Abstract

The existing intact stability criteria (2008 IS-Code) of IMO 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 of Intact Stability Criteria shall ensure sufficient dynamic stability. We have applied the criteria to a reference ship whose stability was precisely assessed during the design by model tests and seakeeping simulations. Curves for the required GM of the ship have been calculated for the criteria. The results showed large scatter in the accuracy of the particular criteria. Compared to the direct assessment, some criteria could assess reasonable stability values and some could not. The fact that some criteria were not able to identify unsafe stability values clearly shows why a criterion based on direct assessment is urgently required before the first two levels can enter into force.

Keywords

Stability criteria; intact stability; parametric rolling; pure loss of stability; stability assessment

Introduction

In 2008, the Maritime Safety Committee of the International Maritime Organization (IMO) adopted the International Code on Intact Stability (2008 IS Code). Already at that time, it was recognized that the adopted criteria do not provide sufficient safety against all types of stability failures. Therefore, IMO documented the necessity for criteria improvement and further research in the preamble of the 2008 IS Code. As a result, the IMO Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety (SLF) began to develop new criteria which shall better take into account the following phenomena in rough weather:

a) Dead ship condition in beam seas
b) Surfriding and broaching-to
c) Parametric rolling
d) Pure loss of stability

Several criteria drafts have been developed for these failure modes, and finalization of the new criteria by adoption to part B of the 2008 IS-Code is planned in the near future (Kobyliński 2012). The adoption of the new criteria will have a strong impact on RoRo–ship designs because these ship types have particularly been found vulnerable to dynamic stability failures in rough weather. Modern RoRo-designs usually have wide and flat stems and high beam to draft ratios which lead to strong stability alterations and substantial decrease of stability in certain wave conditions. To exemplify this impact, a test case has been created in which the Second Generation of Intact Stability Criteria is applied to a representative RoRo-ship design. This RoRo-ship design is in so far quite interesting as it has been intensively investigated during several research projects. During these investigations it was found that the existing stability criteria were not sufficient for the RoRo-ship design and computations showed a substantial risk of capsizing if the ship would operate at the existing stability limit. In addition, intense model tests in tailored wave sequences were conducted and it was indeed found that the ship could capsize if it was operated at the stability limit of the existing criteria. As a result, a direct stability assessment – including further model tests and seakeeping simulations - was performed by the shipyard to investigate the level of stability which was to put on top of the existing criteria to ensure safe operation.

In summary, two outcomes of the research projects are in particular relevant. First, the existing criteria fail to assess the stability of the reference RoRo-ship which attests the vulnerability of the design to some types of dynamic stability failures. Second, the amount of sufficient stability for safe operation in rough weather 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. Moreover, the mentioned outcomes emphasize the necessity for improved intact stability criteria and its relevance for future RoRo-ship designs.

1 The stability limit for one of these designs was in fact governed by the intact stability criteria and not by the damage stability criteria 1 which underlined the fact that the existing stability criteria were not sufficient for some ship types.
This paper describes the application of the Second Generation of Intact Stability Criteria and its impact on RoRo-ship designs in the following order. First, the current drafts of the Second Generation of Intact Stability Criteria are described briefly. Second, the reference RoRo-ship is presented and the inability of existing criteria to assess the stability is shown. In addition, the process of deriving the amount of sufficient stability from a direct assessment, which is crucial for this benchmark, is described. For this purpose, the method of the Insufficient Stability Event Index (ISEI) by Kluwe (2009) is used and explained briefly.

The 2nd Generation of Intact Stability Criteria

Overview and Structure

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 phenomena 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 three level approach is introduced for every failure mode mentioned above. As it is indicated in red in fig. 1, we focus this study on the level 1 and 2 criteria for parametric rolling and pure loss of stability.

![Simplified structure of 2nd Generation of Intact Stability Criteria](image1)

The criteria are applied to the test ship according to the latest definition within the IMO SLF proposal 54/19 (IMO, 2012) All updates of SLF55 in February 2013 are considered as well. According to the latest definition, some details of the criteria are still under discussion. Thus, there exist different proposals or slightly different versions of the same criteria. Therefore, this section is not only a brief description of the criteria but a selection of available criteria options as well.

Parametric Rolling Criteria

Level 1: According to the level 1 criterion, a ship is considered vulnerable to parametric rolling if the ratio of GM alteration due to waves to the GM in calm water exceeds a certain limit. There exist the following two options for the permissible limit $R_{PR}$:

\[ R_{PR} = 0.5 \] (1)

\[ R_{PR} = 0.17 + (2.125 \cdot C_m - 1.7) \cdot \frac{100 \cdot A_{bk}}{L^3} \] (2)

Here, $C_m$, $A_{bk}$, L and B denote midship coefficient, bilge keel area, length and breadth of the ship. The GM alterations are calculated for the ship in longitudinal sinusoidal waves. The wave length $\lambda$ is chosen equal to ship length $L$ and the wave height is determined by a given wave steepness $S_w$ of 0.0167.

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 midship position are considered. In a second simplification, the waterline moments of inertia in crest and trough condition are approximated by the moment of inertia of the calm waterline at two different drafts (see fig. 2). 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.

![Waterline of the reference ship at smaller and larger draft](image2)

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 GM variation in a series of longitudinal sinusoidal waves. The wave series is a simple discretization of a wave spectrum and consists of 16 waves within a wave length range from 22 m to 631 m. Both GM variation and GM average are calculated with the true sinusoidal waterline at different wave positions and balanced trim and sinkage. Each particular wave condition of the wave series is assessed by two criteria based on average and variation of GM. After assessing each particular wave

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2 In this study we only use the limit given by eq. (1), because for the reference ship the limit given by eq. (2) is between 0.46 and 0.51 which results in very similar GM-requirements.
case, a weighted average according to the probability of the wave cases is calculated and compared to a limit $R_{PRI}$ of 0.1. If the weighted average exceeds this limit, the first check considers the ship as vulnerable to parametric rolling. 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 exceeds the level 1 limit of 0.5 or if the average metacentric height becomes negative. The second criterion is violated if the design speed of the ship exceeds the resonance speed $V_{PRI}$. At this speed, 2:1 parametric resonance occurs because the average natural roll period is exactly half the wave encounter frequency. The resonance speed $V_{PRI}$ is calculated for the particular wave by eq. (3).

$$V_{PRI} = \frac{2H}{T_g} \sqrt{\frac{GM(H/\lambda_i)}{6GM}} - \sqrt{\frac{2H}{2GM}}$$

The second check assesses the roll motion in head and following seas for a range of operational speeds. This check considers the ship as vulnerable to parametric rolling if a failure index given by a weighted average of 306 wave cases exceeds a limit of 0.25. For each wave case, the failure index is 1 if the rolling angle exceeds 25 degrees and 0 otherwise. Three methods are proposed to obtain this rolling angle from an equation of uncoupled roll motion.

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 partial equation using numerical simulation technique in time domain. The second option is a steady state solution of the parabolic partial equation using numerical simulation technique in time domain. The second option is a steady state solution of the parabolic partial equation using numerical simulation technique in time domain.

The third option is a numerical steady state solution of the uncoupled roll motion.

In all 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 Kawai and Maki (2011). 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 (2011).

**Pure Loss of Stability**

Both level 1 and level 2 only need to be applied if the service speed Froude number exceeds a certain limit between 0.2 and 0.31. This range indicates that the limit has not been fixed yet. Nevertheless, we applied the criteria to the reference ship having a 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 limit which depends on the draft $d$ and the maximum operational Froude number $F_n$:

$$GM_{\text{min, req}} = \min(1.83 \times d \times F_n^2, 0.05m)$$

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 SLF54/19 the 16 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 angle of vanishing stability must be greater than 30 degree. The minimum angle of loll must not exceed 25 degree. The smallest maximum GZ must not be less than 8(H/\lambda_i) \times d \times 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 limit of 0.06.

**The Reference Ship**

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. 3), and consequently, RoRo-ships are in principle sensitive to any phenomenon that is connected to righting lever alterations in head or following seas (Billerbeck et al., 2010).

Therefore, this ship design is a typical RoRo-freight ferry design and was (among others) chosen as reference ships for the German BMWI-funded research program SINSEE (Billerbeck et al., 2005) 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 as well as the validation of numerical seakeeping codes for the prediction of large roll amplitudes (Hennig et al., 2006). 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. 4). 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:

1. 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.
2. 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.
3. The ship did also never capsize in regular seas.
4. The ship was endangered in irregular seas where the significant period T1 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.
5. 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.
6. 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 GMreq-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. 4).

According to the existing stability criteria, GM value of about 1m (at FS draft), and this is not sufficient. As a matter of fact, the ships ship design included a roll

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3 German Federal Ministry of Economics and Technology
4 Similar experiences were made with other ships tested during the program.
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.  

5 Today, all ships designed and built by FSG have this voluntary stability standard, which is called the ISEI-standard (Insufficient Stability Event Index).

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. The computed GM-required curves are shown in fig. 6. As shown here, the required metacentric height to fulfill both level 1 criteria is more than 3 m for the entire range of operational drafts. Both criteria 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 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 pure loss of stability criterion is about shown in fig. 7. It is about 1.5 m to 1.8 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. At the larger drafts, the criterion requires a GM about 1.5 m. Compared to the required GM of 1.4 m by the direct assessment, this is a very good but still consistent agreement. Considering the simplifications of the level 2 criterion for pure loss of stability, this is a very accurate and excellent stability assessment of the level 2 criterion.

The GM-required curve for the parametric rolling level 2 criterion is shown in fig. 8. At drafts above the design draft about 7 m, the criterion 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 GM_{req}-values are not acceptable from operational point of view. At drafts slightly below the design draft, the criterion requires less stability than the direct assessment. This is inconsistent and shows how the criterion fails to avoid unsafe loading conditions. Moreover, the jump of the curve at a draft about 7 m is not a result of the physical model behind the criterion but a consequence of the polynomial fitting procedure of the leverarm curve which is required for the criterion. At lower drafts, the leverarm curve can accurately enough described by a polynomial of 5th order. At higher drafts,
this is not the case for smaller GM values and consequently the criterion can only be fulfilled for GM values above 2m. According to the structure of the criteria, the level 2 criteria for both, parametric rolling and pure loss of stability must be fulfilled. Due to this fact, the overall GM-required curve is the maximum envelope of both curves. In this envelope, the failure of the parametric rolling criterion due to polynomial fit is still included and relevant.

The Direct Stability Assessment

The limiting stability curves of the second generation of stability criteria were compared to the curves of existing criteria and the curve of a direct stability assessment (fig. 6,7,8). To obtain the latter limiting stability curve, a certain procedure is required. This procedure is described in the following section.

General

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

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

The results of the direct assessment showed that the ship design was considered to be safe if the GM was about 1.40m. Unfortunately, this is neither reflected by the first level of 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 at the Institut fuer Schiffbau, University of Hamburg (Söding 1987). ’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:

\[
\phi = \frac{M_{\text{wind}} + M_{\text{sys}} + M_{\text{wave}} + M_{\text{tank}} + M_{\text{m}} - m (g - \ddot{z}) h_{x}}{I_{xx} - I_{zx} (\ddot{\psi} + \ddot{\phi} \cos \varphi) - I_{zx} (\ddot{\theta} + \ddot{\phi}^2) \sin \varphi} - \frac{m g - (\ddot{\psi} + \ddot{\phi}^2) \cos \varphi}{I_{xx} - I_{zx} (\ddot{\psi} + \ddot{\phi} \cos \varphi)}
\]

where \( M_{\text{wind}} \), \( M_{\text{sys}} \), \( M_{\text{wave}} \) and \( M_{\text{tank}} \) are the roll moments due to wind, sway and yaw, waves and fluid in tanks and flooded compartments, respectively. \( M_{\text{m}} \) is the non–linear damping moment using damping coefficients following Blume (1979). \( \varphi \), \( \theta \) and \( y \) 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 \( h_{x} \) is determined for every time step using Grim’s effective wave (Grim 1961) as modified by Söding (1987). \( I_{xx} \) and \( I_{zx} \) 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).

Fig. 8: GM-required curves for the reference ship including the curve for the Second Generation of Intact Stability Criteria.

Fig. 9: Time history for the wave elevation midships and the roll angle. Top: Two Realizations of a model test. Bottom: Comparison between model test and computation (Hennig et al. 2006).
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 et al. (2006). As an example, fig. 9, bottom, shows the comparison of the computed and the measure roll amplitude and wave elevation at midships of a model test in tailored wave sequences (Hennig et al. 2006). 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 (Hennig et al. 2006). 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 maneuver 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 computation 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. 10. 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.

\(^6\) All findings etc. refer to irregular waves, as regular wave do not represent the worst case with respect to capsizing (in following seas).
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:

\[
ISEI = \int_{T_1=0}^{T_1=0} \int_{H_{1/3}=0}^{H_{1/3}=0} f(H_{1/3}, T_1) \cdot p_{\text{dang}}(H_{1/3}, T_1, \mu, v_s) \cdot \text{d}H_{1/3} \cdot \text{d}T_1
\]

where \( p_{\text{dang}} \) means the two dimensional probability density for the seastate characterized by the significant height \( H_{1/3} \) and period \( T_1 \), and \( p_{\text{dang}} \) 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 \( p_{\text{dang}} \) can be written as follows:

\[
p_{\text{dang}}(H_{1/3}, T_1, \mu, v_s) = p_{\text{rad}}(H_{1/3}, T_1, \mu, v_s) \cdot p_{\mu}(\mu) \cdot p_{\text{r}}(H_{1/3}, T_1, \mu, v_s)
\]

In this equation, \( p_{\text{rad}}(H_{1/3}, T_1, \mu, v_s) \) denotes the probability that the course leading to the encounter angle \( \alpha \) is actually sailed. \( p_{\mu}(H_{1/3}, T_1, \mu, v_s) \) 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, \( p_{\text{dang}} \) can be computed, see Kluwe (2009). Consequently, the ISEI can then be computed as a function of GM_{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 (Krüger and Kluwe 2010) that a limiting value of 10E-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 led to the increased stability limits of the reference ships as shown in fig. 5. It should be noted that neither the level 1 criteria reflect these findings nor the level 2 criteria, a fact which makes is 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. Therefore, the RoRo-ship design presented in this study was identified as a benchmark case for criteria regarding parametric rolling and pure loss of stability. For these failure modes, the 2nd Generation of Intact Stability Criteria was applied to the ship. Compared to the direct assessment, the stability required by the new criteria was drastically higher. 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. However, the stability computed from level 1 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. To compare the results of the new criteria to other state-of-the-art stability assessments, the safety standard ISEI by Kluwe (2009) has been presented and applied to the benchmark ship. In its simplified formulation, the ISEI requires similar computational effort as a level 2 criterion but has shown a more accurate stability assessment.

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