Designing New Generation Intact Stability Criteria on Broaching Associated with Surf-Riding

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ABSTRACT

This paper describes a proposal of new generation intact stability criteria on broaching associated with surf-riding for contributing to discussion at the IMO (International Maritime Organization). It consists of two-layered vulnerability criterion and direct assessment procedures. The first layer vulnerability criterion indicates critical ship speed for avoiding surf-riding in following regular waves, which is determined with sample calculation results of several ships using numerical global bifurcation analyses. Under certain wave conditions, a ship is required to reduce her speed below this critical speed. Alternatively, the ship may use the result of numerical or analytical bifurcation analysis with her own geometric and hydrodynamic data as the critical speed in the use of operational guidance. This is the second layer vulnerability criterion. If the ship fails to comply with both the vulnerability criteria, the direct assessment procedure is applied to her. It requires the failure probability due to broaching associated with surf-riding in the North Atlantic is smaller than the acceptable level. Here the probability is calculated using the combination of deterministic ship dynamics and probabilistic wave theory. If the ship fails it, the failure probabilities for stationary sea states are required to be noted in her ship stability booklet as an onboard operational guidance. For demonstrating feasibility of these criteria, sample calculation results with a fishing vessel and a RoPax ship are shown and impact on design aspects are also investigated.

KEYWORDS

Surf-ring threshold; global bifurcation; broaching probability; operational guidance; rudder size.

INTRODUCTION

At the IMO, new generation intact stability criteria on major capsizing modes are now under development. Broaching associated with surf-riding is one of these major capsizing modes. It was already agreed that the new criteria should be physics-based, consist of vulnerability criteria and direct stability assessment and be supplemented with operational guidance (IMO, 2008). Here the vulnerability criteria could consist of two levels: one shall be simpler but with larger margin and the other shall be more complex but with less conservative (IMO, 2010). The delegation of Japan (2009) submitted the draft criteria on broaching to the 52nd session of the Sub-Committee on Stability, Load lines and on Fishing Vessel Safety (SLF) of the IMO via the ISCG (Intersessional Correspondence Group on Intact Stability) with sample calculation results last year. In the draft vulnerability criteria here, the calm-water Froude number is requested to be smaller than the threshold of surf-riding in regular following waves, which can be regarded as a heteroclinic bifurcation of uncoupled surge model. For the level 1 vulnerability criterion, the surf-riding threshold is empirically determined to be 0.3 as the current operational guidance known as MSC.1/Circ. 1228 (Japan, 1991). For the level 2 vulnerability criterion, it is required to be directly calculated by a numerical or analytical bifurcation analysis (Umeda et al., 2007b) (Maki et al., 2010) together with a comparison of wave-induced and rudder-induced yaw moment. (Yamamura et al., 2009) For the direct stability assessment, a method based on combination of deterministic simulation and probabilistic wave theory is recommended (Umeda et al., 2007a). If the ship can comply with one of the above-mentioned three criteria, it can be regarded as safe within the scheme of the draft proposal in Japan.

At the SLF 52 this January, some delegations expressed their concern that the draft level 1 criterion could penalise all ships having the calm-water Froude number of 0.3 or over and then recommended to consider the ship size. The delegation of IACS (International Association of Classification Societies) is of the opinion that the use of direct stability assessment should be exceptional so that feasibility of vulnerability criteria is essential. And the deadline for proposing new criteria is set to be June 2010 at the IMO. Therefore, drafting a new generation intact stability criteria on broaching associated with surf-riding is an urgent task for member states of the IMO.

Recognising these situations, the authors attempt to contribute to this further development of new generation intact stability criteria on broaching associated with surf-riding. As a whole, it is recommended that new criteria shall be supplemented with ship-dependent operational guidance at each level. Firstly, a new draft level 1 criterion is proposed with hull form effect taken into account. Secondly, a new draft level 2 criterion is developed with effect of ship size taken into account. Here the mutual relationship between the level 2 and the direct stability assessment is carefully adjusted. Finally, a design impact of the direct stability assessment based on the combination of determinstic ship dynamics and probabilistic wave theory is remarked with a sample calculation.

LEVEL 1 VULNERABILITY CRITERION

Background

For broaching, estimation of surf-riding threshold in regular following waves could be used as a vulnerability criterion. This is because the surf-riding is a prerequisite for broaching. In addition, broaching without surf-riding can be generally avoided with appropriate operational efforts such as a differential control (Spyrou, 1997) and an optimal control (Maki & Umeda, 2009).

In the operational guidance, MSC.1/Circ. 1228, surf-riding threshold is assumed to be the calm-water Froude number of 0.3 for all ships. This is based on phase plane analyses of uncoupled surge model in regular following waves with the wave steepness of 0.1 for conventional ships. Theoretically this surf-riding threshold depends on mainly calm-water resistance and the Froude-Krylov surge force. It was recently reported, however, the surf-riding threshold could be smaller than the calm-water Froude number of 0.3 for finer ships. Thus it is important to develop a simple formula to empirically estimate surf-riding threshold as a function of hull form.

Proposal Based on Sample Calculations

For determining the surf-riding threshold, a numerical global bifurcation analysis is applied to several ships. Since surf-riding can be regarded as an equilibrium of the uncoupled surge model defined with a wave-fixed inertia system, a heteroclinic orbit represents a periodic orbit having infinite period. Here the heteroclinic bifurcation point, in which the unstable invariant manifold of a saddle-type equilibrium coincides with the stable invariant manifold of a different saddle-type equilibrium, is identified by the Newton method. (Umeda et al., 2007) The subject ships used here include a RoRo ship, a post Panamax containership, two high-speed slender ships and three fishing vessels. Here their calm-water resistance curves are estimated with conventional model tests and the wave-induced surge force is calculated with the Froude-Krylov assumption. The wave steepness is set to be 1/10 as the current operational guidance and the wavelength is the worst cases in the range of the wavelength to ship length ratio from 1.0 to 2.0. The calculated results are plotted in Fig. 1 as a function of the prismatic coefficient. When the ship becomes finer, the critical speed for surf-riding becomes smaller. This is because the clam-water resistance depends on the prismatic coefficient as shown in Fig. 2. If the prismatic coefficient is small, the calm-water resistance does not increase very much even at higher forward speed. As a result, surf-riding can be more easily realised. Based on these results, an empirical formula is obtained as follows:

$$Fn = 0.28C_p + 0.096 \qquad (1)$$

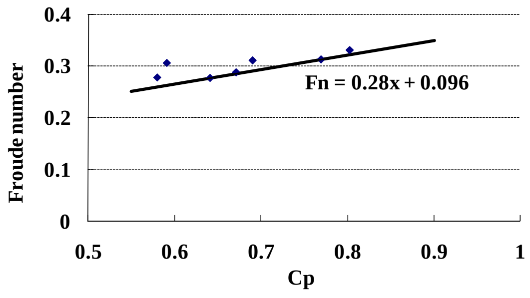


Fig. 1 Surf-riding threshold for the sample ships as a function of the prismatic coefficient (C_p) with the wave steepness of 0.1 and the worst wavelength.

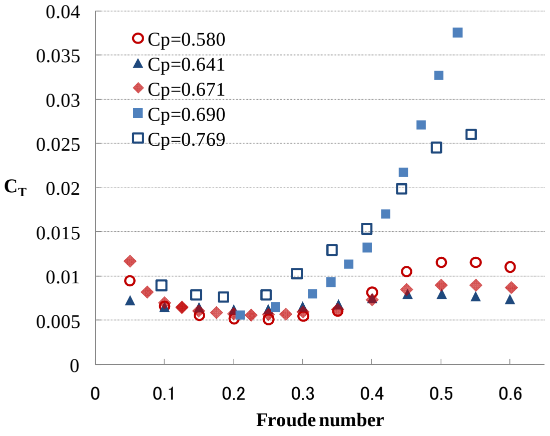


Fig. 2 Calm-water total resistance coefficient (C_T) curves for the sample ships.

This formula can be recommended as the level 1 vulnerability criterion in place of the calm-water Froude number of 0.3. This means that if the operational calm-water Froude number is larger than the value specified by Eq. (1), the ship has a potential danger of surf-riding. In other words, if the nominal speed is reduced to that below this critical value, no danger exists. Thus, it is also recommended to use the Eq. (1) in the operational guidance.

LEVEL 2 VULNERABILITY CRITERION

The level 1 vulnerability criterion is sufficiently simple so that its use for all SOLAS and LL ships seems to be feasible. For unconventional ships, however, this empirical estimation could be conservative because application of wave resistance theory could realise the smaller resistance only at the design speed so that the calm-water resistance could be larger outside the design point. Thus it is useful to allow direct use of global bifurcation analysis as the level 2 criterion. Currently other than the numerical global bifurcation analysis, analytical bifurcation analyses based on the Melnikov approach and piece-wise linear approach are available and well validated with numerical and experimental methods (Maki et al., 2010). These methods can be easily applied to any ships if the calm-water resistance and the propeller thrust can be estimated in advance. At this stage it is important to specify the wave steepness for this calculation. This issue will be revisited with the calculation results of the direct stability assessment later.

DIRECT STABILITY ASSESSMENT (LEVEL 3)

For the direct stability assessment, the combination of deterministic ship dynamics and the probabilistic wave theory can be recommended because the Monte Carlo simulation of ship behaviours in irregular waves requires prohibitively large amount of computations because of very small failure probability and so many operational cases. Umeda et al. (2007a) already proposed a method and well validated it with the Monte Carlo simulation. Firstly, using a numerical simulation code of the surge-sway-yaw-roll model in the time domain with a PD autopilot, the deterministic dangerous zone of stability failure due to broaching is obtained in various regular waves with a wide range of wave steepness and length. Secondly, failure probability due to broaching in irregular waves is calculated using the deterministic dangerous zone together with Longuet-Higgins' probabilistic wave theory (Longuet-Higgins, 1983). Finally if the calculated failure probability per hour in the North Atlantic is smaller than the acceptable value, e.g. 10^{-6}, the ship is judged as safe. Here the wave statistics, as a joint probability density of the significant wave height and mean wave period, in the North Atlantic is required. One of the examples is shown in Fig. 3 for a RoRo ship of 187.7 metres in length. In the current proposal, if the ship fails to comply with this level 3 criterion, it is required to provide the failure probability presented as a function of the significant wave height and mean wave period as shown in Fig. 4 for the ship master in the stability booklet. If the probability is high enough for the relevant sea state, the master is recommended to reduce the propeller revolution.

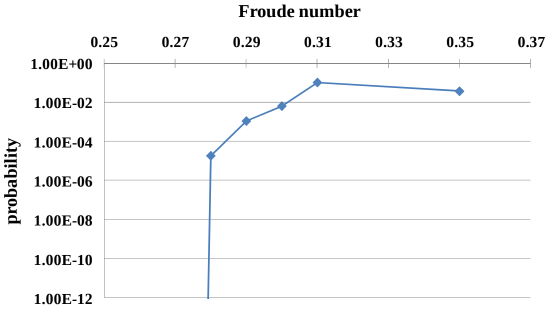
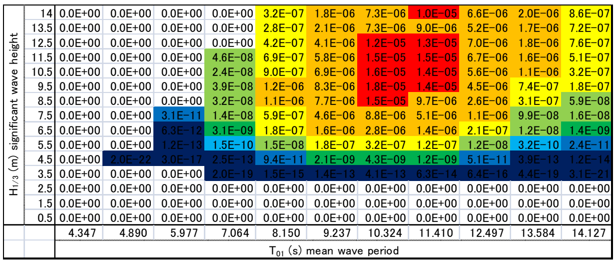


Fig. 3 Calculated stability failure probability per hour for the RoRo ship in the North Atlantic without any operational limitation.



$H_{1/3}$ (m) significant wave height											
14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.2E-07	1.8E-06	7.3E-06	1.0E-05	6.6E-06	2.0E-06	8.6E-07
13.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.8E-07	2.1E-06	7.3E-06	9.0E-06	5.2E-06	1.7E-06	7.2E-07
12.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.2E-07	4.1E-06	1.2E-05	1.3E-05	7.0E-06	1.8E-06	7.6E-07
11.5	0.0E+00	0.0E+00	0.0E+00	4.6E-08	6.9E-07	5.8E-06	1.5E-05	1.5E-05	6.7E-06	1.6E-06	5.1E-07
10.5	0.0E+00	0.0E+00	0.0E+00	2.4E-08	9.0E-07	6.9E-06	1.6E-05	1.4E-05	5.6E-06	1.1E-06	3.2E-07
9.5	0.0E+00	0.0E+00	0.0E+00	3.9E-08	1.2E-06	8.3E-06	1.8E-05	1.4E-05	4.5E-06	7.4E-07	1.8E-07
8.5	0.0E+00	0.0E+00	0.0E+00	3.2E-08	1.1E-06	7.7E-06	1.5E-05	9.7E-06	2.6E-06	3.1E-07	5.9E-08
7.5	0.0E+00	0.0E+00	3.1E-11	1.4E-08	5.9E-07	4.6E-06	8.8E-06	5.1E-06	1.1E-06	9.9E-08	1.6E-08
6.5	0.0E+00	0.0E+00	6.3E-12	3.1E-09	1.8E-07	1.6E-06	2.8E-06	1.4E-06	2.1E-07	1.2E-08	1.4E-09
5.5	0.0E+00	0.0E+00	1.2E-13	1.5E-10	1.5E-08	1.8E-07	3.2E-07	1.2E-07	1.2E-08	3.2E-10	2.4E-11
4.5	0.0E+00	2.0E-22	3.0E-17	2.5E-13	9.4E-11	2.1E-09	4.3E-09	1.2E-09	5.1E-11	3.9E-13	1.2E-14
3.5	0.0E+00	0.0E+00	0.0E+00	2.0E-19	1.5E-15	1.4E-13	4.1E-13	6.3E-14	6.4E-16	4.4E-19	3.1E-21
2.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
1.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	4.347	4.890	5.977	7.064	8.150	9.237	10.324	11.410	12.497	13.584	14.127
	T_{01} (s) mean wave period										

Fig. 4 Probability of stability failure per hour for the various sea states for the RoRo ship with the nominal Froude number of 0.3 in the North Atlantic.

ADJUSTING RELATIONSHIP BETWEEN LEVELS 2 AND 3

For making the relationship between the levels 2 and 3 criteria appropriate, it might be reasonable to determine the wave steepness of the “equivalent” regular wave used in the level 2 criterion using the results of level 3 for sample ships. At this stage the safety level of level 2 could be comparable to that of the level 3. In this proposal, length of sample ships ranging 35 metres to 300 metres and the calculation of the level 3 is executed with the wave statistics truncated with the operational guidance. When the significant wave height is larger than 4 per cent of the ship length, the current operational guidance requires the master to reduce the speed below the surf-riding threshold in regular waves so that the dangers in this wave height or over is ignored in the calculation of the level 3 for the ship length of 100 metres or below.

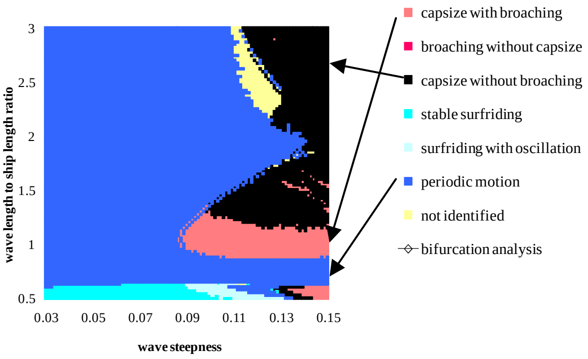


Fig. 5 Deterministic dangerous zone for stability failure due to broaching for the RoRo ship with the nominal Froude number of 0.29 and the rudder gain of 1.0

The subject hull forms used here are a 34.5 metres-long fishing vessel known as the ITTC A2 ship and a 187.7 metres-long RoRo ship. The deterministic failure zone for the RoRo ship is shown in Fig. 5. Critical region for broaching exists in the wavelength to ship length ratio from 1 to 1.5, which are surrounded by global bifurcation lines.

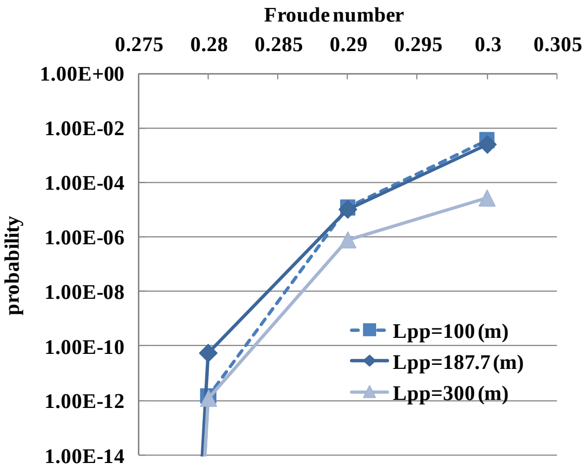


Fig. 6 Calculated stability failure probabilities per hour for the RoRo ships having different lengths in the North Atlantic with operational limitation.

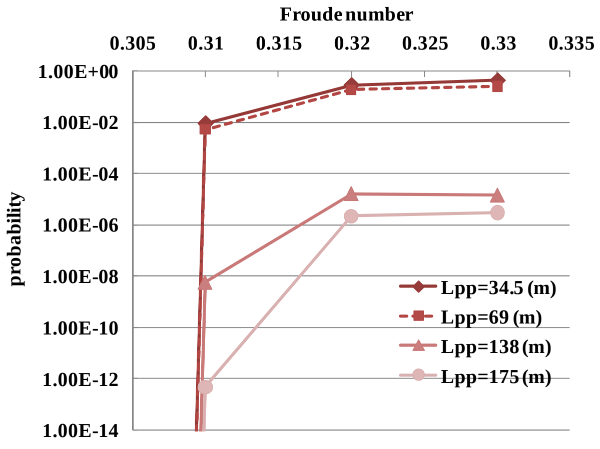


Fig. 7 Calculated stability failure probabilities per hour for the ITTC A2 ships having different lengths in the North Atlantic with operational limitation.

Then the lengths of these ships are systematically changed keeping their geometry for the failure probability calculation. The results shown in Figs. 6-7 indicate that failure probability increases with the calm-water Froude number and longer ships are generally safer. However, it is noteworthy here that the probability of stability failure due to broaching is not negligibly small even for a ship having her length of 300 metres.

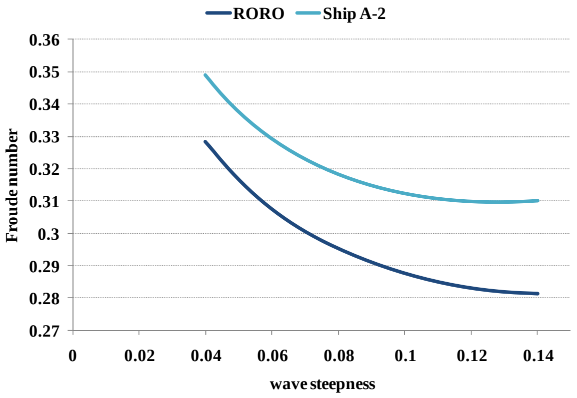


Fig. 8 Deterministic surf-riding threshold for the RoRo ship and the ITTC A2 Ship.

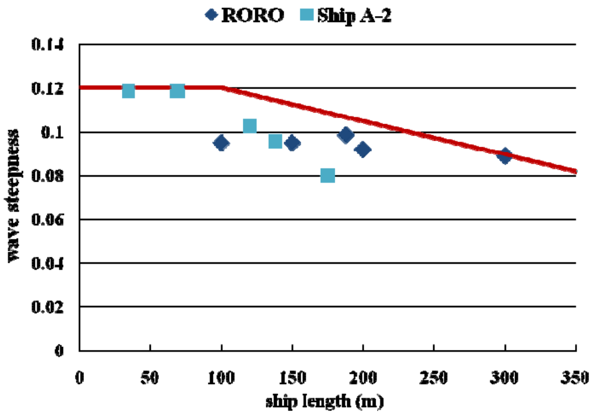


Fig. 9 Equivalent wave steepness for the level 2 vulnerability criterion

The global bifurcation analysis proposed for the level 2 is applied to these two hull forms so that their deterministic surf-riding thresholds, which are normalised with the ship lengths, are obtained as Fig. 8. Here the wavelengths are set to be the worst cases. If the acceptable probability is 10^{-6}, Fig. 6 suggests the critical Froude number for the 300 metres-long RoRo ship is 0.29 so that Fig. 8 indicates the equivalent wave steepness is about 0.09. Repeating this procedure for various ships, the relationship between the equivalent wave steepness ad the ship length is obtained in Fig. 9. This result suggests that effect of ship length on the equivalent wave steepness is significant but effect of hull form is not so. Thus, the following formula for determining the equivalent wave steepness can be recommended:

$$
\begin{aligned}
H/\lambda &= 0.12 & L_{pp} &< 100m \\
&= -0.000152L_{pp} + 0.1352 & L_{pp} &> 100m
\end{aligned}
\tag{2}
$$

In conclusion, if the equivalent wave steepness is determined with Eq. (2), the safety level of the level 2 criterion is comparable to that of the level 3.

DESIGN IMPACT OF DIRECT STABILITY ASSESSMENT

It was already demonstrated that the direct stability assessment is useful for a ship-dependent operational guidance. Obviously this assessment is useful also for ship design. This is because this assessment provides an opportunity for the ship owners to distinguish a safer design. For example, it is possible to evaluate the effect of rudder size on safety against broaching. The direct stability assessment technique is applied to both the RoRo ship having original rudder and that with double sized rudder. The results shown in Figs. 10-11 demonstrated that double sized rudder can exempt the use of operational guidance so that the increase of rudder size is highly recommended in this case.

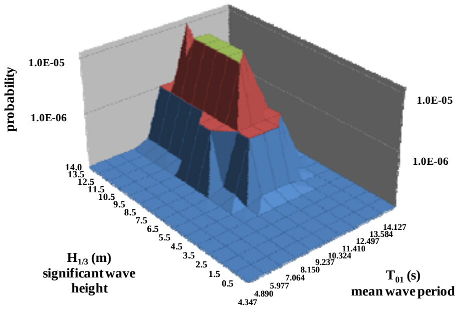


Fig. 10 Probability of stability failure for various sea states for the RoRo ship in the Northern Atlantic with the designed rudder.

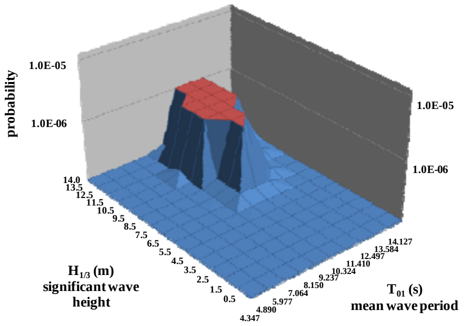


Fig. 11 Probability of stability failure for various sea states for the RoRo ship in the Northern Atlantic with the double-sized rudder.

CONCLUDING REMARKS

The proposed new generation intact stability criteria on broaching associated with surf-riding is summarised below (See also Fig. 12):

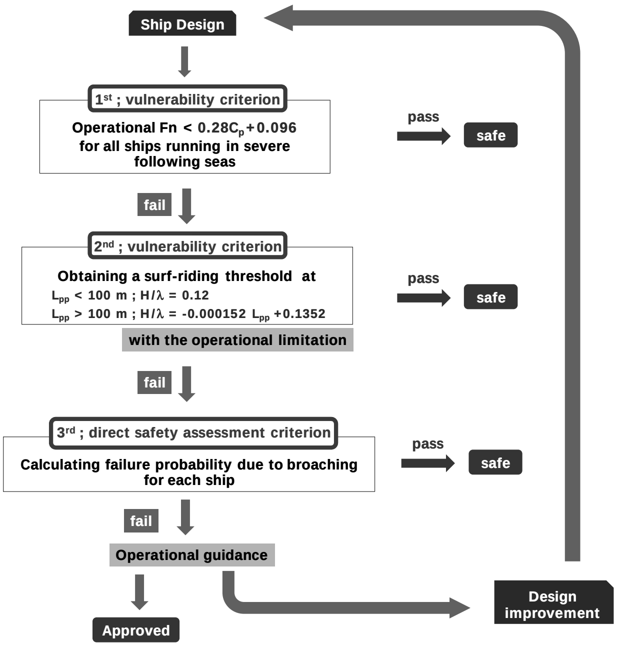


Fig. 12 Structure of newly proposed criteria

- The ship is requested to be operated with the operational speed below the empirical surf-riding threshold as a function of the prismatic coefficient. (Level 1 vulnerability criterion)
- If the ship fails to comply with the above, the ship is requested to be operated with the operational speed below the deterministic surf-riding threshold directly calculated by a numerical or analytical global bifurcation for the specified wave steepness which is a function of the ship length. (Level 2 vulnerability criterion)
- If the ship fails to both the above, stability failure probability in the North Atlantic is required to be calculated by the combination of deterministic ship dynamics and probabilistic wave theory. These results are requested to be supplied to the ship master for identifying the dangerous operational sea states.

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