# Sample Application of Second Generation IMO Intact Stability Vulnerability Criteria as Updated during SLF 55

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## ABSTRACT

A second generation intact stability criteria is currently under development by the International Maritime Organisation (IMO). This paper describes the application of level 1 and level 2 vulnerability criteria, as updated according to the last session of the Sub-Committee on Stability, Load Lines and on Fishing Vessel Safety (SLF). In order to understand the functionality of the proposed levels 1 and 2 criteria for problems related to righting lever variation (parametric roll and pure loss of stability), surf-riding and excessive accelerations, numerical tools have been implemented, updated and tested on a large number of ships, covering a wide range of ship type, size and speed.

## KEYWORDS

Dynamic stability; Vulnerability criteria; Pure loss of stability; Parametric roll; Surf-riding/broaching; Excessive accelerations

## INTRODUCTION

The first generation intact stability criteria was originally codified at IMO as a set of recommendations in Res. A.749(18) (1993) by taking into account, among others, former Res. A.167(ES.IV) ("Recommendation on intact stability of passenger and cargo ships under 100 m in length" which contains statistical criteria, heel due to passenger crowding, and heel due to turn, 1968) and Res. A.562(14) ("Recommendation on severe wind and rolling (weather criterion) for the intact stability of passenger and cargo ships of 24 m in length and over", 1985).

The development of the second generation of intact stability criteria started with the re-establishment of the intact stability working group by IMO's sub-committee SLF (Francescutto 2004, 2007).

The scope of the second generation intact stability criteria is to provide methods to assess ships which may be vulnerable to particular failure modes not adequately assessed by the existing criteria. For this it was decided that the following four dangerous situations (called "failure mode") should be individually addressed:

- Righting lever variation: any ship exhibiting large righting lever variations between wave crest conditions may experience parametric roll, or pure loss of stability.
- Resonant roll in dead ship condition: ship without propulsion or steering ability may

be endangered by resonant roll while drifting freely.

- Broaching and other manoeuvring related phenomena: ship in following and quartering seas may not be able to keep constant course despite maximum steering efforts, which may lead to extreme heel angles.
- Excessive accelerations: any ship, having a large metacentric height may experience excessive accelerations.

The second generation intact stability criteria are based on a multi-tiered assessment approach structured in three levels: vulnerability criteria first level, vulnerability criteria second level, direct assessment and specific operational guidelines is added in the acknowledgment that not all dangerous situations can be avoided only by design prescriptions. For each ship the level i+1 assessment is performed only if the level i fails (Francescutto & Umeda 2010). Note that the operational limitations came out during SLF 55, and the proposal is to use operational limitations if the ship fails to comply with the second level vulnerability criterion. This matter was postponed to be discussed intersessionally.

Hard work was done intersessionally between SLF51, SLF52, SLF53, SLF54 and SLF55 with the active participations of many delegations. As a result several methodologies have been submitted. During SLF54 and SLF55 sessions, significant work was done to harmonize draft vulnerability criteria levels 1 and 2 for some failure modes and their standards. The next section of this paper describes the application of the vulnerability criteria to a large number of ships, an investigation of ships types/ ships characteristics that appear to be vulnerable to stability failure modes and finally some comments of the results are done.

## SAMPLE SHIPS POPULATION

This study is performed on 36 ships of different characteristics and types with length between 20.35 and 349.5 meters; their main particulars are given in table 1. This population has been examined using the proposed methods for vulnerability assessment (levels 1 and 2) for four of the identified failure modes (parametric roll, pure loss of stability, broaching and excessive accelerations). Since the criteria regarding surf-riding did not change during SLF 55, the results are the same contains in Corrignan and Wandji (2012), thus these results are not presented here. 28 ships in this population are real ships, with well-defined geometry and load case. The remaining 8 samples are vessels made available in the correspondence group (ISCG), and for some of these ships, it is known to what stability failure mode there are vulnerable.

**Table 1: Ship types and general characteristics**

| Ship type | L/B | B/T | $C_B$ |
|---|---|---|---|
| Military 1 | 7.979 | 3.418 | 0.535 |
| Military 2 | 7.450 | 3.099 | 0.507 |
| Fishing vessel 1 | 4.539 | 3.040 | 0.597 |
| Fishing vessel 2 | 5.406 | 2.156 | 0.470 |
| Fishing vessel 3 | 2.891 | 2.347 | 0.560 |
| General cargo 1 | 7.007 | 2.496 | 0.700 |
| General cargo 2 | 5.083 | 3.579 | 0.785 |
| Chemical Tanker 1 | 5.686 | 2.550 | 0.760 |
| Chemical Tanker 2 | 5.677 | 3.263 | 0.756 |
| Tanker 1 | 4.891 | 2.875 | 0.893 |
| Tanker 2 | 5.700 | 2.597 | 0.799 |
| Tanker 3 | 6.429 | 2.333 | 0.771 |
| Tanker 4 | 5.371 | 2.255 | 0.772 |
| Containership 1 | 6.550 | 3.118 | 0.562 |
| Containership 2 | 5.515 | 3.200 | 0.667 |
| Containership 3 | 9.167 | 2.913 | 0.554 |
| Containership 4 | 6.826 | 3.303 | 0.699 |
| Containership 5 | 6.084 | 3.079 | 0.607 |
| Containership 6 | 5.846 | 2.957 | 0.666 |
| Containership 7 | 7.046 | 3.078 | 0.697 |
| Containership 8 | 6.142 | 2.745 | 0.635 |
| Containership 9 | 8.261 | 2.382 | 0.652 |
| Containership 10 | 7.000 | 2.400 | 0.635 |

| | | | |
|---|---|---|---|
| Passenger ship 1 | 6.627 | 4.237 | 0.658 |
| Passenger ship 2 | 7.011 | 3.750 | 0.628 |
| Ropax 1 | 5.590 | 4.391 | 0.628 |
| Ropax 2 | 5.659 | 4.300 | 0.553 |
| Ropax 3 | 5.316 | 4.537 | 0.572 |
| Ropax 4 | 5.511 | 4.296 | 0.582 |
| Ropax 5 | 5.680 | 3.745 | 0.635 |
| Supply 1 | 4.288 | 3.000 | 0.758 |
| Bulk carrier 1 | 6.727 | 2.272 | 0.846 |
| Bulk carrier 2 | 6.267 | 2.727 | 0.880 |
| Bulk carrier 3 | 6.143 | 2.726 | 0.800 |
| LNG Carrier 1 | 6.323 | 3.440 | 0.750 |
| LNG Carrier 2 | 6.355 | 2.406 | 0.742 |

## PARAMETRIC ROLL

### *Physical background*

Let's assume that a ship is sailing exactly in longitudinal regular waves. When the ship is located with the wave crest amidships, the immersed portion of the bow and stern sections are narrower than in calm water. Consequently, the waterplane is narrower and the GM is correspondingly decreased than in calm water value. As the restoring is less, the ship will roll further than she would in calm water. In contrast, if a ship is located on a wave trough, the waterplane width is significantly greater than in calm water because the bow and stern parts are more deeply immersed than in calm water and the wall-sided midship is less deep. This makes the waterplane wider with the result that the GM is increased over the calm water value (Shin and al. 2004). As a result, the roll restoring moment of the ship will change as function of the ship's longitudinal position relative to the waves.

### *Level 1 vulnerability criterion*

The criterion is based on simplified formulation of the GM variation in wave. Therefore only the difference between the waterline area moments of inertia in wave crest and trough conditions in simplified form is calculated. The moment of inertia for the wave crest condition is calculated with a horizontal water line positioned at the height equal to the lowest draught of the wave condition. The moment of inertia for the wave trough condition is calculated with a horizontal water line at the height equal to the highest draught of the wave condition. If the ship has tumblehome topside, the variation of metacentric height is to be calculated with the true water line (sinusoidal water line) i.e. considering that the ship is situated on a wave. The environmental condition to use in this case is a regular wave with a constant steepness of 0.0167.

If the ratio of GM variation in wave to GM in calm water is greater than 0.5, the vessel is considered to be vulnerable to parametric roll. Note that in the document SLF 55/WP.3 it is proposed another value of the standard which involves bilge keels area. Since for the studied ship the dimensions of the bilge keels were not available, the standard without these parameters was used.

### *Application and results of first level criterion*

The criterion has been applied to the sample ships. In this work the GM and GZ evaluation in waves were performed using the USA simplified method described in the paper SLF 52/INF.2, annex 6. The area at each station and its moment relative to the vertical axis are expressed as function of the local draft and taking into account sinkage and trim. Therefore, the local draft at each station comes from the formula describing the wave elevations along the hull, and depends on sinkage and trim. The wave profile along the hull is evaluated by satisfying equilibrium conditions. Once sinkage and trim are found, the wave profile is found and the moment of inertia of the waterplane and hydrostatic terms are computed. Finally the value of GM in waves is computed as a function of the position of the wave crest.

Figure 1 below shows results for the level 1 assessment. All vessels which are on the right of the vertical red line are considered to be vulnerable to parametric roll according to level 1 criterion. Thus, all the fishing vessels, general cargo ships, tanker (including chemical and LNG), bulkers and the supply vessel are conventional ships (i.e. not vulnerable to the level 1 criterion). All containerships were found to be vulnerable except one vessel (the biggest containership of this sample ship).

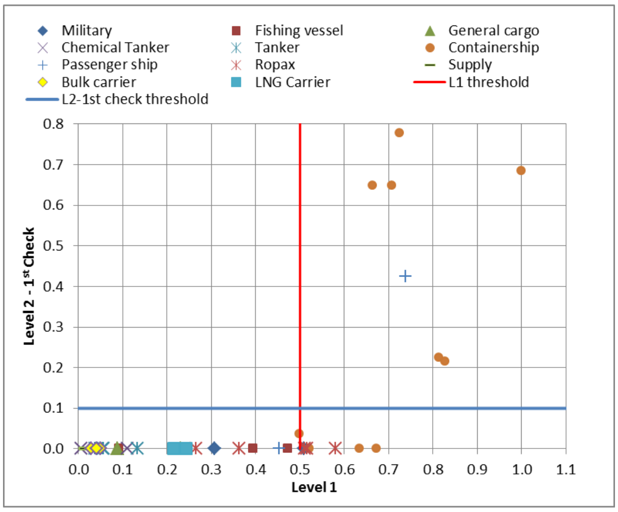


Fig. 1: Level 1 and Level 2 first check vulnerability criteria results for parametric roll.

### *Level 2 vulnerability criteria*

The second level consists in two checks. The first check requires calculations of GM variations for a series of 16 wave cases. In addition, the effect of forward speed with related to wave and roll frequencies is included. The value for the criterion is calculated as a weighted average of a binary condition obtained by GM variations from a set of specified waves (see SLF 55/WP.3 annex 1 for more details). The weighting factors are obtained from a look-up table based on a scatter diagram. The ship is considered vulnerable to parametric roll if the criterion is greater than a threshold value (the value of 0.1 was used in this work).

If the ship is found to be vulnerable to the first check, the second check is to be carried out. The second check is based on roll response in head or following waves evaluated for the range of operational ship speed. In absence of roll decay test data, roll damping may be estimated, using either simplified Ikeda's method or type-specific empirical data if appropriate. Calculation of stability in waves is expected to account for the influence of pitch and heave quasi statically. For the second check, in this work we used the method described in SLF 53/INF.10 annex 2, where the parametric roll amplitude is calculated using an averaging method which is applied on an uncoupled roll model. The GZ curve in calm water is fitted with a polynomial of 5$^{th}$ grade and the damping is fitted with a cubic formula. The amplitude of steady state parametric rolling can be obtained by solving a twelfth algebraic equation. Alternatively, time domain simulation could be used.

The environmental conditions used in this case are based on Grim's effective significant wave concept to calculate wave height for all possible wave heights and zero crossing period appeared in the wave scatter diagram of the North Atlantic and the wave length is equal to the ship length. Then, the probability to meet sea states where the roll amplitude is larger than the threshold (25° in this report) can be evaluated and compared with a required value (the threshold was set to 0.15 in this work which is the lower boundary of the range suggested during SLF 55).

### *Application and results of second level criteria*

The criteria were applied to all the ships of the sample. Regarding the first check, vessels which are vulnerable to this criterion are above the horizontal blue line in figure 1. All ships judged as non-vulnerable to first level criterion were found to be non-vulnerable to the second level first check criterion. Thus, in addition to the categories of ships identified as non-vulnerable according to the level 1 vulnerability criterion, all military vessels, all Ropax ships were judged as non-vulnerable to parametric roll according to the second level first check criterion.

Regarding the second check, vessels which are judged as vulnerable according to this criterion are above the horizontal green line in figure 2. This criterion found more ships as non-vulnerable to parametric roll than the first check. Five containerships and one passenger ship were found to be vulnerable to parametric roll.

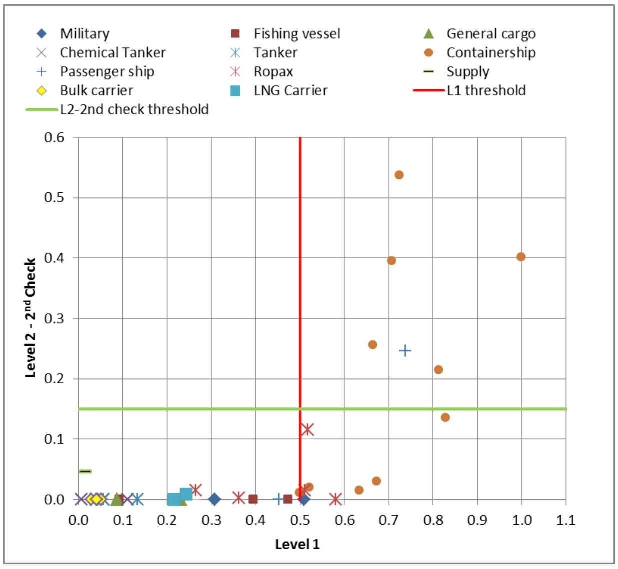


Fig. 2: Level 1 and Level 2 second check vulnerability criteria results for parametric roll.

### *Summary of parametric roll results*

The results are consistent; all ships found as to be non-vulnerable on the level 1 criterion as shown in figure 2, have been found as to be non-vulnerable for the level 2. The levels 1 and 2 criteria can separate a bulk carrier or a tanker from a containership (figure 1 and 2). Containership 1 (C11 class containership) has been identified as vulnerable to parametric roll by the levels 1 and 2 vulnerability criteria, and this ship is known for its vulnerability to this phenomenon (France and al. 2001). It is interesting to note that on the containership and passenger ship groups, some vessels are vulnerable and others not.

Using the previous definition of level 2 criterion for parametric roll, all containerships (10 vessels) were found vulnerable (Corrignan and Wandji (2012)). With the updated level 2 criterion, and using the same vessels and loading condition, 50% of containerships were now found to be non-vulnerable. The respectively selected and suggested environmental conditions and the standard during SLF 55 created a separation in this group of vessels. By classifying a part of containerships (5 out of 10 vessels) as vulnerable to parametric roll, the criteria are less conservative than before.

## PURE LOSS OF STABILITY

### *Physical background*

As the roll restoring moment may be significantly decreased while the wave is located about the midship section, a vessel may suffer large roll angle and even capsize, if she spends long enough time in this situation of decreased stability; this phenomenon is known as pure loss of stability (Belenky and Sevastianov 2007).

### *Level 1 vulnerability criterion*

The criterion will be applied only if the Froude number based on service speed exceeds a threshold (it was set to 0.2 in this work which is the lower boundary of the range suggested during SLF 55). The criterion is based on an approximation of the minimum metacentric height in waves. It evaluates the stability on wave crest with the same simplification as for the level 1 criterion for parametric roll.

The environmental condition to be used in this case is a regular wave with a constant steepness of 0.0334. A ship is considered vulnerable to pure loss of stability if the minimum metacentric height is less than a minimum between a standard which is function of the Froude number and the draft and another standard set to 0.05 m.

***Application and result of first level criterion***

The criterion was applied to the 36 sample ships. The results for the two checks (speed and stability) are shown in figure 3. All ships having Froude number less than 0.2 were judged as non-vulnerable by the level 1 vulnerability criterion (all ships below the horizontal green line and at the right of the vertical black line). All general cargo, all tankers (including chemical and LNG), bulkers and the supply vessel were found to be non-vulnerable to pure loss of stability according to the first level vulnerability criterion. 80% of containerships were judged as vulnerable to pure loss of stability according to the first level criterion.

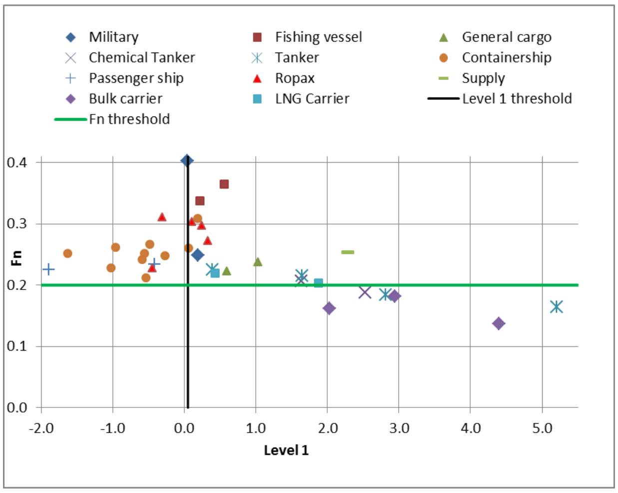


Fig. 3: Level 1 vulnerability criteria results for pure loss of stability.

***Level 2 vulnerability criteria***

The vulnerability check requires calculations of GZ curve variations for specified environmental conditions (waves). The GZ variations are evaluated with three criteria representing a weighted average from the specified waves. The first criterion calculates the angle of vanishing stability and compares it with a standard (30° was used in this work as suggested at SLF 55); the second criterion calculates the loll angle and compares it with a standard (25° as suggested at SLF 55), and the third criterion calculates the maximum of the GZ curve on wave and compares it with a standard function of Froude number, draft and wave characteristic.

Two proposals of environmental conditions have been submitted to SLF55. The simpler one, that consists in a series of 16 waves cases, has been used here. The second proposal is basically the same as the one of second level and second check of Parametric roll, except that instead of using the effective significant wave height, the effective 3% largest wave is used.

A ship is considered vulnerable to pure loss of stability if the maximum of the three criteria is greater than 0.06 (or 0.15 if the second environmental conditions are used).

***Application and results of second level criteria***

The criteria have been applied to the sample ships. The results of the assessment are shown in figure 4. The ships vulnerable to the second level criterion are above the horizontal red line in figure 4. Five ships were judged as vulnerable: one military vessel (military 1), two containerships (containerships 7 and 10), one passenger ship (passenger ship 1, the same which was found to be vulnerable to parametric rolling) and one Ropax vessel (Ropax 5).

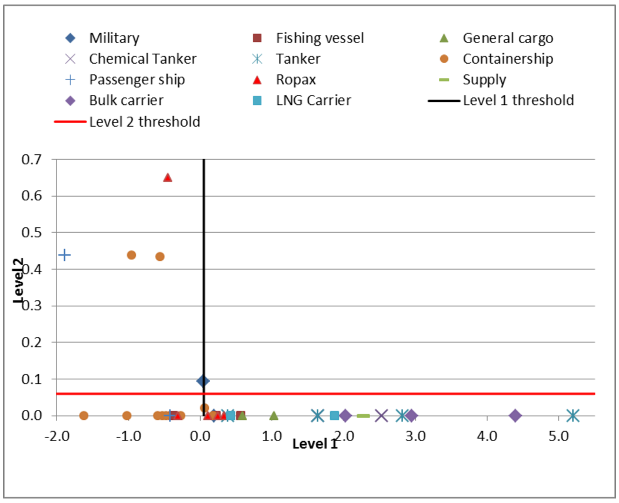


Fig. 4: Level 1 and Level 2 vulnerability criteria results for pure loss of stability.

### *Summary of pure loss of stability results*

More ships were detected as non-vulnerable by the second level criteria than by the first level. The results are consistent i.e. all the vessels non-vulnerable to level 1 were also found to be non-vulnerable to level 2. These criteria confirm the vulnerability of Military 1, which is known for her vulnerability to pure loss of stability (Hashimoto 2009). But one should note that the environmental conditions used in this work should not provide any vulnerability, because in Hashimoto (2009) it was observed during the model experiment that, for this loading condition, the vulnerability was detected when the wave steepness was larger than 0.05, while the maximum steepness of the wave used in the present study is 0.0334. Therefore, the vulnerability of Military 1 could be explained may be by a too low value of the threshold.

Using the previous environmental conditions and standard, over 40% (15 vessels) of the sample ships studied were found to be vulnerable after the second level criterion (Corrignan and Wandji (2012)). Applying now, on the same vessels and loading condition, the environmental conditions and the standard defined during SLF 55, we have about 14% (5 ships) of the sample ships which are considered as vulnerable to pure loss of stability after the second level criterion. The new formulation (criteria + standard + environmental conditions) is less conservative than before.

## EXCESSIVE ACCELERATIONS

### *Physical background*

When a ship has a large GM, the natural roll period is reduced, thus excessive accelerations due to roll motion may occur. These excessive accelerations could result in serious injury of crew and cargo loss.

### *Level 1 vulnerability criterion*

The first level criterion is calculated by evaluating the root mean square (r.m.s) of lateral acceleration on the bridge which is calculated by computing the r.m.s. of roll amplitude. A ship is judged as non-vulnerable if the r.m.s of lateral acceleration is less than 0.2g (where g is the acceleration due to gravity).

### *Application and result of first level criterion*

The criterion was applied to 4 sample ships (one general cargo vessel, one tanker ship, a containership and one LNG carrier). Figure 5 shows the computed r.m.s. of lateral acceleration on the bridge according to level 1 procedure as described in SLF 54/WP.3 annex 2. In this computation, roll damping is estimated using the Ikeda's simplified method. Under the actual loading condition the four ships were found to be vulnerable to level 1 criterion (the ships at the right of the vertical red line are considered as vulnerable to excessive acceleration).

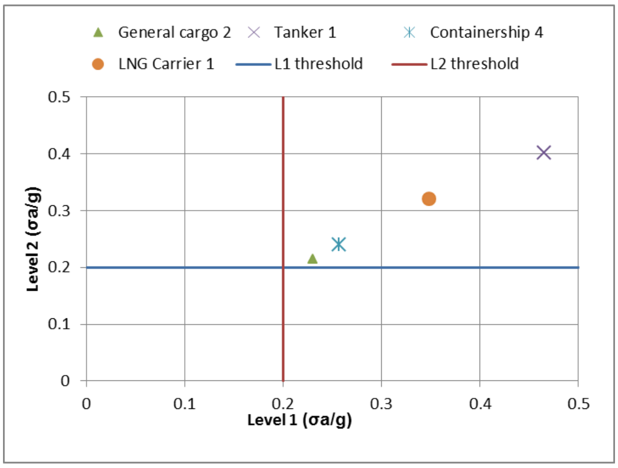


Fig. 5: Level 1 and Level 2 vulnerability criteria results for excessive acceleration.

### *Level 2 vulnerability criterion*

The procedure to compute the second level criterion is similar to the first level criterion procedure, although here the effective roll damping, the effective wave slope and the r.m.s. of roll amplitude are evaluated without simplification. A vessel is considered as non-vulnerable to excessive acceleration according to the second level criterion if the r.m.s of lateral acceleration is less than 0.2g.

***Application and result of second level criterion***

The criterion was applied to the same 4 sample ships used for the level 1 assessment. The effective wave slope coefficient was calculated by using a 3D potential code. The four ships were judged as vulnerable (the ships above the blue line are considered as vulnerable to excessive acceleration).

***Summary of excessive accelerations results***

No vessel was found to be non-vulnerable by levels 1 and 2 criteria, therefore the criteria seem to be restrictive. The outcomes of these two criteria are close (in figure 5 they are around the first bisector).

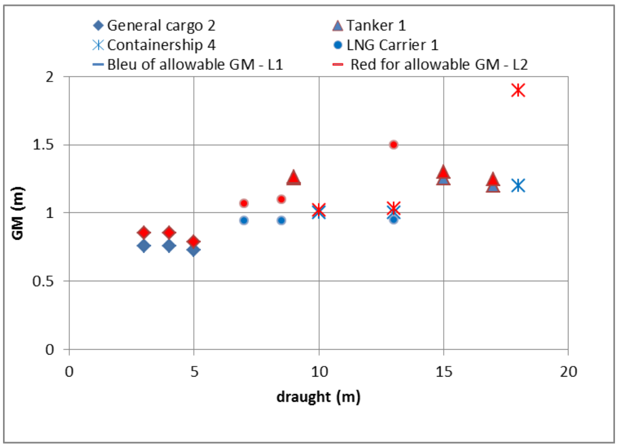


Fig. 6: Maximum allowable GM to comply with excessive accelerations criteria of 4 ships for various loading condition.

The same criteria were used to determine the maximum allowable GM for which the r.m.s of the lateral acceleration fulfils the criteria i.e. smaller than 0.2g. The results are shown in figure 6. In light of the results it is found that, in order for ships to comply with the criteria, the GM value has to be small. For the 4 selected ships, the maximum allowable GM does not conflict with the minimum one as imposed by 2008 IS code. However, it should be noted that small GM values may impede ships to comply with damage stability requirements of SOLAS 2009.

**CONCLUSIONS**

This paper presents the application of level 1 and level 2 vulnerability criteria, as defined in the current state of development (i.e. SLF55), by the International Maritime Organisation (IMO), of the second generation intact stability. Calculation results for a sample population of 36 ships were examined for phenomena related to righting lever variation in waves and 4 ships were used for the stability failure mode related to excessive acceleration.

Selected bulkers, tankers and general cargo are found not to be vulnerable to parametric roll and pure loss of stability. Parametric roll development is observed for containerships and passenger ships. Possible vulnerability for pure loss of stability was detected for containerships, military vessel, Ropax vessel and passenger ships. Regarding excessive accelerations, 4 vessels were tested and they were all found to be vulnerable to this phenomenon. The criteria and the standard of this failure mode seem to be very conservative. The criteria regarding surf-riding and broaching did not change during SLF55 and were already tested and presented in Corrignan and Wandji (2012).

No inconsistency was found between level 1 and level 2 criteria. In general level 2 criteria were less conservative than level 1 criteria i.e. more ships were found to be non-vulnerable with level 2 criteria than with level 1 criteria.

The first level criteria are simple to apply. The second level criteria need specific software and time to prepare the geometric input to compute the GZ curve in waves (for phenomena related to righting lever variation) and the effective wave slope (for excessive acceleration).

The next steps at IMO will be to finalize some standards that are still suggested within an interval and to select the environmental conditions for the second level vulnerability criteria for pure loss of stability out of the two proposals currently proposed.

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