A Numerical Study for Level 1 Second Generation Intact Stability Criteria

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ABSTRACT

During the last International Ship Stability Workshop held in Brest last September, several questions were raised concerning the existing IMO intact stability rules and the new proposed regulations. The lower level (level 1) criteria are conservative but should be easily implemented in stability codes. In this particular study it was investigated if and how an existing and extensively used commercial computer code, in the present case GHS©, could handle level 1 criteria. For simple and realistic cases it was found that a relatively small angle of trim can cause the capsizing of the vessel. These clearly unsafe examples indicate that the existing rules are insufficient. The new intact stability rules aim to deal with failure modes generally associated with extreme weather conditions such as parametric rolling, broaching or pure loss of stability in astern waves but they may also prevent capsizing due to environmental loading. Some of the difficulties encountered with the computation are presented to assess the extent of the necessary development. Finally an illustrative example is presented to verify whether the existing and future regulations can prevent certain obviously dangerous situations.

Keywords: *second generation intact stability, weather criterion, GZ curve*

1. INTRODUCTION

Intact stability is a basic requirement to minimise the risk of the capsizing of vessels. It is a guideline for the ship designer, ship operator and classification society to design, build and commission the ship before it start its service life at sea. A comprehensive background study of intact stability development was written by Kuo & Welaya (Welaya & Kuo, 1981). Their paper "A review of intact stability research and criteria", stated that the first righting arm curve was proposed by Reedin 1868, but the application was presented by Denny in 1887. In addition, in 1935, Pierrottet tried to rationally establish the forces which tend to capsize a ship and proposed a limiting angle at which the dynamic level of the ship must be equal to or greater than the sum of work done by the inclining moments. However, Pierrottet's proposal was too restrictive in the design process and it was not accepted.

Kuo and Welaya also mentioned the famous doctoral thesis written by Jaakko Rahola in 1939. Rohola's thesis evoked widespread interest throughout the world at that time because it was the first comprehensive study and proposed method to evaluate the intact stability which did not require complex calculations.

The First International Conference for ship stability which was held at the University of Strathclyde in 1975, Tsuchiya presented a new method for treating the stability of fishing vessels (Tsuchiya, 1975). He introduced a list of coefficient to define the weather stability criteria. He disregarded the idea of a stability assessment using simple geometrical stability standards such as metacentric height and freeboard, or the shape of the righting arm curve. He proposed a number of factors which, in his opinion, are crucial. He introduced a certain coefficient which should be calculated and plotted on a diagram as a function of metacentric height and the freeboard for every stability assessment. He concluded that his proposed method should be confirmed by a comparison with actual data on fishing boat activities and empirical stability standards.

The first generation intact stability criteria was originally codified at IMO in 1993 as a set of recommendations in Res A.749(18) by taking into account the former Res.A.167 (ES.IV) ("Recommendation on intact stability of passenger and cargo ships under 100 meters in length" which contained statistical criteria, heeling due to passenger crowding, and heeling due to high speed turning, 1968) and Res A.562.(14) ("Recommendation on a severe wind and rolling criterion (Weather Criterion) for the intact stability of passenger and cargo ships of 24 meters in length and over," 1985). These criteria were codified in the 2008 IS Code and became effective as part of both SOLAS and the International Load Line Convention in 2010 in IMO Res MSC.269(85) and MSC.207(85) (Peters et al., 2012).

The actual work to review IS Code 2008 was highlighted during the 48th session of the SLF in Sept. 2005 (IMO, 2005). The work group decided to address three modes of stability failure:

a. Restoring arm variation.
b. Stability under dead ship condition.
c. Manoeuvring-related problems in waves.

There are two conferences that address the development of second generation intact stability criteria. These are the International Conference on Stability of Ship Ocean Vehicles (STAB) and the International Ship Stability Workshop (ISSW). An experimental evaluation of weather criteria was carried out at the National Maritime Research Institute, in Japan. They conducted a wind tunnel test with wind speeds varying from 5m/s to 15 m/s. The results showed some differences compared to the current estimation. For example the wind heeling moment depended on the heel angle and the centre of drift force was higher than half draft (Ishida, Taguchi, & Sawada, 2006). The experimental validation procedures for numerical intact stability assessment with the latest examples was presented by Umeda and his research members in 2014 (Umeda et al., 2014). They equipped the seakeeping and manoeuvring basin of the National Research Institute of Fisheries Engineering in Japan with a wind blower to examine dead ship stability assessment.

A review of available methods for application to second level vulnerability criteria was presented at STAB 2009 (Bassler, Belenky, Bulian, Spyrou, & Umeda, 2009). They concluded that the choice of environmental conditions for vulnerability criteria is at least as important as the criteria themselves. A test application of second generation IMO intact stability criteria on a large sample of ships was presented during STAB 2012. Additional work remains to be carried out to determine a possible standard for the criteria and environment conditions before finalising the second generation intact stability criteria (Wandji & Corrignan, 2012).

During the ISSW 2013, Umeda presented the current status of the development of second generation intact stability criteria and some recent efforts (Umeda, 2013). The discussion covered the five failures modes: pure loss of stability, parametric rolling, broaching, harmonic resonance under dead ship condition and excessive acceleration.

2. BACKGROUND OF IS CODE 2008

The Intact Stability Code 2008 is the document in force. The code is based on the best "state-of-the-art" concept (IMO, 2008). It was developed based on the contribution of design and engineering principles and experience gained from operating ships. In conjunction with the rapid development of modern naval architecture technology, the IS Code will not remain unchanged. It must be re-evaluated and revised as necessary with the contribution of the IMO Committees all around the globe (IMO, 2008).

The IS Code 2008 is divided into 2 parts. Part A consists of the mandatory criteria and Part B contains the recommendation for certain types of ships and additional guidelines. As stated in Part A, the IS Code applies to marine vehicles of 24 metres in length and more. Paragraph 2.2 of Part A lists the criteria regarding the righting arm curve properties and Paragraph 2.3 describes the severe wind and rolling criteria (weather criterion).

The IS Code 2008 Part A 2.2 sets four requirements for righting arm (GZ) curve properties (Grinnaert and Laurens 2013):

a. Area under the righting lever curve,

i. not less than 0.055 meter-radian up to a 30˚ heel angle.

ii. not less than 0.09 meter-radians up to a 40˚ heel angle, or downflooding angle.

iii. not less than 0.03 meter-radians from a 30˚ to 40˚ heel angle or between 30˚ to the downflooding angle.

b. The righting lever GZ shall be at least 0.2m for a heel angle greater than 30˚.

c. The maximum righting lever shall occur at a heel angle not less than 25˚.

d. The initial GM shall not be less than 0.15 meters.

The additional requirement for passenger ships is stated in Part A, Paragraph 3.1. It states that:

a. The angle of heel due to passenger crowding shall not be more than 10˚.

b. A minimum weight of 75kg for each passenger and the distribution of luggage shall be approved by the Administration.

c. The centre of gravity for a passenger standing upright is 1 m and for a seated passenger 0.3 m above the seat.

The IS Code 2008 Part A 2.3 concerns the weather criterion. The ship must be able to withstand the combined effects of beam wind and rolling at the same time. The conditions are:

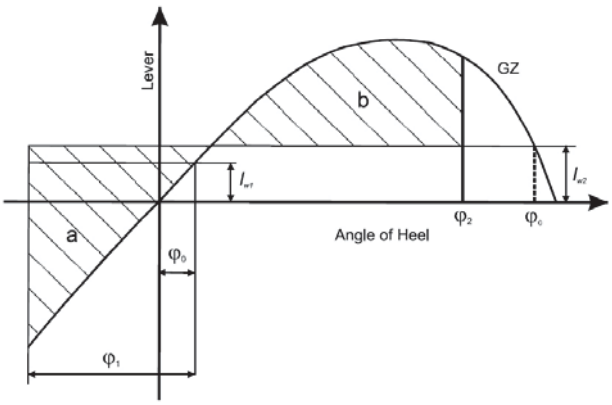
a. the ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever (lw_1).

b. from the resultant angle of equilibrium (φ_0), the ship is assumed to present an angle of roll (φ_1) to windward due to wave action. The angle of heel under action of steady wind (φ_0) should not exceed 16˚or 80% of the angle of deck edge immersion, whichever is less.

c. the ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (lw_2); and under these circumstances, area b shall be equal to or greater than area a, as indicated in Figure 1:

The heeling lever shall be calculated using formula:

$$l_{w1} = \frac{P*A*Z}{1000*g*\Delta} \quad (1)$$



$$l_{w2} = 1.5\ l_{w1} \quad (2)$$

Figure 1 Severe wind and rolling

where lw_1 = steady wind heeling angle, lw_2 = gust wind heeling lever, P = wind pressure of 504 Pa, A = projected lateral area (m^2), Z = vertical distance from the centre of A to the centre of the underwater lateral area or approximately to a point at one half of the mean draught (m), Δ =displacement (t) and g = gravitational acceleration of 9.81 m/s^2).

Part 3.1 of the IS Code 2008 only concerns passenger ships. Passenger ships have to also pass the criteria of Part 2.2 and 2.3. The heeling angle on account of turning should not exceed 10˚, when calculated using the following formula:

$$M_R = 0.200 * \frac{v_0^2}{L_{WL}} * \Delta * (KG - \frac{d}{2}) \quad (2)$$

where: M_R= heeling moment (kNm), v_0 = service speed (m/s), V_{WL} = length of ship at waterline (m), Δ= displacement (tons), d = mean draught (m), KG = height of centre of gravity above baseline (m).

The centrifugal force Fc is equal to $\Delta V_0^2/2$ where R is the radius of gyration. The smaller R, the higher Fc. But the formula proposed in the code is R = $5L_{wl}$ which is the maximum value R can take according to manoeuvring code (Veritas, 2011). The formula is therefore not conservative.

3. DEVELOPMENT OF A SECOND GENERATION IS CODE

The Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety 48th Session IMO (2005) emphasized the requirement of revising the current IS Code. The importance of the work on the comprehensive review of the current IS Code 2008 would significantly affect the design and ultimately enhance the safety of ships (Mata-Álvarez-Santullano & Souto-Iglesias, 2014).

Intact Stability is a crucial criterion that concerns most of naval architects in the design stage. The current Intact Stability (IS) Code 2008 is in force. Except for the weather criterion the IS Code 2008 only concerns the hydrostatics of the ship. It does not cover the seakeeping behaviour of the ship and first and foremost, it always considers a ship with negligible trim angle. In head seas, the ship can take some significant angle of trim which may affect the righting arm. Van Santen, 2009 also presents an example of a vessel capsizing because of the small angle of trim. For the enhancement and improvement of intact stability criteria, the International Maritime Organisation (IMO) introduced the new generation intact stability criteria in 2008 (Francescutto, 2007).

Figure 2 presents the procedure to apply to the second generation intact stability rule.

Once the basic criteria described in Section 2 have been satisfied, each failure mode is verified to satisfaction at the most conservative level.

The development of the second generation intact stability criteria focuses on five dynamical stability failure modes. Performing such a complete calculation of time-depending dynamical phenomena would require well-trained engineers as well as advanced tools (IMO, 2013a). The aim of level 1 is to devise a simple computational method, but the criteria are very conservative. Level 2 criteria are more realistic since wave shape is taken into account but the computation remains static. Level 3 involves seakeeping simulations.

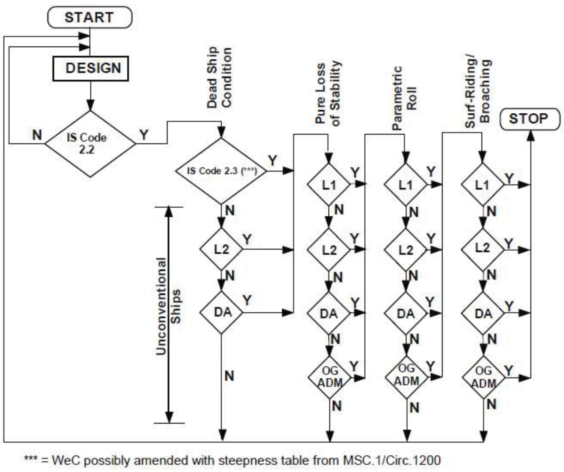


Figure 2 Structure of Second Generation Intact Stability Criteria IMO (2008)

The formula used in this paper is based on SDC1/INF.8 (IMO, 2013b). 1. Parametric rolling stability failure criteria mode as stated in SDC/1 INF.8 Annex 1 (submitted by correspondence group). 2. Pure loss of stability failure mode as stated in SDC/1 INF.8 Annex 2 (submitted by correspondence group). 3. Dead ship stability failure mode as stated in SDC/1 INF.8 Annex 16 (submitted by Italy and Japan). 4. Broaching stability failure mode as stated in SDC/1 INF.8 Annex 15 (submitted by United States and Japan).

3.1 Dead Ship Condition for Level 1

Based on SDC/1 INF.8 Annex 16, for level 1 vulnerability criteria for the dead ship stability failure mode, a ship is considered not to be vulnerable to the dead ship stability failure mode if:

$$b \geq a \qquad (3)$$

where a and b should be calculated according to the "Severe wind and rolling criterion (weather criterion)" in Part A – 2.3 of the Code12, and substituting the steepness factor s in Table 2.3.4-4 in Part A – 2.3, by the steepness factor s specified in Table 4.5.1 in MSC.1/Circ.1200.

3.2 Pure Loss of Stability for Level 1

Based on SDC/1 INF.8 Annex 2, for level 1 vulnerability criteria for the pure loss of stability failure mode, a ship is considered not to be vulnerable to the pure loss of stability failure mode if:

$$GM_{min} > R_{PLA} \qquad (4)$$

where R_{PLA} = [min(1,83 d (Fn)2, 0.05]m and GM_{min} = the minimum value of the metacentric height [on level trim and without taking free surface effects into consideration] as a longitudinal wave passes the ship calculated as provided in 2.10.2.2 (ref SDC/1 INF.8 Annex 2),or

$$GM_{min} = KB + I_L/V - KG \qquad (5)$$

only if $[(V_D - V)/A_W\ (D\text{-}d)] \geq 1.0$ (6)

d = draft corresponding to the loading condition under consideration; I_L = moment of inertia of the waterplane at the draft d_L;

$$d_L = d - \delta d_L \qquad (7)$$

KB = height of the vertical centre of buoyancy corresponding to the loading condition under consideration; KG = height of the vertical centre of gravity corresponding to the loading condition under consideration; V = volume of displacement corresponding to the loading condition under consideration;

$[\delta d_L = \min(d - 0.25 d_{full}, (L.S_W/2)]$ (8)

S_W= 0.0334, D = Depth, V_D= volume of displacement at waterline equal to D, A_W= waterplane area of the draft equal to d.

3.3 Parametric Rolling for Level 1

Based on SDC/1 INF.8 Annex 1 for level 1 vulnerability criteria for the parametric rolling failure mode, a ship is considered not to be vulnerable to the parametric roll failure mode if:

$$\Delta GM/ GM > R_{PR} \quad (9)$$

$$\Delta GM = (I_H - I_L)/2V \quad (10)$$

where ΔGM = amplitude of the variation of the metacentric height when a longitudinal wave passes the ship, GM = metacentric height, R_{PR}= 0.5, I_H = moment inertia of the waterplane at the draft d_H, I_L= moment inertia of the waterplane at the draft d_L,and V = volume of displacement corresponding to the loading condition under consideration.

3.4 Surf-riding/Broaching for Level 1

Based on SDC/1 INF.8 Annex 15 for level 1 vulnerability criterion for the surf-riding (Spyrou, Themelis, & Kontolefas, 2013)/broaching stability failure mode, a ship is considered not to be vulnerable to the broaching stability failure mode if:

$$F_n < 0.3 \text{ or } L_{BP} > 200\text{m} \quad (11)$$

where $F_n = V_{max}/ (L_{BP}.g)^{0.5}$, V_{max} = maximum service speed in calm water (m/s), L_{BP} = the length between perpendicular (m), and g = gravitational acceleration (m/s).

4. PROPOSAL FOR EXPERIMENTAL WORK ON WEATHER CRITERIA

The highest level criterion for the second generation intact stability code is the direct stability assessment using a time-domain numerical simulation. The tools should be validated by experimental results. The guideline of direct stability assessment was produced at the initiative of the United States and Japan as in SDC1/INF.8 in Annex 27(IMO, 2013b).

Recent experiments carried out by Umeda and his research members (Umeda et al., 2014) presented during the ISSW 2014 provide examples of comparisons between model experiments and numerical simulations for stability under dead ship condition and for pure loss of stability in astern waves. The experiment using a model 1/70 CEHIPAR2792 vessel was conducted in a seakeeping and manoeuvring basin. A wind blower consisting of axial flow fans and controlled by inverters with a v/f control law was used to provide the wind input. The experimental setup is shown in Figure 3 and 4. They concluded that for the dead ship condition, an adequate selection of representative wind velocities generated by wind fans is crucial and for the pure loss of stability, an accurate Fourier transform and the reverse transformation of incident irregular waves are important.

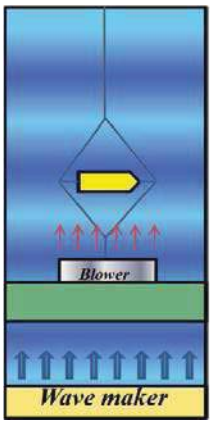


Figure 3 Overview of experimental setup (Umeda et al., 2014).

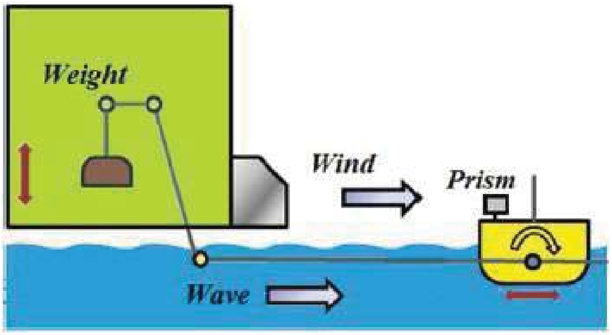


Figure 4 Lateral view of experimental setup (Umeda et al., 2014).

An experimental study will be carried out at the Low-Speed Wind Tunnel of the Aeronautics Laboratory at the University Teknologi Malaysia in 2016. The aim of the study is to validate the weather criterion in the IS Code 2008 using the wind tunnel results. For the dead ship condition, the study will consist of two layered vulnerability criteria and a direct assessment of each failure mode and a ship is requested to comply with at least one of them. This is because the use of expensive numerical simulations for a direct assessment should be minimised in order to realise a feasible application of the new scheme. It is also essential that the numerical simulations used for the direct assessment should be validated by physical model experiments (Kubo, Umeda, Izawa, & Matsuda, 2012).

4.1 Wind Tunnel Specifications

This wind tunnel has a test section of 2 m (width) x 1.5 m (height) x 5.8 m (length). The maximum test velocity is 80m/s (160 knots or 288 km/h). The wind tunnel has a flow uniformity of less than 0.15%, a temperature uniformity of less than 0.2˚C, a flow angularity uniformity of less than 0.15˚ and a turbulence level of less than 0.06% (Mansor, 2008).

The wind tunnel is equipped with a six component balance for load measurements. The balance is a pyramid type with the virtual balance moment at the centre of the test section. The balance has the capacity to measure the aerodynamic forces and moments in 3-D. The aerodynamic loads can be tested as a function of the various wind directions by rotating the model using the turntable. The accuracy of the balance is within 0.04% based on 1 standard deviation. The maximum load range is ±1200N for axial and side loads. It also has the capacity to measure surface pressure using electronic pressure scanners. The balance load range for the wind tunnel is presented in Table 1.

5. STABILITY EVALUATION

A naval ship is used for the stability calculation. The ship is a patrol vessel (Ariffin, 2014) with a cruising speed of 12 knots, and a maximum speed of 22 knots. Its overall length is 91.1 metres, the design draft is 3.4 metres and the maximum draft is 3.6 metres for a displacement of 1800 tons. Finally the vessel's block coefficient, Cb, is 0.448 and the prismatic coefficient, Cp, is 0.695.

The body plan of the ship is shown in Figure 4.

Load Component and Accuracy	Type of balance		
	External	Semi-span	Internal
Axial force, Fx (N)	± 1200	± 900	± 182
Side force, Fy (N)	± 1200	± 900	± 356
Normal force, Fz (N)	± 1200	± 4500	± 445
Roll moment, Mx (Nm)	± 450	± 1362	± 7
Pitch moment, My (Nm)	± 450	± 250	± 62
Yaw moment, Mz (Nm)	± 450	± 450	± 50
Primary accuracy, % (based on ± 1 standard deviation)	0.04	0.04	<0.10

Table 1 Balance load range (Noor & Mansor, 2013)

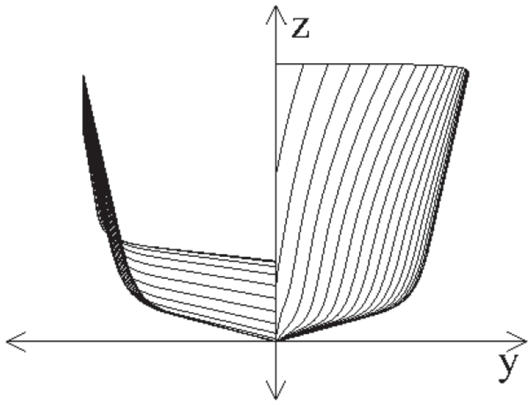


Figure 4 Body plan of the vessel

The level calculations in the present paper are based on a formula in SDC 1/INF.8. Only criteria for level 1 were verified. The results were obtained using the GHS software for the level 1 verification of pure loss of stability and parametric rolling. The VCG for the vessel was varied from 3.0 to 7.0 meters for analysis purposes. Direct calculation was used for the dead ship condition and the surf-riding/broaching.

5.1 Dead Ship Condition for Level 1

Based on SDC/1 INF.8 Annex 16, proposed by Italy and Japan, the steepness factor, s in Part A – 2.3 Table 2.3.4-4 was changed to the steepness factor s in Table 4.5.1 in MSC.1/Circ.1200. In GHS, the steepness factor is defined by $s = 0.0992364 + 0.0058416T - 0.0011127T^2 + 0.0000331T^3$ with $0.035 \leq s \leq 0.1$. Table 4.5.1 in MSC.1/Circ.1200 is the extension of Table 2.3.4.4. The graft of steepness factor, s vs roll period, T in Table 4.5.1 can be computed with the 5th order polynomial $s = 0.016 + 0.0385T - 0.0058T^2 + 0.0003T^3 - 0.000009T^4 + 0.00000009T^5$ with $0.02 \leq s \leq 0.1$.

The vessel passed the level 1 dead ship condition using the proposed amended criteria.

5.2 Pure Loss of Stability for Level 1

As in SDC/1 INF.8 Annex 2, the GM_{min} is calculated based on a range of VCG from 3 to 7m. The result shows that the change of VCG will affect the GM_{min} significantly. With the increment of VCG, the max VCG to pass the IS Code 2008 is 5.46 m and the max. VCG to pass the level 1 pure loss of stability is 6.6 m. The result is shown in Figure 5.

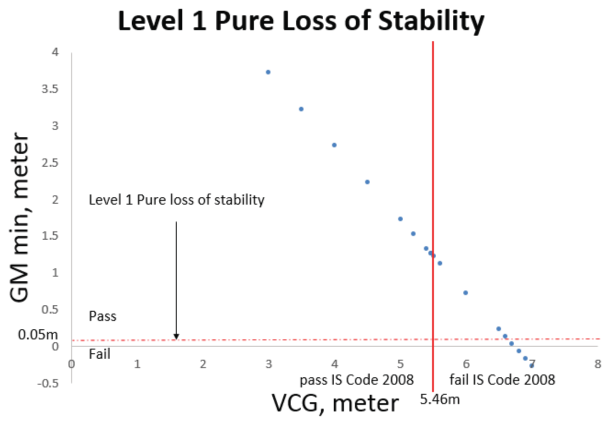


Figure 5 Result of Level 1 Pure loss of stability

It appears that the level 1 pure loss of stability criterion is less restrictive than the existing IS Code 2008 for conventional ships.

5.3 Parametric Rolling for Level 1

The ΔGM/GM is calculated based on a range of VCG from 3 to 7 m in SDC/1 INF.8 Annex 1. The result shows that the change of VCG affects the ΔGM/GM significantly. With the increment of VCG, the max VCG to pass the IS Code 2008 is 5.46 m and the max. VCG to pass the level 1 pure loss of stability is 5.56 m. The results are shown in Figure 6.

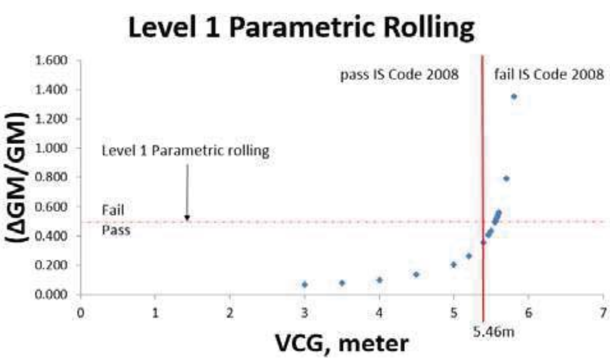


Figure 6 Result of Level 1 Parametric rolling

In this case, the level 1 parametric rolling criterion is less restrictive than the IS Code 2008.

5.4 Surf-riding/Broaching for Level 1

In SDC/1 INF.8 Annex 12, proposed by United Stated and Japan, the criterion is based on ship dimension and maximum speed. The vessel is tested with various speeds. The results show that the maximum speed (22 knots) is vulnerable to broaching and the cruising speed (12 knots) is not vulnerable to broaching. The results are shown in Figure 7. The maximum speed at which the ship is not vulnerable to broaching is 17.4 knots.

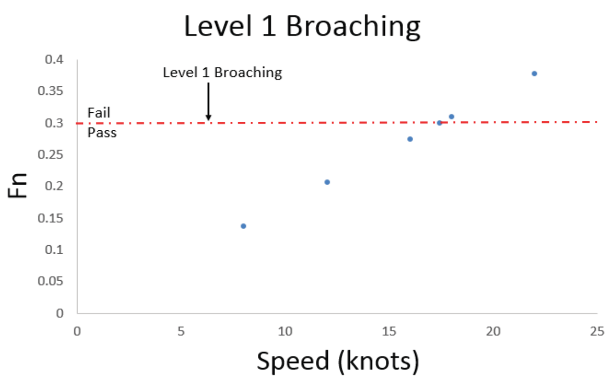


Figure 7 Result of Level 1 Broaching

6. DISCUSSION

The patrol boat whose body plan is presented in Figure 4, passes the level 1 criteria for the dead ship condition, the pure loss of stability and the parametric rolling. But it failed to meet the criteria for broaching at maximum speed.

The GHS© code can currently handle the level 1 verification for pure loss of stability, and parametric rolling. The level 1 verification for broaching does not require GHS© output. The level 1 verification for dead ship condition requires a change of the wave steepness value, s whereas the current code has a range of $0.035 \le s \le 0.1$ but the proposed change for level 1 broaching required a range of $0.02 \le s \le 0.1$.

7. CONCLUSIONS

This paper presents the results for a naval ship for a level 1 verification based on a proposed change of second generation intact stability criteria as outlined in the current state of development by the International Maritime Organisation (IMO).

The vessel which already complied with the existing IS Code 2008, easily passes the level 1 criteria for pure loss of stability and parametric rolling but does not meet the broaching criterion at maximum speed.

The dead ship condition is based on weather criteria and there is no proposed change to the current regulations except for the wave steepness value. The wind tunnel experimental facility will be used to investigate the possibility of proposing some new or amended rules for the weather criterion.

8. ACKNOWLEDGEMENT

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