

Article

Implementation of the IMO Second Generation Intact Stability Guidelines

Kyle E. Marlantes ^{1,*}, Sungeun (Peter) Kim ^{2,†} and Lucas A. Hurt ¹¹ Creative Systems Inc., Port Townsend, WA 98368, USA; support@ghsport.com² American Bureau of Shipping, Spring, TX 77389, USA; SuKim@eagle.org

* Correspondence: kyle@ghsport.com

† These authors contributed equally to this work.

Abstract: This paper provides a discussion of the technical and theoretical ambiguities, requirements, and limitations to develop a practical implementation of the IMO Second Generation Intact Stability criteria. This discussion is the result of industry collaboration, where two implementations of the guidelines were developed jointly, albeit independently. Both implementations were then used to assess four sample cases: C11 container ship, KRISO container ship (KCS), barge, and fishing vessel, for which the detailed particulars and results are given. Conclusions on the practicalities of use, a comparison of the results, and suggestions on how the criteria might be integrated into a workflow are also given.

Keywords: IMO; second generation intact stability; dead ship condition; excessive acceleration; pure loss of stability; parametric roll; surf-riding and broaching



Citation: Marlantes, K.E.; Kim, S.; Hurt, L.A. Implementation of the IMO Second Generation Intact Stability Guidelines. *J. Mar. Sci. Eng.* **2022**, *10*, 41. <https://doi.org/10.3390/jmse10010041>

Academic Editor: Josh Davidson

Received: 16 November 2021

Accepted: 28 December 2021

Published: 31 December 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

A consistent set of criteria to assess the dynamic stability of ships, which are considered at risk of encountering critical stability situations in waves, has garnered considerable international interest in recent years. Such criteria present several technical challenges, most obviously because the dynamics of concern are nonlinear and computationally demanding, and yet the resulting criteria must remain practical and consistent. The demands of direct simulation methods, which push the current state-of-the-art, comprise considerable computational cost, theoretical complexity, and numerical sensitivity.

Nevertheless, the International Maritime Organization (IMO) Maritime Safety Committee (MSC) approved the draft Second Generation Intact Stability (SGIS) guidelines to provide such dynamic stability criteria [1,2]. The guidelines address the vulnerability of a vessel by dividing the dynamic response into five failure modes: dead ship condition (DS), excessive acceleration (EA), pure loss of stability in waves (PL), parametric roll (PR), and surf-riding/broaching (SB), where each mode is further evaluated at different levels of complexity. With initial approval in place, adoption and refinement of the criteria now depends on experience gained from implementation. Of particular interest is the consistency and practicality of the methods in use, as well as details related to implementation, which remains an open question.

The multi-level structure of the guidelines is shown by Figure 1, which illustrates the various paths of evaluation that may be used in a design scenario. The primary concept is that the vulnerability of a vessel may be evaluated using any of the four methods: level 1, level 2, direct assessment, or operational guidance. Each of the methods are given equal regulatory weight, that is, if a vessel passes level 1, it is not necessary to perform a more complex analysis. For this reason, an efficient evaluation may always start with a level 1 analysis, and only move forward as directed by the outcome.

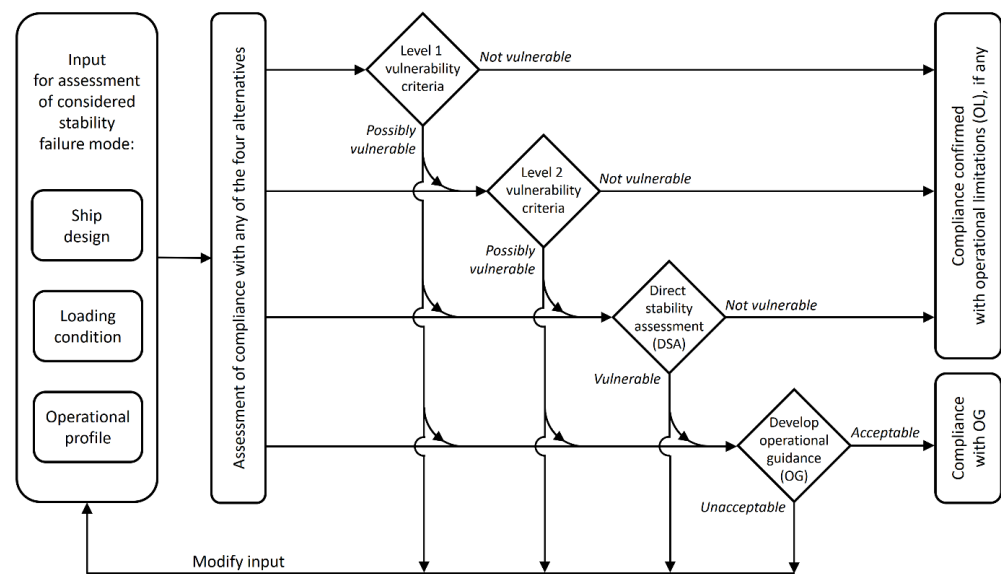


Figure 1. Application logic for IMO Second Generation Intact Stability guidelines [2].

The level 1 methods are decidedly efficient and are intended to be conservative [3,4]. However, some findings suggest that, for certain ships, level 2 will be more conservative [5–7]. In a general sense, these methods are driven by geometric and hydrostatic parameters. This makes them very quick to evaluate. The level 2 methods, on the other hand, are formulated around a long-term probabilistic approach, where vulnerability is assessed in a collection of seaways, and more complex methods are utilized to analyze the vessel. A good review on the historical and theoretical development of the methods can be found in [8], as well as theoretical outlines in [9]. Many researchers have published studies on the application of the criteria to various ship types, which can be found in [6,7,10–12], but most of these studies focus on the dead ship, pure loss, and parametric roll failure modes. In general, few studies have considered all five failure modes in unison, but some examples exist [13]. Excessive acceleration was considered based on early methods in [6], showing the methods were not yet well-developed for general usage, and more recently in [14]. The application of surf-riding/broaching can be found in [15], as well as [16,17], but these latter studies focused on comparing level 2 results to numerical simulation techniques which may be more suited to direct assessment. The level 2 methods are certainly more complex, but they are still simplified from the effort required for a direct dynamical simulation. These types of direct assessments, or level 3, have been studied by many other researchers, including [18–22]. Of note is the work by [23], which focused on the physics that need to be considered to perform a successful numerical simulation of parametric rolling—importance for both direct assessments, but also the level 2 PR time domain requirement. While the state-of-the-art in experimental and computational methods does show promise in providing analysis methods appropriate for direct stability assessments [24], it remains far less practical in terms of numerical sensitivity, availability of knowledge, and cost, for application to a wide range of vessels, especially when variations in environment or loading condition are included [11]. There also exists concern about the successful validation of such tools [22]. Therefore, the focus of this paper is on the implementation of the level 1 and level 2 criterion, and their application to several common test cases, a procedure which may encompass the bulk of practical analyses.

To this end, details deemed important in developing a practical yet flexible implementation of the guidelines, as well as the results obtained in the application of the criteria to the test cases, will be given in the following sections. Given that, during the preparation of this work, no complete commercial or research codes existed, two independent codes were developed: one at the American Bureau of Shipping, which will be referred to as the “ABS Code” in this paper, and one at Creative Systems, Inc., Port Townsend, USA,

which will be referred to as the “CSI Code”. The joint development is to provide a means of verifying the results, but also to explore differences in implementation and prepare a tool for future evaluations.

A practical implementation of the SGIS criteria needs access to multiple data streams: geometric input, hydrostatic information, environmental input, resistance and propulsion input, and seakeeping information. Of particular note is the time-domain method required for the level 2 assessment of the Parametric Roll failure mode, which is a non-trivial calculation that requires, at minimum, a weakly-nonlinear, 3-DOF time domain solver [20]. Aspects of the criteria which are beyond the capability of most standard stability assessment tools are highlighted where appropriate.

It is noted that damping, especially bilge keel area A_k , is highly important to achieving realistic assessments, and this sentiment is reinforced by discussions in [3,15,19,20]. Unfortunately, the influence of damping on several of the modes, perhaps most importantly on the level 2 excessive acceleration and parametric roll, leaves great room for variability of results. Users and reviewers of the criteria must be aware of the influence of damping and seek reasonable input values.

To verify the ABS and CSI codes, four test cases, a generic barge, the C11 container ship, KRISO container ship (KCS), and fishing vessel, are assessed across the five failure modes where applicable. The key results from each code for each test case are presented alongside additional data where available.

2. Methods

The IMO SGIS guidelines are divided into five failure modes: Dead Ship condition (DS), Excessive Acceleration (EA), Pure Loss of stability in waves (PL), parametric roll (PR), and surf-riding/broaching (SB). In this paper, each failure mode can be evaluated using level 1 and/or level 2 methods. A brief description of the technical methods underlying the evaluation of each failure mode are given in this section, with a specific focus on details related to implementation, ambiguities, and the input space.

The level 1 methods are typically rather simple, and are rapidly implemented with access to basic stability utilities (such as waterplanes, buoyancy, GM, etc.). The level 2 criteria all share the commonality that they depend on a long-term probability index. Although the method varies slightly for the PR and SB modes, these methods are characterized by a weighted average over a set of N short-term wave conditions and corresponding short-term failure indices, $C_{s,i}$, as given by Equation (1), where W_i is the weight associated with the number of occurrences of the i th short-term seaway.

$$C = \sum_{i=1}^N W_i C_{s,i}, \quad (1)$$

The long-term wave data are given as a wave scatter diagram, as shown by Table 1, where each box corresponds to a unique short-term wave spectrum, with significant wave heights, H_s , corresponding to each row and zero-up-crossing periods, T_z , corresponding to each column. The value in each box corresponds to the number of observations of each seaway out of the total number of observations, or W_i . Therefore, the probability of any particular short-term seaway occurring is given by the ratio of the corresponding number of observations over the total number of observations.

Each short-term seaway can be described by a wave energy spectrum. While many options exist, the guidelines specifically recommend a Bretschneider spectrum, as given by Equation (2).

$$S_{zz}(\omega) = \frac{H_s^2}{4\pi} \left(\frac{2\pi}{T_z} \right)^4 \omega^{-5} \exp \left(-\frac{1}{\pi} \left(\frac{2\pi}{T_z} \right)^4 \omega^{-4} \right), \quad (2)$$

This family of spectra is often used when little additional information is known about the operating region.

Table 1. Wave scatter data for IMO Second Generation Intact Stability guidelines, adopted from IACS Standard Wave Data [25]. Number of occurrences: 100,000.

H_s (m) / T_z (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.5	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0
2.5	0.0	2.2	197.5	2158.8	6230.0	7449.5	4960.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0
3.5	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0
4.5	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0
5.5	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1
6.5	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1
7.5	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1
8.5	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1
9.5	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1
10.5	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1
11.5	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1
12.5	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0
14.5	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.3	0.7	0.3	0.1	0.1	0.0	0.0
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0

2.1. Dead Ship Condition (DS)

The dead ship condition is the first mode of stability failure, with level 1 adopted by the IMO in 1985 and now embodied in Part A of the 2008 IS Code (often referred to as the “Severe Wind and Roll Criteria”) [26]. The failure mode considers a ship that has lost power and is positioned in beam seas, rolling and drifting under the action of wind and waves. This scenario is often described in stages: First, the ship is adrift in beam seas. The wind is applying a force to the windward side and a reactionary force due to wave and fluid forces is applied to the leeward side, especially when the vessel is nearing a wave crest. At this point, a sudden and sustained wind gust is experienced as the vessel rolls to windward under the action of waves. Under the combined action of wind and waves, the vessel now rolls back to leeward. During this process the speed of drift is increased, the drift reaction has increased, and the vessel will experience a large leeward roll angle. It is at this point in the dynamic process that the vessel is most susceptible to downflooding, as well as loss of positive stability.

2.1.1. DS Level 1

To avoid a stability failure, the level 1 criteria relies on a classical righting energy approach, as shown by Figure 2.

A ship is considered not to be vulnerable to the DS failure mode if, when the ship is subjected to a prescribed steady wind pressure: (1) the area b is equal to or greater than the area a ; and (2) φ_0 should not exceed 16° or 80% of the angle of the deck edge immersion, whichever is less. Note that φ_1 is the rollback angle, which is computed according to Equation (3), where k is a damping factor based on hull geometry and bilge keel area, X_1 and X_2 are geometric factors, r is a semi-empirical non-dimensional measure based on KG (similar to GM), and s is the wave steepness factor, which is given for a range of natural roll periods.

$$\varphi_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}, \quad (3)$$

The wind heeling levers, l_{w1} and l_{w2} , are computed using a pressure of 504 Pa as given by the criteria, and in l_{w2} an additional gustiness factor. However, it is made clear that these values may be reduced if the vessel is to be subjected to operational guidance. Similarly, the wave steepness s may be modified to match the operational environment. For this reason, robust implementations of the DS level 1 failure mode should provide the user the option to vary these parameters systematically. Note that the guidelines permit alternative means to compute φ_1 , l_{w1} and l_{w2} , which might comprise a time or frequency domain simulation, band methods for static wind inclinations, or other methods, some guidance of which is given by the IMO. However, these variations are not specific to the operating environment and may not be considered part of the input space.

A complete process diagram for an algorithmic implementation of DS level 1 is given by Figure 3.

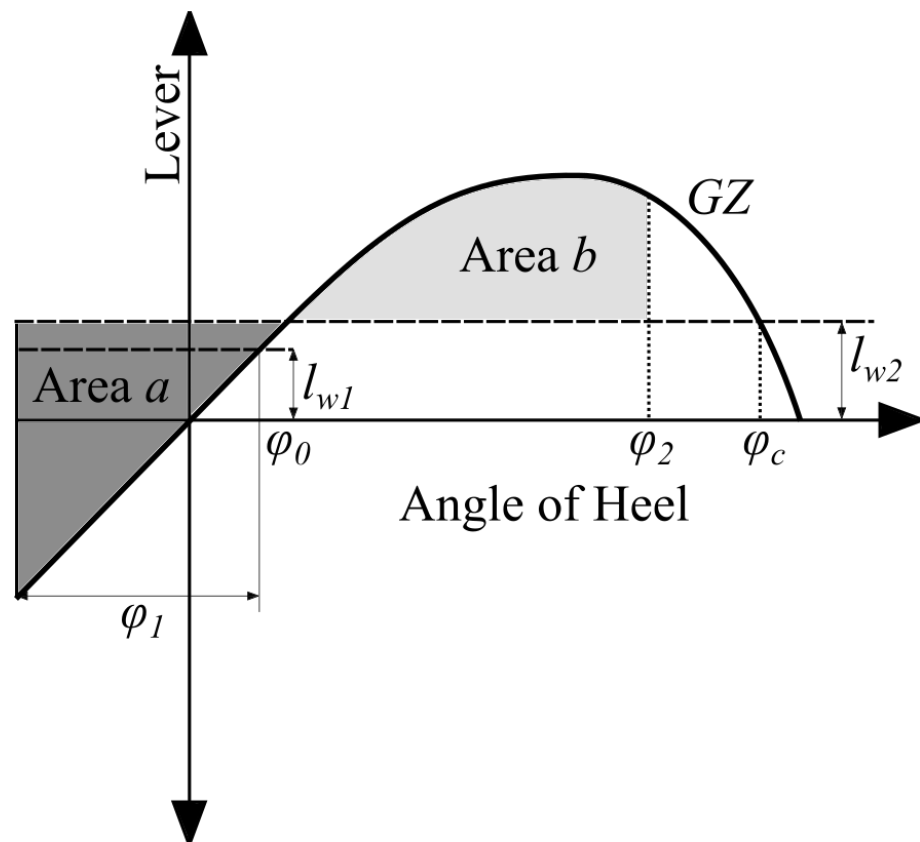


Figure 2. Dead ship level 1 righting arm area definitions.

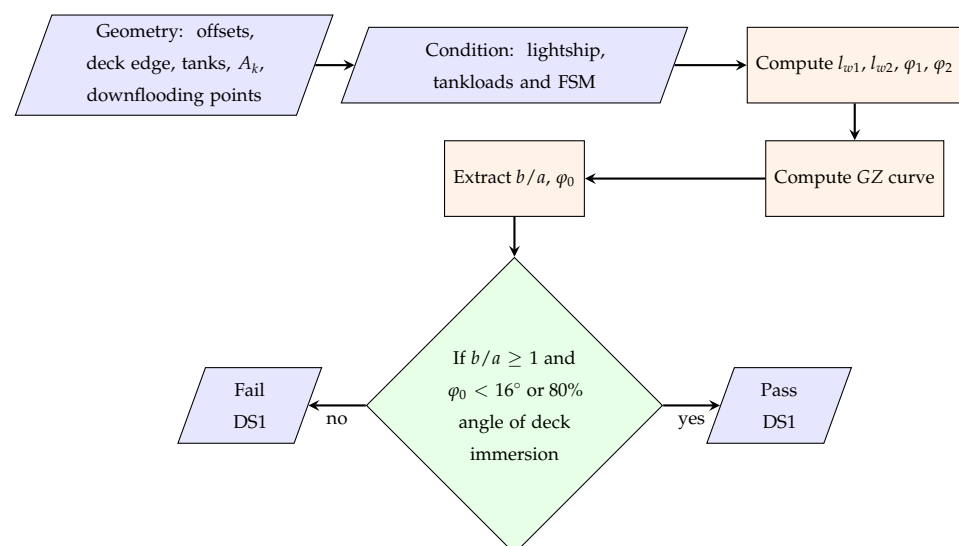


Figure 3. Dead Ship Level 1 algorithm process diagram.

2.1.2. DS Level 2

The level 2 criterion comprises a method to compute a long-term probability index over a set of short-term environmental conditions. The failure mode utilizes the same wave scatter data specified in Table 1. The ship is considered not susceptible to the dead ship condition if the attained index, C , is less than 0.06, where C is defined as the weighted

average over the set of wave conditions, as given by Equation (1), where in this case $C_{s,i}$ are the short-term failure indices.

The short-term failure indices, $C_{s,i}$ are computed according to the stability characteristics of the vessel in each short-term wave environment. The $C_{s,i}$ is considered to be equal to 1, i.e., complete failure, if the mean wind heeling lever, $\bar{l}_{wind,tot}$, exceeds the righting lever, GZ , at all angles of heel to leeward, or the equilibrium angle of heel due to steady wind exceeds the angle of failure to leeward. Obviously, these are reasonable criteria for complete failure.

Partial failure, i.e., $0 < C_{s,i} < 1$, is computed from a cumulative distribution function (CDF) describing the probability of failure given an exposure time, T_{exp} , of 3600 s in each short-term seaway. The probability is given by Equation (4), where r_{EA} is a measure of the rate of roll motion computed from an equivalent area (EA) method.

$$C_{s,i} = 1 - \exp(-r_{EA}T_{exp}), \quad (4)$$

The method to compute r_{EA} comprises the bulk of the effort in implementing DS level 2. The quantity depends on two distinct computations: an equivalent area GZ-curve method which determines linearized leeward and windward ranges of residual stability (i.e., stable roll angles), $\delta\phi_{res,EA+}$ and $\delta\phi_{res,EA-}$, respectively; as well as a spectral method, which determines the standard deviation of effective relative roll motion, σ_{C_s} , in the given seaway. The ratio between these two quantities yields a statistical measure of the stability of the vessel in the seaway, which is used to derive the probability of failure, as shown by Equation (6).

$$r_{EA} = \frac{1}{T_{x,C_s}} \left[\exp\left(-\frac{1}{2RI_{EA+}^2}\right) + \exp\left(-\frac{1}{2RI_{EA-}^2}\right) \right] \quad (5)$$

$$RI_{EAi} = \frac{\sigma_{C_s}}{\delta\phi_{res,EAi}}, \quad i = + \text{ or } -, \quad (6)$$

The GZ-curve method to compute $\delta\phi_{res,EA+}$ and $\delta\phi_{res,EA-}$ is described as follows. The method attempts to linearize the vessel's restoring moment so it may be adequately used to compute an effective range of dynamic roll stability. The environment is introduced using a mean wind heeling lever, $\bar{l}_{wind,tot}$, which is considered constant across all angles of heel and is computed using a classical wind moment equation based on the wind velocity, a shape-specific coefficient, and the projected lateral topside area and centroid. The wind velocity, U_w , is computed according to an empirical proportionality relationship with the significant wave height, H_s , corresponding to the i th short-term wave condition. This results in the following relationship between $\bar{l}_{wind,tot}$ and H_s :

$$\bar{l}_{wind,tot} \propto H_s^{4/3}, \quad (7)$$

The $\delta\phi_{res,EA+}$ and $\delta\phi_{res,EA-}$ is simply the range from the equilibrium angle of heel due to the steady wind, ϕ_S , and the leeward or windward virtual limits of stability, ϕ_{EA+} or ϕ_{EA-} , respectively. These angles are illustrated on the example GZ curve shown by Figure 4. Note that ϕ_{EAi} are linearized angles in that they balance the area under the linearized righting arm (the GM line) and the area under the GZ curve.

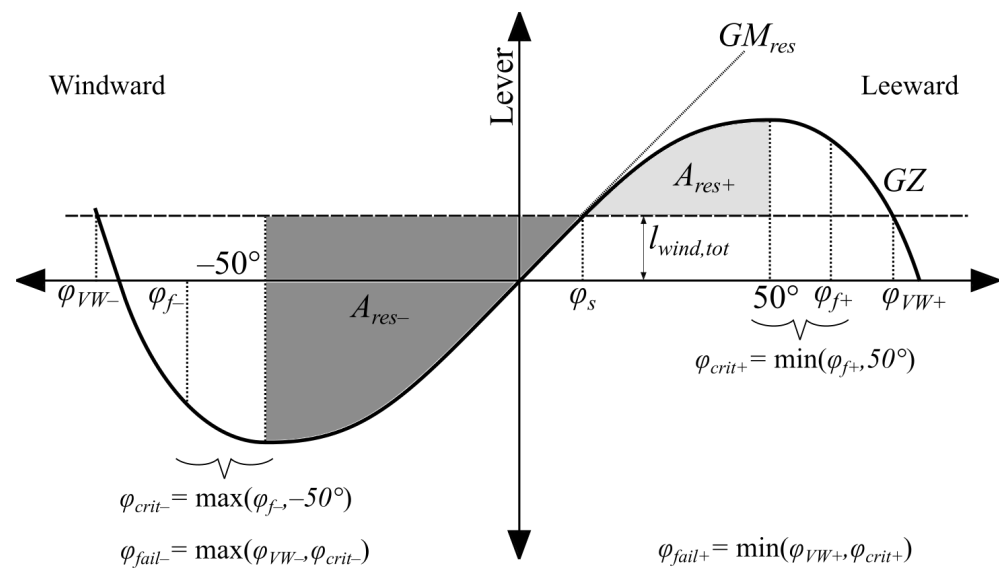


Figure 4. Dead ship level 2 equivalent righting arm area definitions.

If the GZ-curve for the vessel is known, it is straightforward to compute the angles given in Figure 4 and obtain $\delta\phi_{res,EA+}$ and $\delta\phi_{res,EA-}$. The guidelines do make the assumption that the leeward side is to starboard (following typical conventions) and that the vessel is largely symmetric. In addition, less regular GZ-curves, which may include features such as loll, which occur in practice, may present numerical and theoretical challenges which require special consideration.

The spectral method to compute σ_{C_s} is described as follows. Assuming the short-term environment is a stationary, zero-mean process, it is possible to design an effective relative roll response spectrum, $S(\omega)$, as a function of the wave frequency ω . It follows that σ_{C_s} is statistically equivalent to the standard deviation of the response, or $\sqrt{m_0}$, where m_0 is the first moment of the response distribution. Similarly, T_{z,C_s} is defined as the average period between zero-up-crossings, or $2\pi\sqrt{m_0/m_2}$, where m_2 is the second moment. The expression for $S(\omega)$ is lengthy and explicitly given in [9], so it will not be presented here, suffice to say that it is composed of the superposition of two primary spectra: the relative response due to the short-term wave spectrum and the relative response due to a wind gustiness spectrum. The former requires knowledge of the effective wave slope function, $r(\omega)$ and the short-term wave spectrum, $S_{zz}(\omega)$. The latter requires a spectral expression for the moment on the vessel due to wind gusts. The guidelines provide such an expression, again based on the wind velocity, a shape-based aerodynamic constant, and the projected lateral topside area and lever arm, superimposed with a gustiness spectrum. The gustiness spectrum is given as a standard, semi-empirical expression based on the approximate wind velocity. In addition, the formulations require the equivalent linear roll damping coefficient, μ_e . A complete process diagram for an algorithmic implementation of DS level 2 is given by Figure 5.

The computation of $r(\omega)$ is a key aspect of the assessment of level 2, for which a simplified method is provided, based on Froude–Krylov forcing on equivalent area sections. However, the guidelines permit computational-based methods, which should reasonably include the methods described in [27]. Since most implementations of the guidelines will likely have access to a geometric model of the vessel, it is reasonable to assume that a computational method, based on a linear potential flow strip theory or panel method, would offer an equivalently robust manner to compute $r(\omega)$. To this end, both the simplified method and the strip-method were implemented. Figure 6 gives a comparison between the methods for a generic box barge. One will notice the considerable difference between the results, which raises a question as to which method is preferred.

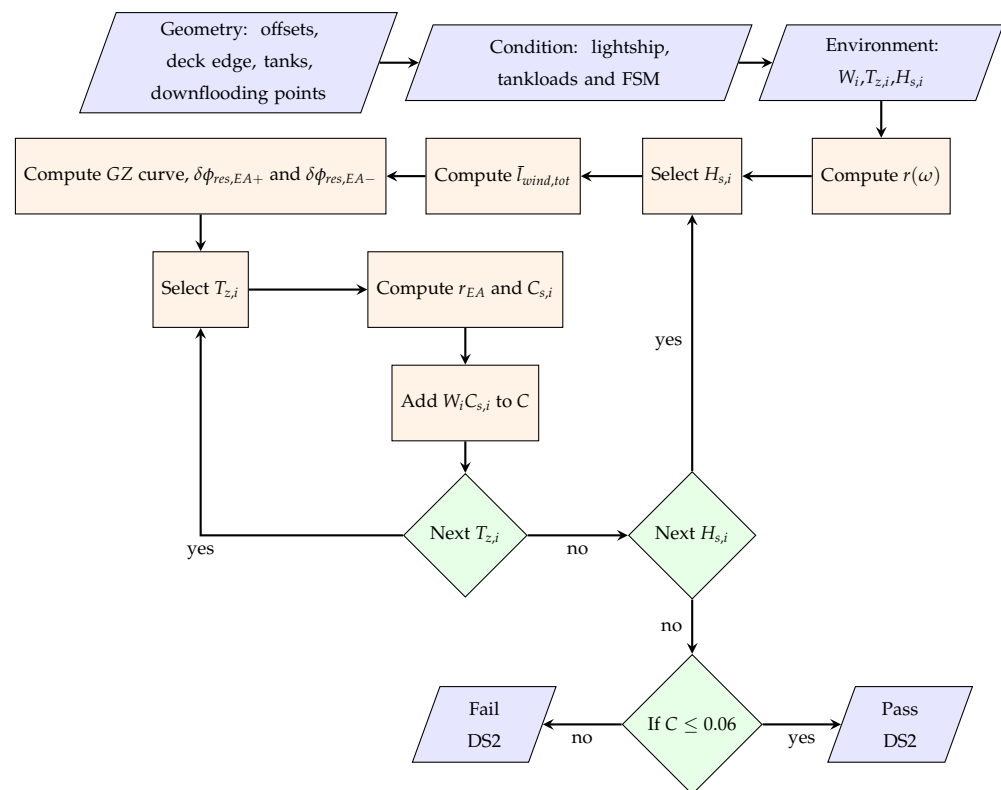


Figure 5. Dead Ship Level 2 algorithm process diagram.

The specification of μ_e remains ambiguous, despite the definition indicating that the coefficient should be linearized based on the RMS roll velocity in each short-term wave environment. In the implementations considered here, two methods were utilized. In the more complex approach, the RMS roll velocity is computed in each short-term wave environment by first computing the vessel's roll RAO. The total roll damping coefficient (radiation, skin friction, eddy components) is then linearized based on this velocity using the methods given in [28]. In the less complex approach, simplified coefficients are based on semi-empirical formulas.

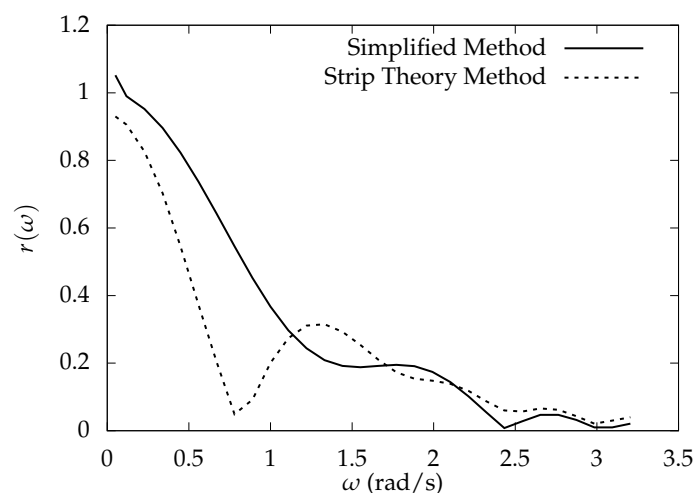


Figure 6. Effective wave slope function computed using simplified “formal” method and strip theory “direct” method for a simple barge geometry.

Implementing the spectral method is the most demanding component of the criterion. Suitable discretization and numerical integration methods are required to compute $S(\omega)$, choices which will invariably impact the results but may be unsuitable as input parameters.

These numerical issues become a greater concern if the wave spectrum may be varied (which is a reasonable expectation given the premise of operational guidance). Similarly, the computation of $r(\omega)$ is non-trivial if the simplified method is not utilized, such that, at minimum, a 2D potential flow solver is required to solve for the hydrodynamic moments, which many stability-oriented software programs do not have.

Moreover, an accurate prediction of μ_e is difficult to obtain numerically, and even modern methods do not fully capture the physics [29]; however, the state-of-the-art remains in the application of CFD [30] or experimental results [31]. Simplified methods, such as “Ikeda” methods [32–36], to predict μ_e could be too conservative, or alternatively an over-predicted μ_e could have serious consequences on the attained vulnerability. A possible compromise could be the methods described in [37]. For this reason, implementations should expose μ_e as an input parameter, for which users should be aware of the possible implications and seek to obtain reliable values. A possible example would be a critical damping ratio.

2.2. Excessive Acceleration (EA)

The excessive acceleration (EA) condition is the second mode of stability failure. The mode considers the vulnerability of a ship to large lateral accelerations due to synchronous resonance. Lateral accelerations are computed at locations where crew or passengers are expected to be present. Synchronous resonance, which occurs when the vessel’s natural period is close to the modal period of the seaway, can lead to large roll amplitudes resulting in dangerous lateral accelerations, which can threaten crew and passengers, as well as damage or dislocate cargo or equipment.

Roll accelerations are related in part to the GM of the vessel. That is, the linear roll restoring force is proportional to GM . For this reason, if the GM is low enough, in this case 8% of the breadth of the ship, the restoring forces would be low enough to cause low roll accelerations. In other words, the system is not very stiff. Similarly, if the highest vertical location of crew or passengers is below 70% of the breadth of the vessel above the mean waterline, then the lateral accelerations at crew locations will be small due to the relatively small amplification of the lateral accelerations at remote locations (assuming the roll motion is about the waterline). In these cases, the vessel is not considered susceptible to excessive acceleration, and is therefore not subject to this failure mode.

In regions of resonance, the inertial forces nearly balance the restoring forces, and so the damping forces dominate the response. For this reason, the prediction of accurate lateral accelerations requires an accurate model of the damping forces, which are inherently nonlinear and difficult to predict numerically. Both level 1 and level 2 require parameters which relate to the roll damping of the vessel.

2.2.1. EA Level 1

The level 1 vulnerability criteria computes a simplified estimate of the lateral acceleration at each location of crew or passengers according to Equation (8), where φ is the characteristic roll amplitude, k_L is a spatial factor which accounts for roll-yaw-pitch coupling, h_r is the height of the crew or passenger location above the assumed roll axis, and T_r is the roll period. The vessel is considered safe if the attained accelerations for all locations are below a threshold acceleration of 4.64 m/s^2 .

$$\varphi k_L \left(g + 4\pi^2 h_r / T_r^2 \right), \quad (8)$$

T_r can be reasonably estimated with approximate methods, such as those given in [26]. The determination of φ is semi-empirical and is given by Equation (9), where r is the effective wave slope coefficient, s is the wave steepness, and $\sqrt{\delta_\varphi}$ is the log-decrement of roll decay.

$$\varphi = 4.43 \frac{rs}{\sqrt{\delta_\varphi}}, \quad (9)$$

The guidelines give an entirely geometric formulation for r , so it is readily computed. s matches the wave steepness table given for DS, but is also an environmental parameter which may be varied. $\sqrt{\delta\varphi}$ can be computed with approximate, semi-empirical methods, but it may also be computed using a roll decay experiment or numerical simulation. As the log-decrement captures the damping forces, this parameter should be provided as an input parameter, as it will have an important effect on the predicted acceleration.

A complete process diagram for an algorithmic implementation of EA level 1 is given by Figure 7.

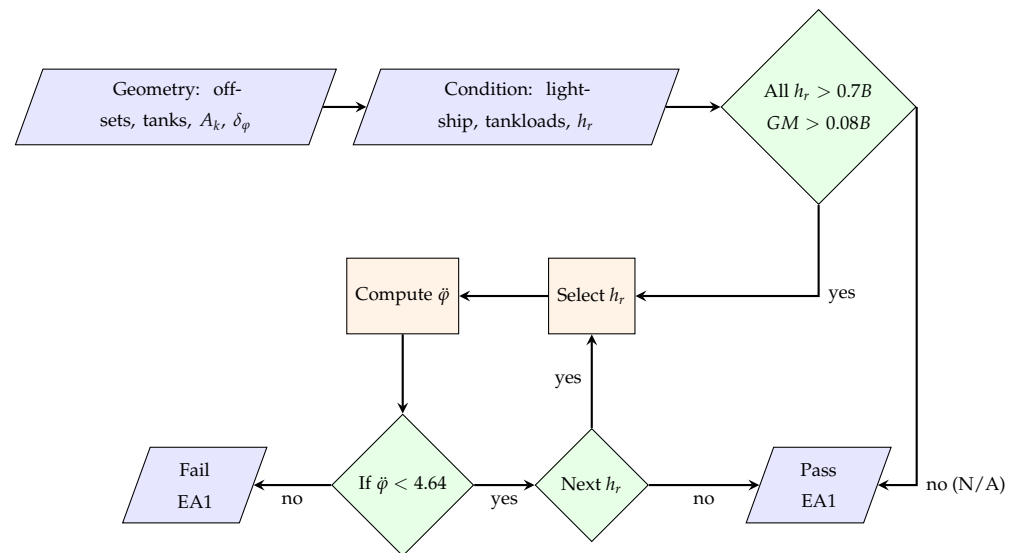


Figure 7. Excessive acceleration Level 1 algorithm process diagram.

2.2.2. EA Level 2

The level 2 excessive acceleration criteria again requires the computation of a long-term vulnerability index, C , conforming to Equation (1). In this mode, the short-term failure index is given by Equation (10), where σ_{LAI} is the standard deviation of the lateral acceleration at zero speed and in beam seas for the corresponding short-term wave environment.

$$C_{s,i} = \exp(-g^2 / (2\sigma_{LAI}^2)), \quad (10)$$

The expression estimates the probability that the lateral acceleration experienced in a particular seaway will exceed 1 g. σ_{LAI} is computed by integrating the lateral acceleration response spectrum for each location of interest, according to Equation (11).

$$\sigma_{LAI}^2 = \frac{3}{4} \sum_{j=1}^N (a_y(\omega_j))^2 S_{zz}(\omega_j) \delta\omega, \quad (11)$$

The guidelines make clear that Equation (11) is only one possible method to obtain the standard deviation. Other numerical schemes could be utilized. However, the guidelines do provide guidance on the discretization of the spectrum, calling for not less than 100 samples, a minimum frequency limit of $\max((0.5/T_r), 0.2)$, and an upper limit of $\min((25/T_r), 2.0)$, and that ω_j shall be taken at the mid-point of the frequency band.

The determination of $a_y(\omega_j)$, the lateral acceleration per unit wave amplitude (effectively an acceleration RAO), is the most demanding calculation in EA level 2. The expression is given by Equation (12), where k_L and h_r are the same as in level 1, and $\varphi_a(\omega_j)$ is the roll RAO. A complete process diagram for an algorithmic implementation of EA level 2 is given by Figure 8.

$$a_y(\omega_j) = k_L \left(g + h_r \omega_j^2 \right) \varphi_a(\omega - i), \quad (12)$$

The guidelines offer a simplified method to compute $\varphi_a(\omega_j)$, which relies on a Froude–Krylov assumption and is based on a linearized single degree-of-freedom model to compute the real and imaginary parts of the roll response amplitude. The method includes damping forces by introducing an equivalent linear roll damping coefficient, $B_e = 2J_{T,roll}\mu_e$, where $J_{T,roll}$ is the approximate roll moment of inertia computed from the vessel GM and natural period. Although the simplified method reduces some numerical effort, it is not unreasonable to compute $\varphi_a(\omega_j)$ directly using a strip-method, where the response can be less approximate. Furthermore, if this is done, the damping coefficient μ_e may also be computed for each short-term environment, for which the RMS roll velocity must be known anyhow. The CSI implementation utilizes this approach, where the ABS implementation uses the simplified method. Moreover, in most stability situations, a detailed roll moment of inertia is known from weight estimates and loading conditions, so the approximate calculation of J_T is easily replaced by a more accurate physical quantity.

It should be reiterated that the damping values μ_e will have a significant effect on the computed responses.

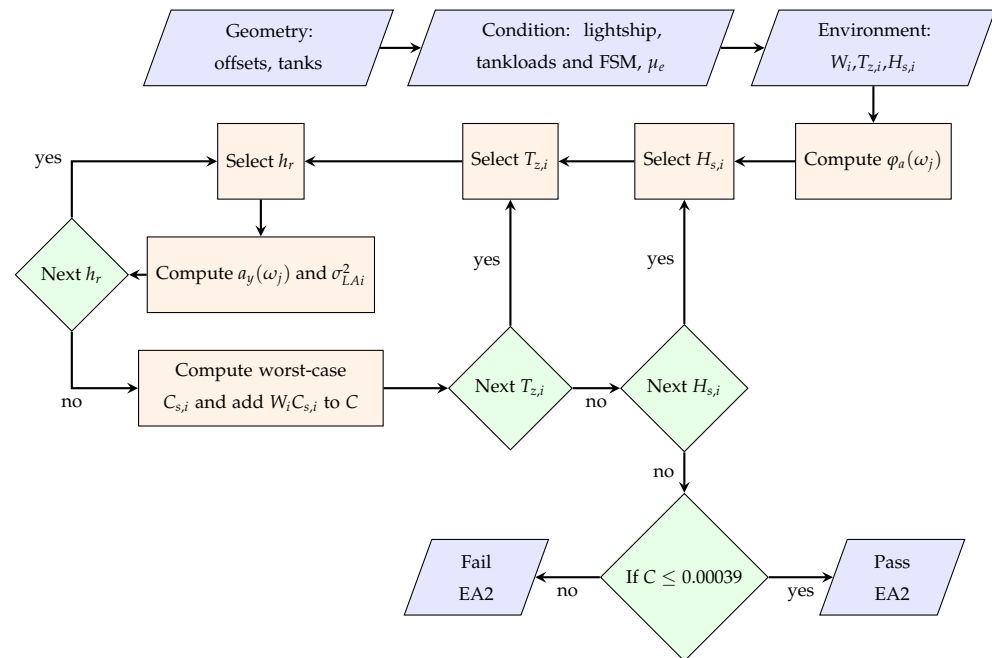


Figure 8. Excessive acceleration level 2 algorithm process diagram.

2.3. Pure Loss of Stability (PL)

The pure loss failure mode considers the vulnerability of a ship to capsize via complete loss of stability due to a sudden and significant change in the waterplane in the action of waves. Such sudden and complete loss of stability can quickly lead to capsize. The methods provided to evaluate this failure mode investigate, primarily, the variation in a vessel's GM when subjected to waves.

2.3.1. PL Level 1

The level 1 assessment considers two measures of stability: the minimum GM, GM_{min} and a displaced volume ratio. The GM_{min} is computed according to Equation (13), where KB is the metacentric height, I_{TL} is the transverse moment of inertia of the waterplane at the draft d_L , ∇ is the displaced volume, and KG is of course the vertical center of gravity above the keel. The draft d_L is an average draft between the condition draft and the maximum draft, which is specified in the guidelines.

$$GM_{min} = KB + \frac{I_{TL}}{\nabla} - KG, \quad (13)$$

The displacement ratio is given by Equation (14), where ∇_D is the volumetric displacement at the vessel's moulded depth, D , ∇ is the volumetric displacement at the draft under consideration, d , and A_W is the waterplane area at d . The ratio is therefore a measure of volumetric variation.

$$\frac{\nabla_d - \nabla}{A_W(D - d)}, \quad (14)$$

If GM_{min} according to Equation (13) is greater than 0.05 m and the volume ratio from Equation (14) is greater than or equal to at least 1.0, the vessel is not considered vulnerable to pure loss of stability. All required information in Equations (13) and (14) are readily computed using standard hydrostatic solvers. A complete process diagram for an algorithmic implementation of PL level 1 is given by Figure 9.

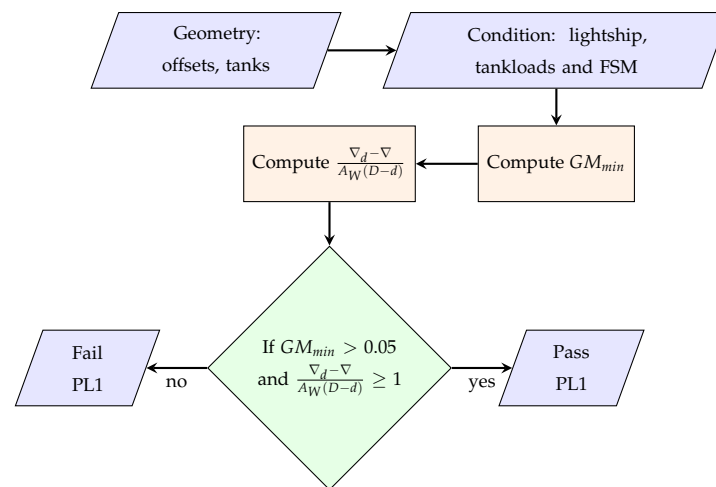


Figure 9. Pure Loss Level 1 algorithm process diagram.

2.3.2. PL Level 2

The level 2 criteria utilize a similar form to Equation (1), however, in this failure mode two different long term vulnerability indices are considered, CR_1 and CR_2 , where both indices must be below a probability of 0.06, such that $\max(CR_1, CR_2) \leq 0.06$. The short-term failure indices (equivalent to $C_{s,i}$ in Equation (1)) for each of these cases are $C1_i$ and $C2_i$, respectively.

The first criterion considers the minimum angle of vanishing stability, φ_V , as illustrated by Figure 10, and the second evaluates the maximum angle of equilibrium, φ_{SW} , of the vessel subjected to a heeling lever, l_{PL2} , which corresponds to a wave-induced moment. To compute these quantities, the vessel is subjected to ten different wave heights, h_i , ranging from 0.01 L to 0.1 L. For each of these waves, l_{PL2} is computed according to the relationship $8(h_i/L)dF_n^2$, where h_i is the i th wave height, L is the vessel length, d is the draft, and F_n is the service speed Froude number. Then, for each wave height, ten different crest locations along the length of the ship are considered, ranging from 0.4 L aft of midships to 0.5 L forward of midships. For each crest location, the φ_V and φ_{SW} are computed. Across all crest locations, only the minimum φ_V and maximum φ_{SW} are retained, effectively the 'worst case' values for the given h_i . The result of this process is a curve describing the φ_V and φ_{SW} over a range of wave heights.

Using these curves, the φ_V and φ_{SW} for each short-term wave spectrum is computed by computing the 3% largest wave height from each short-term seaway and then interpolating the corresponding φ_V and φ_{SW} from the curves. The guidelines specifically indicate that the wave spectrum should be "filtered according to ship length". The filtering process is not explicitly given, but it can be found in [5], where each spectral ordinate is multiplied by a length-based factor. The interpolated values of φ_V and φ_{SW} are then compared to prescribed limits: 30 degrees for φ_V and 15 or 25 degrees for φ_{SW} , depending on whether

the vessel under consideration is a passenger ship or otherwise. A complete process diagram for an algorithmic implementation of PL level 2 is given by Figure 11.

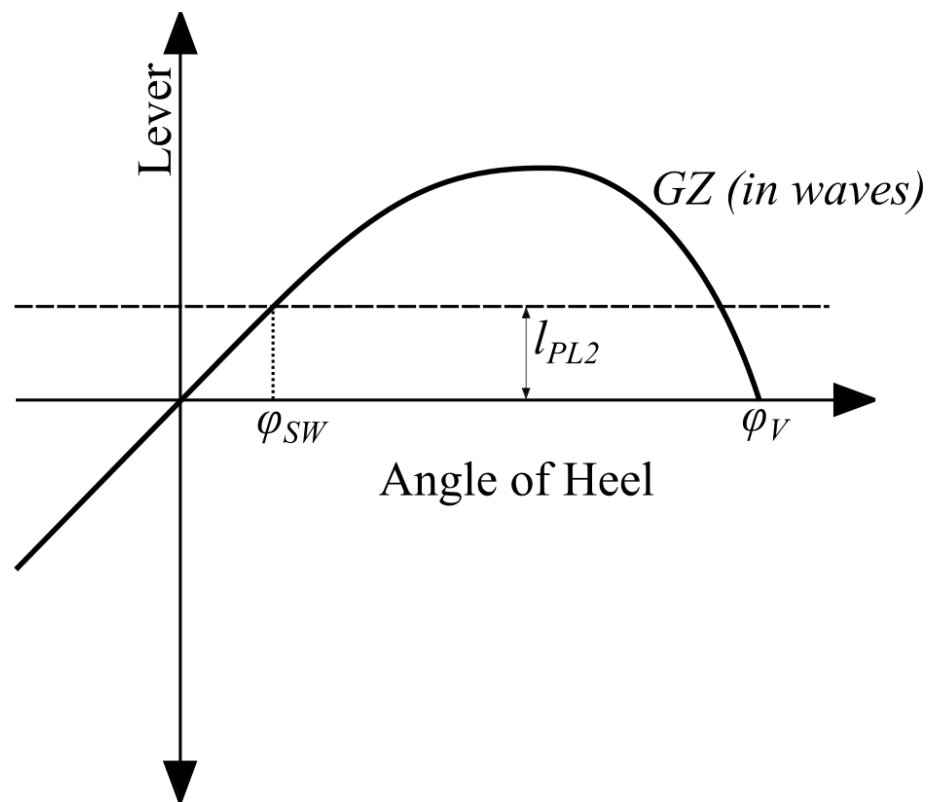


Figure 10. Pure loss of stability level 2 righting arm definitions. Note that multiple *GZ* curves are computed in different quasi-static wave conditions.

Because all aspects of level 2 depend only on computing *GZ*-curves in waves, it is more readily implemented within the scope of existing hydrostatic solvers.

2.4. Parametric Roll (PR)

The parametric roll failure mode considers the vulnerability of a ship to parametric roll resonance in waves. Parametric roll occurs when the transverse stability of a vessel varies synchronously with incident waves. This typically occurs when the encounter frequency of the waves is approximately twice that of the vessel's roll natural frequency. The nature of the response is nonlinear, as it depends on the variation in the roll-restoring moment due to the variation of underwater hull geometry, which is not captured by linear methods. Furthermore, it typically occurs in predominately head or following seas.

As the vessel passes through wave crests, when the crests are near the bow and stern, the vessel may experience a momentary negative *GM*, and thus begin to roll. As the vessel rolls, the increasing submerged volume generates a restoring force which, if strong enough and lightly damped, will roll the vessel to the opposite side through the moment when the next passing crest reduces transverse stability. Through successive wave crests the process can reach a resonance, such that roll angles become large and damage to ship or cargo can occur. In extreme cases, the resonance can lead to capsize.

Much like other roll responses, the influence of damping is important. With sufficient damping, parametric roll may not develop. This again highlights the importance of an accurate roll damping prediction, despite that roll damping is difficult to accurately predict numerically.

Parametric roll is also sensitive to forward speed, as this will alter the encounter frequency of the incident waves. Therefore, if the vessel begins to experience parametric roll in head seas, speed changes may reduce the effect. Similarly, a change in speed may

lead to an onset of parametric roll, if the vessel is traveling at an encounter frequency near the $2\omega_{4,n}$ point.

2.4.1. PR Level 1

The level 1 criterion to evaluate the vulnerability of a vessel to parametric roll is similar to that of pure loss. It considers two quantities: a GM ratio and the same volumetric ratio given in pure loss level 1. Since the volume ratio is given in the previous section (Equation (14)) it will not be given here. The GM ratio is given by Equation (15).

$$\frac{\delta GM}{GM} \leq R_{PR}, \quad (15)$$

R_{PR} is based on a semi-empirical measure based on a vessel's basic geometric particulars including L , B , C_M . The measure is highly sensitive to bilge keel area A_k , a parameter defined in [26]. If A_k is omitted, the R_{PR} drops to 0.17 for all cases, but can be as high as 1.87. This highlights the importance, and sensitivity, of an accurate value for A_k . Effectively, this value includes the effects of damping in the level 1 criterion. The δGM is computed using a simplified method, which considers the difference in the waterplane transverse moments, as shown by Equation (16).

$$\frac{I_{TH} - I_{TL}}{2\nabla}, \quad (16)$$

I_{TH} and I_{TL} are the transverse waterplane moments at a higher and lower draft, respectively. The drafts are determined based on the draft for the condition under consideration, the vessel depth D , and the maximum or full load draft d_{full} . While these formulas will not be given here, the method enforces a minimum draft increment based semi-empirically on L . This ensures that an approximate, and conservative, variation in the waterplane can be obtained.

A complete process diagram for an algorithmic implementation of PR level 1 is given by Figure 12.

2.4.2. PR Level 2

The level 2 criterion for parametric roll failure is again similar to Equation (1) in form, but instead two long term measures are considered, $C1$ and $C2$, where $C1 \leq 0.06$ and $C2 \leq 0.025$. To consider the vessel insusceptible to parametric roll, either $C1$ or $C2$ must be satisfied. As will be discussed in the following section, this has a major impact on the necessary complexity of the simulation.

For $C1$, short term indices C_i (similar to $C_{s,i}$ in Equation (1)) are computed as either 0 or 1. In this case, however, the weights are taken from a specific table of values in the guidelines, and not over the scatter data given in Table 1. The criterion is a measure of GM variation and vessel speed in waves. For $C1$ to be 0, that is, the vessel is not vulnerable in that particular wave case, the vessel should pass either a check of GM variation or a check of forward speed. In the GM variation check, two criteria must be satisfied for each wave condition, as shown by Equations (17) and (18).

$$GM(H_i, \lambda_i) > 0, \quad (17)$$

$$\frac{\delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} < R_{PR}, \quad (18)$$

Again, R_{PR} is computed in the same manner as for PR level 1. $GM(H_i, \lambda_i)$ is defined as the average GM computed by placing the vessel in the range of waves. This is a quasi-static method, as the waterplane is replaced with the corresponding wave defined by H_i and λ_i , and then the GM is computed hydrostatically, with the vessel free to heel and trim. For each wave, the crest is located at 10 different locations along the vessel length. $\delta GM(H_i, \lambda_i)$

is computed over the same wave range and is derived from the values of $GM(H_i, \lambda_i)$, as it is one-half the distance between the maximum and minimum GM values computed.

In the forward speed check, Equation (19) must be satisfied.

$$\left| \frac{2\lambda_i}{T_r} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g \frac{\lambda_i}{2\pi}} \right| > V_s, \quad (19)$$

In this check, the vessel service speed V_s simply must be below a critical speed associated with the onset of parametric roll. The critical speed varies in each wave condition according to λ_i .

For C2, the evaluation procedure is considerably more complex, where the index is the weighted average of long term failure indices computed over twelve forward speeds, in both head and following seas, as shown by Equation (20), where Fn_i is the i th Froude number computed according to the twelve speed factors given in the guidelines, β is the wave heading, where a subscript h indicates head seas, and f indicates following seas.

$$C2 = \left[\sum_{i=1}^{12} C2(Fn_i, \beta_h) + \frac{1}{2} (C2(0, \beta_h) + C2(0, \beta_f)) + \sum_{i=1}^{12} C2(Fn_i, \beta_f) \right] / 25, \quad (20)$$

Each $C2(Fn_i, \beta)$ is computed according to Equation (1), over the long term scatter data, where the short term indices $C_{s,i}$ are taken as 1 if a maximum roll angle exceeds 25 degrees and 0 otherwise. The maximum roll angles are computed via a nonlinear time domain simulation of the parametric roll motion in regular waves. To avoid this expensive simulation in each short term seaway, maximum roll angles are instead computed directly for ten wave heights at a wavelength equal to L , and this is done for each Fn_i . This results in a matrix of roll angles which can be interpolated to find expected maximum roll angles in each short term seaway.

Certainly, a nonlinear roll simulation presents a great computational cost, as the minimum simulation, which would adequately predict the onset of parametric roll requires body-exact restoring and inertial forces and must be at least 3-DOF (heave, roll, and pitch) [20,23]. This is a nontrivial simulation to implement, and this type of dynamic simulation capability is not common in most stability software. It also introduces a number of practical considerations, such as sensitivity to initial conditions, numerical stability, the degree of nonlinearity (weakly nonlinear versus fully-nonlinear), roll damping, and others, which will invariably result in differences between implementations [22,38].

Because C2 is considerably more expensive to evaluate, it is recommended that C1 is always checked first, and C2 only evaluated if C1 does not pass or if there are design-specific reasons to force the nonlinear simulation. With this approach, the time domain simulation method in C2 is not invoked unless absolutely necessary.

A complete process diagram for an algorithmic implementation of PR level 2 is given by Figure 13.

2.5. Surf-Riding and Broaching (SB)

The surf-riding and broaching failure mode considers the vulnerability of a ship to surf-riding, during which a following wave accelerates a ship forward, and broaching, which is a violent uncontrollable turn that often follows surf-riding and may cause stability failure. Because of the correlation between surf-riding occurrence preceding broaching events, the methods given here attempt to predict the onset of surf-riding as a means to avoid conditions which could lead to broaching. For surf-riding to occur, the vessel must meet three conditions: the wave length should be between one and three times the ship length, the wave must be steep, and the ship speed should be close to the wave speed [1]. The first and last requirements set a limit to ship lengths for which surf-riding can occur due to high speed of larger water waves. For this reason, ships with an L less than 200 m

are not considered susceptible to surf-riding/broaching failure. Similarly, ships traveling very slowly, with a $Fr \leq 0.3$, are not considered susceptible.

For surf-riding to occur, the vessel must find itself in surf-riding equilibrium, where the surging forces from the wave, the resistance of the hull, and the propulsion force, are balanced. Beyond this point, the surge forces and propulsion forces will no longer balance, and the vessel will be propelled forward down the wave crest. This process occurs on the forward side of the crest, where the forces will move out of equilibrium.

2.5.1. SB Level 1

The level 1 criterion to evaluate the vulnerability of a vessel to surf-riding/broaching is based on the length and Froude number limits outlined earlier. Simply, if $L \geq 200$ m and $Fr \leq 0.3$ the vessel is not considered vulnerable and passes level 1.

2.5.2. SB Level 2

The level 2 criterion for surf-riding/broaching vulnerability depends on a long term vulnerability index C , which must be less than 0.005. Much like Equation (1), C is evaluated as the weighted sum over each short term seaway, where the weighting factors are also taken from Table 1. However, the short term indices (equivalent to $C_{s,i}$ in Equation (1)) are given by Equation (21).

$$C_{s,i} = \sum_{i=0}^{N_\lambda} \sum_{j=0}^{N_a} w_{ij} C_{2ij}, \quad (21)$$

The w_{ij} are weights which depend on the short term wave conditions. The summations over N_λ and N_a , vary the wavelength to ship length ratio ($\lambda/L \in [1.0, 3.0]$) and the wave steepness ($H/\lambda \in [0.03, 0.15]$), respectively. The C_{2ij} indices are then evaluated for each wave steepness and wavelength to ship length ratio according to a critical Froude number, Fn_{cr} , where if the service speed Fn is greater than Fn_{cr} , C_{2ij} is taken as 1 (indicating short term vulnerability for that wave condition).

The calculation of Fn_{cr} is nontrivial, in that it depends on the resistance and propulsion characteristics of the vessel, where Fn_{cr} corresponds with a critical speed u_{cr} . The u_{cr} is the speed at which Equation (22) is satisfied, where T_e is the thrust delivered by the vessel's propulsor, and R is the resistance of the ship.

$$T_e(u_{cr}; n_{cr}) - R(u_{cr}) = 0, \quad (22)$$

The guidelines propose a quadratic expression to represent T_e , where the polynomial coefficients are inputs for a given ship. This may not be wholly adequate, so a third-degree polynomial may be necessary. Regardless, the purpose is the same: to represent the thrust versus rotational frequency of the propulsor. Similarly, R is considered a fifth-degree polynomial, where the coefficients are given for the ship.

The above equation implies further that a critical number of revolutions n_{cr} of the propulsor must be determined. Finding n_{cr} comprises the bulk of the computations in SB level 2 and requires finding the solution to a quadratic equation in terms of n_{cr} , as shown by Equation (23).

$$2\pi \frac{T_e(c_i, n_{cr}) - R(c_i)}{f_{ij}} + 8a_0 n_{cr} + 8a_1 - 4\pi a_2 + \frac{64}{3} a_3 - 12\pi a_4 + \frac{1024}{15} a_5 = 0, \quad (23)$$

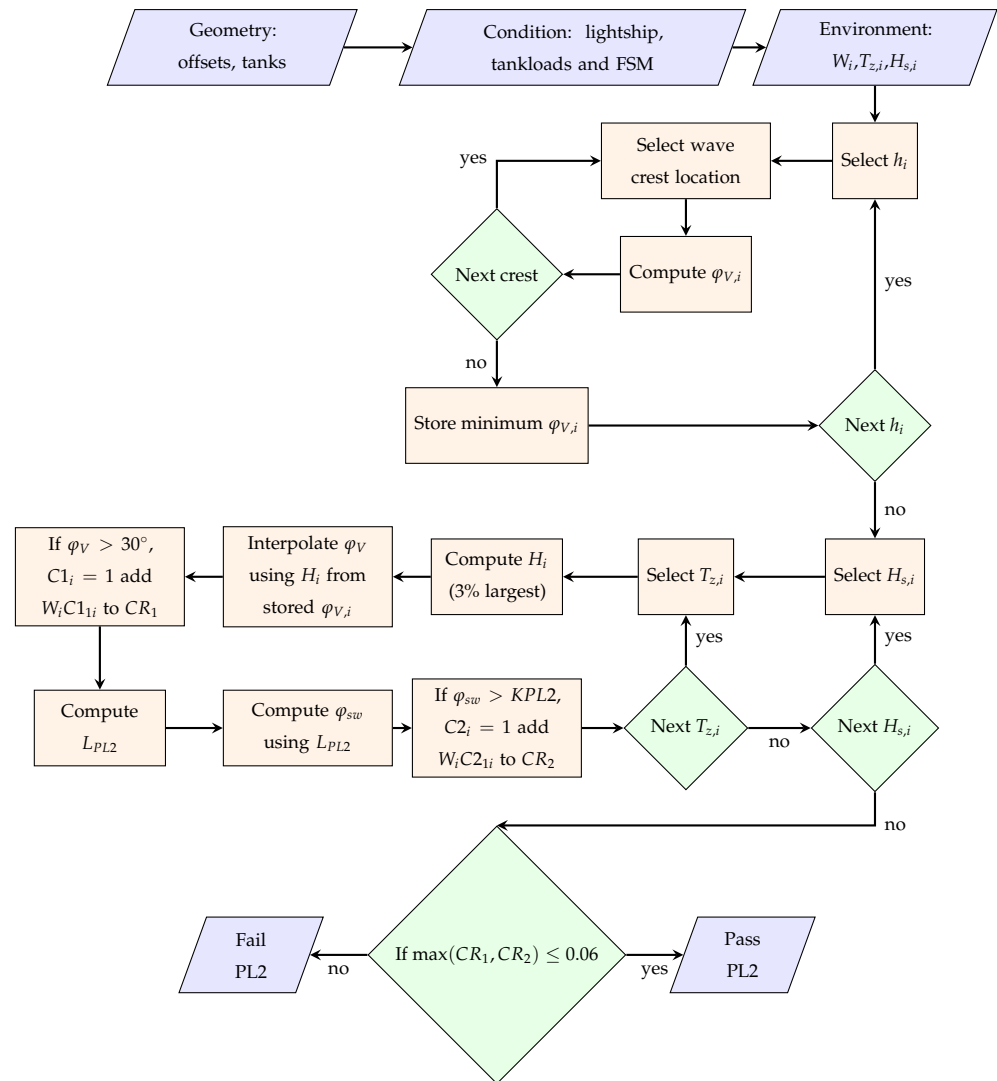


Figure 11. Pure loss level 2 algorithm process diagram.

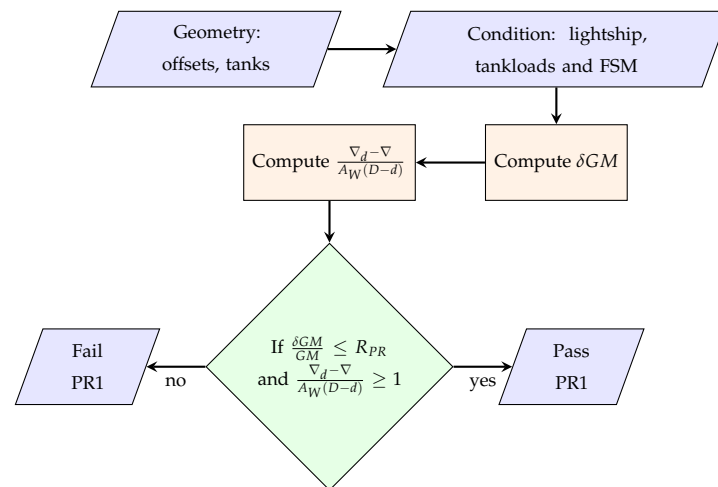


Figure 12. Parametric Roll Level 1 algorithm process diagram.

The equation includes T_e computed at the wave celerity, R at the wave celerity, and the wave surge force f_{ij} , computed using a simplified Froude–Krylov method. Solving for n_{cr} can be done directly, that is, not using numerical root finding methods, and this will lead to better results. Once n_{cr} is determined, it is relatively easy to compute T_e and R from the polynomial expressions, and then iterate to find u_{cr} and $F_{n_{cr}}$. A complete process diagram for an algorithmic implementation of SB level 2 is given by Figure 14.

Resistance and propulsion characteristics are typically not considered in most stability programs, so the input, variation, and/or import with other programs is a necessary step in implementing SB level 2. Other than this, the SB criteria are relatively self-contained.

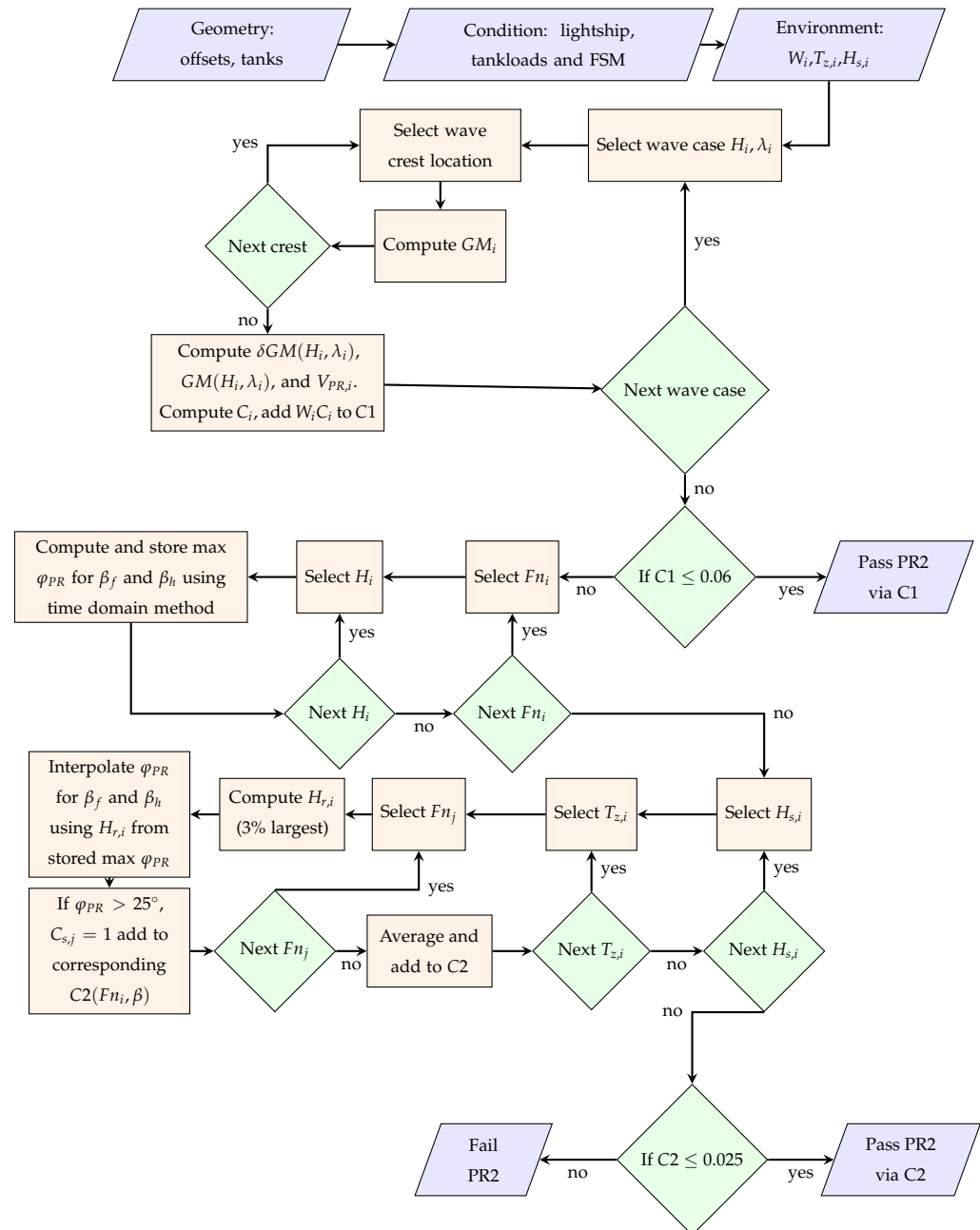


Figure 13. Parametric roll level 2 algorithm process diagram.

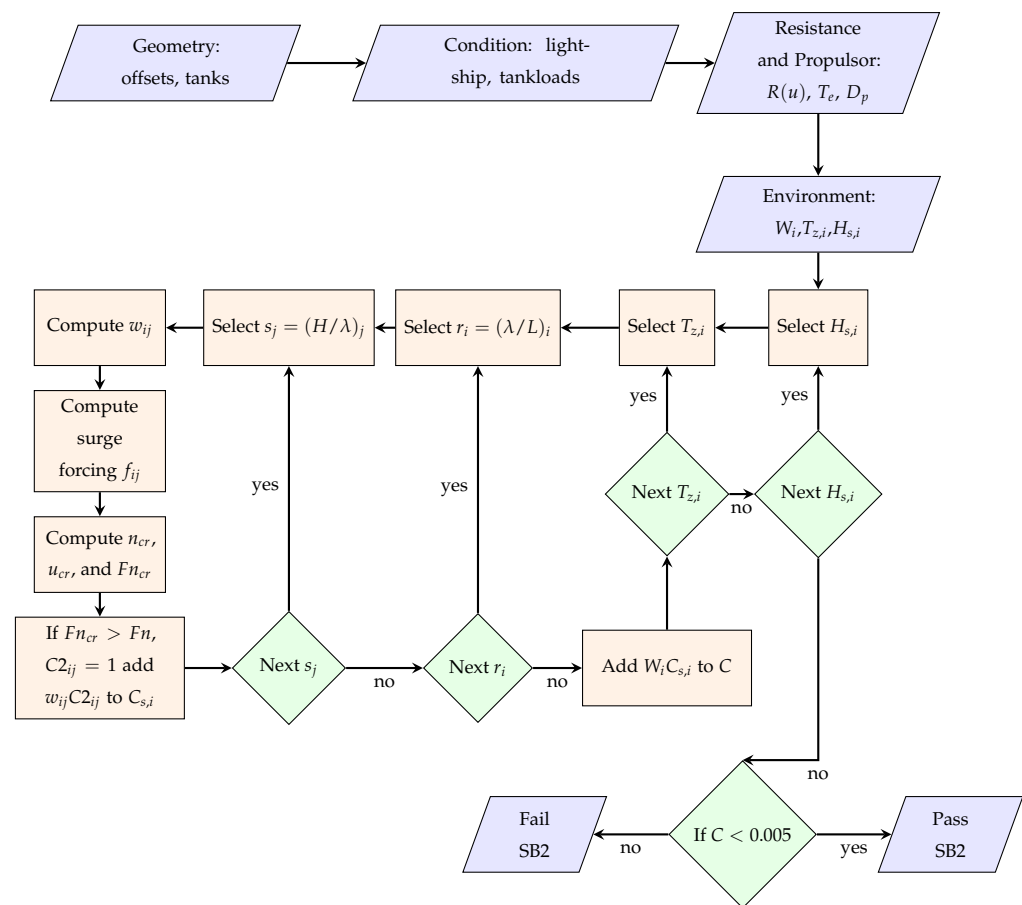


Figure 14. Surf-riding/broaching level 2 algorithm process diagram.

3. Matrix Calculations

The guidelines mention the ability to determine safe zones as functions of GM , draft, and trim based on the criteria defined for each failure mode. To accomplish this, the criteria would need to be applied to a range of $VCGs$ (GMs), for example, and the limiting value would be obtained by interpolation or successively refined simulations. For level 1 criteria, this is a relatively reasonable undertaking, as the criteria have little overhead and run quickly, however, research shows that the conservative nature of the level 1 criteria would yield traditional minimum GM curves that would be too restrictive [3]. For level 2 criteria, the methods are more suitable due to their less conservative nature, but for the same reason the computations become much more cumbersome. This is especially true in the case of the PR level 2 assessment, where the complexity of the simulation is impractical over a large range of conditions, especially as the dimensionality of the input space increases (i.e., considering variations in both GM and draft).

Furthermore, different criteria respond inversely with changes in certain parameters. In the case of GM , the vulnerability in the EA mode will likely go down with decreased GM , yet the vulnerability in the DS, PL, and PR modes will increase. For certain vessels, there may not exist a condition which passes all modes simultaneously, even if the vessel demonstrates conditions in each mode which are safe [6,7]. Moreover, failure modes such as PL, PR, and SB are forward speed dependent, so variations in service speed would also need to be considered.

4. Environmental Input Parameters

Although official recommendations for operational guidance have not yet been released by the IMO, a number of researchers have investigated the topic [3,11,39]. In these discussions, the primary variables in the development of operational guidance are environ-

mental (such as waves and wind) and operational (such as ship heading and speed). Of interest to those who wish to implement the methods, there are various places where the criterion could be customized to provide the necessary input parameters. As mentioned, these parameters are largely related to environmental conditions, and as such, other variations in the guidelines (such as alternative calculation methods for things like heeling arms and roll angles) are not considered. Here these parameters are summarized where the criteria may be tailored to a specific operating environment, as shown by Table 2.

Table 2. Summary of input parameters which may be varied to match specific operating environment.

Parameter	Description	Applicable Failure Modes
P	Wind pressure	DS
U_w	Wind speed	DS
$S_v(\omega)$	Gustiness spectrum	DS
s	Wave steepness factor	DS, EA, SB
W_i	Short-term seaway probability of occurrence	DS, EA, PL, PR, SB
$H_{s,i}$	Short-term seaway significant wave height	DS, EA, PL, PR, SB
$T_{p,i}$	Short-term seaway peak period	DS, EA, PL, PR, SB
$S_{zz}(\omega)$	Short-term wave spectrum	DS, EA, PL, PR
r	Wavelength to ship length ratio	SB
V_S	Ship speed	PR, SB

The most significant environmental input across all modes is the long term wave scatter data that defines W_i , $H_{s,i}$, and $T_{p,i}$. This data, which governs the severity of individual seaways but also their probability of occurrence, could be adjusted depending on a region of operation. Varying this data will result in a significant change in the attained vulnerability indices, primarily in level 2 evaluations [7]. For an implementation of the criteria that hopes to allow for operational guidance, the ability to input and modify these parameters will be critical.

5. Results

The level 1 and level 2 criteria discussed in Section 2 are implemented as two independent codes: one at the American Bureau of Shipping, the “ABS Code”, and one at Creative Systems, Inc, the “CSI Code”, to both provide a means of verifying the results, but also to explore differences in implementation and prepare a tool for future evaluations.

The ABS Code is implemented largely in the Python programming language, with access to ABS in-house numerical tools such as NLOAD3D (a nonlinear 3D panel code) and an Excel-based input interface. The CSI Code is implemented in the Modula-2 programming language, with access to the General HydroStatics (GHS) hydrostatic solver and linear strip-method seakeeping code [40]. The CSI Code also encompasses a bespoke 3-DOF (heave–roll–pitch) nonlinear solver to predict parametric rolling. The geometry and loading condition input for the CSI Code were developed in terms of GHS geometry and condition files, with input syntax designed for commercial use.

Four different vessels are evaluated using each code. This includes a generic barge, the C11 container ship, KRISO container ship (KCS), and fishing vessel. The following sections give the particulars and results for each of these vessels for both the ABS Code and the CSI Code. In certain cases, results submitted to the DYNASTY working group of the Cooperative Research Ship (CRS) group are also included [41].

5.1. Barge

The barge test case encompasses a simple uniform rectangular cross section. Figure 15 shows the barge geometry definition in isometric view. Note that the deck edges are marked, as the location of the deck edge is important in the assessment of the righting arms in the DS and PL failure modes. The principal dimensions of the barge are also given in Table 3. Table 4 shows the loading condition of the barge test case.

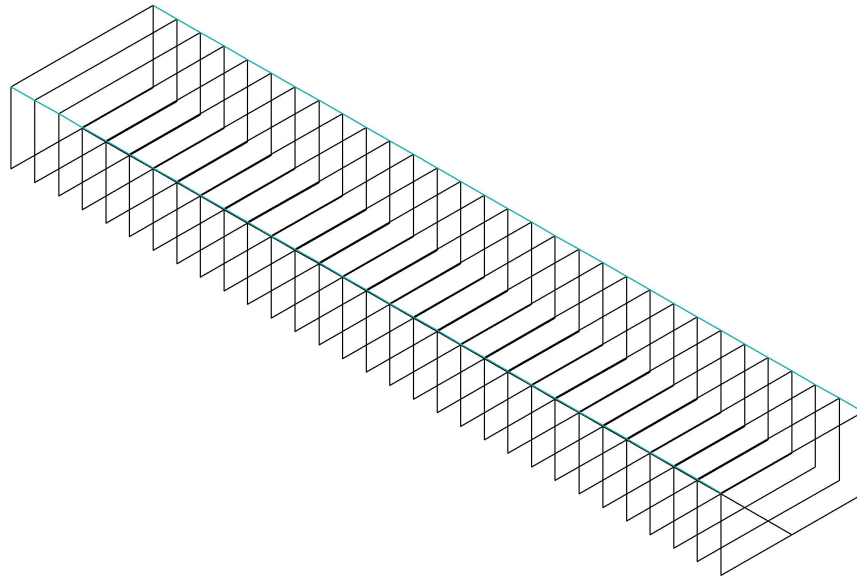


Figure 15. Isometric view of barge geometry in a section-based GF format. Blue lines mark the deck edge. See Section 6 for a link to download this geometry file.

Table 3. Principal dimensions of barge.

L	100.00	m
B	20.00	m
D	10.00	m
d_{full}	5.00	m
C_B	1.00	
C_M	1.00	
V_s	5.00	knots
A_k	50.00	m ²

Table 4. Loading condition of barge.

d_{aft}	5	m	Daft at aft perpendicular
d_{fore}	5	m	Draft at forward perpendicular
KG	7	m	Vertical center of gravity
GM	2.167	m	Metacentric height
∇	10,000	m ³	Volumetric displacement
T_r	12	s	Natural roll period
A_L	500	m ²	Projected lateral area above WL
Z	5	m	Vertical distance from $d/2$ to center of A_L
ϕ_f	40	deg	Angle at which openings immerse
z	40	m	Highest vertical location of the crew area from BL
x	30	m	Longitudinal distance of the location of the crew from AP

5.1.1. Level 1 Assessment of Dead Ship (DS) of Barge

For the level 1 assessment of the dead ship condition, the calculation of a GZ curve is required. Figure 16 shows the GZ curve of the barge calculated by both codes. The key results of the level 1 assessment from the ABS code and the CSI code are compared in Table 5. As shown in the table, both ABS and CSI results indicate that the vessel is not vulnerable to the level 1 dead ship condition failure mode.

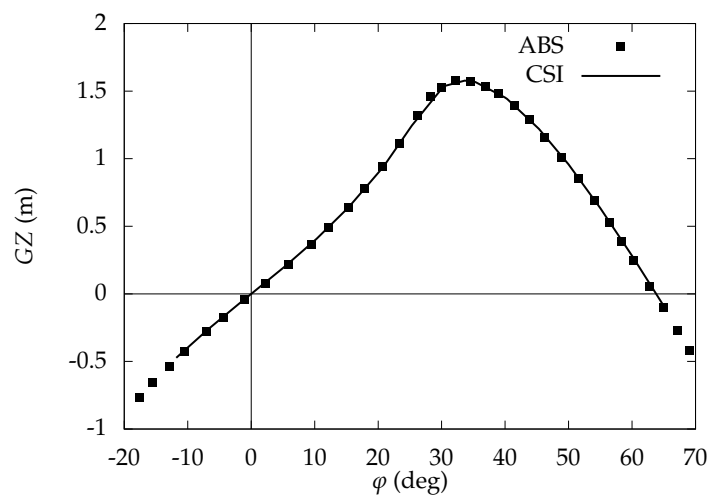


Figure 16. GZ curve for barge test case for the assessment of dead ship level 1.

Table 5. Level 1 assessment of dead ship failure mode for barge.

Level 1 Dead Ship Condition	ABS	CSI
Area A	3.083	2.947
Area B	33.652	35.079
Ratio of B/A	10.917	11.904
Check if B/A > 1	Pass	Pass

5.1.2. Level 2 Assessment of Dead Ship (DS) for Barge

For the level 2 assessment of the dead ship failure mode, the calculation of the effective wave slope is required. Figure 17 shows the effective wave slope of the barge calculated by the ABS code and CSI code. Note that these results are computed using the simplified method shown in Figure 6. The key results of the level 2 assessment from the ABS code and CSI code are compared in Table 6. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 dead ship condition failure mode.

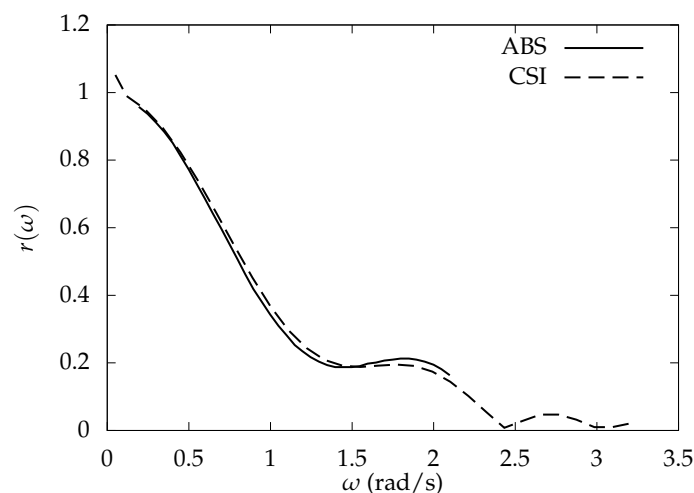


Figure 17. Effective wave slope function for barge computed using the simplified “formal” method.

Table 6. Level 2 assessment of dead ship failure mode for barge.

Level 2 Dead Ship Condition	ABS	CSI
C	2.92×10^{-10}	0.000
R_{DS0}	0.06	0.06
Check if $C < R_{DS0}$	Pass	Pass

5.1.3. Level 1 Assessment of Excessive Acceleration (EA) for Barge

The key results of level 1 assessment of excessive acceleration for the barge test case are compared in Table 7. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 excessive acceleration failure mode.

Table 7. Level 1 assessment of excessive acceleration failure mode for barge.

Level 1 Excessive Acceleration	ABS	CSI
r effective wave slope	0.910	0.910
s wave steepness	0.032	0.032
ϕ characteristic roll amplitude (rad)	0.093	0.091
$\ddot{y}$ acceleration estimated (m/s^2)	1.221	1.2
R_{EA1} (m/s^2)	4.64	4.64
Check if $\ddot{y} < R_{EA1}$	Pass	Pass

5.1.4. Level 2 Assessment of Excessive Acceleration (EA) for Barge

The key results of level 2 assessment of excessive acceleration for the barge test case are compared in Table 8. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 excessive acceleration failure mode.

Table 8. Level 2 assessment of the excessive acceleration failure mode for barge.

Level 2 Excessive Acceleration	ABS	CSI
C	0.000	0
R_{EA2}	0.00039	0.00039
Check if $C < R_{EA2}$	Pass	Pass

5.1.5. Level 1 Assessment of Pure Loss of Stability (PL) for Barge

The key results of the level 1 assessment of pure loss of stability for the barge test case are compared in Table 9. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 pure loss of stability failure mode.

Table 9. Level 1 assessment of the pure loss of stability failure mode for the barge.

Level 1 Pure Loss of Stability	ABS	CSI
Displacement Ratio	1.00	1.00
Check if Displacement Ratio ≥ 1	Pass	Pass
d_L	3.33	3.397
I_{TL}	66,667	66,667
KB	2.5	2.5
$GM_{\min}$	2.167	2.167
R_{PLA}	0.05	0.05
Check if $GM_{\min} > R_{PLA}$	Pass	Pass

5.1.6. Level 2 Assessment of Pure Loss of Stability (PL) for Barge

The key results of level 2 assessment of pure loss of stability for the barge test case are compared in Table 10. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 Pure Loss of stability failure mode.

Table 10. Level 2 assessment of the pure loss of stability failure mode for barge.

Level 2 Pure Loss of Stability	ABS	CSI
$CR1$	0	0
$CR2$	0.03	0
R_{PL0}	0.06	0.06
Check if $\max(CR1, CR2) < R_{PL0}$	Pass	Pass

5.1.7. Level 1 Assessment of Parametric Roll (PR) for Barge

The key results of level 1 assessment of parametric rolling for the barge test case are compared in Table 11. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 parametric rolling failure mode.

Table 11. Level 1 assessment of parametric roll failure mode for barge.

Level 1 Parametric Roll	ABS	CSI
Displacement Ratio	1.00	1.00
Check if Displacement Ratio ≥ 1	Pass	Pass
δGM		0.0
GM		2.167
$\delta GM/GM$	0.000	0.000
R_{PR}	1.23	1.28
Check if $\delta GM/GM < R_{PR}$	Pass	Pass

5.1.8. Level 2 Assessment of Parametric Roll (PR) for Barge

For the level 2 assessment of parametric rolling, time domain simulations in waves are required, as discussed in Methods. In the ABS code, this is achieved through the use of the ABS in-house seakeeping program NLOAD3D. In the CSI code, a nonlinear 3-DOF strip method is implemented, but only invoked if the vessel fails the check of C1. The key results of the level 2 assessment of parametric rolling are compared in Table 12. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 parametric rolling failure mode. Note that C2 was not calculated by the CSI criteria because C1 already passes the criteria.

Table 12. Level 2 assessment of parametric roll failure mode for barge.

Level 1 Parametric Roll	ABS	CSI
C1	0	0
R_{PR1}	0.06	0.06
C2	0.000	N/A
R_{PR2}	0.025	N/A
Check if $C1 < R_{PR1}$ or $C2 < R_{PR2}$	Pass	Pass

5.2. C11 Container Ship

A C11 container ship is selected as a test case because this vessel has been used in many studies of dynamic stability. Figure 18 shows the geometry of C11 container ship used in this assessment. Again note that the deck edges are marked. Table 13 shows the principal dimensions and bilge keel area of the vessel. Table 14 shows the draft, KG, GM, roll natural period, lateral wind area, and crew location at a specific loading condition of the vessel.

Table 13. Principal dimensions of C11 container ship.

L	262.00	m
B	40.00	m
D	24.45	m
d_{full}	12.5	m
C_B	0.56	-
C_M	0.96	-
V_s	24.5	knots
A_k	61.02	m ²

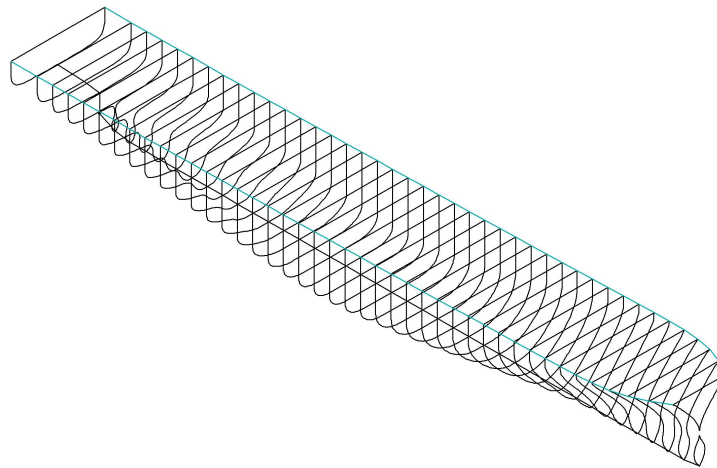


Figure 18. Isometric view of C11 container ship geometry in section-based GF format. Blue lines mark the deck edge. See Section 6 for a link to download this geometry file.

Table 14. Loading conditions of C11 container ship.

d_{aft}	11.50	m	Daft at aft perpendicular
d_{fore}	11.50	m	Draft at forward perpendicular
KG	18.40	m	Vertical center of gravity
GM	1.40	m	Metacentric height
∇	67,384.00	m ³	Volumetric displacement
T_r	25.10	s	Natural roll period
A_L	7093.00	m ²	Projected lateral area above WL
Z	7.71	m	Vertical distance from $d/2$ to center of A_L
ϕ_f	50.00	deg	Angle at which openings immerse
z	40.00	m	Highest vertical location of crew area from BL
x	30.00	m	Longitudinal distance of the location of the crew from AP

5.2.1. Level 1 Assessment of Dead Ship (DS) for C11 Container Ship

For the level 1 assessment of the dead ship condition, the calculation of a GZ curve is required. Figure 19 shows the GZ curve of the C11 container ship calculated by the ABS and CSI codes. The key results of level 1 assessment are compared in Table 15. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 dead ship condition failure mode. The difference between the results of the ABS and CSI codes stems from the difference in the lateral wind area. In the CSI calculations, the wind area due to containers is omitted.

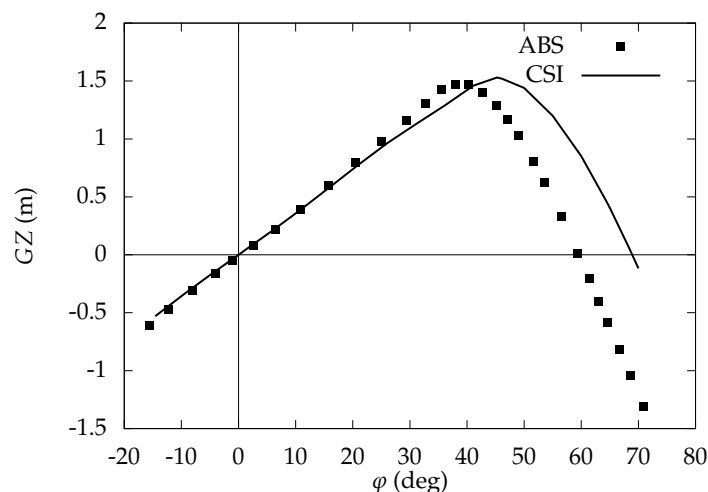


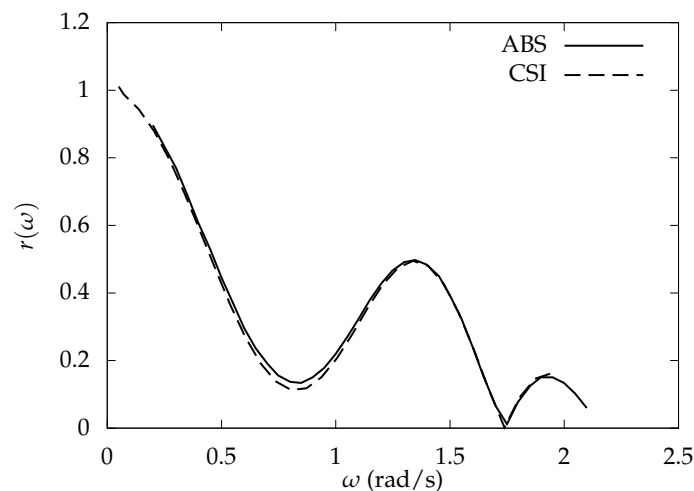
Figure 19. GZ curve for C11 container ship test case for the assessment of dead ship level 1.

Table 15. Level 1 assessment of dead ship failure mode for C11 container ship.

Level 1 Dead Ship Condition	ABS	CSI
Area A	3.481	4.675
Area B	36.275	41.075
Ratio of B/A	10.420	8.774
Check if B/A > 1	Pass	Pass

5.2.2. Level 2 Assessment of Dead Ship (DS) for C11 Container Ship

For the level 2 assessment of dead ship condition, the calculation of the effective wave slope is required. Figure 20 shows the effective wave slope of the C11 container ship calculated by the ABS code and the CSI code. The key results of the level 2 assessment are compared in Table 16. As shown in the table, both the ABS and CSI codes indicate that the vessel is not vulnerable to the level 2 Dead Ship condition failure mode, this also agrees with the CRS results [41].

**Figure 20.** Effective wave slope function for C11 container ship computed using simplified “formal” method.**Table 16.** Level 2 assessment of dead ship failure mode for C11 container ship.

Level 2 Dead Ship Condition	ABS	CSI	CRS
C	1.22×10^{-10}	0.000	1.28×10^{-7}
R_{DS0}	0.06	0.06	0.06
Check if $C < R_{DS0}$	Pass	Pass	Pass

5.2.3. Level 1 Assessment of Excessive Acceleration (EA) for C11 Container Ship

The key results of the level 1 assessment of excessive acceleration are compared in Table 17. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 excessive acceleration failure mode.

Table 17. Level 1 assessment of the excessive acceleration failure mode for C11 container ship.

Level 1 Excessive Acceleration	ABS	CSI
r effective wave slope	0.942	0.940
s wave steepness	0.024	0.024
ϕ characteristic roll amplitude (rad)	0.133	0.123
$\ddot{y}$ acceleration estimated (m/s^2)	1.600	1.476
R_{EA1} (m/s^2)	4.64	4.64
Check if $\ddot{y} < R_{EA1}$	Pass	Pass

5.2.4. Level 2 Assessment of Excessive Acceleration (EA) for C11 Container Ship

The key results of the level 2 assessment of excessive acceleration are compared in Table 18. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 Excessive Acceleration failure mode.

Table 18. Level 2 assessment of the excessive acceleration failure mode for C11 container ship.

Level 2 Excessive Acceleration	ABS	CSI
C	0.000	0
R_{EA2}	0.00039	0.00039
Check if $C < R_{EA2}$	Pass	Pass

5.2.5. Level 1 Assessment of Pure Loss of Stability (PL) for C11 Container Ship

The key results of the level 1 assessment of the pure loss of stability are compared in Table 19. As shown in the table, the results from ABS, CSI, and CRS indicate that the vessel is vulnerable to the level 1 Pure Loss of stability failure mode.

Table 19. Level 1 assessment of the pure loss of stability failure mode for the C11 container ship.

Level 1 Pure Loss of Stability	ABS	CSI	CRS
Displacement Ratio	1.191	1.2	
Check if Displacement Ratio ≥ 1	Pass	Pass	Pass
d_L	7.1246	7.118	
I_{TL}	659,945	657,754	
KB	6.537	6.54	
GM_{min}	−2.069	−2.1	−2.065
R_{PLA}	0.05	0.05	0.05
Check if $GM_{min} > R_{PLA}$	Fail	Fail	Fail

5.2.6. Level 2 Assessment of Pure Loss of Stability (PL) for C11 Container Ship

The key results of the level 2 assessment of the pure loss of stability are compared in Table 20. As shown in the table, the results from ABS and CSI indicate that the vessel is not vulnerable to the level 2 pure loss of stability failure mode.

Table 20. Level 2 assessment of pure loss of stability failure mode for C11 container ship.

Level 2 Pure Loss of Stability	ABS	CSI
$CR1$	0	0
$CR2$	0.004	0.01
R_{PL0}	0.06	0.06
Check if $\max(CR1, CR2) < R_{PL0}$	Pass	Pass

5.2.7. Level 1 Assessment of Parametric Roll (PR) for C11 Container Ship

The key results of the level 1 assessment of parametric rolling are compared in Table 21. As shown in the table, the results from ABS, CSI, and CRS indicate that the vessel is vulnerable to the level 1 Parametric Rolling failure mode.

Table 21. Level 1 assessment of parametric roll failure mode for C11 container ship.

Level 1 Parametric Roll	ABS	CSI	CRS
Displacement Ratio	1.191	1.2	
Check if Displacement Ratio ≥ 1	Pass	Pass	Pass
δGM	2.187	2.5491	
GM	1.990	1.944	
$\delta GM/GM$	1.099	1.310	1.097
R_{PR}	0.420	0.420	0.420
Check if $\delta GM/GM < R_{PR}$	Fail	Fail	Fail

5.2.8. Level 2 Assessment of Parametric Roll (PR) for C11 Container Ship

For the level 2 assessment of parametric rolling, a time domain simulation in waves is required. The key results of the level 2 assessment of parametric rolling are compared in Table 22. Note the general agreement between the three evaluations with respect to C2, which is derived from the time domain simulations. The ABS code used a 6-DOF nonlinear 3D panel method, where the CSI code used a 3-DOF nonlinear strip method. As shown in the table, the results from ABS, CSI, and CRS indicate that the vessel is vulnerable to the level 2 Parametric Rolling failure mode.

Table 22. Level 2 assessment of parametric roll failure mode for the C11 container ship.

Level 1 Parametric Roll	ABS	CSI	CRS
C1	0.436	0.440	0.436
R_{PR1}	0.06	0.06	0.06
C2	0.074	0.090	0.1
R_{PR2}	0.025	0.025	0.025
Check if $C1 < R_{PR1}$ or $C2 < R_{PR2}$	Fail	Fail	Fail

5.3. KCS Container Ship

A KCS container ship is selected as a test case for this study because this vessel has been used in many studies of dynamic stability. Figure 21 shows the geometry of the KCS container ship used in this assessment and the principal dimensions are given by Table 23. The loading condition and resistance and propulsion characteristics are also given by Tables 24 and 25, respectively.

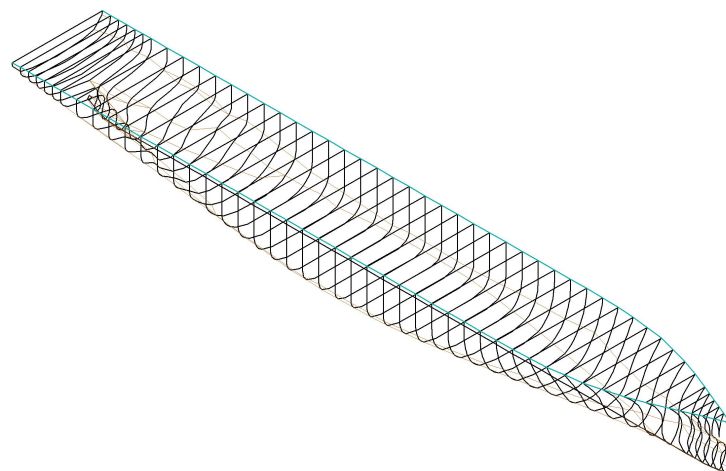
**Figure 21.** Isometric view of the KCS container ship geometry in section-based GF format. Blue lines mark the deck edge. See Section 6 for a link to download this geometry file.

Table 23. Principal dimensions of the KCS container ship.

L	230.00	m
B	32.20	m
D	17.20	m
d_{full}	11.0	m
C_B	0.64	-
C_M	0.94	-
V_s	24.0	knots
A_k	64.00	m ²

Table 24. Loading conditions of KCS container ship.

d_{aft}	10.80	m	Daft at aft perpendicular
d_{fore}	10.80	m	Draft at forward perpendicular
KG	13.674	m	Vertical center of gravity
GM	1.32	m	Metacentric height
∇	54,148.00	m ³	Volumetric displacement
T_r	25.10	s	Natural roll period
A_L	6000.00	m ²	Projected lateral area above WL
Z	12.00	m	Vertical distance from $d/2$ to center of A_L
ϕ_f	50.00	deg	Angle at which openings immerse
z	35.00	m	Highest vertical location of crew area from BL
x	30.00	m	Longitudinal distance of the location of the crew from AP

Table 25. Resistance and propulsion parameters of KCS container ship.

D_p	7.9	m	Propeller diameter
t_p	0.13	-	Thrust fraction
w_p	0.26	-	Wake fraction
r_0	0	N	0th-order resistance regression coefficient
r_1	375,181.0	N/(m/s ²) ¹	1st-order resistance regression coefficient
r_2	−255,614.0	N/(m/s ²) ²	2nd-order resistance regression coefficient
r_3	63,275.0	N/(m/s ²) ³	3rd-order resistance regression coefficient
r_4	−6149.0	N/(m/s ²) ⁴	4th-order resistance regression coefficient
r_5	210.34	N/(m/s ²) ⁵	5th-order resistance regression coefficient
k_0	0.53	-	0th-order thrust regression coefficient
k_1	−0.48	-	1st-order thrust regression coefficient
k_2	−0.02	-	2nd-order thrust regression coefficient

5.3.1. Level 1 Assessment of Dead Ship (DS) for KCS Container Ship

For the level 1 assessment of the dead ship condition, the calculation of a GZ curve is required. Figure 22 shows the GZ curve of the KCS container ship calculated by the ABS and CSI codes. The key results of the level 1 assessment are compared in Table 26. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 dead ship condition failure mode. The minor difference between the results of ABS and CSI comes from the difference in the lateral wind area. In the CSI calculation, the wind area due to containers has been included by a simple geometric model of the topsides, which achieves equivalent area.

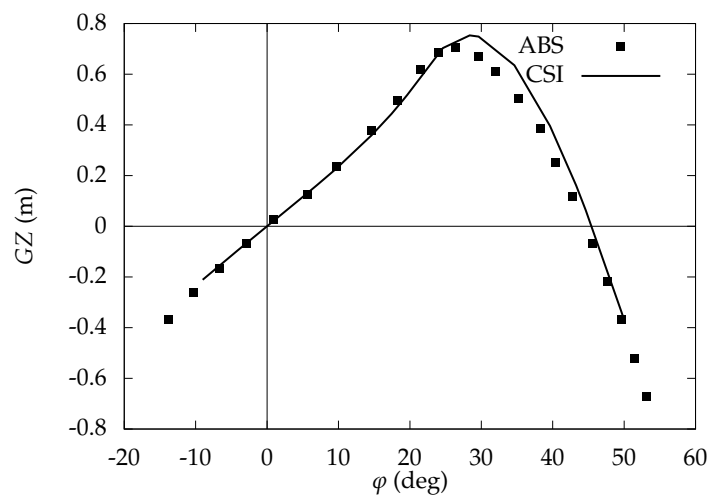


Figure 22. GZ curve for KCS container ship test case for the assessment of dead ship level 1.

Table 26. Level 1 assessment of dead ship failure mode for KCS container ship.

Level 1 Dead Ship Condition	ABS	CSI
Area A	2.780	2.896
Area B	13.684	12.167
Ratio of B/A	4.922	4.135
Check if B/A > 1	Pass	Pass

5.3.2. Level 2 Assessment of Dead Ship (DS) for KCS Container Ship

For the level 2 assessment of the dead ship condition, the calculation of the effective wave slope is required. Figure 23 shows the effective wave slope of the KCS container ship calculated by the ABS code and CSI code. The key results of the level 2 assessment are compared in Table 27. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 dead ship condition failure mode.

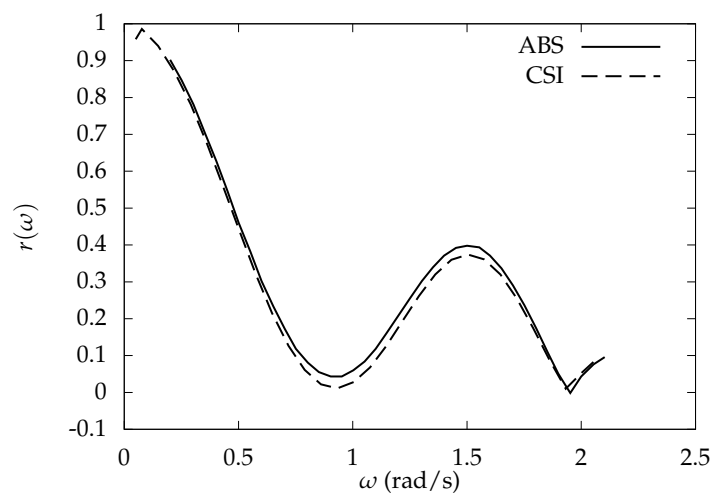


Figure 23. Effective wave slope function for KCS container ship computed using the simplified “formal” method.

Table 27. Level 2 assessment of the dead ship failure mode for KCS container ship.

Level 2 Dead Ship Condition	ABS	CSI
C	4.22×10^{-9}	0.000
R_{DS0}	0.06	0.06
Check if $C < R_{DS0}$	Pass	Pass

5.3.3. Level 1 Assessment of Excessive Acceleration (EA) for KCS Container Ship

The key results of the level 1 assessment of excessive acceleration are compared in Table 28. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 excessive acceleration failure mode.

Table 28. Level 1 assessment of the excessive acceleration failure mode for KCS container ship.

Level 1 Excessive Acceleration	ABS	CSI
r effective wave slope	0.932	0.939
s wave steepness	0.024	0.024
ϕ characteristic roll amplitude (rad)	0.132	0.133
$\ddot{y}$ acceleration estimated (m/s^2)	1.552	1.53
R_{EA1} (m/s^2)	4.64	4.64
Check if $\ddot{y} < R_{EA1}$	Pass	Pass

5.3.4. Level 2 Assessment of Excessive Acceleration (EA) for KCS Container Ship

The key results of the level 2 assessment of excessive acceleration are compared in Table 29. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 excessive acceleration failure mode.

Table 29. Level 2 assessment of the excessive acceleration failure mode for the KCS container ship.

Level 2 Excessive Acceleration	ABS	CSI
C	0.000	0
R_{EA2}	0.00039	0.00039
Check if $C < R_{EA2}$	Pass	Pass

5.3.5. Level 1 Assessment of Pure Loss of Stability (PL) for KCS Container Ship

The key results of the level 1 assessment of pure loss of stability are compared in Table 30. As shown in the table, both the ABS and CSI results indicate that the vessel is vulnerable to the level 1 pure loss of stability failure mode.

Table 30. Level 1 assessment of pure loss of stability failure mode for KCS container ship.

Level 1 Pure Loss of Stability	ABS	CSI
Displacement Ratio	1.004	1.09
Check if Displacement Ratio ≥ 1	Pass	Pass
d_L		6.974
I_{TL}		360,118
KB		5.94
$GM_{\min}$	−1.062	−0.76
R_{PLA}	0.05	0.05
Check if $GM_{\min} > R_{PLA}$	Fail	Fail

5.3.6. Level 2 Assessment of Pure Loss of Stability (PL) for KCS Container Ship

The key results of the level 2 assessment of pure loss of stability are compared in Table 31. As shown in the table, the ABS and CSI results indicate that the vessel is not vulnerable to the level 2 pure Loss of stability failure mode.

Table 31. Level 2 assessment of the pure Loss of stability failure mode for KCS container ship.

Level 2 Pure Loss of Stability	ABS	CSI
CR1	0.045	0.04
CR2	0	0
R_{PL0}	0.06	0.06
Check if $\max(CR1, CR2) < R_{PL0}$	Pass	Pass

5.3.7. Level 1 Assessment of Parametric Roll (PR) for KCS Container Ship

The key results of the level 1 assessment of parametric rolling are compared in Table 32. As shown in the table, all the results from ABS and CSI indicate that the vessel is vulnerable to the level 1 parametric rolling failure mode.

Table 32. Level 1 assessment of parametric roll failure mode for KCS container ship.

Level 1 Parametric Roll	ABS	CSI
Displacement Ratio	1.004	1.09
Check if Displacement Ratio ≥ 1	Pass	Pass
δGM	0.991	1.2271
GM	1.327	1.303
$\delta GM/GM$	0.747	0.94
R_{PR}	0.354	0.35
Check if $\delta GM/GM < R_{PR}$	Fail	Fail

5.3.8. Level 2 Assessment of Parametric Roll (PR) for KCS Container Ship

For the level 2 assessment of parametric rolling, a time domain simulation in waves is required. The key results of the level 2 assessment of parametric rolling are compared in Table 33. Here there is a larger discrepancy in the predicted C2 index from the time domain simulations in each code. However, as shown in the table, both the ABS and CSI results indicate that the vessel is vulnerable to the level 2 parametric rolling failure mode.

Table 33. Level 2 assessment of parametric roll failure mode for the KCS container ship.

Level 2 Parametric Roll	ABS	CSI
C1	0.436	0.436
R_{PR1}	0.06	0.06
C2	0.062	0.12
R_{PR2}	0.025	0.025
Check if $C1 < R_{PR1}$ or $C2 < R_{PR2}$	Fail	Fail

5.3.9. Level 1 Assessment of Surf-Riding and Broaching (SB) for KCS Container Ship

The key results of the level 1 assessment of surf-riding/broaching are compared in Table 34. As shown in the table, both the ABS and CSI results indicate that the vessel is not vulnerable to the level 1 surf-riding/broaching failure mode.

Table 34. Level 1 assessment of surf-riding and the broaching failure mode for the KCS container ship.

Level 1 Surf-Riding and Broaching	ABS	CSI
Check if $L > 200$ m	Pass	Pass
F_n	0.26	0.26
Check if $F_n < 0.3$	Pass	Pass

5.3.10. Level 2 Assessment of Surf-Riding and Broaching (SB) for KCS Container Ship

The key results of the level 2 assessment of surf-riding/broaching at $F_n = 0.26$ are compared in Table 35. As shown in the table, the results from ABS and CSI indicate that the vessel is not vulnerable to the level 2 surf-riding/broaching failure mode.

Table 35. Level 2 assessment of surf-riding and broaching failure mode for the KCS container ship.

Level 2 Surf-Riding and Broaching	ABS	CSI
C	0.000	0.001
R_{SR}	0.005	0.005
Check if $C < R_{SR}$	Pass	Pass

5.4. Fishing Vessel

A fishing vessel is selected as a test case for the surf-riding/broaching failure mode. The fishing vessel presented in [5] is considered, with a geometric model scaled to closely match the published particulars, as shown by Figure 24. The principal dimensions and ship speed of the fishing vessel are shown in Table 36. Note that the ship design speed of 14.29 knots corresponds to a Froude number of $Fn = 0.4$. The loading conditions of the vessel are shown in Table 37. For the assessment of the surf-riding/broaching failure mode, additional information on the resistance and propulsion characteristics of the vessel are required, which are given in Table 38.

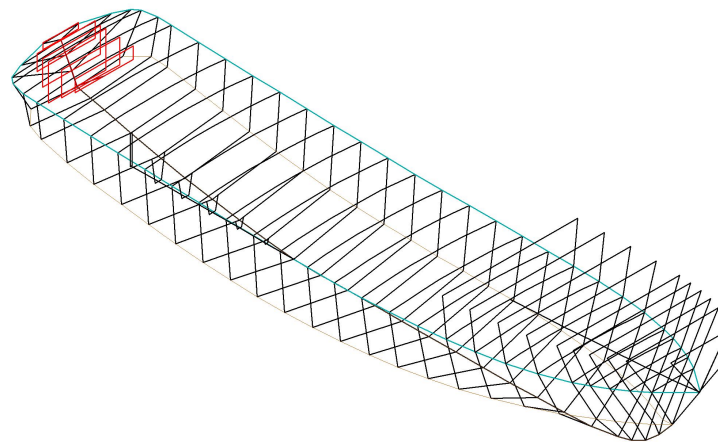


Figure 24. Isometric view of fishing vessel geometry in section-based GF format. Blue lines mark the deck edge. See Section 6 for a link to download this geometry file.

Table 36. Principal dimensions of fishing vessel.

L	34.5	m
B	7.6	m
D	3.5	m
d_{full}	2.65	m
C_B	0.60	-
C_M	0.97	-
V_s	14.29	knots

Table 37. Loading conditions of fishing vessel.

d_{aft}	2.65	m	Draft at aft perpendicular
d_{fore}	2.65	m	Draft at forward perpendicular
KG	0	m	Vertical center of gravity
GM	2.988	m	Metacentric height
∇	414.81	m ³	Volumetric displacement
T_r	25.1	s	Natural roll period
A_L	7093	m ²	Projected lateral area above WL
Z	8.208	m	Vertical distance from $d/2$ to center of A_L
ϕ_f	40.15	deg	Angle at which openings immerse
z	10	m	Highest vertical location of crew area from BL
x	10	m	Longitudinal distance of the location of the crew from AP

Table 38. Resistance and propulsion parameters of the fishing vessel.

D_p	2.6	m	Propeller diameter
t_p	0.142	-	Thrust fraction
w_p	0.156	-	Wake fraction
r_0	0	N	0th-order resistance regression coefficient
r_1	-435.63	$N/(m/s^2)^1$	1st-order resistance regression coefficient
r_2	763.62	$N/(m/s^2)^2$	2nd-order resistance regression coefficient
r_3	-271.98	$N/(m/s^2)^3$	3rd-order resistance regression coefficient
r_4	41.611	$N/(m/s^2)^4$	4th-order resistance regression coefficient
r_5	-1.7335	$N/(m/s^2)^5$	5th-order resistance regression coefficient
k_0	0.2244	-	0th-order thrust regression coefficient
k_1	-0.2283	-	1st-order thrust regression coefficient
k_2	-0.1373	-	2nd-order thrust regression coefficient

5.4.1. Level 1 Assessment of Surf-Riding and Broaching (SB) for Fishing Vessel

The key results of the level 1 assessment of surf-riding/broaching are compared in Table 39. As shown in the table, all the results from ABS, CSI, and IMO [5] indicate that the vessel is vulnerable to the level 1 surf-riding/broaching failure mode.

Table 39. Level 1 assessment of surf-riding/broaching failure mode for fishing vessel.

Level 1 Surf-Riding and Broaching	ABS	CSI	IMO
Check if $L > 200$ m	Fail	Fail	Fail
F_n	0.4	0.4	0.4
Check if $F_n < 0.3$	Fail	Fail	Fail

5.4.2. Level 2 Assessment of Surf-Riding and Broaching (SB) for Fishing Vessel

The key results of the level 2 assessment of surf-riding/broaching are compared in Table 40. All the results from ABS, CSI, and IMO indicate that the vessel is vulnerable to the level 2 surf-riding/broaching failure mode. As the vessel is vulnerable to SB failure at the ship speed corresponding to $F_n = 0.4$, further assessments are carried out to determine possible operational guidance on the ship speed. The results of the vulnerability check at the reduced speeds of $F_n = 0.3$ and $F_n = 0.35$ are shown in Figure 25. As demonstrated in the figure, the vulnerability of the fishing vessel to the surf-riding/broaching failure mode is significantly reduced as the ship speed is reduced. Therefore, it would be recommended that, for a ship operation in the following sea condition, the ship speed is to be reduced below $F_n = 0.3$ to avoid any possible dynamic stability failure due to surf-riding and broaching.

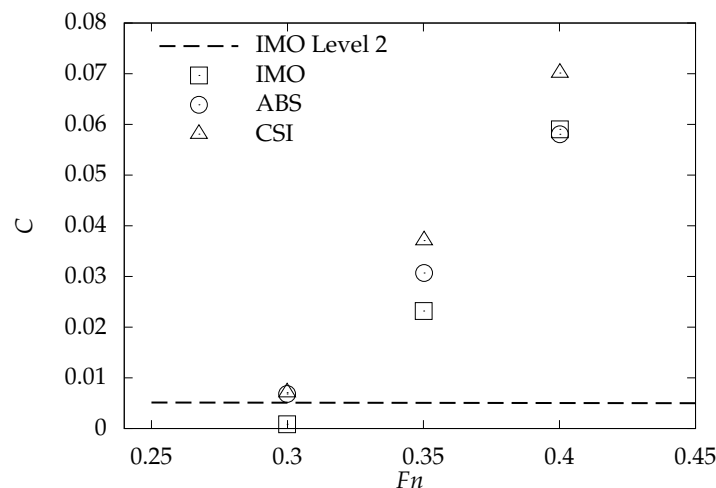
**Figure 25.** Level 2 surf-riding and broaching assessment for fishing vessel test case at various Froude numbers.

Table 40. Level 2 assessment of surf-riding and broaching failure mode for fishing vessel.

Level 2 Surf-Riding and Broaching	ABS	CSI	IMO
C	0.0586	0.07	0.0591
R_{SR}	0.005	0.005	0.005
Check if $C < R_{SR}$	Fail	Fail	Fail

6. Discussion

The verification of two independent implementations of the IMO SGIS guidelines has been successfully carried out for four benchmark cases. The results of the level 1 and level 2 vulnerability checks for the five failure modes are summarized in Table 41. The results of the CSI code are compared with the ABS code, as well as the CRS results for the C11 containership. As demonstrated in Table 41, all vulnerability checks for the four vessels are consistent between the implementations. Note that surf-riding and broaching is only considered for the KCS container ship and the fishing vessel due to the limited availability of the required resistance and propulsion information.

Table 41. Level 1 and level 2 assessment of five failure modes for four ships.

Ship	Failure Mode	Level	ABS	CSI	CRS	IMO
Barge	Dead Ship	1	Pass	Pass		
		2	Pass	Pass		
	Excessive Acceleration	1	Pass	Pass		
		2	Pass	Pass		
	Pure Loss of Stability	1	Pass	Pass		
		2	Pass	Pass		
	Parametric Rolling	1	Pass	Pass		
		2	Pass	Pass		
	C11 Container Ship	1	Pass	Pass		
		2	Pass	Pass	Pass	
		1	Pass	Pass		
		2	Pass	Pass		
		1	Fail	Fail	Fail	
		2	Pass	Pass	Pass	
	Parametric Rolling	1	Fail	Fail	Fail	
		2	Fail	Fail	Fail	
KCS Container Ship	Dead Ship	1	Pass	Pass		
		2	Pass	Pass		
	Excessive Acceleration	1	Pass	Pass		
		2	Pass	Pass		
	Pure Loss of Stability	1	Fail	Fail	Fail	
		2	Pass	Pass	Pass	
	Parametric Rolling	1	Fail	Fail	Fail	
		2	Fail	Fail	Fail	
	Surf-riding and Broaching	1	Pass	Pass		
		2	Pass	Pass		
Fishing Vessel	Surf-riding and Broaching	1	Fail	Fail		Fail
		2	Fail	Fail		Fail

Some differences are observed between the two implementations. For the DS, PL, and EA modes, good agreement is achieved. The variation in predicted values for C2 for the PR level 2 assessment of both the C11 and KCS container ships is expected, although notable. For the KCS case, the CSI code predicts a vulnerability index almost twice that of the ABS code. The values are closer to agreement in the C11 test case, with the CSI value comparing well to the value reported by the CRS report. The computational methods utilized to compute this index present the greatest uncertainty and variability between methods, and this sentiment has been echoed by other researchers [38]. The ABS code utilizes the 3D

panel code NLOAD 3D, whereas the CSI code utilizes a purpose-built 3-DOF solver that uses a body-exact strip theory. The results suggest the low-fidelity method utilized by the CSI code is conservative, but this may lead to an over prediction of vulnerability. Similarly, in the SB level 2 results, the CSI code is also consistently more conservative than the ABS code. This may be due in large part to the geometry-based methods used in the CSI code, where the ABS code uses the specific section area data provided for the test case.

Based on the results presented here, it is concluded that the ABS and CSI implementations demonstrate general consistency for the four test vessels across the five failure modes. Future work should include refinements to the simulation methods underlying the PR level 2 check. Consideration should also be given to variability introduced by differences in damping, especially on the EA level 2 mode. With a consistent framework in place, the variation of input parameters, such as loading conditions or environmental data, especially the data given in Table 1, may also be readily considered. While the focus of this work is on the implementation of the guidelines, and the requirements thereof, the ability to rapidly assess loading conditions and environmental conditions is an important step in developing operational guidance, which is the fourth evaluation procedure shown in Figure 1. Rapid and on-demand checks of SGIS vulnerability for a given sailing condition and route could prove to be valuable to the ship owner or operator.

Author Contributions: Conceptualization, K.E.M. and S.K.; methodology, K.E.M. and S.K. and L.A.H.; software, K.E.M. and S.K. and L.A.H.; validation, S.K. and L.A.H.; resources, S.K.; writing—original draft preparation, K.E.M. and S.K.; writing—review and editing, S.K. and L.A.H.; visualization, K.E.M.; supervision, K.E.M. and S.K.; project administration, K.E.M. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The geometry files and run files used to produce the CSI results are available at: <https://www.ghsport.com/support/IMOSGIS.HTM> (accessed on 15 November 2021). Readers are encouraged to contact the authors to obtain any additional data or resources that are not included here.

Acknowledgments: The authors wish to thank the Cooperative Research Ships (CRS) group for permission to use the CRS results for comparison in the evaluation of the C11 containership test case.

Conflicts of Interest: The authors are employees of their respective companies. Both the American Bureau of Shipping (ABS) and Creative Systems, Inc. (CSI) derive some portion of their profits from evaluation, implementation, or review of stability regulations. This work was done in collaboration between ABS and CSI, and the results are deemed useful to the maritime community at large for further implementation, verification, and validation purposes. The decision to publish the results is not intended to promote the services of either company.

Abbreviations

The following abbreviations are used in this manuscript:

ABS	American Bureau of Shipping
CSI	Creative Systems, Inc.
GHS	General HydroStatics
IMO	International Maritime Organization
CRS	Cooperative Research Ship
RAO	Response Amplitude Operator
SGIS	Second Generation Intact Stability
DS	Dead Ship
EA	Excessive Acceleration
PL	Pure loss of stability

PR Parametric Roll
 SB Surf-riding and Broaching

References

1. IMO. *SDC 7/WP.6 Finalization of Second Generation Intact Stability Criteria—Report of the Drafting Group on Intact Stability*; IMO: London, UK, 2020.
2. IMO. *MSC.1-Circ.1627 Interim Guidelines on the Second Generation Intact Stability Criteria*; IMO: London, UK, 2020.
3. Tompuri, M.; Ruponen, P.; Forss, M.; Lindroth, D. Application of the Second Generation Intact Stability Criteria in Initial Ship Design. In Proceedings of the SNAME Maritime Convention, Houston, TX, USA, 22–24 October 2014.
4. Ariffin, A.; Mansor, S.; Laurnes, J.-M. A Numerical Study for Level 1 Second Generation Intact Stability Criteria. In Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles, Glasgow, UK, 14–19 June 2015.
5. IMO. *SDC 4-5-1/Add.1/2/3/4/5 Report of Correspondence Group (Parts 2–6)*; IMO: London, UK, 2016.
6. Schroter, C.; Lutzen, M.; Erichsen, H.; Jensen, J.J.; Kristensen, H.O.; Hagelskjaer Lauridsen, P.; Tunccan, O.; Baltersen, J.P. Sample Applications of the Second Generation Intact Stability Criteria—Robustness and Consistency Analysis. In Proceedings of the 16th International Ship Stability Workshop, Belgrade, Serbia, 5–7 June 2017.
7. Gonzalez, M.M.; Casas, V.D.; Rojas, L.P.; Agras, D.P.; Ocampo, F.J. Investigation of the Applicability of the IMO Second Generation Intact Stability Criteria to Fishing Vessels. In Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles, Glasgow, UK, 14–19 June 2015.
8. Peters, W.; Belenky, V.; Bassler, C.; Spyrou, K.; Umeda, N.; Bulian, N.; Altmayer, B. The Second Generation Intact Stability Criteria: An Overview of Development. *SNAME Trans.* **2011**, *121*.
9. Bulian, G.; Francescutto, A. A simplified modular approach for the prediction of the roll motion due to the combined action of wind and waves. *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **2004**, *218*, 189–212. [\[CrossRef\]](#)
10. Wandji, C.; Corrigan, P. Sample Application of Second Generation IMO Intact Stability Vulnerability Criteria as Updated during SLF 55. In Proceedings of the 13th International Ship Stability Workshop, Brest, France, 23–26 September 2013.
11. Umeda, N.; Francescutto, A. Current state of the Second Generation Intact Stability criteria—Achievements and remaining issues. In Proceedings of the 15th International Ship Stability Workshop, Stockholm, Sweden, 13–15 June 2016.
12. Shin, D.M.; Chung, J. Application of dead ship condition based on IMO second-generation intact stability criteria for 13K oil chemical tanker. *Ocean. Eng.* **2021**, *238*, 109776. [\[CrossRef\]](#)
13. Petacco, N.; Pitardi, D.; Podenzana Bonvino, C.; Gualeni, P. Application of the IMO Second Generation Intact Stability Criteria to a Ballast-Free Container Ship. *J. Mar. Sci. Eng.* **2021**, *9*, 1416. [\[CrossRef\]](#)
14. Boccadamo, G.; Rosano, G. Excessive Acceleration Criterion: Application to Naval Ships. *J. Mar. Sci. Eng.* **2019**, *7*, 431. [\[CrossRef\]](#)
15. Shin, D.M.; Moon, B.Y.; Chung, J. Application of surf-riding and broaching mode based on IMO second-generation intact stability criteria for previous ships. *Int. J. Nav. Archit. Ocean. Eng.* **2021**, *13*, 545–553. [\[CrossRef\]](#)
16. Umeda, N.; Usada, S.; Mizumoto, K.; Matsuda, A. Broaching probability for a ship in irregular stern-quartering waves: Theoretical prediction and experimental validation. *J. Mar. Sci. Technol.* **2016**, *21*, 23–37. [\[CrossRef\]](#)
17. Gualeni, P.; Paolodello, D.; Petacco, N.; Lena, C. Seakeeping time domain simulations for surf-riding/broaching: Investigations toward a direct stability assessment. *J. Mar. Sci. Technol.* **2020**, *25*, 1120–1128. [\[CrossRef\]](#)
18. Bu, S.X.; Gu, M.; Abdel-Maksoud, M. Study on Roll Restoring Arm Variation Using a Three-Dimensional Hybrid Panel Method. *J. Ship Res.* **2019**, *63*, 94–107. [\[CrossRef\]](#)
19. Lu, J.; Gu, M.; Boulougouris, E. Model experiments and direct stability assessments on pure loss of stability of the ONR tumblehome in following seas. *Ocean. Eng.* **2019**, *194*, 106640. [\[CrossRef\]](#)
20. Gu, M.; Bu, S.; Lu, J. Study of parametric roll in oblique waves using a three-dimensional hybrid panel method. *J. Hydrodyn.* **2020**, *32*, 126–138. [\[CrossRef\]](#)
21. Lu, J.; Gu, M.; Boulougouris, E. Model experiments and direct stability assessments on pure loss of stability in stern quartering waves. *Ocean. Eng.* **2020**, *216*, 108035. [\[CrossRef\]](#)
22. Bulian, G.; Francescutto, A. Second Generation Intact Stability Criteria: On the validation of codes for direct stability assessment in the framework of an example application. *Pol. Marit. Res.* **2013**, *4*, 52–61. [\[CrossRef\]](#)
23. Lu, J.; Gu, M.; Umeda, N. Experimental and numerical study on several crucial elements for predicting parametric roll in regular head seas. *J. Mar. Sci. Technol.* **2017**, *22*, 25–37. [\[CrossRef\]](#)
24. Kapsenberg, G.; Wandji, C.; Duz, B.; Kim, P.S. A Comparison of Numerical Simulations and Model Experiments on Parametric Roll in Irregular Seas. *J. Mar. Sci. Eng.* **2020**, *8*, 474. [\[CrossRef\]](#)
25. IACS. *No. 34 Standard Wave Data*; IACS: London, UK, 2001.
26. IMO. *International Code of Intact Stability*; IMO: London, UK, 2008.
27. Rudakovic, S.; Bulian, G.; Backalov, I. Effective wave slope coefficient of river-sea ships. *Ocean. Eng.* **2019**, *192*, 106427. [\[CrossRef\]](#)
28. ITTC. *Numerical Estimation of Roll Damping*; ITTC: Zurich, Switzerland, 2011.
29. Wilson, R.V.; Carrica, P.M.; Stern, F. Unsteady URANS method for ship motions with application to roll for a surface combatant. *Comput. Fluids* **2006**, *35*, 501–524. [\[CrossRef\]](#)
30. Kianejad, S.S.; Enshaie, H.; Duffy, J.; Ansarifard, N.; Ranmuthugala, D. Ship Roll Damping Coefficient Prediction Using CFD. *J. Ship Res.* **2019**, *63*, 108–122. [\[CrossRef\]](#)

31. Alexandersson, M.; Mao, W.; Ringsberg, J.W. Analysis of roll damping model scale data. *Ships Offshore Struct.* **2021**, *16*, 85–92. [[CrossRef](#)]
32. Ikeda, Y.; Himeno, Y.; Tanaka, N. *On Eddy Making Component of Roll Damping Force on Naked Hull*; University of Osaka Prefecture, Department of Naval Architecture: Osaka, Japan, 1978.
33. Ikeda, Y.; Himeno, Y.; Tanaka, N. *Components of Roll Damping of Ship at Forward Speed*; University of Osaka Prefecture, Department of Naval Architecture: Osaka, Japan, 1978.
34. Ikeda, Y.; Komatsu, K.; Himeno, Y.; Tanaka, N. *On Roll Damping Force of Ship—Effect of Hull Surface Pressure Created by Bilge Keels*; University of Osaka Prefecture, Department of Naval Architecture: Osaka, Japan, 1978.
35. Himeno, Y. *Prediction of Ship Roll Damping—State of the Art*; University of Michigan, Department of NA&ME: Ann Arbor, MI, USA, 1981.
36. Ikeda, Y. *On the Form of Nonlinear Roll Damping of Ships*; Technical University of Berlin: Berlin, Germany, 1983.
37. McTaggart, K. *Appendage and Viscous Forces for Ship Motions in Waves*; Defence Research and Development Canada—Atlantic Research Center: Dartmouth, Nova Scotia, 2004.
38. Spanos, D.; Papanikolaou, A. SAFEDOR International Benchmark Study on Numerical Simulation Methods for the Prediction of Parametric Roll of Ships in Waves. In Proceedings of the 10th International Conference on Stability of Ships and Ocean Vehicles, St. Petersburg, Russia, 22–26 June 2009.
39. Petacco, N.; Gualeni, P. IMO Second Generation Intact Stability Criteria: General Overview and Focus on Operational Measures. *J. Mar. Sci. Eng.* **2020**, *8*, 494. [[CrossRef](#)]
40. Creative Systems, Inc. *GHS-SK User Manual*; Creative Systems, Inc.: Port Townsend, WA, USA, 2021.
41. Cooperative Research Ships. *CRS DYNASTY Technical Report Task 1.1 Documentation for IMO Levels 1&2 Tools*; Bureau Veritas: Paris, France, 2018.