# Second Generation Intact Stability Criteria—Robustness and Consistency Analysis

**Carsten Schrøter, Marie Lützen, Henrik Erichsen, Jørgen Juncher Jensen, Hans Otto Kristensen, Preben Hagelskjær Lauridsen, Onur Tunccan, and Jens Peter Baltsersen**

**Abstract** The formulation of the Second Generation of Intact Stability Criteria was finalized by the International Maritime Organization (IMO) in 2020. The criteria have been developed for a future incorporation into the 2008 IS Code, however they require testing before using them as a mandatory criterion. Member states are by IMO invited to use the Interim Guidelines and report back the experience. The criteria are formulated for five failure modes, each of which is analyzed by two vulnerability levels and, if needed, a direct numerical simulation. The present paper summarizes results testing the vulnerability levels in these new stability criteria. The calculations are carried out for 17 ships using the full matrix of operational

C. Schrøter
Knud E. Hansen A/S, Elsinore, Denmark
e-mail: cas@knudehansen.com

M. Lützen (✉)
University of Southern Denmark, Odense, Denmark
e-mail: mlut@iti.sdu.dk

H. Erichsen · O. Tunccan
Lloyds Register Marine, Copenhagen, Denmark
e-mail: henrik.erichsen@lr.org

O. Tunccan
e-mail: onur.tunccan@lr.org

J. J. Jensen
Technical University of Denmark, Lyngby, Denmark
e-mail: jjj@mek.dtu.dk

H. O. Kristensen
HOK Marineconsult ApS, Copenhagen, Denmark
e-mail: hokmarine@mail.dk

P. H. Lauridsen
OSK-ShipTech A/S, Aarhus, Denmark
e-mail: pl@osk-shiptech.com

J. P. Baltsersen
DFDS A/S, Copenhagen, Denmark
e-mail: jebal@dfds.com



K. J. Spyrou et al. (eds.), *Contemporary Ideas on Ship Stability*, Fluid Mechanics and Its Applications 134, https://doi.org/10.1007/978-3-031-16329-6_4

draughts, trims and GM values. Each failure mode criterion is examined individually regarding construction of a GM limit curve for the full range of operational draughts. The consistency of the outcomes has been analyzed, and finally examined whether the new criteria tend to be more or less conservative compared to the present rules by evaluating approved loading conditions. The analyses were performed in 2016 and based on criteria developed in 2015 and 2016 and amended by the Sub-Committee on Ship Design and Construction of IMO. Work performed in IMO up to Spring 2020 relevant for the analysis is described.

**Keywords** IMO · Second generation intact stability criteria · Sample calculations · GM limit curves

## 1 Introduction

The Second Generation of Intact Stability Criteria, which differ very much from the formulations in the current IS Code 2008 [3], is based on first principles with the stability examined for the ship sailing in waves. The new intact stability criteria are formulated for five failure modes: pure loss of stability, parametric roll, dead ship condition, excessive acceleration and surf-riding/broaching. Each of these failure modes is divided into three levels—two vulnerability levels and a third level, which consists of numerical simulations of the ship's behavior in waves.

Several papers have already presented results for specific vessels. Tompuri et al. [8] discuss in details computational methods to be used in the Second Generation Intact Stability Criteria, focusing on level 1 and level 2 procedures for parametric roll, pure loss of stability and surf-riding/broaching. They also provide detailed calculations and sensitivity analyses for a specific RoPax Vessel and stress the need for software able to do the extensive calculations. The detailed discussions attached to Tompuri et al. [8] give a very valuable insight in the current status of development of the new criteria.

The present paper summarizes results performed for testing the Second Generation of Intact Stability Criteria. The paper deals with all five failure modes, with the first four modes evaluated for level 1 and 2 whereas the last criterion, surf-riding/broaching, is evaluated for the first level only. The calculations are carried out for 17 ships for the full matrix of operational draughts (light service condition to summer draught), trims (even keel and two extreme trims forward and aft) and GM values. The results are presented as GM limit curves from the two levels and compared with the approved GM limit curve from the stability book.

The criteria used in the present calculations are based on Second Generation Intact Stability Criteria as amended in February 2015 and January 2016 by the Sub-Committee on Ship Design and Construction of IMO. Furthermore, the explanatory notes from [5], Annex 3–7 are consulted.

- Pure loss of stability ([4] Annex 1 (2.10.2.1 + 2.10.2.3))
- Parametric roll ([4] Annex 2 (2.11.2.1 + 2.11.2.3)

- Surf-riding /Broaching ([4] Annex 3)
- Dead ship condition ([5] Annex 1)
- Excessive acceleration ([5] Annex 2)

Three types of analysis have been performed:

1. Each criterion has been examined individually for the possibility of obtaining usable results for construction of a GM limit curve for the full range of operational draughts.
2. The relationship between level 1 and level 2—the requirement that level 1 is more restrictive in GM limits than level 2 has been examined.
3. Will the new regulation be more or less conservative? The analysis has been performed for approved loading conditions.

### *1.1 Subsequent Discussions in IMO*

Since the formulations investigated and presented in this paper an SDC working group and an intersessional correspondence group has developed and agreed on formulations for the stability criteria for the assessment of dynamic stability failure modes in waves as instructed.

At SDC 7 in 2020 the proposal from the working group was brought forward to SDC and accepted as MSC circular: Interim guidelines on the second generation intact stability criteria [7]. The document contains formulations not only for Guidelines on vulnerability criteria, as addressed in this paper, but also "Guidelines for direct stability failure assessment" and "Guidelines for operational measures" to complete the work with all levels as agreed. In fact, most of the work and studies done after 2017 has been focusing on the direct stability failure assessment and operational measures to be able to finalize the text to the scheduled deadline.

However, in the text of the draft MSC Circ. it is made clear that the robustness of the new criteria is not the same for the different stability failure modes and they require testing before using them as mandatory criteria. For that reason, Member States are invited to use the Interim guidelines as complementary measures when applying the requirements of the mandatory criteria and to give feedback to IMO. Based on the feedback the Organization will be able to subsequently refine the Second Generation Intact Stability Criteria.

A modification to the application logic is made as illustrated in Figs. 1 and 2.

While the previous application logic was sequential (following the arrows in the routing scheme) the modified approach allows the user to be guided by a sequential logic of the Interim guidelines, but it is also acceptable that the users apply any alternative design assessment or operational measure option. For example, a user may wish to immediately commence with the application of direct stability assessment procedures without passing through Levels 1 and 2 of the vulnerability criteria or develop operational measures without performing design assessment. In this case the

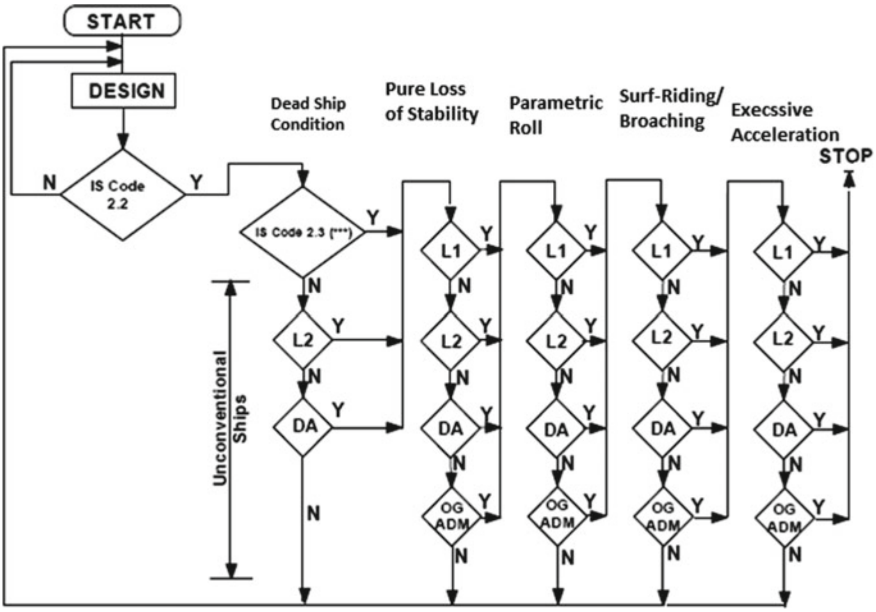


Fig. 1 Previous application logic (SDC 2 and SDC 3)

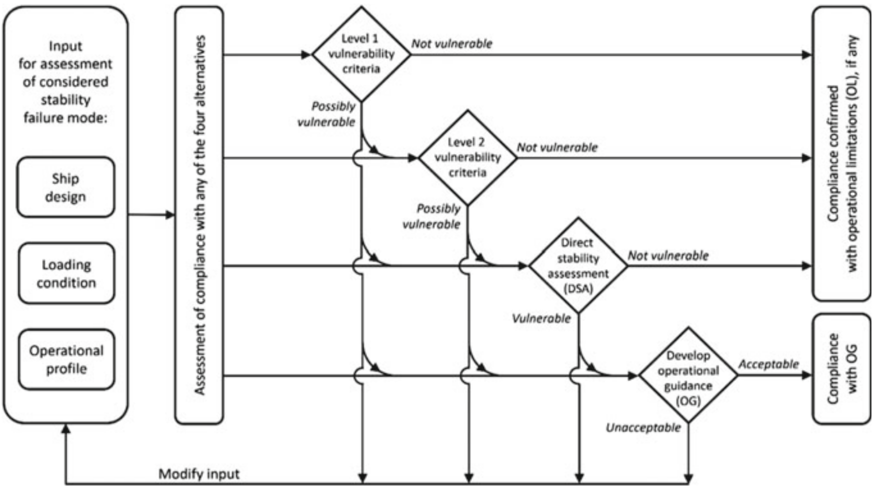


Fig. 2 Modified application logic (SDC 7—draft MSC Circ.)

documentation result of Levels 1 and 2 of the vulnerability criteria is irrelevant and need not to be presented.

This draft MSC Circular was submitted to MSC but the agenda item has not yet been addressed at present time due postponement of the meeting because of the Covid-19 situation.

Examples of assessments and interpretation of the Guidelines on vulnerability criteria will be addressed in the Explanatory notes that is at present time (August 2021) under development with the aim of finalizing at SDC8 in 2022. It is the intention to do a separate draft MSC Circ. to be submitted to MSC for acceptance.

## 2 Sample Ships

The sample ships used for the calculation comprise 17 existing vessels. They include eight RoRo ships (six passenger and two cargo vessels); two installation vessels (jack-up vessels); three supply vessels—one standby vessel, one cable layer and one anchor handler; one bulk carrier and three container vessels. The sample ship particulars can be seen in Table 1.

**Table 1** Principal particulars of the sample ships

| Id | Type | L [m] | Fn | Built |
|---|---|---|---|---|
| 1 | RoRo passenger | 159.3 | 0.303 | 2016 |
| 2 | RoRo passenger | 135.0 | 0.262 | 1997 |
| 3 | RoRo passenger | 183.6 | 0.298 | 2009 |
| 4 | RoRo passenger | 92.3 | 0.246 | 2010 |
| 5 | RoRo passenger | 88.8 | 0.298 | 2013 |
| 6 | RoRo passenger | 39.6 | 0.287 | 2011 |
| 7 | Ro-Ro cargo | 180.5 | 0.261 | 2009 |
| 8 | Ro-Ro cargo | 185.9 | 0.241 | 2014 |
| 9 | Installation vessel | 155.6 | 0.170 | 2009 |
| 10 | Installation vessel | 79.3 | 0.169 | 2011 |
| 11 | Supply standby | 39.2 | 0.315 | 2011 |
| 12 | Supply cable layer | 120.4 | 0.175 | 2016 |
| 13 | Supply anchor handler | 81.6 | 0.310 | 2000 |
| 14 | Bulk carrier | 174.6 | 0.173 | 2012 |
| 15 | Container ship | 382.6 | 0.208 | 2006 |
| 16 | Container ship | 324.6 | 0.222 | 1997 |
| 17 | Feeder vessel | 154.1 | 0.250 | 1991 |

# 3 Analysis

The analysis is performed for the full matrix of operational draughts from light ship to summer draught and for three trims—even keel and two extreme trims forward and aft. The calculations are carried out for the five modes of stability failure:

- Pure loss of stability
- Parametric roll
- Dead ship
- Excessive acceleration
- Surf-riding/Broaching

All calculations have been carried out using NAPA stability software XNAPA Release B137 2016.0 sgis. This is the same software as used in Tompuri et al. [8]. A more detailed description of the analysis can be seen in an information paper submitted to SDC 4 [6].

All modes are evaluated for criteria levels 1 and 2, except the last failure mode, where only level 1 is carried out. This last criterion, surf-riding/broaching is a function of length and speed of the vessel and does not depend on GM of the vessel. The criterion pure loss of stability applies only to ships for which the Froude number exceeds 0.24.

In the mode 'Pure loss of stability' in criteria level 2, ships with low weather deck/low buoyant hull can give some unexpected results. The problem is possibly caused by a loss of stability on the wave crest combined with water accumulated on the weather deck, see Fig. 3. How to deal with this is not yet defined in the explanatory notes.

However, as the whole idea with the criteria is to understand the ships behavior to certain stability failure modes in waves, the hull form is some cases slightly modified, resulting in a more 'appropriate' hull form including all parts that provides buoyancy, even though they are not fully watertight due to freeing ports, mooring holes etc.

## 3.1 *Construction of Limiting GM Curves*

Each criterion is examined for the possibility of obtaining usable results for construction of a GM limit curve for the full range of operational draughts. A summary of the results is shown in Table 2.

**Fig. 3** Illustration of "water on deck" problem

**Table 2** Evaluation of each failure mode criterion for 17 ships—summary table

| | Pure loss of stability | | | | | | Parametric roll | | | | | | | | | Dead ship | | | | | | Excessive acceleration | | | | | | Surfr. - Broaching |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Level 1 | | | Level 2 | | | Level 1 | | | Level 2 - C1 | | | Level 2 - C2 | | | Level 1 | | | Level 2 | | | Level 1 | | | Level 2 | | | |
| ID | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | |
| 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | a | | | | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | | | | | b | b | b | | b | b | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | | | | | | | | | | b | | | b | b | | | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | | | | | | | | | | b | b | | b | b | b | b | b | b | | | | | | | | | | |
| 15 | | | | | | | | | | | | | b | b | b | b | b | b | | b | b | | | | b | b | b | |
| 16 | | | | | | | | | | | | | b | b | b | b | b | b | b | b | b | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Green: OK—only one GM limit for a given draught
Red: Not OK—several GM limits for a given draught
Blue: Computational problems—no useful results
White: Not calculated—criterion does not apply to ship (Fn lower than 0.24)
Yellow: Ship does not comply with criterion (surf-riding)
a: No results for smaller draughts
b: Results for smaller draughts only/no results for higher draught

For some vessels, inconsistency is seen in the results for GM—meaning that there is more than one GM limit for a given draught; these cases are marked in red in Table 2. It is seen that this specially applies to the two criteria parametric roll level 2 (C2) and dead ship condition level 2, where the vessel might experience resonance due to waves. The vessel can be exposed to different conditions of failures for same draught; therefore, the two criteria are not suited for presentation using GM limit curves. These criteria might be handled as operational criteria used for specific loading conditions—maybe as an operational polar plot or GM plot marked with restricted and allowable areas, but this would change the criteria to be operational and loading condition dependent.

Matrices and diagrams that show the inconsistency in the GM results and the corresponding GM limit curve are constructed for all vessels, examples can be seen in Figs. 4 and 5 for the RoRo vessel no. 3. For vessels having inconsistency in the results for GM, it was decided to use the largest GM value, which may result in a fluctuating GM curve, this can also be seen in Figs. 4 and 5.

For one of the vessels, RoRo ship no. 3, the inconsistency in the results is so extreme that it is not possible to construct a GM limit curve.

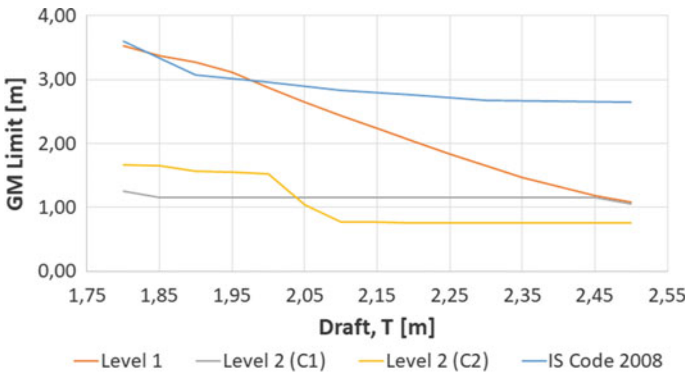


**Fig. 4** GM limit (T), Ship no. 6. Parametric roll—Trim Aft

T [m] ->

| GM [m] | 1,80 | 1,85 | 1,90 | 1,95 | 2,00 | 2,05 | 2,10 | 2,15 | 2,20 | 2,25 | 2,30 | 2,35 | 2,40 | 2,45 | 2,50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,50 | 0,999723 | 0,999829 | 0,999723 | 0,999723 | 0,999784 | 0,99967 | 0,99967 | 0,999776 | 0,981413 | 0,944753 | 0,908074 | 0,907975 | 0,886717 | 0,889628 | 0,944701 |
| 0,60 | 0,401473 | 0,364694 | 0,361204 | 0,328152 | 0,300658 | 0,283079 | 0,273732 | 0,275306 | 0,225042 | 0,213733 | 0,195643 | 0,194949 | 0,195595 | 0,196629 | 0,204251 |
| 0,70 | 0,215928 | 0,165096 | 0,175596 | 0,175266 | 0,175206 | 0,140461 | 0,151135 | 0,150762 | 0,138891 | 0,149063 | 0,136287 | 0,145698 | 0,136399 | 0,147018 | 0,136335 |
| 0,80 | 0,067038 | 0,067038 | 0,067038 | 0,030251 | 0,030251 | 0,030177 | 0,030171 | 0,007609 | 0,005674 | 0,005674 | 0,005674 | 0,005686 | 0,001864 | 0,002227 | 0,002245 |
| 0,90 | 0,000534 | 0,012973 | 8,94E-05 | 2,39E-05 | 2,39E-05 | 0 | 0 | 0 | 0 | 0,000006 | 0 | 0,000006 | 2,99E-05 | 0,000006 | 0,000101 |
| 1,00 | 0,197816 | 0,194187 | 0,095044 | 0,098178 | 0,093651 | 0,081699 | 0,03876 | 0,013907 | 0,004161 | 0,000837 | 0,000137 | 2,39E-05 | 0,000006 | 0,000006 | 0,000006 |
| 1,10 | 0,146763 | 0,096828 | 0,052496 | 0,050534 | 0,050101 | 0,020118 | 0,007909 | 0,003346 | 0,001991 | 0,005639 | 0,005106 | 0,004137 | 0,00146 | 0 | 0 |
| 1,20 | 0,043295 | 0,024114 | 0,012728 | 0,021842 | 0,019676 | 0,019084 | 0,015468 | 0,014867 | 0,030147 | 0,022974 | 0,013974 | 0,012894 | 0,004137 | 0,002922 | 0,000528 |
| 1,30 | 0,019541 | 0,044308 | 0,044299 | 0,035102 | 0,023469 | 0,030476 | 0,043653 | 0,043646 | 0,030411 | 0,014422 | 0,005021 | 0,001367 | 0,001358 | 0,000249 | 8,21E-05 |
| 1,40 | 0,068124 | 0,076644 | 0,07618 | 0,05439 | 0,054279 | 0,054277 | 0,051917 | 0,030382 | 0,013203 | 0,004226 | 0,001367 | 0,000303 | 9,34E-05 | 2,43E-05 | 2,61E-05 |
| 1,50 | 0,056533 | 0,079934 | 0,078108 | 0,07688 | 0,06791 | 0,037428 | 0,015637 | 0,005355 | 0,001438 | 0,000459 | 8,91E-05 | 0,000006 | 0,000006 | 0 | 0 |
| 1,60 | 0,084153 | 0,080295 | 0,048096 | 0,046692 | 0,031957 | 0,015002 | 0,005364 | 0,001527 | 9,51E-05 | 2,39E-05 | 0 | 0 | 0 | 0 | 0 |
| 1,70 | 0,048589 | 0,037025 | 0,015895 | 0,015086 | 0,005983 | 0,00222 | 0,000532 | 8,91E-05 | 0,000006 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1,80 | 0,015895 | 0,005993 | 0,004396 | 0,002213 | 0,000797 | 0,000162 | 2,39E-05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1,90 | 0,001924 | 0,000791 | 0,000241 | 8,91E-05 | 2,39E-05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2,00 | 0,000156 | 0,000006 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Fig. 5** Matrix (T, GM), Ship no. 6. Parametric roll, Level 2 (C2)—Trim Aft

It must also be noted that the Ikeda [1] parameter limits are exceeded for all vessels at certain draughts—especially in the criteria for dead ship condition and excessive acceleration. How this affects the results is not clear and it should be examined to which extent the roll damping results are reliable when extrapolating outside the parameter range for which Ikeda's empirical equations are valid.

### *3.2 Inconsistency Between Level 1 and Level 2*

When analyzing the results from level 1 and level 2, it is expected that level 1 is more restrictive in GM limits than level 2. As the failure mode surf-riding/broaching is not based on a GM evaluation, it is not included in this analysis. For vessels exposed to resonance phenomenon and thereby different conditions of failures for same draught, the highest GM value is chosen.

The results from the analysis are shown in Table 3. The green color indicates that there is a proper relationship between the levels i.e. level 1 is more conservative than level 2 for all operational draughts. The red color indicates the opposite—if the whole or a part of the GM limit curve for level 2 is more restrictive than level 1, the cell is marked red. When it was not possible to obtain results for one of the levels, the consistency between the levels could not be evaluated; this is indicated with white or blue cells in the table.

**Table 3** Evaluation of the failure mode criteria—inconsistency between level 1 and level 2

| | |
|---|---|
| Green | OK GM limit for L1 > GM for L2 (except for excessive acceleration, where it is opposite) |
| Red | Not OK - GM limit for L1 < GM for L2 (except for excessive acceleration, where it is opposite) |
| Blue (light) | No results - Computational problems for one or both levels |
| Grey | No results – no GM limit curve available due to inconsistency in results |
| White | No results – criterion does not apply to ship (Fn lower than 0.24) |

| | Pure loss of stability | | | Parametric roll C1 | | | Parametric roll C2 | | | Dead ship | | | Excessive acc. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd | Aft | Even | Fwd |
| 1 | Red | Red | Red | Green | Green | Green | Green | Green | Green | Green | Green | Green | White | White | White |
| 2 | Red | Red | Red | Red | Red | Green | Green | Green | Green | Red | Green | Red | Green | Green | Green |
| 3 | Red | Red | Red | Green | Green | Green | Green | Green | Green | Grey | Grey | Grey | Green | Green | Green |
| 4 | White | White | White | Red | Red | Red | Green | Green | Green | Red | Red | Red | Green | Green | Green |
| 5 | Blue | Red | Red | Green | Green | Red | Blue | Red | Red | Red | Red | Red | Red | Red | Green |
| 6 | Red | Red | Red | Green | Green | Green | Green | Red | Red | Red | Red | Red | Green | Green | Green |
| 7 | Red | Red | Red | Green | Green | Green | Green | Green | Green | Blue | Blue | Blue | Green | Green | Green |
| 8 | Red | Red | Red | Red | Red | Red | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| 9 | White | White | White | Red | Red | Red | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| 10 | White | White | White | Blue | Blue | Blue | Red | Red | Red | Red | Red | Red | Green | Green | Green |
| 11 | Red | Red | Red | Blue | Blue | Blue | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| 12 | White | White | White | Red | Red | Red | Red | Red | Red | Red | Red | Red | Green | Green | Green |
| 13 | Red | Red | Red | Red | Red | Red | Red | Red | Green | Red | Red | Red | Red | Red | Red |
| 14 | White | White | White | Green | Green | Green | Blue | Blue | Blue | Blue | Blue | Blue | Green | Green | Green |
| 15 | White | White | White | Green | Green | Green | Blue | Blue | Blue | Blue | Blue | Blue | Blue | Blue | Blue |
| 16 | White | White | White | Green | Green | Green | Blue | Blue | Blue | Blue | Blue | Blue | Blue | Blue | Blue |
| 17 | Red | Red | Red | Green | Green | Green | Green | Green | Green | Red | Red | Red | Green | Green | Green |

Green: OK—GM limit for L1 > GM for L2 (except for excessive acceleration, where it is opposite)
Red: Not OK—GM limit for L1 < GM for L2 (except for excessive acceleration, where it is opposite)
Blue (light): No results—Computational problems for one or both levels
Grey: No results—no GM limit curve available due to inconsistency in results
White: No results—criterion does not apply to ship (Fn lower than 0.24)

Table 3 shows that in nearly half of the cases, level 2 results are more conservative than level 1; for the criterion pure loss of stability, it is the case for all vessels.

### *3.3 Loading Condition Analysis*

The analysis is performed for approved operational loading conditions taken from the ship stability booklet. The results are summarized in Table 4.

**Table 4** Evaluation of loading conditions

| | |
|---|---|
| Green | All loading conditions comply with the criteria |
| Red | One or more loading conditions do not comply with the new criteria. The number in the cell indicates the percentage of loading conditions not complying. |
| Blue | No useful results for GM limit (whole or part of curve). |
| White | Not calculated – criterion does not apply to ship (Fn lower than 0.24) |

| | Pure loss of stability | | Parametric roll | | | Dead ship | | Excessive acc. | |
|---|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L1 | L2 C1 | L2 C2 | L1 | L2 | L1 | L2 |
| 1 | | 37 | | | | | | | |
| 2 | | | | | | | | 100 | |
| 3 | | | 100 | 100 | | | | 100 | 100 |
| 4 | | | | | | | 100 | 100 | 100 |
| 5 | | | | | | | 100 | 33 | |
| 6 | | | | | | | 100 | 100 | 100 |
| 7 | 77 | 77 | 100 | 92 | 77 | | | 23 | 23 |
| 8 | | | | | | | | 13 | |
| 9 | | | | | | | 100 | 100 | 100 |
| 10 | | | | | | 100 | | | |
| 11 | 100 | 100 | | | | 33 | 100 | 100 | 100 |
| 12 | | | | | | | 25 | 55 | 18 |
| 13 | | 55 | | | | 9 | 72 | | 27 |
| 14 | | | | | | | | 74 | 52 |
| 15 | | | 50 | 12 | | | | 25 | |
| 16 | | | 100 | 100 | | | | | |
| 17 | 50 | 67 | | | | | | 82 | 33 |

Green: All loading conditions comply with the criteria
Red: One or more loading conditions do not comply with the new criteria. The number in the cell indicates the percentage of loading conditions not complying
Blue: No useful results for GM limit (whole or part of curve)
White: Not calculated—criterion does not apply to ship (Fn lower than 0.24)

## 4 Discussions

A series of 17 existing vessels have been evaluated against Second Generation Intact Stability Criteria as amended in February 2015 and January 2016 by the Sub-Committee on Ship Design and Construction of IMO.

Three analysis have been performed.

- Inconsistency analysis
- GM limit curves
- Approved loading condition check

### *4.1 Inconsistency Analysis*

The relationship between level 1 and level 2—the requirement that level 1 is more restrictive in GM limits than level 2 has been examined. The analysis showed that none of the vessels shows a consistent result when applying level 2 versus level 1 analysis for all failure modes, see Table 3. For more than half of the cases the limiting GM required by level 2 would be higher (more restrictive) than for level 1 analysis, which is not the intention.

### *4.2 GM Limit Curves and Approved Loading Condition Check*

Each criterion has been examined individually for the possibility of obtaining usable results for construction of a GM limit curve for the full range of operational draughts, see Table 2. With one or two exceptions for the vessels considered, it is not possible to derive the GM curve. This is the case for the parametric roll and dead ship failure modes, i.e. at a given draught multiple permissible GM values would be obtained for most of the vessels.

It must be noted that the new draft MSC Circ. does not include or consider a GM limit curve as it is required in the vessel's stability booklet following current regulation. The new criteria is based on calculation of the actual loading condition of the vessel.

When evaluated at realistic operational GM (or KG) conditions allowed according to the current intact and damage stability criteria—loading conditions from the vessel's stability booklet, none of the vessels satisfies all of the SGISC failure modes, see Table 4. The majority of vessels satisfy some of the failure modes under certain loading conditions. Some of the vessels satisfy the parametric roll criteria for all loading conditions considered. Very few vessels satisfy the excessive acceleration criterion in any loading condition.

### 4.3 Evaluating Stability Criteria Based on Current Loading Condition

According to SOLAS chapter II-1 [2], the master must be provided with reliable information on the ship's stability that is necessary to enable him to get exact guidance in a fast and simple manner about the ship's stability under various operating conditions.

As the new criteria is not suitable for implementation in an intact or combined intact and damage stability limit curve, it requires a loading computer that can handle the SGISC requirements as direct calculation of all intact stability criteria in each loading case during the entire voyage. This loading computer is not available at the market of today. But this is assumed to be possible, as it basically can be based on the same available philosophy as used today, apart from implementing the calculation routines behind SGISC. However, with the nature of some of the criteria to form "islands" of noncompliance rather than a well-defined border between safe and unsafe area (equals a limit curve), the user must be guided towards a more holistic review of the expected entire voyage in order to see if unsafe areas are passed on the way. In other words, a kind of 3D limit figure instead of a 2D limit curve must be introduced and made visible for the user. It is foreseen, that if this shall become operationally safe, precise guidelines on number of steps, intended change in tank-configuration etc. during the voyage etc. shall be pre-defined and verified against the SGISC criteria. In case changes are made from the pre-planned voyage/tank configuration etc., revised calculations must be carried out and verified for compliance.

Another concern linked to the direct calculations and the 3D limit figure is that over a longer voyage, the vessels draught, trim and GM will change, thus also cause the 3D "landscape" to change and the unsafe "islands" might very well change, leading to an even more complicated matrix of loading condition variations to be checked. Obviously, the longer voyage/larger consumption, the larger change in the foundation for evaluation of the stability.

Adding further to the complexity is the increasing usage of other operational support systems like weather routing and trim optimization—systems that are also providing guidance to the operation/ballasting of the vessel, not seldomly varying over the length of a voyage. That input also needs to be considered when assessing the voyage from a stability compliance perspective.

All in all, something that is manageable but understood to require quite some new thinking in terms of development of enhanced instructions to the user (navigator) related to voyage planning and guidelines to graphical user interface development for the supplier of the new type of loading computer.

## 5 Conclusions

A series of 17 existing vessels have been evaluated against the current version of Second Generation Intact Stability Criteria (SGISC). These criteria comprise five failure modes: Pure loss of stability, parametric roll, dead ship, excessive acceleration and surfriding/broaching. Results have been analyzed for different loading and trim conditions in terms of limiting GM curves.

Conclusions from the analyses are that using conventional GM limiting curves are not possible when applying SGISC. The vessel must be equipped with a loading computer having the SGISC routines implemented. These computers, which are not available at the market of today, must besides evaluating the actual condition of the ship also be able to consider all conditions encountered during an entire voyage.

**Acknowledgements** The work described in this paper has been financed by The Danish Maritime Fund.

The work was carried out by a consortium consisting of: Project group: IDA Maritime, The Society of Engineers, OSK-ShipTech A/S, Knud E. Hansen A/S, Odense Maritime Technology A/S, Maersk Maritime Technology, Lloyds Register Marine, Technical University of Denmark and University of Southern Denmark.

The work has been assisted by an advisory board consisting of: American Bureau of Shipping, ABS, Maersk Maritime Technology, MMT, Baltic and International Maritime Council, BIMCO, DFDS, and Danish Maritime Authority.

## References

1. Ikeda Y, Himeno Y, Tanaka N (1978) A prediction method for ship roll damping. Report of Department of Naval Architecture, University of Osaka Prefecture, Report no. 00405
2. IMO (1974) International convention for the safety of life at sea (SOLAS). www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx. Accessed 15 July 2020
3. IMO (2008) The international code on intact stability (IS Code 2008)
4. IMO (2015) SDC 2/WP.4, development of second generation intact stability criteria. Report of the working group, London, UK
5. IMO (2016) SDC 3/WP.5, development of second generation intact stability criteria. Report of the working group, London, UK
6. IMO (2016) SDC 4/INF.9, sample ship calculation results, Submitted by Denmark, London, UK
7. IMO (2020) MSC.1/Circ.1627, Interim guidelines on the second generation intact stability criteria
8. Tompuri, M, Ruponen P, Forss M, Lindroth D (2015) Application of the second generation intact stability criteria in initial ship design. Transactions—Society of Naval Architects and Marine Engineers 122:20–45