An Overview of Vulnerability Criteria for Pure Loss of Stability

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ABSTRACT

This paper presents the current state of development of the second generation of intact stability criteria based on pure loss of stability. The concept of a multi-tiered evaluation process is based on the physics of the stability failures addressing the interaction between hull and waves in a seaway condition. After having a brief review of the recent history of related IMO development, the paper describes the framework of the new criteria in which they are complementary to the existing IMO criteria. The new criteria can be applied only to those designs that may be susceptible to one of the modes of stability failure using a set of formalized procedures of vulnerability checks. The ideas, proposals and justifications of these procedures represent the novel contents of the paper. Finally, the paper reviews pure loss of stability as a failure mode for performance-based criteria including restoring arm variation and critical stability related problems in waves.

Keywords: Pure Loss of Stability, Multi-tiered approach, Vulnerability Criteria, Intact Stability.

1. Introduction

The origin of the first-generation intact stability criteria that are included in the foundation of the International Code on Intact Stability, the 2008 IS Code (IMO, 2009) can be traced to the pioneering works of Rahola (1939), as well early versions of the weather criterion developed in the 1950s. The history of development and the background of these criteria are described by Kobylinski & Kastner (2003); a summary of the origin of these criteria is also available in chapter 3 of the Explanatory Notes to the International Code on Intact Stability (MSC.1/Circ.1281[1]).

The first generation intact stability criteria was originally codified at IMO in 1993 as a set of recommendations in Res. A.749(18) by taking into account, among other things, former Res. A.167(ES.IV) ("Recommendation on intact stability of passenger and cargo ships under 100 metres in length" which contained statistical criteria, heel due to passenger crowding, and heel due to turn, 1968) and Res. A.562(14) ("Recommendation on a severe wind and rolling criterion (Weather Criterion) for the intact stability of passenger and cargo ships of 24 metres in length and over," 1985). These criteria were codified in the 2008 IS Code and became effective as a part of both the SOLAS and International Load Line Conventions in 2010 (IMO Res. MSC.269(85) and MSC.270(85)).

The criteria in Part A of 2008 IS Code are based on a traditional empirical/statistical approach, with the exception of the Weather Criterion. The criteria for passenger vessels associated with heeling due to turn and the crowding of passengers to one side are formulated using a physics-based mathematical model of ship heeling. The Weather Criterion is based upon a mathematical model of a ship heeling under the action of a sudden wind gust after being excited by regular waves and a steady wind. The parameters of the Weather Criterion were "tuned" using a sample population of ships, which limits the applicability of the Weather Criterion, in addition to the assumptions of the mathematical model used. In response to this, an alternative experimental approach for the Weather Criterion was also adopted by IMO (*cf.* MSC.1/Circ.1200 and MSC.1/Circ.1227).

The introduction of ships with characteristics and/or modes of operation which are significantly different from the reference population of ships on which the first generation criteria was based challenges the assumption that adequate intact stability is provided using the current criteria. A series of stability-related accidents, involving ships such as the *APL China*, M/V *Aratere*, and *Chicago Express*, clearly demonstrates that intact stability criteria must be revisited.

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[1] References to IMO documents such as "MSC.1/Circ.1281" appear in the list of references with an "IMO" prefix, *i.e.* as: IMO MSC.1/Circ.1281. As there is no ambiguity in the names of the IMO citations, the year will be omitted from the citations.

The increasing of the maritime trade demand in terms of goods transport capacity, the need of short navigation time and less fuel consumption, lead to design a new generation of ships faster and with a larger deadweight than the previous one. The new hull shapes are apparently more sensitive to stability failures in a seaway. Suddenly, the first generation of intact stability criteria appears to be not exhaustive for the upcoming world fleet. They are based on a static approach and tuned on statistical data that in same cases are not fully representative for innovative ship. In this perspective, the International Maritime Organization (IMO) decided to proceed with the renovation of the Intact Stability Code and its integration. It was decided that the new criteria would be based directly on the physics of the stability failures considered and not on a database of statistics and accidents, as it was for the previous criteria. Other relevant difference from the old generation criteria is that, instead to consider the vessel in still water in a zero-speed condition, the new criteria address the interaction between hull and waves in a seaway condition.

The development of the second generation intact stability criteria started in 2002 with the re-establishment of the intact stability working group by IMO's Subcommittee on Stability and Load Lines and on Fishing Vessels Safety (SLF) (*cf.* Francescutto, 2004, 2007). However, due mainly to the priority of revising the IS Code for approval, the actual work on the second-generation intact stability criteria did not commence in earnest until the 48th session of the SLF in September 2005. The Working Group decided that the second-generation intact stability criteria should be performance-based and address three modes of stability failure (SLF 48/21, paragraph 4.18):

- *Restoring arm variation* events, such as pure loss of stability,
- *Critical stability under dead ship conditions* (i.e., loss of steering ability or propulsion, and possible endangerment by resonant roll while drifting freely), as defined by SOLAS regulation II-1/3-8; and
- *Maneuvering related problems in waves*, (e.g., broaching-to in following and quartering seas when a ship may not be able to maintain a constant course, which in turn may lead to extreme angles of heel).

A similar formulation was included in the preamble of the 2008 IS Code, indicating the direction of the long-term development. However, the restoring arm variation problem was considered as two problems: modes of parametric roll and pure loss of stability.

During this initial development, there was general agreement that the second-generation criteria should be based on the physics of the specific phenomena leading to stability failure. The design and modes of operation of new ships take on characteristics that cannot rely solely on the statistics of failures and regression-based methods. There was also general agreement on the desirability of relating the new criteria to probability, or some other measures of the likelihood of stability failure, as methods of risk analysis have gained greater acceptance and become standard tools in other industries (*e.g.* SLF 48/4/12).

These considerations led to the formulation of the framework for the second generation intact stability criteria, described in SLF 50/4/4 and discussed at the 50th session of SLF (May 2007). The key elements of this framework were the distinction between performance-based and parametric criteria, and between probabilistic and deterministic criteria. Special attention was paid to probabilistic criteria; the existence of the *problem of rarity* was recognized for the first time and a definition was offered. The evaluation of the probability of failure with numerical tools was also recognized as a significant challenge due to the rarity of stability failures.

By that time (2007), there was already some experience in the maritime industry on how to handle some issues related to dynamic stability. Following a parametric roll accident on the *APL China* (France, *et al.*, 2003), the American Bureau of Shipping (ABS) issued a guide for the assessment of parametric roll for containerships (ABS, 2004). The guide was based on a multi-tiered assessment procedure. The first level-the susceptibility criteria, was built upon evaluation of changing GM in regular waves and the Mathieu equation. If the ship was found to be susceptible to parametric roll, then a more complex criterion was applied. This "severity" criterion involved the calculation of the full GZ curve in waves and numerical integration of the roll equation. If the roll response was "severe enough," then advanced numerical simulations were applied and ship-specific operational guidance was developed using a program such as the Large Amplitude Motion Program (LAMP) (Lin & Yue, 1990). While conservative, the susceptibility and severity criteria were still capable of identifying ships for which parametric roll was not possible.

Also at that time, the work of Germanischer Lloyd was focused on numerical assessment procedures using the advanced numerical code, GL Simbel (Brunswig & Pereira, 2006, Shigunov & Pereira, 2009). Furthermore, the Germanischer Lloyd development was focused on the preparation of ship specific operational guidance for the avoidance of parametric roll (Shigunov, 2009).

Besides the efforts by classification societies, significant progress was achieved in developing training programs in order to increase crew awareness of parametric roll. An instructional video, produced by Herbert Engineering Corporation, is one successful example of this activity[2].

Analysis of these experiences led to an understanding that a multi-tiered approach should be applied for the development of the second generation intact stability criteria as a way to avoid unnecessary work. In view of this, the idea of vulnerability criteria was first formulated in the paper by Belenky, *et al.* (2008). The paper also gave a broad review of the physical background of the modes of dynamic stability failure considered. By virtue of its greater detail, this paper provided "explanatory notes" to SLF 50/4/4 and was submitted to the 51st session of SLF (SLF 51/INF.4) as additional information.

The framework of the second-generation intact stability criteria took shape based on the work of the intersessional correspondence group (SLF 51/4/1 Annex 2). This document formalized the concepts contained in SLF 50/4/4; in particular, a clear distinction was made between a criterion and a standard, the former being "an instrument of judging," while the latter is a boundary between acceptable and unacceptable.

In 2005, the Japan Society of Naval Architects and Ocean Engineers (JASNAOE) established a Strategic Research Committee on Estimation Methods for Capsizing Risk for the IMO New Generation Stability Criteria (SCAPE Committee). The outcome of this program was reported in five sessions of JASNAOE; some other results were reported in English at the Osaka Colloquium (Ikeda, *et al.,* 2008). An overview of this work is available from SLF 51/INF.6. In the meantime, certain developments in the field were affected by the increasing consideration and practical formulation of the so-called "critical wave groups" approach. This was used for probabilistic intact stability assessment during the European SAFEDOR project *(e.g.* Themelis & Spyrou, 2007), which allowed for a practical interface between the deterministic and probabilistic viewpoints. SNAME established a Dynamic Stability Task Group whose purpose is to provide a detailed review of developments in the field of dynamic stability (SLF 53/3/3).

Vulnerability criteria were the focus of the 1st and 2nd International Workshops on Dynamic Stability Consideration in Ship Design (DSCSD) (Kobylinski, 2009). The development of the second-generation intact stability criteria was intensively discussed during the 10th International Conference on Stability of Ship and Ocean Vehicles and in the following 11th and 12th International Ship Stability Workshops (Degtyarev, 2009; van Walree, 2010; Belenky, 2011). In particular, a review was presented that examined the suitability of methods for vulnerability criteria (Bassler, *et al.*, 2009).

The consideration of excessive accelerations was also recently added to the list of stability failure modes (SLF 53/19, paragraph 3.28) following the partial stability failure of *Chicago Express*, which resulted in crew injuries and loss of life (BSU, 2009). While, technically, this issue is well-known, it has not yet been included in the regulatory framework. In a recent study, Shigunov *et al.* (2011) considered a vulnerability check for excessive accelerations based on initial GM and roll damping. These discussions and developments were formed into proposals presented and discussed at the 52nd and 53rd sessions of SLF; (cf. SLF 52/3/1, SLF 52/INF.2, SLF 53/3/1, SLF 53/3/7, SLF 53/3/8, SLF53/3/9, SLF 53/INF.8, SLF 53/INF.10).

The assessment of dynamic stability in realistic wave conditions is a formidable task. The 2008 IS Code recognized this:

> *"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. Motion of ships in a seaway should be treated as a dynamical system and relationships between ship and environmental conditions such as wave and wind excitations are recognized as extremely important elements. Based on hydrodynamic aspects and stability analysis of a ship in a seaway, stability criteria development poses complex problems that require further research."*

A realistic seaway is also random, *i.e.* described as a stochastic process; therefore, the problem must also be considered in a probabilistic context. Further, the occurrence of stability failure (a random event) is rare such that the natural period of roll can be considered as infinitely small in comparison with the expected time before such an event. The existence of the problem of rarity makes direct, brute force numerical simulation impractical for the evaluation of dynamic stability failure. The solution may include numerical simulations using hydrodynamic codes, which may include model testing. While these tools represent the current state of

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[2] Trailer available from www.herbert.com/videos/ParametricRoll/

the art (*cf.* Beck & Reed, 2001), their application is expensive and requires proper justification of the necessity of their application, because not all ships are vulnerable to these stability failures.

This justification can be completed in the form of a multi-tiered approach (see Figure 1), whereby a ship would be checked for vulnerability in the first tiers and, if found vulnerable, then the ship would be evaluated using state-of-the art direct stability assessment methods. Taking into account the intended regulatory application, two tiers of vulnerability criteria would be applied. The first level is meant to be very simple and conservative. Its main purpose is to distinguish ships (and the loading conditions) that clearly are not vulnerable to a given stability failure mode, from those that, in principle, may be. Because further analysis of the vessels that are not vulnerable would be redundant, the cost of performing such further analysis should be avoided.

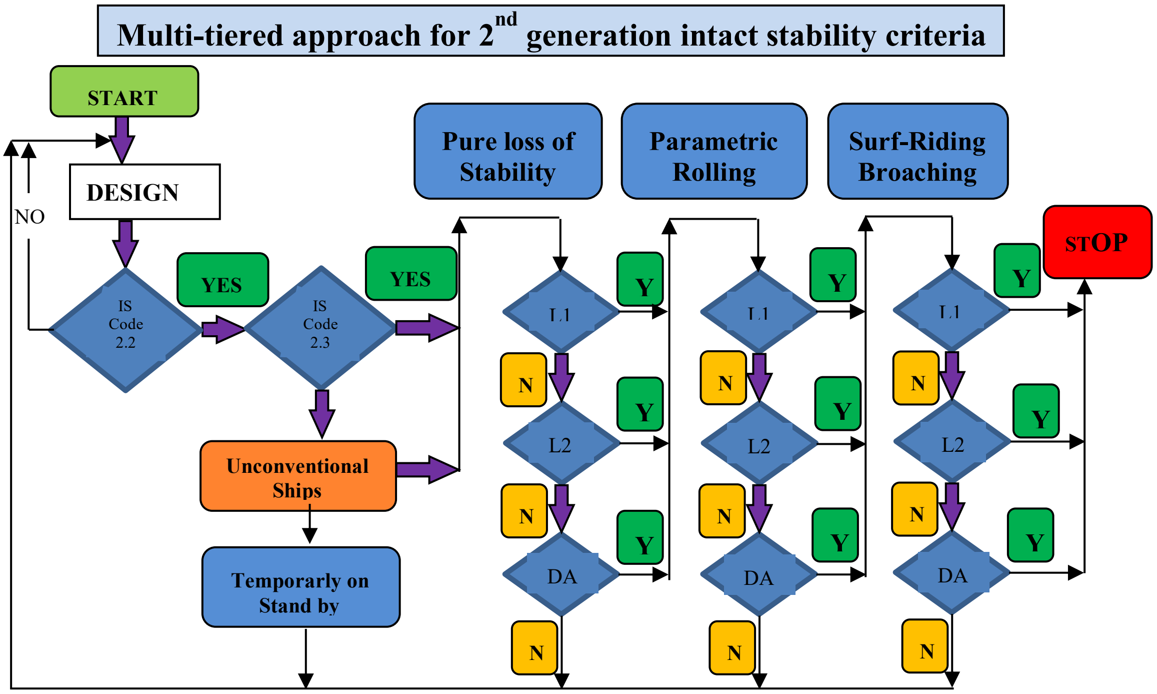

Figure 1. Multi-tiered Approach for the Second Generation Intact Stability Criteria (SLF53/WP.4 Annex 3)

As an example, very large crude carriers are wall-sided for the most of the length of the hull and, therefore, cannot experience significant stability changes in waves. Therefore, this type of ship is not expected to be vulnerable to the righting lever variation problems of either parametric roll or pure loss of stability. By basing the first-level vulnerability criteria on the geometry characteristics of the hull and speed, an easy first assessment of vulnerability may be made. Therefore, the criteria will remain valid for any novel ship design. Because the level-one criteria are to be simple and conservative, some occasional “false positives” may be expected. Again, to reduce the time and cost of stability assessment, a second level of vulnerability criteria is introduced. The second level is meant to be less conservative than the first, based on simplified physics and involving calculations with reduced computational efforts and straightforward applications following suitable guidelines. There has been very active development of the vulnerability criteria since 2009, when a review of eligible methods was prepared (Bassler, *et al*., 2009).

The vulnerability criteria for Pure Loss of Stability with physical background is given in Section 2. The details of the level 1 and level 2 in multi-tiered approach are also presented in Section 2. The conclusions of the study with related discussions are given in Section 3.

2. Vulnerability Criteria for Pure Loss of Stability

When a ship is sailing through waves, the submerged portion of the hull changes. These changes may become especially significant if the length of the wave is comparable to the length of the ship. The influence of wave profile on the stability performance is described taking into account the most significant situations, i.e. both the wave crest and the wave trough located amidships considering a wave-length equal to ship length.
For example, let us examine the changes that occur when the trough of a wave is located amidships, applicable for the most monohull vessels (see Figure 2a). The upper part of the bow section is usually wide, due to bow flare, which makes the waterplane larger if the upper part of the bow section is partially submerged. The upper part of the aft section is even larger than the bow section; thus, the aft part of the waterplane becomes larger once the upper part of the aft section is submerged. Unlike the bow and aft sections, the midship section is wall-sided for most displacement hulls. This means that very little change occurs in the waterplane width with draft when the wave trough is amidships, the draft at the midship section is low, but the waterplane does not change much. As a result, when the wave trough is around the midship section, the waterplane is larger than it is in calm water.

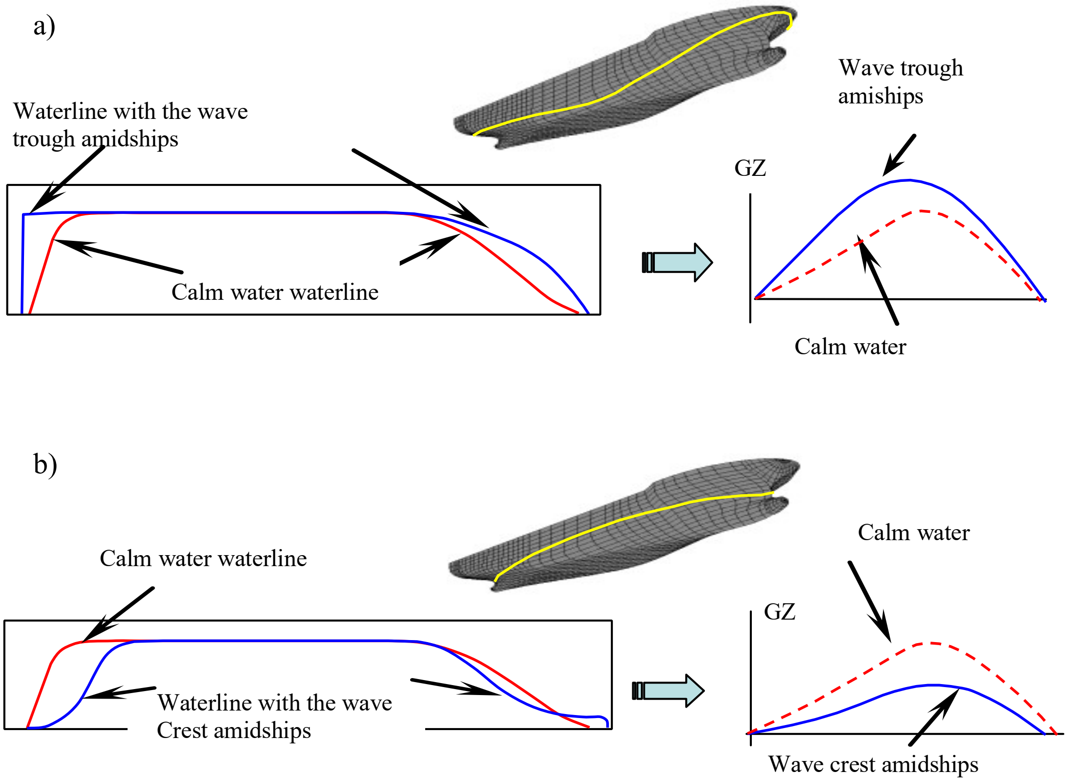

Figure 2. Effects of wave trough and wave crest located amidships (Belenky, C.C. Bassler, and K.J. Spyrou, 2011).

When the wave crest is located around the midship section, the situation changes dramatically, see Figure 2b. When the wave crest is located amidships, a wave trough is located near the fore and aft sections. The underwater part of the bow section is usually quite narrow, especially around the waterline and the underwater part of the aft section is also very narrow. Thus, when troughs are fore and aft, the draft at the bow and the stern becomes shallow, which makes the waterplane very narrow. It is well known from ship hydrostatics that the waterplane area has a significant effect on ship stability because it is directly related to the inertia of the waterplane. If the waterplane area is reduced, then the GZ effort is also reduced.

Pure loss of stability is related to prolonged reduction of the GZ curve on (or near) the wave crest. This situation occurs in following and stern-quartering seas when the ship speed is close to the wave celerity. If an additional heeling (or rolling) moment (e.g. lateral gusty wind load, short-crested wave effect or centrifugal force due to course keeping) is applied, a ship may attain a large roll angle and even capsize.

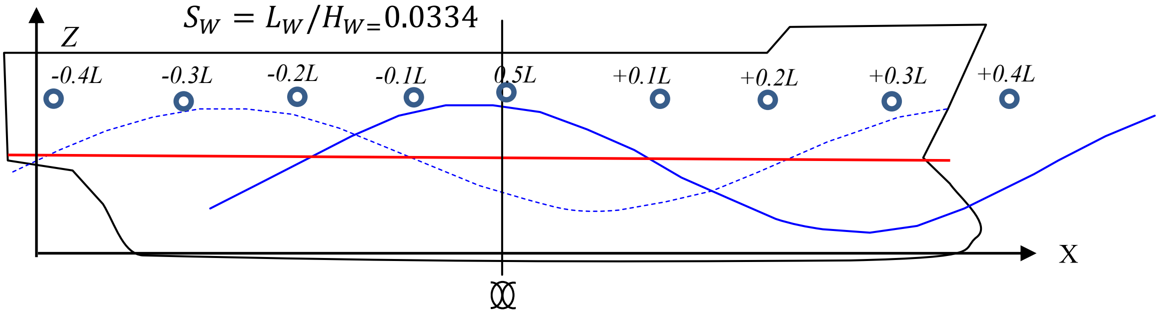

Figure 3. Application of direct procedure at pure loss of stability

A typical scenario where the pure loss of stability phenomenon may occur is the following: a wave with the wavelength comparable to the ship length reaches from the stern a ship sailing in following seas characterised by a relatively high speed and low metacentric height (Figure 4a). If the wave celerity of the approaching waves is just faster than the ship speed, it takes a long time to pass the ship (Figure 4b). Thus, the condition of wave crest amidships and the influence on stability can lasts enough time to be dangerous. This may lead to a large heel angle or even capsize. Once the wave crest moves away from amidships (Figure4c), the stability is re-gained and the ship returns to the upright position, only if she has not heeled too far.

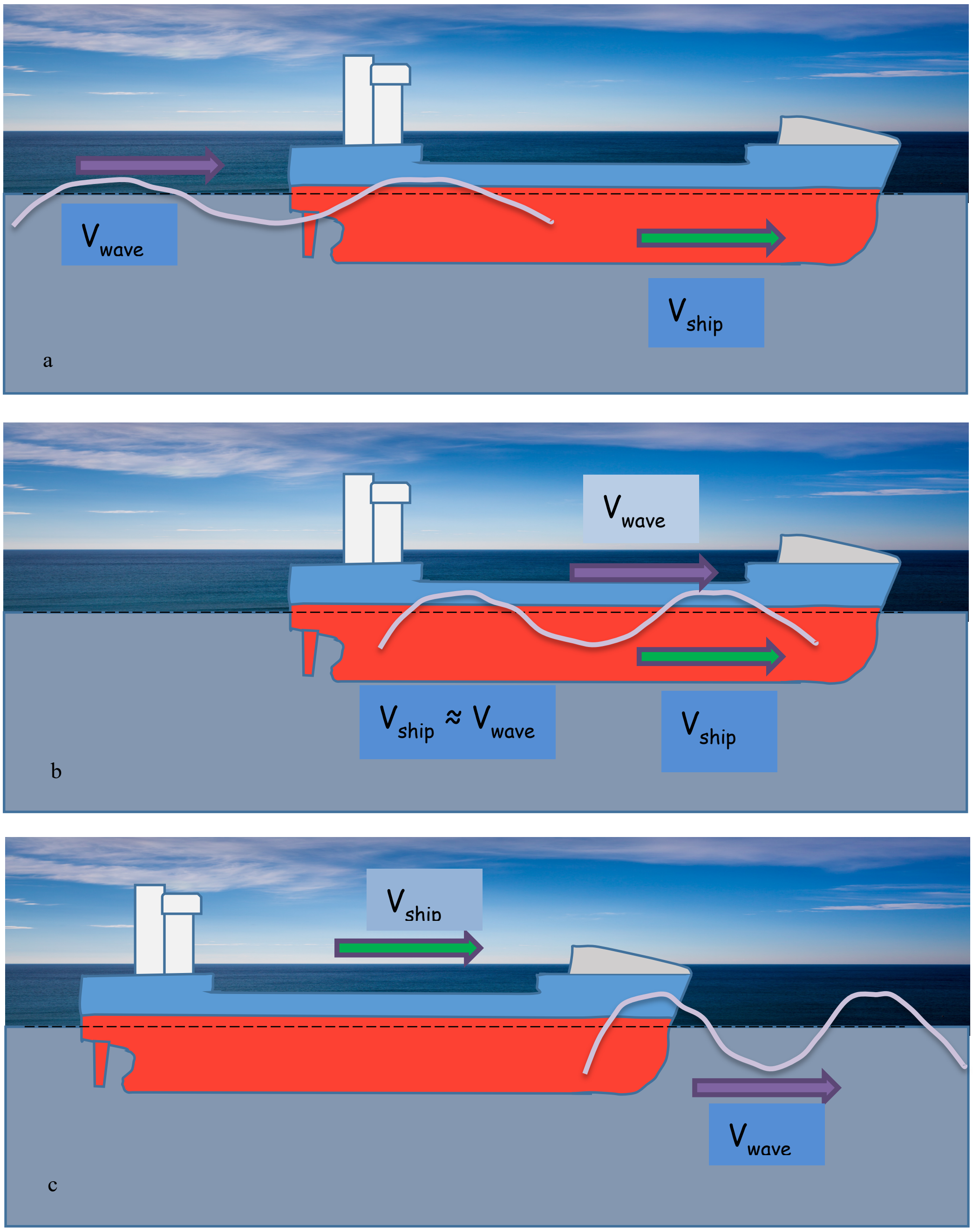

Figure 4. Typical scenario of pure loss of stability failure

Level 1 Vulnerability Criteria for Pure Loss of Stability

Some hulls are more prone to pure loss of stability than others do. A hull with large freeboard and significant change of geometry in the fore and aft sections, but with a small GM value, may suffer from significant loll angle due to deterioration of stability on the wave crest. As can be seen from Figure 5, loll angles resulted in large angles of heel when the wave crest was passing near the midship section.

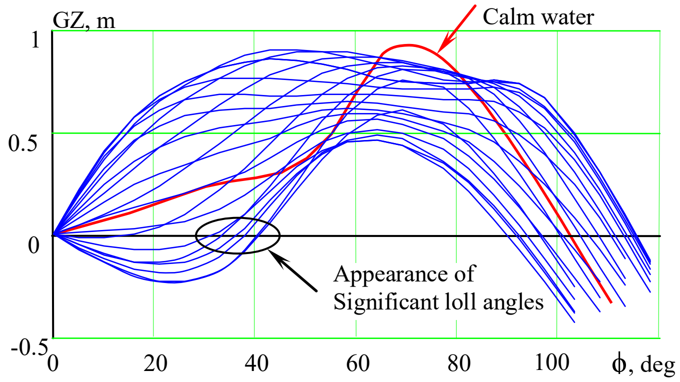

Figure 5. Wave Passing Effect on GZ Curve of a RoPax Ship in IMO-critical Loading Conditions

Pure loss of stability is driven by stability changes in longitudinal waves. As discussed above, certain features of the hull shape are "responsible" for stability change. One of the possible options proposed for the Level 1 Criterion is focused on these geometric features (SLF 53/INF.10 Annex 5).

The criterion is the average value of the vertical wallsidedness coefficients for the fore and aft quarter portions of the hull, both above and below the waterline. The coefficient for vertical "wall-sidedness," C_{VWS}, measures the variation of the fore or aft quarter of the waterplane area; either from the base line to the design draft or from the design draft up to the shear line (see Figure 6). The threshold value as the standard should be determined from sample calculations.

The coefficient is taken relative to the maximum waterplane area of the fore or aft portion over the specified range of drafts,

$$C_{CWS}^{below} = \frac{\int_0^d A_{WP}(z)dz}{\max\left(A_{WP}(z)\right)\cdot d}$$

$$C_{CWS}^{above} = \frac{\int_d^D A_{WP}(z)dz}{\max\left(A_{WP}(z)\right)\cdot (D-d)} \qquad (1)$$

where d is draft, D is depth, and A_{WP} is waterplane area of fore or after quarter of the waterplane.
According to the fundamental of the physics of the phenomenon, both vulnerability Level 1 and Level 2 need not to be applied to all ships for which the Froude number (Fn) corresponding to the service speed, complies with the following formula:

$$F_n = \frac{V_s}{\sqrt{g.L}} < 0.24 \qquad (2)$$

Where, *'g'* is gravitational acceleration of 9.81, (m/sec^2); *'L'* is ship length, (m); *'Vs'* is service ship speed, (m/sec).
The first level of vulnerability does not consider a ship vulnerable to the pure loss of stability failure mode if:

$GM_{min} > R_{PLA}$

Where, 'GM_{min}' is the minimum value of the metacentric height in waves, (m); 'R_{PLA}' = 0.05, (m).

Two different procedures are available to compute the amplitude of the metacentric height variation in waves. The first one is more precise and it takes into account directly a longitudinal wave while the second method is a simplified procedure applicable only under certain conditions.

In the direct procedure, the minimum metacentric height (GM_{min}) may be determined considering the vessel balanced in sinkage and trim on a series of waves having a length equal to the ship length ($\lambda = L$) and a steepness coefficient equal to SW = 0.0334. The wave crest should be centered amidships and moved forward and aftward from 0.1L to 0.5L in both directions with steps of 0.1L (see Figure 3). The wave should be modeled by a sinusoidal wave without hydrodynamic disturbance due to the ship presence.

According to the simplified procedure, the minimum metacentric height as a conditional value of 'GM_{min}' is computed as follows (SLF 53/INF.10 Annex 2):

$$GM_{min} = KB + \frac{I_L}{V} - KG \qquad (3)$$

where 'KB' is the distance of the center of buoyancy from the base line, 'V' is the volumetric displacement calculated for the design draft, and 'KG' is the distance from the base line to the center of gravity in design-loading conditions. 'I_L' is the moment of inertia of the water plane calculated for a fraction of the draft, which normally should be determined as the intersection between the flat of side and the bilge radius at amidships. Since the waterplane breadth in the midship section is almost unchanged, the waterplane area on the wave crest can be approximated with that in calm water but with the smallest draft. As a result, the required value of 'I_L' can be taken from an existing hydrostatic table so that no additional calculations using hull geometry are required. In this case, the threshold value as the standard can be regarded as zero. Another advantage of the criterion is its potential ability to differentiate between multiple loading conditions.

The aim of the simplified procedure is to avoid the calculation of wavy waterlines. They are simplified with straight lines to calculate the moment of inertia of water plane area. The equivalent metacentric height (GM_{eq}) is evaluated on the waterplane associated to the highest draught of the wave profile. Nevertheless, the results obtained by this procedure are more conservative than the Direct Procedure.

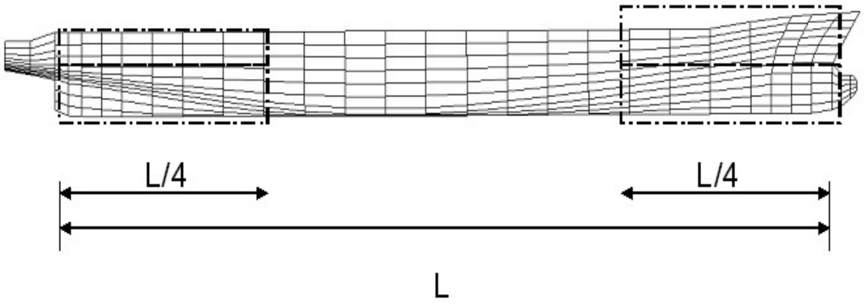

Figure 6. Notional Ship Profile with the Four Portions of the C_{VWS} Considered for the Level 1 Vulnerability Assessment

Both criteria are based on understanding that the vertical variability of the hull shape at bow and stern, but not at the midship section, is responsible for stability changes in waves. The results of calculations for 40 sample ships are presented in Tables 1 and 2 (see Appendix B). The value 0.8 was considered as a tentative standard for the criterion (1) in SLF 53/INF.10 Annex 5, while $GM_{min}>0$ was proposed in the Annex 2 of SLF 53/INF.10. Preliminary analysis needs to be done while criteria (1) and (2) are still considered "draft" (as well as all other criteria considered in this paper). First, the criteria (1) and (2) seem to agree for most of the cases considered. The only exceptions are the two multi- purpose vessels (MPVs) (L = 135 m and 105 m), the 5500 DWT bulk carrier, the 110 m tanker and both tugs.

The ONR flared topside configuration (Naval Combatant 1) represents the hull shape of a notional conventional destroyer. The extensive operational experience of conventional destroyer hulls shows that they are not known for any pure loss of stability failures. Therefore, both criteria are conservative in this case because the hull shape causes significant change of waterplane area, while the KG-value is low enough to compensate for degradation of stability in a wave crest. Similar situations can be observed for the Japanese Purse Seiner, the small tanker (L = 110 m), the 105 m MPV and both tugs. The situation with the 135 m MPV and the 5500 DWT bulk carrier seems to be the opposite: the change of water-plane area is not dramatic, but the reserve KG may be insufficient to counter the decrease of stability on a wave crest.

Both criteria unanimously exclude from vulnerability large tankers and the rest of the bulk-carriers; this exclusion does not require any comment as these ship types have never suffered from pure loss of stability. Both criteria detect vulnerability to pure loss of stability for both RoPax ships and the ONR Tumblehome topside hull form (Naval Combatant 2) for which vulnerability to pure loss of stability seems to be plausible, as these types of ships are known for such failures (Maritime New Zealand, 2007; Hashimoto, 2009). Both criteria detect vulnerability to pure loss of stability for all the tested container carriers. This seems to be result of dramatic changes of the waterplane area for which containerships are known. It is also known that these changes are capable of causing parametric resonance, but not necessarily pure loss of stability. The Level 2 Vulnerability Criterion, then, is expected tested against this fact.

In general, it seems that criteria (1) and (2) complement each other; criterion (1) offers better accounting for the details of ship hull shapes, while criterion (2) provides a value that is specific for a given loading condition. Choice of the appropriate set of loading conditions remains to be done, as well as tuning computational parameters.

Level 2 Vulnerability Criteria for Pure Loss of Stability

As a first approximation, pure loss of stability may be considered as a single wave event because the changes in stability are instantaneous and do not have a memory. Typically, the worst-case wavelength is close to the length of the ship, $\lambda/L \approx 1.0$. However, in order to account for the effect of ship size relative to wave conditions, righting lever variations must be evaluated in irregular waves.

An irregular seaway can be presented as a series of encounters with sinusoidal waves with random length or wave number (spatial frequency) and height or amplitude. A joint distribution of these quantities is available from Longuet-Higgins (1957, 1976, 1984), which is based on the theory of an envelope of stochastic process (Rice, 1944/45). Based on Longuet-Higgins, each wave encounter can be associated with a statistical weight:

$$W_{ij} = \int_{a_i-\Delta a}^{a_i+\Delta a} \int_{k_j-\Delta k}^{k_j+\Delta k} f(a,k)\, dk\, da \tag{4}$$

where ‘a_i’ and ‘k_i’ are amplitudes and wave numbers presented with a certain discretization over the probability density function:

$$f(a,k) = f(a)f(k|a) = \frac{a^2}{\sqrt{k_2^2-k_1^2}\sqrt{2\pi V_W^3}} exp\left(-\frac{a^2}{2V_w}\right) \times$$

$$\left(exp\left(-\frac{a^2}{2V_w}\frac{(k-k_1)^2}{(k_2^2-k_1^2)}\right) + exp\left(-\frac{a^2}{2V_w}\frac{(k+k_1)^2}{(k_2^2-k_1^2)}\right)\right) \tag{5}$$

where ‘V_W’ is the variance of the wave elevations, ‘k_1’ is the mean wave number and ‘k_2’ is related to the mean width of spectrum s(ω) expressed in terms of wave numbers using the dispersion relation:

$$k_1 = \frac{1}{V_W}\int_0^\infty \frac{\omega^2}{g} s(\omega)\, d\omega \tag{6}$$

$$k_2 = \sqrt{\frac{1}{V_W}\int_0^\infty \frac{\omega^4}{g^2} s(\omega)\, d\omega} \tag{7}$$

The value of 'k_2' includes a fourth spectral moment. Not all approximations for sea spectra allow straightforward calculation of the fourth moment. It is known that calculations of the fourth moment for Bretschneider-type spectra are only possible if the frequency range is limited (Bishop & Price, 1978; St. Denis, 1980).

The criterion formulated for a regular wave relates wave-length and height to a measure of deterioration of stability, while this wave passes the ship. Then the criterion for irregular waves can be sought as a mean value of a deterministic function of random variables: wave number and wave amplitude.

$$Ci = \sum_i \sum_j Cr(a_i, k_j) W_{ij} \tag{8}$$

where '*Cr*' is the criterion for a regular wave characterized with the wave number, *k*, and amplitude, *a*, while '*Ci*' is the same criterion averaged for irregular waves defined using a given spectrum. Alternatively, the second level vulnerability check can be done using just a series of regular waves systematically covering the entire range of possible steepness values. Here, the wavelength is assumed equal to the ship length as the worst-case scenario, while the range of steepness values remains to be determined.

Three criteria for regular waves are considered below. The first criterion is based on time duration while stability is degraded due to the passing wave. The time while stability is decreased can be easily found if the instantaneous '*GM*' is considered a function of the wave crest position. To evaluate this function, the instantaneous '*GM*' is calculated on a series of wave water planes corresponding to different positions of the wave crest relative to the midship section (see Figure 7). Points 'x_1' and 'x_2' (Figure 8) show the distance when the '*GM*' remains below a critical level while the wave passes the ship.

The "time -below-critical GM", *tbc*, can be calculated as:

$$tbc = \frac{x2 - x1}{|c - V_S|} \tag{9}$$

where '*c*' is wave celerity and 'V_s' is ship speed. The time-below critical '*GM*' is a random number in irregular waves. Its mean value is estimated as:

$$m(tbc) = \sum_i \sum_j tbc_{ij} W_{ij} \tag{10}$$

Obviously, waves that produce celerity that is too close to ship speed must be excluded to avoid the singularity in Equation (9). The criterion value 'Cr_1' is proposed as the following ratio:

$$CR_1 = \frac{m(tbc)}{T_\varphi} \tag{11}$$

where 'T_ϕ' is a time scale of roll motions (not necessarily the period in calm water).

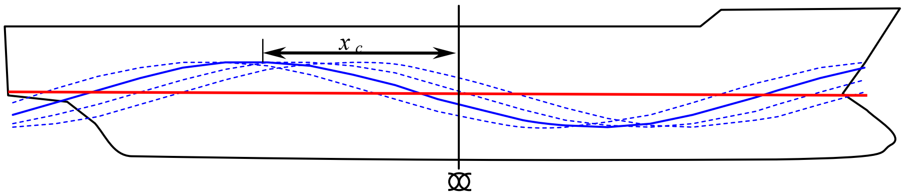

Figure 7. On Calculation of the Instantaneous GM in Waves

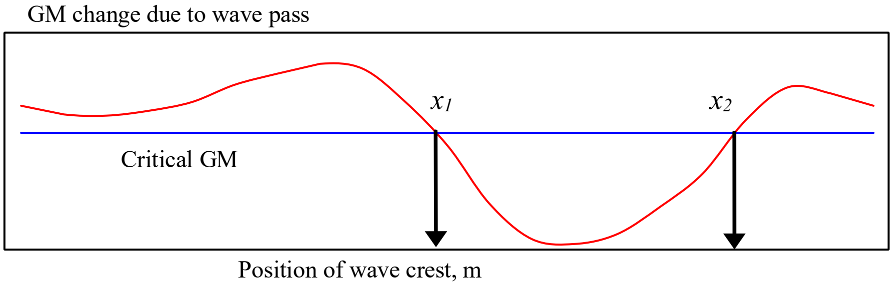

Figure 8. Calculation of “Time-Below-Critical-GM”

This criterion assesses the significance of stability changes in waves. If stability is degraded only for a short duration, this degradation may not be significant. However, for longer durations of decreased stability below the critical level, the restoring moment may be degraded enough to result in a dangerously large roll angle. More details on this criterion as well as sample calculations on notional naval ships is available from Belenky & Bassler (2010). This criterion may be further refined by including a simple model for surging, as the surge motion affects phases and therefore may change the timing.

The second criterion, ‘Cr_2’, is set to detect if there are significant durations of negative ‘*GM’* (Figure 9). Appearance of an angle of loll may lead to the development of partial stability failure sooner, as the upright equilibrium is no longer stable. It is quite possible that some ships will more vulnerable to these types of failure than others do. The second criterion is based on the time during which the angle of loll exceeds a certain limit angle, ‘ϕ_{lim}’. The time while the angle of loll is too large during the wave pass is expressed as:

$$tbz = \sum_k z_k \Delta t \tag{12}$$

where value, ‘z_k’ is an indicator, ‘Δt’ is the time-step and index ‘k’ corresponds to a particular time instant during the wave pass. For the k-th position of the wave crest along the hull crest, the indicator value, ‘z_k’ is calculated as:

$$z_k = \begin{cases} 0 \;\; if \;\; \varphi_{loll} < \varphi_{lim} \\ 1 \;\; if \;\; \varphi_{loll} \geq \varphi_{lim} \end{cases} \tag{13}$$

(30 degrees was used as ‘φ_{lim}’ in this example). Obviously, the angle of loll, ‘φ_{loll}’, can only be obtained from the *GZ* curve in waves. Calculations of the instantaneous ‘*GZ’* curve in waves are done in the same way as described for the instantaneous ‘*GM’* (Paulling, 1961). Since the encounter frequency is low, the influence of heave and pitch can be approximated quasi-statically through balancing trim and draft. Sometimes the ‘GZ’ in waves can be approximated by using a calm-water ‘*GZ’* curve and the instantaneous ‘*GM’* in waves. However, caution has to be exercised as there are known cases when such approximations are not conservative (Annex 9, SLF 53/INF.10).

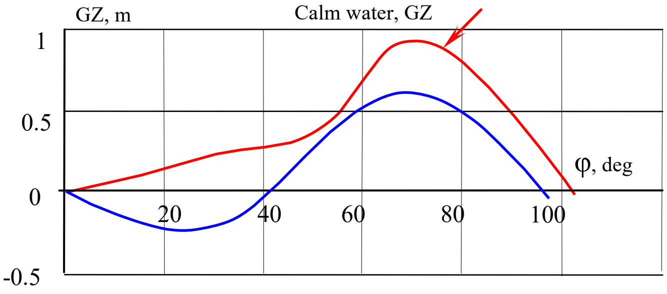

Figure 9. Deterioration of GZ Curve near the Wave Crest

Formulation of the second criterion is similar to the first one:

$$CR_2 = \frac{m(tbz)}{T_\varphi} \tag{14}$$

where 'T_ϕ' is the chosen time scale, and '$m(tbz)$' is the weighted average over the wave encounters:

$$m(tbz) = \sum_i \sum_j tbz_{ij} W_{ij} \tag{15}$$

The third proposed criterion is based on the maximum of the '*GZ*' curve in waves. The suggested standard is zero, so the ship is considered vulnerable if the '*GZ*' curve becomes completely negative at least once during the series of calculations:

$$CR_3 = \min\left(GZ_{max}(x_c, a, k)\right) < 0 \tag{16}$$

Sample calculations for the criteria (14), (15), and (16) can be found in Annexes 2 and 5 of SLF 53/INF.10.

The second level consists of a probabilistic approach of the phenomenon associated with a wave scattering table. For an unrestricted sailing area, the new regulation imposes that included in the IACS Recommendation 34 corresponding to the Northern Atlantic (Table 2, from [69]).
The second level of vulnerability consists of two different checks: the first one judges the ship vulnerability on the basis of the vanishing angle while the second check takes into account the stable heel angle due to an external heeling lever, both considering the ship statically positioned in waves of defined height and length.
According to second level of vulnerability, a ship is considered not to be vulnerable at pure loss of stability if:

$$\max(CR_1, CR_2, CR_3) < R_{PLO} \quad \Rightarrow \quad R_{PLO} = 0.06 \quad \text{weighted criteria}$$

$$CR_1 = \sum_{i=1}^{N} w_i \cdot C1_i \qquad CR_2 = \sum_{i=1}^{N} w_i \cdot C2_i \qquad CR_3 = \sum_{i=1}^{N} w_i \cdot C3_i \tag{17}$$

Where, 'CR_1' is the criterion of the first check, 'CR_2' is the criterion of the second check, 'w_i' is the weighting factor of wave case occurrences obtained from wave data and 'N' is the number of wave cases corresponding to non-zero probabilities in wave case occurrences table. The value of the standard 'R_{PL0}' has been determined according to the reports of major large heel incidents of RO-RO ships.

Criterion 1:

In the first criterion, the minimum angle of vanishing stability ($\phi_{V.min}$) and the maximum angle of stable equilibrium ($\phi_{S.max}$) are computed for the 197 non-zero-weighted waves of the wave scatter diagram and used to calculate '$C1_i$' and '$C2_i$' as follows:

$$C1_i = \begin{cases} 1, & \phi_v < R_{PL1} = 30^0 \\ 0, & otherwise \end{cases} \tag{18}$$

The minimum angle of vanishing stability among all wave crest position, 'ϕ_v', with the free surface correction, may be determined as the minimum value calculated for the ship, corresponding to the loading condition under consideration. The wave crest centered at the longitudinal center of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof.

Criterion 2:
In the second criterion based on a calculation of the ship's angle of loll:

$$C2_i = \begin{cases} 1, & \phi_{smin} > R_{PL2} = 25^0 \\ 0, & otherwise \end{cases} \tag{19}$$

'R_{PL2}'= 25^0 (15^0 for passenger vessels)

The angle of heel under action of heeling lever, 'ϕ_s', with the free surface correction, may be determined as the minimum value calculated for the ship, corresponding to the loading condition under consideration.

Criterion 3:
In the third criterion based on a calculation of the maximum value of the righting lever curve:

$$C3_i = \begin{cases} 1, & GZ_{max} < R_{PL3} \\ 0, & otherwise \end{cases} \tag{20}$$

'GZ_{max}'is determined as the smallest of maxima of the righting lever curves calculated for the ship, with free surface correction, corresponding to the loading condition under consideration. For each wave, the heeling lever 'R_{PL3}'is defined as follows:

$$R_{PL3} = 8\frac{H_i}{\lambda} dF_n^2 \tag{21}$$

The calculation of stability in waves should assume the ship balanced in sinkage and trim on a series of waves with a length equal to the ship length and the following wave heights:

- For calculating the restoring moment in waves, the following wave length and wave height should be used:
  Wave length, $\lambda = L$
  Wave height, $h_j = 0.01 \times jL$ where, j = 1, 2, ..., 10

- Specified wave cases for evaluation of the requirements given in Table 2. For use in Option B, '*N*' is taken as 197. For each combination of '*Hs*' and '*Tz*', '*Wi*' is obtained as the value in Table 2 divided by 100000, which is associated with a 'H_i' calculated above and 'λ_i' is taken as equal to '*L*'. Then, the indices for each 'H_i', should be interpolated from the relationship between '*h*' and the indexes obtained above.

For each studied wave, the wave crest is to be centered amidships and shifted aftward and forward, with steps of 0.1L, from 0.1L to 0.5L.

The stability analysis should be carried out for each value of 'h_j'. Thereafter, for each sea state defined by the wave scatter diagram, a 3% largest effective wave height (H_i) should be evaluated according to the procedure. Both the vanishing angle and the stable heel angle associated to the representative wave height are obtained by linear interpolation among the corresponding indexes computed for the different wave heights (h).

For the evaluation of the above requirement, the wave scatter diagram should be selected to the satisfaction of the Administration. In case of no specific data, the rule text suggests the wave scatter diagram provided by International Association of Classification Societies (IACS) Recommendation No.34 (Appendix A).

In the assessment of relationship between 'Level 1' and 'Level 2', as it is in the general philosophy of SGISc, the Vulnerability 'Level 1' is modeled as a simplified version of the second level. The righting arm curve and the maximum heeling angle achieved in specific wave conditions are considered by the second level of vulnerability, while, in the first level, only the minimum metacentric height is judged. Small metacentric heights does not always lead to weak values of righting arm in waves. Therefore, the first level of vulnerability is more conservative than the second one because it considers only the metacentric height instead of the complete righting arm diagram. In order that a critical situation happens, besides the restoring moment reduction due to hull and wave profile interaction, a heeling moment is required. This is because if no heeling moment exists, the upright position can be kept. Therefore, a relevant external moment is required such as a wave exciting roll moment due to oblique wave heading or a transversal moment induced by a centrifugal force due to ship manoeuvring motions.

3. Conclusions

The concept of the second-generation intact stability criteria is based on a multi-tiered evaluation process. Because the direct stability assessment of ship-stability performance may incur substantial additional design analysis expense, a vulnerability check needs to be performed first, to exclude cases where the modes of stability failure are not a concern. Vulnerability checks are performed at two levels to ensure simplicity and prevent unnecessary conservatism. The 'level 1' vulnerability check is simple, but conservative, while the 'level 2' is less conservative, but involves more calculations. The 'level 1' vulnerability criteria for pure loss of stability is based on geometry of the hull, reflecting how dramatic changes of waterplane increase the likelihood for stability failure. The 'level 2' vulnerability check is performed with the GZ curve changing in waves, using different parameters as the criteria. The next objective in the development of the second-generation intact stability criteria is defining the requirements and procedures necessary for direct assessment. This is a formidable task. Not only must the most advanced technologies available be used, but they also need to be available worldwide.

At this moment, advanced potential-flow hydrodynamic codes with empirical models for lifting and viscous forces seem to be the most appropriate tools for predicting pure loss of stability. Development of validation procedures for time-domain simulation tools is another difficult, but necessary task. As direct stability assessment is meant done under realistic conditions, the stochastic nature of the environment needs to be fully considered. This means that stability failures must be regarded as random events and, since they are rare, the problem of rarity needs to be addressed with a set of appropriate probabilistic extrapolation procedures. Development and verification of these procedures is just as important as the development and validation of numerical tools. In addition, an additional mode of intact stability failure, excessive accelerations, needs to be addressed with suitable vulnerability criteria and direct stability assessment methods.

Once the criteria development is complete, two more stages will be needed. First, standards or acceptance boundaries must be established for the various criteria. This task will involve agreeing on socially acceptable risks of maritime activity. While this problem has been tackled in other fields of engineering, it has not yet been adequately addressed as far as intact stability is concerned. Second, issues of implementation of the second-generation intact stability regulations will need to be addressed. Implementation will rely on careful testing of the new criteria and a comprehensive analysis of the impact of new regulations on exiting and future fleets.

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APPENDIX A: SAMPLE CALCULATIONS ON PURE LOSS OF STABILITY BASED ON SHIPS FROM SLF 53/INF.10

Table 1. Sample Calculations on Pure Loss based on Ships from SLF 53/INF.10 Annex 5

Ship	**Description**	***L*, m**	***Cvwp*2**	***GM***	**GM_{min}**
Bulk Carrier 1		275	0.89	6.32	4.03
Bulk Carrier 2		145	0.87	1.53	0.27
Containership 1	Post-panamax	322.6	0.73	1.30	-6.23
Containership 2	Post-panamax	376	0.74	1.84	-6.23
Containership 3	Post-panamax	330	0.73	2.08	-3.08
Containership 4	Panamax	283.2	0.73	0.46	-4.01
Containership 5	C11 Class	262	0.67	1.9	-3.01
Fishing Vessel 1	Japanese Purse Seiner	34.5	0.68	1.00	-0.84
Fishing Vessel 2		21.56	0.69	0.73	-0.19
General Cargo 1	Series 60 $C_B = 0.7$	121.9	0.84	0.75	0.04
General Cargo 2	C4 Class	161.2	0.76	1.10	-0.53
LNG Carrier		267.8	0.85	3.40	0.34
Naval Combatant 1	ONR Flared	150	0.74	1.08	-1.75
Naval Combatant 2	ONR Tumblehome	150	0.71	2.06	-0.77
Passenger Ship		276.4	0.71	3.70	-0.49
RoPax		137	0.67	1.76	-0.58
Tanker		320	0.89	9.85	6.76

Table 2 Sample Calculations on Pure Loss based on Ships from SLF 53/INF.10 Annex 9

Ship	**Description**	***L*, m**	***Cvwp*2**	***GM***	**GM_{min}**
Bulk Carrier	5500 DWT	190	0.79	2.84	1.91
Bulk Carrier		180	0.8	2.10	1.17
Containership	> 10000 TEU	360	0.75	0.80	-3.88
Containership	> 10000 TEU	360	0.76	0.7	-3.96
Containership	> 6000 TEU	320	0.74	0.70	-3.174
Containership	> 6000 TEU	320	0.73	0.80	-2.88
Containership	> 4000 TEU	250	0.7	0.5	-2.14
Containership	> 4000 TEU	250	0.71	0.6	-2.09
Containership	> 1000 TEU	210	0.71	0.60	-2.22
Containership	> 1000 TEU	200	0.7	0.60	-1.98
Containership	> 1000 TEU	170	0.69	0.5	-2.17
Containership	> 1000 TEU	160	0.7	0.16	-1.16
Containership	> 500 TEU	135	0.68	0.58	-1.00
Containership	> 500 TEU	125	0.67	0.70	-1.16
Cruise Vessel		240	0.76	2.71	-1.05
LNG Carrier	1000 cbm	110	0.74	1.06	-0.11
MPV		135	0.83	0.65	-0.05
MPV		125	0.8	0.17	-0.53
MPV		120	0.71	1.00	-0.33
MPV	7500 DWT	105	0.81	0.70	-0.01
Tanker	30000 DWT	320	0.83	6.35	4.69
Tanker		110	0.72	1.31	0.6
Tug		30	0.73	2.23	0.69
Tug		25	0.67	3.60	2.01