On the application of the 2nd Generation Intact Stability Criteria to Ro-Pax and Container Vessels

Stefan Krueger, Hannes Hatecke

Hamburg University of Technology, Germany

Paola Gualeni, Luca Di Donato

University of Genoa, Italy

ABSTRACT

A new set of intact stability criteria is under development at IMO with the aim to address the stability failures of a ship in a seaway. These criteria are structured in a three level approach. The first two levels consist of calculations characterized by different levels of accuracy. The third level is named "direct assessment" and typically a numerical tool for hydrodynamics calculations is envisaged for the assessment. However, at present no criteria or procedures have been developed for this third level.

In the various scenarios of modern merchant ships, Ro Ro-Passenger vessels represent a very interesting field of investigation for intact stability vulnerability assessment especially for the righting lever variations in waves. For the specific stability failures of parametric roll and pure loss of stability, in the present paper, we apply the 2nd Generation of Intact Stability Criteria to some typical Ro Ro-Passenger ferries and results are presented in terms of computed curves of minimum required GM. We have also carried out a direct assessment of the stability using the "Insufficient Stability Event Index" (ISEI- concept) and compared the obtained GMReq – curves.

This comprehensive investigation has the purpose to assess the reliability of the newly proposed criteria as technically consistent and harmonized safety rules.

To this aim the investigation domain has been enhanced to the cargo ships field, in particular considering three selected containerships that have suffered serious accidents in a heavy seaway.

Keywords: *Intact stability failure modes, direct assessment, GM required curves, safety level.*

1. INTRODUCTION

In the latest years, under the specific agenda item named "second-generation intact-stability criteria," IMO has been active on the development of vulnerability criteria for the assessment of ship behaviour in a seaway. The importance of this issues is already pointed out in the Preamble of the Intact Stability code (2008): "It was recognized that in view of a wide variety of types, sizes of ships and their operating and environmental conditions, problems of safety against accidents related to stability have generally not yet been solved. In particular, the safety of a ship in a seaway involves complex hydrodynamic phenomena which up to now have not been fully investigated and understood"

Among the failure modes recognised by the IMO are:

-Pure loss of stability
-Parametric roll
-Dead ship condition in beam seas
-Surf-riding and broaching-to

Only the first two are faced in the present investigation, in the specific field of Ro-Pax ships. For a larger perspective on the subject, also three Container vessels` behaviour has been analysed.

If a ship is susceptible to a stability failure that is neither explicitly nor properly covered by the existing intact stability regulations, the ship is regarded as an "unconventional ship" in terms of that particular stability failure mode.

"Second-generation intact-stability criteria" are based on a multi-tiered assessment approach: for a given ship design, each stability failure mode is evaluated relying on two levels of vulnerability assessment, characterized by different levels of accuracy and computational effort.

A ship which fails to comply with the first level is assessed at the second-level criteria. In turn, if unacceptable results are found again, the vessel must then be examined by means of a direct assessment procedure based on tools and methodologies corresponding to the best state-of-the-art prediction methods in the field of ship-capsizing prediction. This third-level criteria should be as close to the physics of capsizing as practically possible.

Direct assessment procedures for stability failure are intended to employ the most advanced technology available, ant to be sufficiently practical to be uniformly applied, verified, validated, and approved using currently available infrastructure. Ship motions in waves, used for assessment on stability performance, can be reproduced by means of numerical simulations or model tests.

Where model tests have the disadvantage that investigations in short crested, irregular seas are hardly possible.

Calculations performed in the current work are structured in three phases.

First, all the ships are judged with the mandatory intact stability regulation (IS Code, 2008), in order to define the safety level at present. Then a direct assessment is performed by means of non-linear time domain, computations, able to compute the so called "insufficient stability event index" (ISEI). A more thorough description of ISEI is given in the next paragraphs. Following the above mentioned calculations, GMReq sets of values are obtained from both the IS code criteria (usually for Ro-Pax corresponds to the Weather Criterion) and the direct assessment method. A gap, in terms of GMReq , between the two approaches is the obtained result, as it could be expected.

At this point the Second Generation Intact Stability Criteria are introduced to complete the outline of the situation.

The aim of this work is to show how suitably the new stability requirements apply in addressing parametric roll and pure loss problems, filling the range between the mandatory and the numerically simulated stability safety level. In the following the structure of the new criteria is explained, as well as a description of the direct assessment methodology. Finally, results for the case studies are presented and properly discussed.

2. 2ND GENERATION INTACT STABILITY CRITERIA

In this work the IMO document used for the calculations is the SDC 1 Inf. 8 with the updates of the SDC/ISCG of the latest months. All the amendments have been implemented in the ship design software package E4 of the

Hamburg University of Technology, developed in Fortran90 language.

In the following the first two levels of vulnerability criteria, for the specific failure modes of Parametric roll and Pure Loss of stability, are briefly explained.

2.1 Level 1 Vulnerability Criteria

The first level consists of simple formulae based on the ship hydrostatics and regards the GM sensitiveness to waterline variation due to wave profile. In fact, as an effect of a wave passing the ship, the lever arm as well as the metacentric height will face a change due to the modification of the water plane area and the immersed volume distribution, considering the ship to be balanced in sinkage and trim. It is recognized that most of the times the worse situation in terms of stability is represented by the wave crest situated amidships.

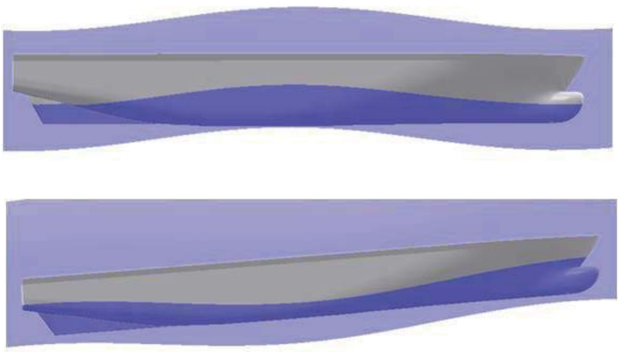

Figure 1: Wave with the length of the ship with crest and trough located at amidships.

Parametric Roll: A ship is vulnerable to parametric roll, according to level 1, if the ratio between the amplitude of the GM variation in waves and the GM in still water is less than a certain value. The formula reads as follows:

$$\frac{\Delta GM}{GM} \leq R_{PR}$$

Where Rpr is taken as 0.5 or as a value function of the midship section coefficient Cm and the bilge keel area, whichever is the less. Longitudinal sinusoidal waves with a length λ and steepness Sw of 0.0167 are taken for the calculation of the ΔGM. The wave crest is centred at the longitudinal centre of gravity at each 0.1 forward and aft thereof.

Pure loss of stability: For cases with speed corresponding to Froude number of significantly high values (in the draft proposal threshold value for example 0.31), a ship is considered potentially dangerous to this phenomenon. In such case the criterion reads as follows:

$$GM_{MIN} > R_{PLA}$$

GMMIN is the minimum value of the metacentric height as a longitudinal wave passes the ship. It has been observed that the most critical situation is quite often presenting the wave crest in the surrounding of the amidships longitudinal position. RPLA is defined as: min(1.83 d (Fn)2 , 0.05) , with d the draft of the loading condition under consideration. The wave length considered to compute the GM is the same of the ship length and the steepness in this case is 0.0334 (the double of the one applied for parametric roll).

2.2 Level 2 Vulnerability Criteria

The compliance with the first level is in principle always possible provided that the sufficient (usually high) level of stability (for example in terms of GM) is met. One of the reasons for that could be also the conservative approach of the described formulae (i.e. the high safety margin implied). To this regard it is worth mentioning that a very high GM value might imply also some shortcomings and recently at IMO attention has also been given to the issue of excessive accelerations. It should also be mentioned that unrealistically high values of GM pose a severe burden to the design of the ship.

Therefore for both parametric roll and pure loss more complex formulations are needed in order to get a more realistic stability level. The way to gain this target consists basically of developing an averaged assessment on a larger set of environment conditions. For the purpose of this paper a series of longitudinal sinusoidal waves (proposed as an option in the draft rule text) from a length λ of 22m to 630m are used for the computation of a weighted average.

Parametric Roll: The first check the ship has to pass requires that the weighted average among all the wave cases is less than a certain value RPR (in our case 0.1).

$$\frac{\Delta \mathrm{GM}(\mathrm{H_i}, \lambda_\mathrm{i})}{\overline{\mathrm{GM}}(\mathrm{H_i}, \lambda_\mathrm{i})} < \mathrm{R_{PR}}$$

At the same time it is also requested that:

$$V_{PRI} < V_D$$

Therefore, besides that check on GM also the design speed VD of the ship shall not exceed the resonance speed VPRI.

Moreover, if this check is not overcome, the roll motion has to be assessed in head and following seas for a range of operational speeds. Different options are possible for this computation: a numerical transient solution, an analytical steady state solution or a numerical steady state solution. In this work the second option has been attempted using the updated formula of the working group when the 5th degree polynomial fitting of the righting lever curve was not precise enough. No satisfactory results have been obtained with this approach, therefore we considered the first check as the only possible requirement in the evaluation of the GM required curves. It should in this context be mentioned that if the criteria will be made mandatory, it must be guaranteed that they are numerically stable.

Pure loss of stability: The same wave cases, with double of the steepness are applied for this second level. Three criteria have to be assessed, addressing the issues of a limit for the vanishing stability angle, for the maximum loll angle and for the maximum value of the righting arm. For the angle parameters we applied the proposed standards of 30 degrees, 25 degrees respectively. The standard value for the criterion addressing the maximum righting arm is expressed as a function of wave steepness, Fn, and ship draft.

3. DIRECT ASSESSMENT

As already mentioned, if the ship is found to be vulnerable under the first two levels (or more realistically, if the GMReq in order to comply with is too high), a direct assessment is required, possibly related with the quantification of a capsizing risk. No rules are actually available for this procedure, therefore the numerical tool E4ROLLS, developed by Söding Kroeger and Petey provided by the Hamburg University of Technology, has been applied. With this tool, the 6-DOF motion of the ship is computed in an irregular short-crested seaways. While heave, pitch, sway and yaw are computed by means of strip theory in the frequency domain, roll and surge, due to their nonlinear nature, are determined in the time domain.

For the roll motion the following equation has been used (Kröger 1987):

$$\ddot{\varphi} = \frac{M_{wind} + M_{sy} + M_{wave} + M_{tank} - M_d - m(g - \ddot{\zeta})\mathrm{h_s}}{I_{xx} - I_{xz}(\psi sin\varphi + \vartheta cos\varphi)} + \frac{I_{xz[(\ddot{\vartheta}+\vartheta\dot{\varphi}^2)sin\varphi-(\ddot{\psi}+\psi\dot{\varphi}^2)cos\varphi]}}{I_{xx}-I_{xz}(\psi sin\varphi+\vartheta cos\varphi)} -$$

here Mwind , Msy, Mwave and Mtank are the moments due to wind, sway, waves and fluid in tanks respectively. The damping is considered in Md and the restoring moment in the term hs, representing the restoring arm in the seaway according to the Grim's concept of the equivalent wave modified by Söding. Ixx and Ixz are the moments of inertia around the longitudinal axis and the product of inertia, respectively, calculated for the actual mass distribution, introduced for the yaw moment influence. As a result of the calculations, a polar plot produced by a computation can be represented for example in figure 2. The diagram is characterized by representative wave length (and period as well), different speed on each circle, different encounter angles and wave height (coloured). All calculations are carried out for short crested irregular seas. The limiting significant wave height which identifies a situation as dangerous derives either from the Blume criterion or from a maximum roll angle of 50 degrees, whichever is the less:

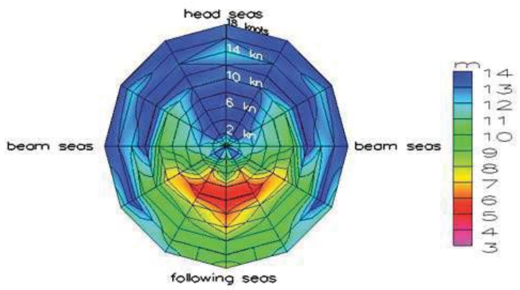

Figure 2: Polar Plot for a single significant wave period Each colour represents the limiting significant wave height.

To determine if the loading condition under analysis is safe or not, the direct assessment makes use of the ISEI concept. The Insufficient Stability Event Index, developed by Krueger and Kluwe , gives a failure index in terms of long term prediction:

$$ISEI = \int_{T_1=0}^{\infty}\int_{H_{1/3}}^{\infty}\int_{\mu=-\pi}^{\pi}\int_{v_s}^{v_{max}} p_{sea}(H_{1/3},T_1)\cdot$$
$$\cdot\, p_{dang}(H_{1/3},T_1,\mu,v_s)\cdot dv_s\cdot d\mu\cdot dH_{1/3}\cdot dT_1$$

Here psea represents the environmental context by means of a two dimensional probability density function for a sea-state characterized by significant height H1/3 and period T1, whereas pdang denotes the probability that the stability condition under consideration is dangerous in the current seastate, using the two failure criteria mentioned before.

Psea is taken from the North Atlantic Area according to the Global Seaway Statistics by Söding.

The limit between the safe and the unsafe situation is defined by the threshold value of the index 1·10-3 . Six wave periods are typically used for each calculation which should be arranged around the period representing a wave length corresponding to ship length.

4. APPLICATION CASES

For the investigation, four Ro-Pax of significantly different geometry are analysed. For each ship the main dimensions are shown below.

RoPax 1

Lpp [m]	171
B [m]	27
T [m]	6.6
V [kn]	23

Table 1: Main dimensions of RoPax1

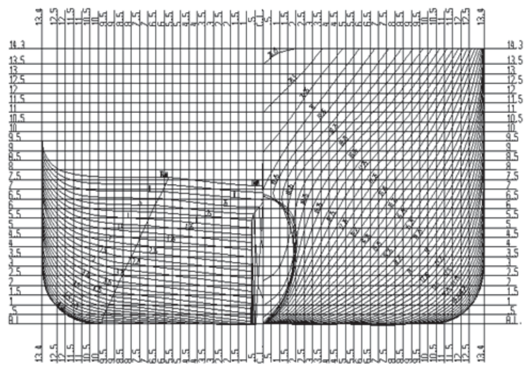

Figure 3: Body plan of the RoPax1

RoPax 2

Lpp [m]	186
B [m]	30
T [m]	7.8
V [kn]	25

Table 2: Main dimensions of RoPax2

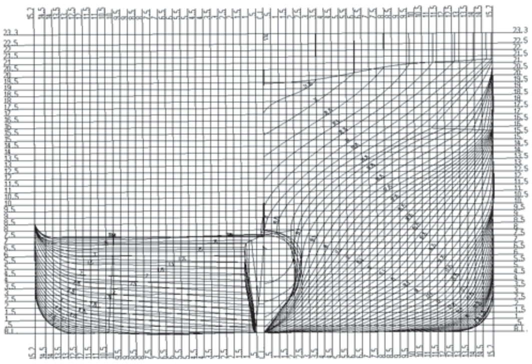

Figure 4: Bodyplan of the RoPax 2

RoPax 3

Lpp [m]	110
B [m]	15
T [m]	6
V [kn]	25

Table 3: Main dimensions of RoPax3

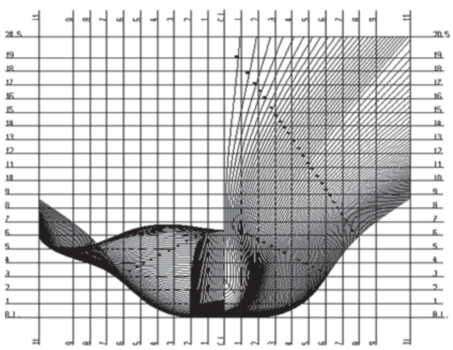

Figure 5: Body plan of the RoPax 3

RoPax 4

Lpp [m]	156
B [m]	19
T [m]	6.86
V [kn]	17
GM accident [m]	1.691

Table 4: Main dimensions of RoPax4

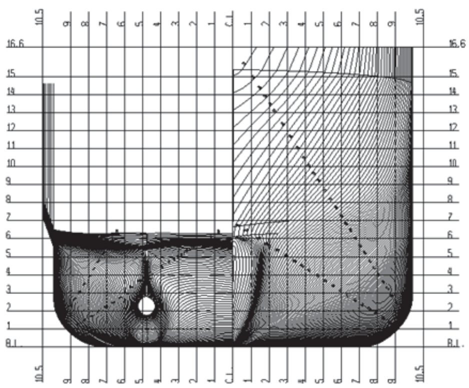

Figure 6: Bodyplan of RoPax4

This last Ropax4 ship has a geometry which has experienced a capsizing due to the dynamic phenomena studied by the new criteria. It has been analysed in order to check if the two levels of parametric roll and pure loss of stability recognize a stability problem at the loading condition of the accident.

5. CALCULATIONS AND RESULTS

General procedure

As mentioned before, three calculation phases are covered to obtain all the final results useful for the comparison purposes, aim of this paper:

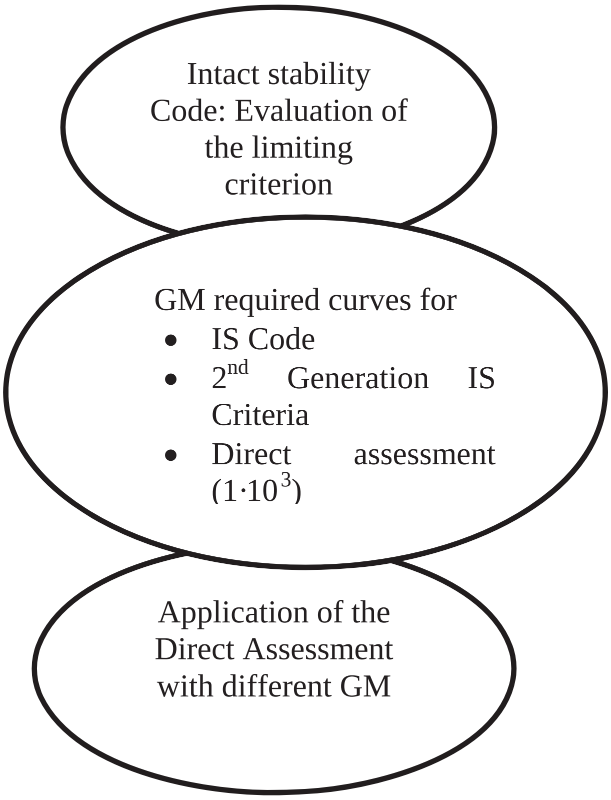

Figure 7: Procedure adopted

As a general comment, it is worth mentioning that usually the limiting GM for a RoRo passenger ferry, neglecting the damage condition, is represented by the weather criterion. With E4ROLLS this GMReq- value is compared with the results obtained by the ISEI concept. Beyond the level 1 of Parametric Roll and Pure Loss of Stability, very conservative, the level 2 is the one in charge to smoothly converge to the direct assessment GM requirements.

RoPax 1

As already mentioned, at first the limiting GM curve with reference to IS Code has been identified. At the design draft this ferry fulfils the weather criterion, with a GM of 0.8m. At this loading condition the direct assessment has been applied, showing an insufficient stability in following seas. This is evident from the polar plot representation and quantitatively by the ISEI value higher than the 10-3.

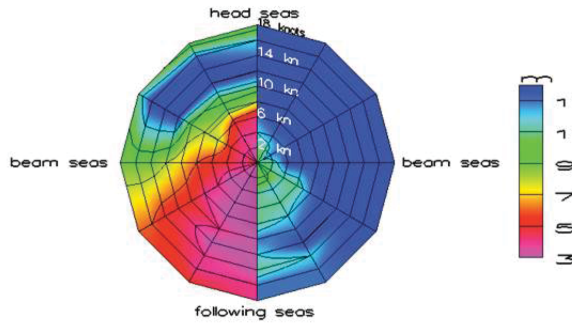

Figure 8 Two polar plots for limiting capsizing wave height for a wave length of 172m. Left: GM=0.8m Right: GM=1.9m

After few iterations, a value of ISEI of 1·10-3 is found at a GM of 1.9m, more than one meter increment compared to the present regulations. In figure 8 results are reported for calculations performed at both GM values (GM= 0.8 m left, GM= 1.9 m right). It can be observed that the ship faces already several problems in following seas with wave heights of 3m for the GM required by the weather criterion (0.8m). From a direct assessment, there isn't any sharp boundary between a parametric roll and a pure loss of stability failure; each dangerous situation is often a combination of both. The GMReq curves read as follows:

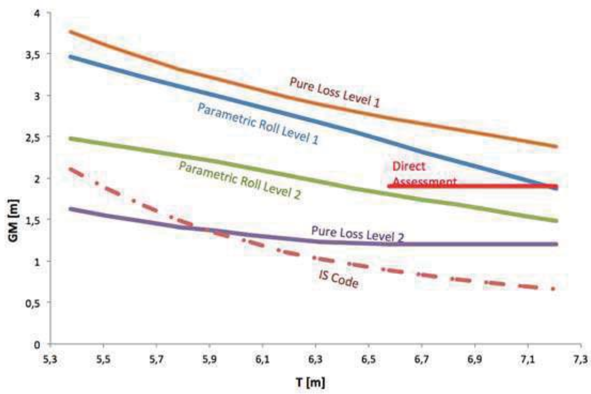

Figure 9 : GM_{Req} curves for the RoPax 1

In figure 9, results derived by the direct assessment are represented by straight horizontal line, as an extrapolation of the calculation carried out at draft 6.6 m and GM= 1.9 m. The second levels of parametric roll and pure loss of stability criteria seem to work properly in the range of the GM limiting values, between the IS Code and the Direct Assessment curves. For the design draft of 6.6m, the first levels requires a GM up to three meters, not so high considering the conservative approach of these two criteria. For the second level it is evident that the limiting criterion is the one relevant to the parametric roll, in this case very close to the direct assessment requirements.

RoPax 2

The second Ro-Pax, larger in size than the first one, requires a GM of 1.1m at the design draft in accordance with the weather criterion. Applying the direct assessment, E4ROLLS shows again more the need of more than one meter increment between the IS Code requirement and the GM corresponding to the ISEI of 1·10-3. The results with the two different GM values are reported in figure 10.

Curve trends in figure 11 for RoPax2 represent nearly the same behaviour of RoPax1. It is possible again to identify the conservative nature of levels 1 criteria and, as far as level 2 is concerned, the strong difference in terms of GM requirements between pure loss and parametric roll criteria.

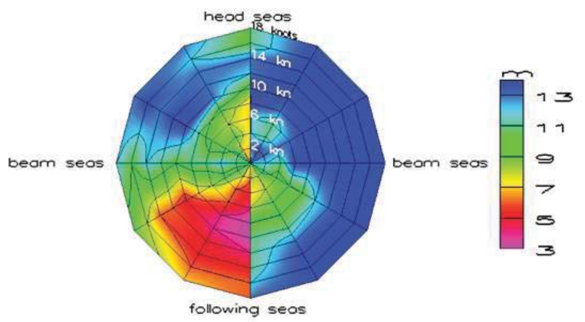

Figure 10: Two polar plots for limiting capsizing wave height for a wave length of 172m. Left: GM=1.1m Right: GM=2.179m

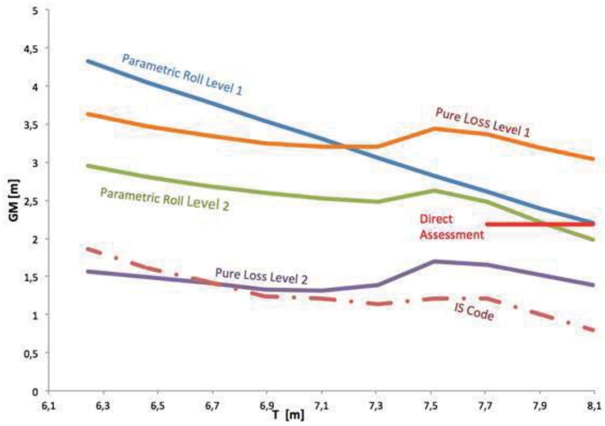

Figure 11: GM req curves for the RoPax 2

RoPax 3

This high speed ferry was designed to meet the ISEI- standard. The limiting GM resulting from the IS Code therefore corresponds more or less to the one computed by the direct assessment i.e. 3.2m. The second level assessments requires values identifying even lower curves. On the other hand, the first levels are extremely conservative, leading to 5-7 m of required GM. Compared to the other two examples, it can be observed an inversion of the level 2 between parametric roll and pure loss of stability; the last one for high drafts requires more stability. As the righting lever curve of this particular ship strongly deviates from the linear representation by GM (fig 12), the example clearly shows that the proposed criteria have problems to cope with such kind of ships.

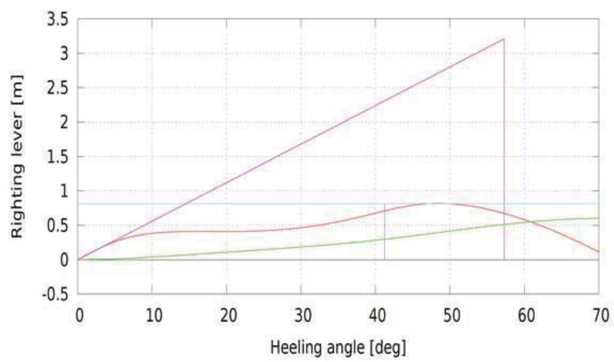

Figure 12: GZ curve for RoPax3

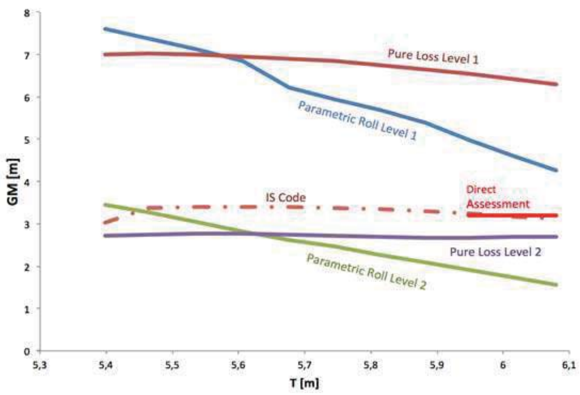

Figure 13: GM required curves for the RoPax 3

RoPax 4

As introduced before, for this ferry the conditions of the accident have been reproduced in the direct assessment computational tool, in order to analyse if the 2nd generation criteria could have prevented that situation. The ship was sailing at a draft of 6.86m with a GM of 1.691m; the direct assessment has been already applied by Kluwe and Krueger resulting in a required metacentric height of 1.89m to fulfil the usual ISEI of 10-3. Considering only the level 2, it is evident for a range of realistic drafts, that criteria show GM results differing (in positive and negative gap) of nearly 0.2 from the IS Code requirements. Actually, a not negligible detail is to be mentioned, i.e. the ship was sailing with a threshold GM value (exactly on the IS Code curve). At the same time, it appears how the criterion for the second level-parametric roll for that draft requires a lower GM value in comparison with the one at the time of the accident (fig.14).

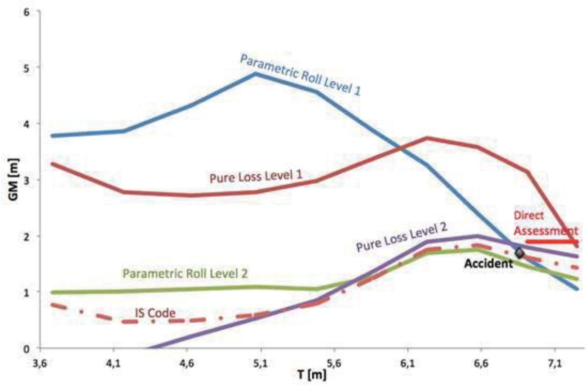

Figure 14: GM required curves for the RoPax 4

Further Cases

So far only problems related to minimum stability requirements have been addressed. It is well known anyway, that an excessive stability can produce problems as well, resulting in excessive accelerations. In figures 11-13-14-15, the level 1 criteria point out a possible problem of this kind, with GM required up sometimes to 7 or 8 meters. Therefore to conclude this investigation, three Container ships are analysed. All these three examples have experienced problems of excessive acceleration as a consequence of sailing with high GM in ballast condition. In the following, the computed curves for the new criteria are presented.

Container 1

This ship was sailing with 8.1 m of draft with a GM of 7.712 m. The limiting criterion for low drafts in this case is the maximum GZ arm position at 25°. The condition of the accident lies in the middle of parametric roll and pure loss limiting curves derived from level 1, leaving space for discussion about the excessive stability requirements (fig. 15).

Container 2

For this ship the accident occurred at a draft of 5.59m and a GM of 4.52m From the curves, it appears that the accident condition is moderately above any present and future rules (fig.16).

Container 3

The ship experienced the accident at a draft of 5.72m and a GM of 5.67. In this example the accident condition is well above the level 1 criteria for both parametric roll and pure loss of stability (fig. 17).

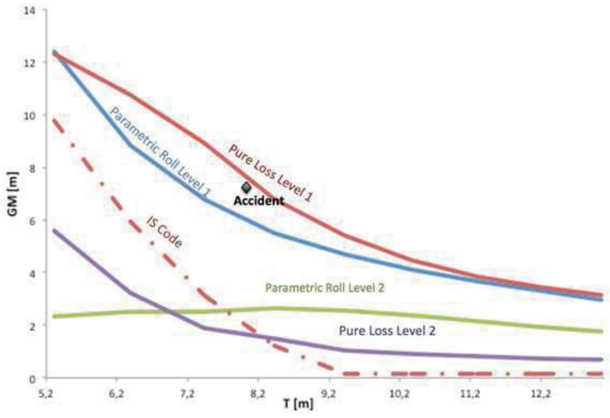

Figure 15: GM required curves for the Container 1

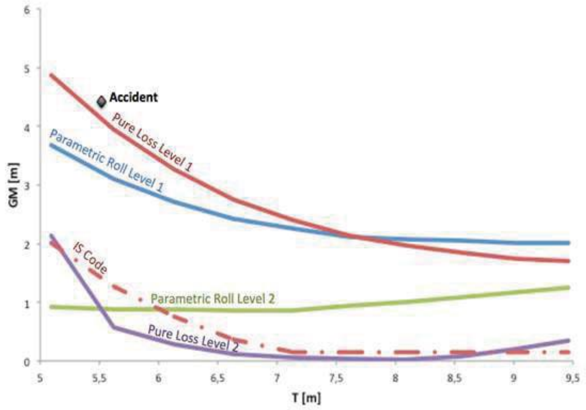

Figure 16: GM required curves for the Container 2

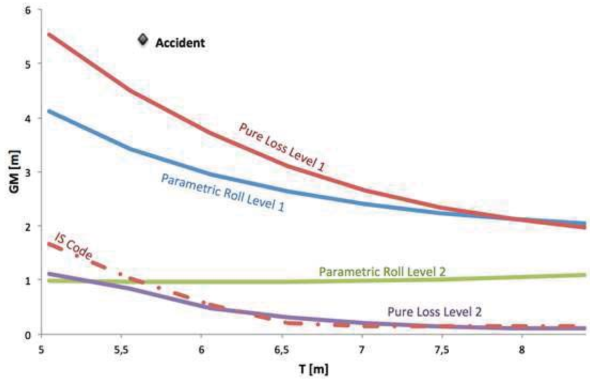

Figure 17: GM required curves for the Container 3

4. CONCLUSIONS

The second generation intact stability criteria, as at present proposed in draft by IMO, have been applied to a selected set of ships for the specific stability failure modes of parametric roll and loss of stability in waves.

In particular the interest has been focused on the Ro-Ro passenger ship typology and four vessels have been investigated.

Nevertheless, some other special cases have been analysed as well, for the discussion of possible shortcomings due to excessive accelerations. With this purpose, the attention has shifted to the field of containers ships referring to three ships that suffered serious incident.

For the above mentioned ships, comprehensive calculations have been carried out, starting from the present Intact Stability Code requirements, addressing the two lower vulnerability levels up to the direct assessment approach. For this final level, a specified tool is not described by the IMO draft rules text and, for the purpose of this paper, a computational tool available at Hamburg University of Technology has been applied.

Results shows a rather satisfactory consistency among the different assessment levels that has been ascertained by means of the minimum GM curves for a range of drafts.

However, criteria show some difficulties to cope with ships where the righting lever curve strongly deviates from the linear representation by the initial GM. This is a consequence of the approach the criteria are based on. This deficiency clearly points out the necessity for establishing a direct assessment.

An important issue is represented by the high level of GM required in some occasions to comply with the second generation intact stability criteria: From the analysis of the accidents reports it appears how in any case this has not prevented the ship to suffer stability failures in waves, with the further negative implication of high accelerations. This finding also points out the necessity for establishing a direct assessment.

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