases is calculated and compared to a standard. If the weighted average exceeds this standard, the first check considers the ship as vulnerable to parametric rolling. Aligned with the level 1 check, where we use the least conservative standard, we use the least conservative standard of 0.4 available in literature for level 2 [8, 9] as well.

For each wave, the first check assesses the particular condition as vulnerable if the following two criteria are violated simultaneously. The first criterion is violated for the particular wave if the ratio of the amplitude of GM variation to the calm water GM
The resonance speed natural roll period is exactly half the wave encounter frequency. At this speed, 2:1 parametric resonance exists because the average equation (1).

\[ V_{PRi} = \frac{2 \lambda_i}{T_\phi} \sqrt{\frac{GM(H_i, \lambda_i)}{\phi}} - \sqrt{\frac{\lambda_i}{2\pi g}}. \]  

In this equation, \( \lambda_i, H_i, T_\phi, GM(H_i, \lambda_i), GM \) and \( g \) denote wave length, wave height, natural roll period in calm water, average metacentric height during the pass of the wave, metacentric height in calm water and gravity acceleration.

The second check assesses the roll motion in head and following seas for a range of operational speeds. Two methods are proposed to assess the roll motion. Both methods use the wave options of the first check and assess the ship as vulnerable to parametric rolling if the maximum roll angle exceeds a standard of 25 degree.

The first option is the evaluation of a transient state solution of an one degree of freedom ordinary differential equation using numerical simulation technique in time domain. The equation of roll motion is solved for the pass of a wave group taking into account trim and sinkage quasi-statically.

The second option is a steady state solution of the parametric rolling amplitude of an uncoupled roll model. The amplitude \( A \) can be obtained by solving a twelfth order algebraic equation which is based an averaging method by Maki [10]. This algebraic equation considers variation and mean of metacentric height, linear and cubic roll damping as well as nonlinearities of the GZ curve up to the fifth order. According to the initial proposal in [11], 2:1 resonance conditions are assumed to obtain the algebraic equation for the roll amplitude. Hence, it is assumed that the roll frequency is half the encounter frequency \( \omega_{enc} \).

\[ \phi = A \cos \left( \frac{1}{2} \omega_{enc} - \varepsilon \right) \]  

Here, \( \phi \) and \( \varepsilon \) denote the instantaneous roll angle and phase shift.

In both options, roll damping can be modeled by either simplified Ikeda’s method or roll decay test data. We applied simplified Ikeda’s method as proposed in [12]. With this amount of roll damping, we observed very high and unrealistic roll motions at higher speeds which result in violating the second check regardless of the stability. Therefore we added an additional component for lift of bilge keels and hull in forward speed according to ITTC [13].

### Pure Loss of Stability

Both level 1 and level 2 only need to be applied if the service speed Froude number exceeds a certain standard between 0.2 and 0.31. This range indicates that the standard has not been fixed yet. Nevertheless, we applied the criteria to a ship with an service speed Froude number of 0.274.

#### Level 1:

Level 1 considers a ship vulnerable to pure loss of stability if the minimum metacentric height in waves falls below a standard which depends on the draft and maximum operational Froude number \( F_n (GM_{req} = 1.83 d F_n^2) \). To avoid hydrostatic calculations in waves, the criterion uses the same approximations for the minimum metacentric height in waves as the level 1 criterion for parametric rolling. Only the wave steepness differs and is twice as high as for parametric rolling.

#### Level 2:

Similar to level 2 for parametric rolling, this criterion requires stability calculations in a series of longitudinal sinusoidal waves. According to the criteria proposal in [54/19] the wave cases have same wave length and probability as for parametric rolling but double height. For each wave case, the GZ curve is calculated with the true sinusoidal waterline at different wave positions and balanced trim and sinkage. Three criteria are applied to the set of GZ curves which correspond to a particular wave case: The minimum metacentric height must not be less than 0.05 m. The minimum angle of loll must not exceed 25 degree. The smallest maximum GZ must not be less than 8(H_i/\lambda_i)d F_n^2. According to the probability of the wave cases, a weighted average is calculated for each criterion. The ship is considered as vulnerable to pure loss of stability if the maximum of all weighted averages exceeds a certain standard. In this study we use the least conservative standard applied in literature of 0.9 [8].

### Application of the Criteria to the Reference Ship

The second generation criteria are applied to the reference ship with the practical objective of generating a stability booklet. Similar as for existing stability criteria, a \( GM_{req} \) curve for the range of operational drafts is to be computed.

We experienced several difficulties when we calculated these \( GM_{req} \) curves. First, it is impossible to derive a curve for the second check of level 2 for parametric rolling, because there does not exist any GM which fulfills the criterion. In most of the situations with reasonable stability only small roll angles occurred. Large roll angles only occurred under a very few wave and speed conditions. Hence, the criterion is still violated because only the maximum roll angle of all cases is taken into account. A reasonable improvement is proposed in IMO ISCG 54/41 [7]. In this ISCG study, similar problems occurred which
should be overcome by appropriate improvements in the near future.

Second, there exist some wave and speed combinations according to second check of level 2 for parametric rolling where the encounter frequency is about zero. At zero encounter frequency both options of the for parametric rolling are not applicable. In the first option, the wave group cannot pass the ship at zero encounter frequency and in the second option, assumption (2) is inadequate for $\omega_{enc} \approx 0$. 5

Third, the confidence range of Ikeda’s method is violated for certain drafts and GM values. So far, there does not exist any proposal other than using the violated threshold values to estimate roll damping.

The computed GM-required curves are shown in fig. 4. For the reasons explained above, level 2 criterion for parametric rolling only consists of the first check.

As shown in fig. 4 the required metacentric height to fulfill both level 1 criteria is more than 3 m for the entire range of operational drafts. Although we used the least restrictive formulation of these two criteria, both require a stability which is more than twice as high as found by direct assessment. It was also found by the direct assessment that these high stability values lead to excessive accelerations. Moreover, the stability to fulfill the parametric roll level 1 criterion at partial drafts is greater than 5 m and would lead to even higher accelerations.

The required metacentric height to comply with the level 2 parametric roll criterion is about 2 m to 3 m for the entire draft range. These stability values are in principle consistent with the three level approach, which means that the level 2 curve is below the level 1 and above the direct assessment curve. Nevertheless, for parametric rolling, level 2 requires additional stability of ca. 50% compared to the direct assessment. At least for our test ship, this fact leaves room for discussion, because the least conservative standards are applied here and the $GM_{req}$ values are not acceptable from operational point of view.

For the pure loss level 2 criterion, the least conservative standards are applied as well. Hence, the curve represents the lowest GM-required curve possible for level 2 of parametric rolling criterion. By applying the least conservative standard, an inconsistency is created because direct assessment would require higher stability values. Thus, we conclude that a standard of $R_{PL0} = 0.9$ is not safe.

FIGURE 4. GM REQUIRED CURVES OF THE REFERENCE SHIP INCLUDING THE SECOND GENERATION INTACT STABILITY CRITERIA.

This procedure is described in the following section.

General

The direct stability assessment conducted during the design of the ships consisted of the following steps:

- Further validation of the seakeeping code E4ROLLS used for the computations by the model tests
- Development and validation of failure criteria in irregular seas
- Development of a stability index
- Development of threshold values and limiting stability values

The results of the direct assessment showed that that ship design was considered to be safe if the GM was abt. 1.40 m. Unfortu-
nately, this is neither reflected by the first level on the new intact stability criteria nor the second level. This indicates that the third level is definitively required to make the stability regime work. As a direct assessment of the stability was applied during the investigation, this procedure is in the following briefly explained.

The Numerical Code E4ROLLS

Ship motion computations are carried out using the program ‘E4ROLLS’ originally developed by Söding, Kroeger and Petey [14] at the Institut fuer Schiffbau, University of Hamburg. ‘E4ROLLS’ simulates the motion of intact and damaged ships in time domain in all six degrees of freedom in regular waves and irregular long or short crested sea ways. For four motions, namely heave, pitch, sway and yaw, response amplitude operators (RAO) are used, calculated linearly by means of strip theory. The surge motion is simulated assuming a hydrostatic pressure distribution under the water surface for the determination of the surge–inducing wave forces. While the roll motion is simulated non–linearly using the following equation:

\[
\dot{\phi} = \frac{M_{\text{wind}} + M_{\text{sw}} + M_{\text{wave}} + M_{\text{tank}} - M_d - m \left(g - \ddot{\zeta}\right) h_s}{I_{xx} - I_{xc} \left(\psi \sin \varphi + \dot{\vartheta} \cos \varphi\right)}
\]

(3)

where \(M_{\text{wind}}, M_{\text{sw}}, M_{\text{wave}}\) and \(M_{\text{tank}}\) are the roll moments due to wind, sway and yaw, waves and fluid in tanks and flooded compartments, respectively. \(M_d\) is the non–linear damping moment using damping coefficients following Blume [15]. \(\varphi, \vartheta\) and \(\psi\) are the roll, pitch and yaw angles, respectively, while \(m\) is the mass of the ship and \(g\) the gravitational acceleration. The righting arm in the seaway \(h_s\) is determined for every time step using Grim’s effective wave [16] as modified by Söding [14]. \(I_{xx}\) and \(I_{xc}\) are the moment of inertia about the longitudinal axis and the product of inertia, respectively, calculated for the actual mass distribution (light ship and cargo).

The numerical code E4ROLLS was extensively validated during three consecutive German BMWI funded research projects: ROLLS, SINSEE and LASSE. A good overview about these validations is given by Hennig [4]. As an example, fig. 5, bottom, shows the comparison of the computed and the measured roll amplitude and wave elevation at midships of a model test in tailored wave sequences [4]. The comparison shows reasonable agreement, which is a proof that the numerical code is able to compute the roll motion with appropriate accuracy. Such validations are quite complex, as the two time series on top demonstrate: There, two realizations of the same model test parameters are shown [4]. The wave signal at midships is perfectly reproduced, but the roll response differs slightly towards the end of the run: In one sequence the ship capsized, in the other, it did not. It is obvious that such kind of validations must be performed very carefully.

Short crested seas

In a typical model basin, only long crested waves can be generated. This is due to the configuration of the wave maker. This is sometimes a problem to get the roll motion started \(^6\). During all the experiments we conducted it was found that for some ships it was possible to initiate the roll motion from the initial disturbance present during the model tests. This does practically mean that a slight course deviation of about 3-5 degree from the wave direction was sufficient to generate a sufficient roll moment to start a roll motion. On the other hand, the course deviation should be as small as possible to allow a maximum distance traveled in the tank before a rudder manoeuvre is required. For other ships tested during the program it was hardly possible to get the roll motion started from this initial disturbance and the ship did consequently not capsize. If that disturbance was increased, the roll motion got started and the ship capsized. This observation is important as it is an indication for the fact that long crested waves are not necessarily conservative with respect to capsizing. Short crested waves always provide sufficient transversal disturbances to get a roll motion started, and from this it can be concluded that the direct assessment of ship motions must take place in irregular and short crested sea state realizations. As the numerical code E4ROLLS uses Grim’s effective wave concept, the compu-

\(^6\) All findings etc. refer to irregular waves, as regular wave do not represent the worst case with respect to capsizing (in following seas).
tation is independent from the complexity of the seastate realization, and consequently we analyze ship motions always in short crested irregular seas. This is nicely illustrated in fig. 6. The polar diagram shows the limiting significant wave height computed for a capsize. The radial axis shows the ship speed, the circumferential the encounter angle. The left polar is computed for long crested waves (model test condition), the right polar diagram for short crested seas (both JONSWAP-spectrum, $T_1 = 10.5s, \cos^2$ distribution is assumed for the short crested waves). It can nicely be observed that in long crested waves, the ship is only endangered in a stripe of about 45 degree in following seas. Here, the deviation to the wave propagation direction is sufficient to start a roll motion and capsize the ship. This was not possible in the model tests due to restrictions in the beam of the tank. The short crested waves provide sufficient energy in transversal direction to start the roll motion and capsize the ship.

Influence of Stability

The time series computed by E4ROLLS for different parameters $T_1$ and $H_{1/3}$ can be evaluated according to different failure criteria, and if the calculations are repeated for different significant wave heights, the significant wave height can be adjusted in such a way that the selected failure criterion is met. Most useful has been either to directly compute capsizing frequencies in artificially amplified wave heights according to Söding [17] or to compute the so-called Blume-criterion [18], [1]. These computations can be repeated for several course and speed combinations to obtain polar plots for this so called limiting significant wave height. If the stability of the ship is also subject to variation, these computations can be performed for a series of stability values. The results of such computations performed for the reference ship are shown in fig. 7. The left side of the polar shows the computations for the stability situation according to the rules. Further, some model test situations are also plotted in the diagram. The computations show that the ship may capsize in following seas at low speeds close the very distinct 2:1 resonance. In short crested waves, the computations also indicate that the ship may capsize if a 1:1 resonance in following seas is met. In head seas, the computations indicate no problem beyond a certain critical speed. These computations refer to the stability situation 1m of GM according to the rules. The situation looks very different if the stability is increased to 1.40m (right polar diagram). The critical situations have more or less disappeared and the significant wave heights required for a capsize are shifted to values that are rare for this significant period. The comparison shows the well known fact that small increases in stability have a large impact on the safety of the ship.

**Stability Limit Curves**

The total long term probability that for a specific stability situation a dangerous situation will occur can be defined by the insufficient stability event index (ISEI), which is given by the following equation:

$$ISEI = \int_{T_1=0}^{\infty} \int_{H_{1/3}=0}^{\infty} \int_{\mu=-\pi}^{\pi} \int_{v_s=V_{min}}^{V_{max}} p_{sea}(H_{1/3}, T_1) \cdot$$

$$p_{dang}(H_{1/3}, T_1, \mu, v_s) \cdot dv_s \cdot d\mu \cdot dH_{1/3} \cdot dT_1$$

(4)

where $p_{sea}$ means the two dimensional probability density for the seastate characterized by the significant height $H_{1/3}$ and period $T_1$, and $p_{dang}$ means the probability that this stability condition may lead to a dangerous situation in the seastate given by $H_{1/3}$ and $T_1$. This probability $p_{dang}$ can be written as follows:

$$p_{dang}(H_{1/3}, T_1, \mu, v_s) = p_{fail}(H_{1/3}, T_1, \mu, v_s) \cdot p_{\mu}(\mu) \cdot$$

$$p_v(H_{1/3}, T_1, \mu, v_s)$$

(5)
In this equation, \( p_{\mu}(H_{1/3}, T_1, \mu, v_s) \) denotes the probability that the course leading to the encounter angle \( \mu \) is actually sailed. \( p_v(H_{1/3}, T_1, \mu, v_s) \) denotes the probability that the ship speed \( v_s \) of that situation is actually traveled. From the same numerical results that have been used to plot the polar diagrams, \( p_{\text{lang}} \) can be computed, see Kluwe [1]. Consequently, the ISEI can then be computed as a function of \( GM_{\text{req}} \). If a limiting value for the ISEI is known, this results in a minimum GM requirement. It has been shown by systematic evaluation of full scale accidents [19], that a limiting value of 1.E−3 for this index is roughly equivalent to the existing stability criteria when they are applied to those ships they have been intended for. This additional requirement - which may be seen as a kind of level 3 assessment - has lead to the increased stability limits of the reference ships as shown in fig. 2. It should be noted that neither the level 1 criteria reflect these findings nor the level 2 criteria, a fact which makes it necessary to implement the direct stability assessment. It should also be noted that it could be a problem from statutory point of view if the level 1 or level 2 criteria assign problems to a specific ship design which in fact not the ship has, but only the criteria. And the minimum stability values attained by the criteria should be preferably below such stability values where high lateral accelerations are to be expected.

CONCLUSION

The second generation of intact stability criteria have been applied to a RoRo ship design where a direct stability assessment has been carried out. For this particular reference ship the direct assessment - computations and model tests - have shown that stability according to the existing stability criteria is not sufficient. The application of the new stability criteria for parametric rolling and pure loss was challenging, as it was difficult to compute the necessary \( GM_{\text{req}} \)-curves. It is at present unclear whether these difficulties can be overcome. More challenging was the absolute level of stability computed for our reference ship: The stability required by the new criteria was drastically higher compared to the direct assessment. Formally, this is in line with the general concept of the criteria. The level 1 and level 2 showed consistency as well, because level one requires more stability than level 2. But even for the least conservative formulation, the stability computed from level 1 and 2 was that high that excessive accelerations will occur. And a minimum stability requirement should not lead to stability values that are above the level of maximum requirements.

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