FINALIZATION OF SECOND GENERATION INTACT STABILITY CRITERIA
DRAFT INTERIM GUIDELINES FOR DIRECT STABILITY ASSESSMENT

Submitted by Germany to Correspondence Group on Intact Stability

BACKGROUND

1 The Sub-Committee, at its fifth session, re-established the Correspondence Group on Intact Stability, under the coordination of Japan.

2 The group was instructed to finalize, in their essential aspects, the Interim Guidelines for direct stability assessment, based on document SDC 4/WP.4 and considering the comments made and decisions taken at SDC 5 (ref. document SDC 5/15, paragraph 6.15.1), in particular, to

.1 provide definition of stability failure, including heel angle and lateral acceleration, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7;

.2 identify and select specific direct stability assessment procedures, in particular, environment (scatter table or design sea states), wave directions and ship speeds, and evaluated criteria (failure rate or other measures), taking into account documents SDC 5/6/3, SDC 5/6/9, SDC 5/6/13 and SDC 5/INF.7;

.3 provide the design scenarios, including sea states, wave directions and ship speeds for all failure modes, if relevant, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7;

.4 provide general descriptions of selected direct stability assessment procedures, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7; and

.5 provide interim acceptance standards, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7.

Proposal of revised draft interim guidelines for direct stability assessment

3 In the Annex to this document Germany submits a revised draft of the interim guidelines for direct stability assessment, based on the document SDC 4/WP.4 and the comments made and decisions taken at SDC 5, for further discussion and finalization by the distinguished delegations. In particular, addressing the terms of reference in the paragraph 2,

.1 definition of stability failure is proposed, including heel angle and lateral acceleration, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7 and harmonised with the proposal for draft interim guidelines for operational measures submitted by Germany earlier;

.2 direct stability assessment procedures are proposed, which are based on two alternative environments (full scatter table and design sea states) and employ stability failure mode-specific design situations and two alternative types of evaluated criteria (probabilistic and non-probabilistic), taking into account documents SDC 5/6/3, SDC 5/6/9, SDC 5/6/13 and SDC 5/INF.7;

.3 detailed design scenarios (sea states, wave directions and ship speeds) are provided for all failure modes excluding surf-riding/broaching, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7;

.4 descriptions of direct stability assessment procedures are provided, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7; and

.5 interim acceptance standards are proposed, taking into account documents SDC 5/6, SDC 5/6/9, SDC 5/INF.4 and SDC 5/INF.7, as well as documents MSC 83/INF.8, MSC 83/INF.3, MEPC 58/INF.2, MSC 85/INF.2, MSC 85/INF.3 and MSC 88/INF.8.

4 This submission includes the following elements:

.1 Annex, containing the proposal for the revised text of draft interim guidelines for direct stability assessment. In this text, the proposed changes are underlined. Note that addition of new elements has required also some restructuring of the existing text from the document SDC 4/WP.4; changes related to the restructuring are not highlighted;

.2 Appendix, which is not a part of the Guidelines, containing background information based on the results of a research project conducted in Germany. Compared to the last submission of this background information to the Correspondence group, this document was substantially updated, extended and rewritten, therefore, changes are not highlighted.

Discussion items

5 The aim of this submission is to provide a consolidated version as a starting point for further discussions and finalisation of the Guidelines.

6 Germany would like to draw attention to some topics for which an early discussion would be helpful, which are listed below together with the position of Germany to these topics for information.

.1 definition of the failure mode-specific design situations is based on direct assessment results for several ships, none of which is typical with respect to the pure loss of stability and surf-riding/broaching failure modes; therefore, whereas selection of wave directions and ship speeds for design situations concerning these failure modes seems straightforward, selection of the wave period requires further assessment results;

.2 during the discussions and finalisation of these Guidelines, it should be kept in mind that the criteria, procedures and standards should remain harmonised with those in the Guidelines for operational measures;

.3 regarding the selection of loading conditions for direct assessment, Germany suggests that

  .1 selection of loading conditions should not be part of these Guidelines, as well as Guidelines for vulnerability assessment and Guidelines for operational measures, noting that selection of loading conditions is not addressed in the 2008 IS Code;

  .2 if the selection of loading conditions needs to be addressed, it is more efficient to not handle it separately in the Guidelines for direct stability assessment, Guidelines for vulnerability assessment and Guidelines for operational measures since harmonisation will require many revisions involving many people;

.3 instead of this, the Guidelines for direct stability assessment, Guidelines for vulnerability assessment and Guidelines for operational measures should relate to any one loading condition, whereas the selection of loading conditions and combination of different levels of design assessment and operational measures should be handled in a small dedicated Guideline; and

.4 therefore, section 6.2 Loading conditions should be taken out of these Guidelines;

.4 section 5.4, concerning approval of software by the Administration, should be removed, since Administrations presently do not certify software used for demonstration of compliance, do not have the necessary control infrastructure and perform approval by independent verification of the results, independently from the software used in design (which also reveals possible user errors);

.5 referring to section 6.5 of these Guidelines, we see it difficult for Administrations to verify extrapolation procedures. We propose to include in the first release of these Guidelines only already validated and applied extrapolation procedures, together with a detailed description of their application. Because of time restrictions, the missing elements (application examples, validation and descriptions) need to be provided during this intersessional period to be finalised at the expert group meeting at SDC 6;

.6 concerning the requirements to the accuracy of numerical methods, note that:

.1 using unspecific relative errors means that, for example, a difference between 1 degree In computations and 1.5 degrees in measurements of roll amplitude would be unacceptable. We propose to reformulate the accuracy requirements to consider the maximum (e.g. over encounter frequency) response;

.2 for regulatory purposes, it is not necessary to limit conservative errors, e.g. overprediction of roll motions, therefore, only under-prediction should be limited;

.3 in the Annex, a revised text is proposed realising these suggestions.

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ANNEX

DRAFT INTERIM GUIDELINES FOR DIRECT STABILITY ASSESSMENT PROCEDURES FOR USE WITH THE SECOND GENERATION INTACT STABILITY CRITERIA

1 Objective

1.1 These Guidelines provide specifications for direct stability assessment procedures for the following stability failure modes:

.1 pure loss of stability;

.2 parametric roll;

.3 surf-riding/broaching;

.4 dead ship condition; and

.5 excessive acceleration~~s~~.

1.2 The criteria, procedures and standards recommended in these Guidelines ensure a safety level corresponding to the average stability failure rate not exceeding ~~[10^{-4}]~~ [$2.6 \cdot 10^{-3}$] per ship per year.

2 Nomenclature and definitions

2.1 The following nomenclature is used in these Guidelines:

Symbol	Unit	Definition
d	m	mean draught of ship
GM	m	metacentric height of ship
h_r	m	height of considered location above assumed roll axis
h_s	m	significant wave height
k_{xx}	m	dry roll radius of inertia with respect to centre of gravity
k_{yy}	m	dry pitch radius of inertia with respect to centre of gravity
k_{zz}	m	dry yaw radius of inertia with respect to centre of gravity
L_{pp}	m	length of ship between perpendiculars
N	-	number of simulations
f_s	$(m \cdot s)^{-1}$	joint probability density of sea state (probability of sea states per unit range of significant wave heights and mean zero-upcrossing periods)
r	1/s	rate of stability failures, i.e. mean number of stability failures per unit time
T	s	mean time to stability failure
T_r	s	linear natural roll period of ship in calm water
T_z	s	mean zero-upcrossing wave period
v_s	m/s	ship forward speed
φ	deg	roll angle (positive for starboard down)
μ	deg	mean wave direction with respect to ship centre plane: 0^o following waves, 90^o waves from starboard, 180^o head waves
θ	deg	trim angle of ship (positive for bow down)
ω_r	rad/s	linear natural roll frequency of ship

2.2 General definitions:

.1 *Loading condition* is the condition of loading of the ship, specified, in the scope of these Guidelines, by the mean draught d, trim θ, metacentric height GM and radii of inertia k_{xx}, k_{yy}, k_{zz};

.2 *Scatter table* is a table containing probabilities of each range of sea states encountered in the considered operational area or operational route; in these Guidelines, the probabilities contained in a full scatter table are defined to sum up to one;

.3 *Sea state* is the stationary condition of the free water surface and wind at a certain location and time, described in these Guidelines by the significant wave height h_s, mean zero-upcrossing wave period T_z, mean wave direction μ, wave energy spectrum S_{zz}, and mean wind speed, gustiness characteristics and direction;

.4 *Sailing condition* is a short notation for the combination of the ship forward speed v_s and mean wave direction μ with respect to the ship centre plane;

.5 *Situation* is a short notation for sailing condition in a sea state, thus, defined in these Guidelines by the ship forward speed v_s, mean wave direction μ with respect to the ship centre plane, significant wave height h_s, mean zero-upcrossing wave period T_z and mean speed and direction and gustiness characteristics of wind;

.6 *Design situation* is the situation that is used for direct stability assessment with respect to a particular stability failure mode.

3 Requirements

~~3.1 The criterion is the estimate of average rate of stability failure.~~

~~3.2 A ship in a given condition of loading is considered compliant with the requirements if the criterion does not exceed a standard~~ ~~S_{DSA} = [10^{-4} per ship year].~~

~~3.3 The average rate of stability failure is calculated as a weighted average over relevant sea states as defined in section 6.3.4. The weights are specific for a region or are global for unrestricted service.~~

3.1 Unless stricter requirements are deemed to be necessary for particular ships or ship types, the failure event is defined as

.1 *Exceedance of roll angle*, defined as the minimum of 40 degrees, angle of vanishing stability in calm water and angle of submergence of unprotected openings in calm water; or

.2 *Excessive of lateral acceleration* of [9.81] m/s^2.

3.2 To simplify the evaluation of motion criteria, instead of the requirement in paragraph 3.1.2, an equivalent maximum acceptable roll angle, defined as $57.3/(1+h_r\omega_r^2/9.81)$, in degree, can be used. For this calculation, the roll axis can be assumed at the midpoint between the waterline and the centre of gravity of the ship.

3.3 Active means of motion reduction, such as active anti-roll fins and anti-roll tanks, can significantly reduce roll motions in seaway if appropriately used. However, the safety of ship should be ensured in cases of failure of such devices, therefore, the assessment according to these Guidelines should be conducted with such devices switched off.

3.4 Direct assessment procedures for stability failure are intended to employ state-of-the-art technology while being ~~yet be~~ sufficiently practical ~~so as~~ to be uniformly applied, verified, validated and approved using currently available infrastructure.

3.5 The procedure for direct stability assessment consists of two major components:

.1 ~~requirements for~~ a method that adequately replicates ship motions in waves (see section 4); and

.2 a prescribed procedure that identifies the process by which input values are obtained for the assessment, how the output values are processed, and how the results are evaluated (see section 6).

4 Requirements for method to adequately predict ship motions

4.1 General considerations

4.1.1 The motion of ships in waves, used for the assessment of stability performance, can be predicted by means of numerical simulations or model tests.

4.1.2 The choice between numerical simulations, model tests, or their combination should be agreed with the Administration on a case-by-case basis taking into account these Guidelines.

4.1.3 The procedures, calibrations, and proper application of technology involved in the conduct of model tests should follow "Recommended Procedures, Model Tests on Intact Stability, 7.5-02-07-04.1" issued by the ITTC.

4.1.4 Numerical simulation of ship motions may be defined as the numerical solution of the motion equations of a ship sailing in waves including or excluding the effect of wind (see section 4.2).

4.2 General Requirements

4.2.1 Modelling of waves

4.2.1.1 The mathematical model of waves should be consistent and appropriate for the calculation of the forces.

4.2.1.2 Modelling of irregular waves should be statistically and hydrodynamically valid. Caution should be exercised to avoid a self-repetition effect. The absence of self-~~repeating~~ repetition effect should be demonstrated.

4.2.2 Modelling of roll damping: avoiding duplication

4.2.2.1 Roll damping forces should include wave, vortex (i.e. eddy-making) and skin friction components.

~~4.2.2.2 The preferred source of the data to be used for the calibration of roll damping is a roll decay/forced roll test. CFD results may be substituted for this only after sufficient agreement with experimental results in terms of roll damping is demonstrated.~~

4.2.2.2 The data to be used for the calibration of roll damping may be defined from

.1 roll decay or forced roll test;

.2 CFD computations, if sufficient agreement with experimental results in terms of roll damping is demonstrated;

.3 existing databases of measurements or CFD computations for similar ships, if suitable range is available; or

.4 empirical formulae, applied within their applicability limits.

4.2.2.3 If the wave component of roll damping is already included in the calculation of radiation forces, measures should be taken to avoid including these effects more than once.

4.2.2.4 Similarly, if any components of roll damping (e.g. cross-flow drag) are directly computed ~~while~~ whereas the others are taken from the calibration data, similar measures should be taken to exclude these directly computed elements from the calibration data used.

4.2.2.5 Consideration of the essential roll damping elements more than once can be avoided through use of an iterative calibration procedure in which the roll decay or forced roll test are replicated in numerical simulations. The results must be determined to be reasonably close to the original calibration model test dataset.

4.2.3 Mathematical modelling of forces and moments

4.2.3.1 The Froude-Krylov and hydrostatic forces should be calculated using body-exact formulations at least for roll mode, for instance using panel or strip-theory approaches.

4.2.3.2 Radiation and diffraction forces should be represented in one of three ways: one is to use approximate coefficients and the other two involve either a body linear formulation or a body-exact solution of the appropriate boundary-value problem.

4.2.3.3 Resistance forces must include wave, vortex and skin friction components. The preferred source for ~~this~~ these data is model test ~~data~~. The ~~additional~~ added resistance in waves can be approximated, if this element is not already included in the calculation of diffraction and radiation forces. If the radiation and diffraction forces are calculated as a solution of the hull boundary-value problem, measures must be taken to avoid including these effects more than once.

4.2.3.4 Hydrodynamic reaction sway forces, roll moment and yaw moments could be approximated, to the satisfaction of the Administration, based on:

.1 coefficients derived from model tests in ~~still~~ calm water with planar motion mechanism (PMM) or in stationary circular tests by means of a rotating arm or an xy-carriage[1].

.2 CFD computations, provided that sufficient agreement is demonstrated with a model experiment in terms of values of sway force and yaw moment. If the radiation and diffraction forces are calculated as a solution of the hull boundary-value problem, measures must be taken to avoid including these effects more than once.

[1] The captive model test procedure should be based on the ITTC recommended procedure, 7.5-02-06-02. The stationary circular test by means of an x-y carriage can reproduce a circular model motion with any specified drift angle by combining the motion of an x-y carriage and a turn table.

.3 empirical data~~ / formula~~ base or empirical formulae, applied within their applicability range~~ in agreement with to the satisfaction of the Administration~~.

4.2.3.5 Thrust may be obtained by use of a coefficient-based model with approximate coefficients to account for propulsor-hull interactions.

4.3 Requirements for particular stability failure modes

4.3.1 For parametric roll, ship motion simulations should include at least the following three degrees of freedom: heave, roll and pitch.

4.3.2 For pure loss of stability, ship motion simulations should include at least four degrees of freedom: surge, sway, roll and yaw. For other degrees of freedom, static equilibrium should be assumed or fully coupled with the degrees of freedom being modelled.

4.3.3 For surf-riding and broaching,

.1 ship motion simulations should include at least the following four degrees of freedom: surge, sway, roll and yaw; for other degrees of freedom, static equilibrium could be assumed;

.2 hydrodynamic forces due to vortex shedding from a hull should be properly modelled. This should include hydrodynamic lift forces and moments due to the coexistence of wave particle velocity and ship forward velocity, other than manoeuvring forces and moments in calm water.

4.3.4 For dead ship condition,

.1 ship motion simulations should include at least the following four degrees of freedom: sway, heave, roll and pitch;

.2 three-component aerodynamic forces and moments generated on topside surfaces may be evaluated using model test results. CFD results may be admitted upon demonstration of sufficient agreement with a model experiment in terms of values of aerodynamic force and moments. Empirical data or formulae could be applied within their applicability range to the satisfaction of the Administration.

5 Requirements ~~for~~ to validation ~~and approval~~ of software for numerical simulation of ship motions

5.1 Validation

5.1.1 Validation is the process of determining the degree to which a numerical simulation is an accurate representation of the real physical world from the perspective of the intended uses of the model or simulation, the assessment whether ~~i.e. does~~ the theory and the software that implements the theory accurately model the relevant physical problem of interest~~?~~. The answer to this question often depends on what degree of accuracy is considered to be adequate.

5.1.2 Different physical phenomena are responsible for different modes of stability failure, therefore the validation of software for the numerical simulation of ship motions is failure-mode specific.

[5.1.3 The validation data should be compatible with the general characteristics of the ship for which the DSA is intended to be carried out.]

5.1.4 The process of validation should be performed in two phases: one qualitative and the other quantitative. In the qualitative phase, the objective is to demonstrate that the software is capable of reproducing the relevant physics of the failure mode considered. The objective of the quantitative phase is to determine the degree to which the software is capable of predicting the specific failure mode considered.

5.2 Qualitative validation requirements

5.2.1 Table 5.2 provides the requirements and acceptance criteria for qualitative validation.

Table 5.2 – Requirements and acceptance criteria for qualitative validation

Item	Required for	Objective	Acceptance criteria
Periodic properties of roll oscillator	software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation	demonstration of consistency between calculated roll backbone curve (dependence of roll frequency in calm water on initial roll amplitude) and GZ curve in calm water	based on the shape of calculated backbone curve. The backbone curve must follow the trend ~~of instantaneous GM with increasing heel angle~~ <u>which is consistent with the righting lever</u>
Response curve of roll oscillator	software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation	demonstration of consistency between the calculated roll backbone curve and the calculated roll response curve (dependence of amplitude of excited roll motion on the frequency of excitation)	based on the shape of the roll response curve. The roll response curve must "fold around" the backbone curve and <u>may</u> show hysteresis when magnitude of excitation is increased
Change of stability in waves	software where hydrostatic and Froude-Krylov forces are calculated with body exact formulation. Additional capability to track the instantaneous GZ curve in waves may be required	demonstration of capability to reproduce wave pass effect	typically in head and following waves, the stability decreases when the wave crest is located near the midship section (within the quarter of length) and the stability increase<u>s</u> when the wave trough is located near the midship section (within the quarter of length)
Principal parametric resonance	software where hydrostatic and Froude-Krylov forces are calculated with a body exact formulation	demonstration of capability to reproduce principal parametric resonance	usually, observing an increase and stabilization of amplitude of roll oscillation in exact following or head seas when encounter frequency is about

			twice ~~of~~ the natural roll frequency
Surf-riding equilibrium	software for numerical simulation of surf-riding and broaching	demonstrate capability to reproduce surf-riding, while yaw motions are disabled	observing sailing with the speed equal to wave celerity when the propeller RPM is set for the speed in calm water which is less than the wave celerity. Longitude position of centre of gravity is expected to be located near wave trough
Heel during turn	software for numerical simulation of surf-riding and broaching	demonstrate capability to reproduce heel caused by turn	observing development of heel angle during the turn
Turn in calm water	software for numerical simulation of surf-riding and broaching	demonstrate correct modelling of manoeuvring forces	observing correct direction of turn with large rudder angles
Straight captive run in stern quartering waves	software for numerical simulation of surf-riding and broaching	demonstrate correct modelling of wave forces including effect of wave particle velocity	observing correct tendency of phase difference of wave force to incident waves
Heel caused by drift and wind	software for numerical simulation of ship motions in dead ship condition	demonstrate capability to reproduce heel caused by a moment created by aerodynamic load and drag caused by drift	observing slowly developed heel angle after applying aerodynamic load

5.3 Quantitative validation requirements

5.3.1 There are two objectives of quantitative validation of numerical simulation. The first is to find the degree to which the results of numerical simulation differ from the model test results. The results of a model test carried out in accordance with ITTC guidelines ~~(~~7.5-02-07-04.1~~)~~ should be recognized as the reference values. The second objective is to judge if the observed difference between simulations and model tests is sufficiently small or conservative for direct stability assessment to be performed for the considered modes of failure.

[5.3.2 Note that all quantitative numbers ~~appeared~~ appearing as the acceptance standards below should be considered as tentative unless the sufficient evidence of their feasibility is submitted to the Organization.]

Table 5.3 – ~~Requirements~~ Indicative requirements and acceptance criteria for quantitative validation

	Required for	Objective	Acceptance criteria
Response curve for parametric roll in regular waves	parametric roll	to demonstrate ~~reasonable~~ agreement between numerical simulation and the models test of the amplitude of the roll response	~~[10%] of amplitude if below angle maximum of GZ curve in calm water and [20%] if above the angle of maximum of the GZ curve in calm water~~ The under-prediction of the maximum over

			encounter frequency roll amplitude below and above angle of maximum GZ in calm water should not exceed [10%] and [20%], respectively
Response curve for synchronous roll in regular waves	all modes	to demonstrate ~~reasonable~~ agreement between numerical simulation and the models test on the roll amplitude ~~of the roll response~~	~~[10%] of amplitude if below angle maximum of GZ curve in calm water and [20%] if above the angle of maximum of the GZ curve in calm water water~~ The under-prediction of the maximum over encounter frequency roll amplitude below and above angle of maximum GZ in calm water should not exceed [10%] and [20%], respectively
Variance test~~/~~ for synchronous roll	software for numerical simulation of dead ship condition and excessive accelerations	demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	~~probability that the difference between the ensemble estimates of variance of roll is caused by the random reasons is above the significant level of [5%]~~ reproduction of experimental result either within [95%] confidence interval or conservative
Variance test~~/~~ for parametric roll	software for numerical simulation of parametric roll	demonstrate correct (in terms of statistics) modelling of roll response in irregular waves	~~probability that difference between the ensemble estimates of variance of roll is caused by the random reasons is above the significant level of [5%]~~ reproduction of experimental result either within [95%] confidence interval or conservative
Wave conditions for surf-riding and broaching	software for numerical simulation of surf-riding and broaching	demonstrate correct modelling of surf-riding and broaching dynamics in regular waves	wave steepness causing surf-riding and broaching at the wave length [0.75-1.5] of ship length is within [15%] of difference between model test and numerical simulation; speed settings are also within [15%] difference between model test

			and numerical simulation

[~~***5.4 Approval***~~

~~4.4.1 Approval of the software by the Administration must be sought for a specific mode of stability failure for a particular group of vessels.~~]

6 Procedures of direct stability assessment

6.1 General description

6.1.1 The procedures for direct stability assessment contain a description of the necessary calculations of ship motions including the choice of input data, pre- and post-processing.

6.1.2 The direct stability assessment procedure is aimed at the estimation of a likelihood of a stability failure in an irregular wave environment and because the stability failures may be rare, the direct stability assessment procedure may require a solution of the problem of rarity. This arises when the average time before stability failure may occur is very long in comparison with the natural roll period that serves as a main time-scale for the roll motion process. The solution of the problem of rarity essentially requires a statistical extrapolation; for this reason, the validation must be performed for all elements of the direct stability assessment procedure.

6.1.3 These Guidelines provide two general approaches to circumvent the problem of rarity, namely assessment in design situations and assessment using non-probabilistic criteria; besides, mathematical techniques are provided that reduce the required number of simulations or simulation time and can be used to accelerate assessment~~, both the full assessment and the assessment performed in design situations~~.

[~~***6.2 Loading conditions***~~

~~6.2.1 The loading conditions chosen for the direct stability assessment must be representative for the intended service of the ship.~~

~~6.2.2 [The loading conditions for the direct stability assessment are to be chosen from the anticipated loading condition. As there may be too many loading conditions, the Administration may allow the loading conditions to be grouped to control computational costs. Grouping of the loading conditions should ensure that the majority of the open sea loading conditions are covered.][The loading conditions should be selected appropriately to define a stability limiting curve through the investigated loading conditions.]~~]

6.3 Environmental and sailing conditions

6.3.1 General approaches to selection of environmental and sailing conditions

6.3.1.1 The environmental conditions chosen for the direct stability assessment must be representative for the intended service of the ship.

6.3.1.2 Environmental conditions are defined by the type of wave spectrum and statistical data of its integral characteristics, such as the significant wave height and the mean zero-upcrossing wave period. For ships in unrestricted service, the environment should be described by the IACS Rec.34 wave scatter table. For ships of restricted service, the wave scatter diagram should be approved by the Administration.

6.3.1.3 It is recommended to use the Bretschneider wave energy spectrum and cosine-squared wave energy spreading with respect to the mean wave direction. [If short-crested waves are considered impracticable in model tests [or numerical simulations], long-crested waves can be used.]

6.3.1.4 For a given set of environmental conditions, the assessment can be performed using any of the following equivalent alternatives:

.1 full probabilistic assessment according to section 6.3.2;

.2 assessment in design situations using probabilistic criteria according to section 6.3.3;

.3 assessment in design situations using non-probabilistic criteria according to section 6.3.4.

6.3.2 Full probabilistic assessment

6.3.2.1 In this approach, the criterion used is the estimate of the mean long-term rate of stability failures, which is calculated as a weighted average over all relevant sea states, wave directions with respect to the ship heading and ship forward speeds, for each addressed loading condition.

6.3.2.2 To satisfy the requirements of this assessment, this criterion should not exceed the standard of $2.6 \cdot 10^{-8}$ 1/s. This standard exceeds the value in paragraph 1.2 since the full probabilistic assessment for unrestricted service is conducted assuming full design life operation in a severe North Atlantic wave climate in one loading condition, neglecting routing, heavy-weather avoidance and choice of safer speed and course in heavy weather.

6.3.2.3 The probabilities of the sea states are defined according to the wave scatter table, see paragraph 6.3.1; mean wave directions with respect to the ship heading are assumed uniformly distributed.

6.3.2.4 In the definition of the probabilities of the ship forward speeds, it is recommended to take into account the following factors:

.1 Maximum attainable forward speed in wave directions from head waves to 60 degree off-bow regarding ship's engine capacity. This speed can be defined from model tests or numerical computations. If such model tests or numerical computations are not available, assessment in bow wave directions should be conducted at zero forward speed.

.2 Maximum forward speed in wave directions from head waves to 60 degree off-bow from the point of view of loads and vertical motions and accelerations. This speed can be defined from model tests or numerical computations or, alternatively, set to 30% of the service speed in calm water.

.3 Ability of the ship to keep course in bow waves for the assessment of excessive lateral accelerations. If such data are not available, assessment should be performed in beam seaway.

6.3.3 Assessment in design situations using probabilistic criteria

6.3.3.1 Compared to the full probabilistic assessment, this approach significantly reduces the required simulation time and number of simulations since the assessment is conducted in few design situations, which are specified for each stability failure mode as combinations of the ship forward speed, mean wave direction with respect to the ship heading, significant wave height and mean zero-upcrossing wave period, for each addressed loading condition.

6.3.3.2 In this approach, the criterion is the maximum (over all design situations corresponding to a particular stability failure mode) short-term mean stability failure rate defined in each design situation.

6.3.3.3 To satisfy the requirements of this assessment, this criterion should not exceed the threshold corresponding to one stability failure per either

.1 2 hours in design sea states with probability density 10^{-5} $(m\cdot s)^{-1}$; or

.2 40 minutes in design sea states with probability density 10^{-6} $(m\cdot s)^{-1}$.

6.3.3.4 Table 6.1 shows the design situations for particular stability failure modes, including mean wave direction with respect to the ship heading, ship forward speed and the range of the mean zero-upcrossing wave periods; the step of the mean zero-upcrossing wave period in the specified ranges should not exceed 0.5 s.

Table 6.1 – Design situations for particular stability failure modes

Stability failure mode	Wave directions	Forward speeds	Wave period, T_z/T_r
Pure loss of stability	following	full	TO DISCUSS
Parametric roll	head	zero	0.3 to 0.5
Surf-riding/broaching	following	full	TO DISCUSS
Dead ship condition	beam	zero	0.7 to 1.3
Excessive acceleration	beam	zero	0.7 to 1.3

6.3.3.5 For each mean zero-upcrossing wave period, the significant wave height is selected accordingly to the probability density of the sea state in the scatter table as specified in the paragraph 6.3.3.3. For the unrestricted service, the significant wave heights are shown in Table 6.2 depending on the mean zero-upcrossing wave period.

Table 6.2 – Significant wave heights for design sea states with probability density 10^{-5} and 10^{-6} $(m\cdot s)^{-1}$ for unrestricted service

T_z, s	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
10^{-5}:	2.8	5.5	8.2	10.6	12.5	13.8	14.6	15.1	15.1	14.8	14.1	12.9	10.9	-
10^{-6}:	3.7	6.8	9.8	12.3	14.3	15.7	16.6	17.1	17.3	17.2	16.7	15.9	14.7	12.9

6.3.4 Assessment in design situations using non-probabilistic criteria

6.3.4.1 Probabilistic assessment may require long simulation time even using design situations and, besides, makes difficult using model tests instead of numerical simulations. Applying non-probabilistic criteria, such as mean three hour maximum roll amplitude, significantly reduces the required simulation time and, besides, makes easier using model tests, together with or instead of numerical simulations. However, the inaccuracy of this approach needs to be compensated by additional conservativeness.

6.3.4.2 In this approach, the criteria are the maximum (over all design situations for a particular stability failure mode) mean three-hour maximum roll amplitude and lateral acceleration, for each addressed loading condition.

6.3.4.3 To satisfy the requirements of this assessment, these criteria should not exceed half of the values in the definition of stability failure in paragraph 3.1.

6.3.4.4 The simulations or model tests for each design situation should comprise at least 15 hours. This duration can be divided into several parts; the results should be post-processed to provide at least five values of the three hour maximum amplitude of roll angle and lateral acceleration, which are averaged to define the mean three hour maximum amplitudes.

6.3.4.5 This approach uses design situations with the same mean wave directions with respect to the ship heading, ship forward speeds and the ranges of the mean zero-upcrossing wave periods for particular stability failure modes as shown in Table 6.1; the step of the mean zero-upcrossing wave period in the specified ranges should not exceed 0.5 s.

6.3.4.6 For each mean zero-upcrossing wave period, the significant wave height is selected accordingly to the probability density of the sea state in the scatter table equal to $7{\cdot}10^{-5}$ $(m{\cdot}s)^{-1}$. For the unrestricted service, these significant wave heights are shown in Table 6.3 depending on the mean zero-upcrossing wave period.

Table 6.3 – Significant wave heights for design sea states with probability density $7{\cdot}10^{-5}$ $(m{\cdot}s)^{-1}$ for non-probabilistic assessment for unrestricted service

T_z,s	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
h_s,m	2.0	4.4	6.9	9.1	10.9	12.1	12.8	13.1	13.0	12.5	11.3	9.0

6.4 Direct counting procedure

6.4.1 The direct counting procedure is the simulation of ship motions in multiple independent realisations of an irregular seaway and counting of the stability failures to provide the estimate of the mean rate of stability failures, required in the full probabilistic assessment and in the probabilistic assessment in design situations ~~approach~~.

6.4.2 The counting procedure should ensure independence of the counted stability failure events.

6.4.3 One possibility to ensure independence of the counted stability failure events is to carry out simulation in each realisation of an irregular seaway only until the first stability failure:

.1 result of such direct counting procedure are the values of the time until stability failure T_i, s, from each realisation; the estimate of the mean time to stability failure T, s, can be calculated as the mean of these values;

.2 maximum likelihood estimate of the rate of stability failures r, 1/s, is r=1/T;

.3 probability that at least one stability failure happens during time t, s, is p=1-exp(-rt)=1-exp(-t/T);

.4 estimate of time to stability failure should be provided together with its 95% confidence interval; for this estimate, time to stability failure can be assumed exponentially distributed random variable with the standard deviation σ_T=T and variance $Var_T=T^2$, and the mean time to stability failure can be assumed normally distributed random variable with the standard deviation $\sigma=\sigma_T/N^{0.5}$, where N is the number of the encountered stability failures;

.5 if direct counting is unfeasible due to too large computational time, extrapolation procedures may be used as specified in section 6.5.

~~6.4.3 The results of direct counting can be applied if at least [30] [200] of relevant stability failures for each considered situation is encountered. If the required number of stability failures is not encountered during [N hours] simulation time, extrapolation procedures should be used for this sea state.~~

6.5 Extrapolation procedures

6.5.1 ~~Extrapolation cautions~~ Cautions

6.5.1.1 The extrapolation method may be applied to provide the estimate of the mean rate of stability failures required in the full probabilistic assessment and probabilistic assessment in design situations ~~approach~~ if the direct counting procedure is impractical.

6.5.1.2 Caution should be exercised because extrapolation increases uncertainty caused by the nonlinearity of a dynamical system describing ship motions in waves.

6.5.1.3 The statistical uncertainty of the extrapolated values should be provided in a form of boundaries of the confidence interval evaluated ~~[with a method approved by the Administration]~~ with a confidence ~~probability~~ level of [95%].

6.5.1.4 To control the uncertainty~~,~~ caused by nonlinearity, the principle of separation ~~is recommended~~ may be used. Extrapolation methods based on the principle of separation consist of at least two numerical procedures addressing different aspects of the problem: "non-rare" and "rare".

6.5.1.5 The "non-rare" procedure is focused on estimation of ship motions or waves of small to moderate level, for which the ~~exceedance~~ stability failure events can be characterized statistically with acceptable uncertainty.

6.5.1.6 The "rare" procedure(s) is (are) focused on ship motions of moderate-to-severe level, which are rare to require numerical simulation. Large motions ~~should~~ may be separated from the rest of the time domain data to obtain practical estimates of these motions.

6.5.1.7 Different extrapolation methods based on the separation principle may use different assumptions on how the separation is introduced.

[6.5.1.8 A partial list of methods based on the principle of separation is given below.

6.5.2 Peak-over-threshold (POT) and envelope peak-over-threshold (EPOT)

6.5.2.1 The "non-rare" procedure involves direct counting of the exceedance events for the threshold where non-linearity of the righting lever curve may be significant.

6.5.2.2 The "rare" procedure involves a statistical extrapolation of the time domain data above the threshold with the possible use of extreme value distributions.

6.5.2.3 This method is applicable for the level of stability failure not exceeding the maximum of the GZ curve. The method can be applied to both experimental and simulation data. The method is applicable to the roll motions and the envelope of roll motions.

6.5.3 Split-time method

6.5.3.1 The "non-rare" procedure is the direct counting of the exceedance events for the threshold on or below the level of maximum of the righting lever curve.

6.5.3.2 The "rare" procedure is a numerical iteration procedure to find a roll rate at the exceedance threshold that leads to stability failure.

6.5.3.3 The method can be applied for any level of stability failure and may be combined with the POT/EPOT method.

6.5.4 Critical wave/wave group method

6.5.4.1 The "non-rare" procedure is evaluation or estimation of probability of encounter of a single large wave or a wave group that are characterized by exceedance of values of parameters while initial conditions belong to a specified range.

6.5.4.2 The "rare" procedure is the determination of the parameters of single wave/wave group and initial conditions that lead for stability failure.

6.5.4.3 The method can be applied both to experimental and simulation data.]

6.5.5 Extrapolation over wave height

6.5.5.1 Extrapolation of the mean time to stability failure or mean rate of stability failures over significant wave height is a technique allowing reducing the required simulation time by performing numerical simulations or model tests at greater significant wave heights than those required in the assessment and extrapolating the results to lower significant wave heights.

6.5.5.2 The extrapolation is based on the approximation $\ln T = A + B/h_s^2$, where T, s, is the mean time to stability failure; h_s, m, is the significant wave height; and A, B are coefficients which do not depend on the significant wave height but depend on the other parameters specifying situation (wave period, wave direction and ship forward speed).

6.5.5.3 The extrapolation can be performed when at least three values of the mean time to stability failure are available, obtained for a range of significant wave heights of at least 2 m; each of these values should not be less than 20 natural roll periods of the ship.

6.5.6 Reduced number of realisations

6.5.6.1 A high accuracy of estimates is necessary only in marginal cases, i.e. cases that are close to the acceptance boundary. In most situations, the conclusion about the outcome of the assessment can be done after a small number of realisations.

6.5.6.2 If reduced number of realisations is applied, statistical uncertainty of the estimate must be provided. For example, if the estimate of the lower (or upper) boundary of a 95% confidence interval of the mean time to failure exceeds (or is below, respectively) the acceptance threshold, the loading condition can be judged as acceptable (or unacceptable, respectively) without further realisations.

[***6.6. Validation of extrapolation procedures***

6.6.1 Extrapolation procedures used for direct stability assessment should be validated.

6.6.2 Validation of an extrapolation procedure is a demonstration that the extrapolated value is in reasonable statistical agreement with the result of the direct counting, if such volume of data would be available.

6.6.3 The data for validation of the extrapolation procedure may be produced by a mathematical model of reduced complexity (e.g. a set of ordinary differential equations instead of a numerical solution of a boundary value problem) or by running the full model on significantly more environmental severe and /or more dangerous loading conditions. The objective is to decrease the computational costs by which a large data set can be obtained (the validation dataset).

6.6.4 The direct counting procedure applied to the validation dataset should produce "the correct value". The extrapolation procedure applied to a minimally required fraction of the validation data set [(subset)] is the "tested" value.

6.6.5 [Validation of the extrapolation procedure should be performed for [50] statistically independent data subsets~~,~~ and evaluated at multiple levels for partial stability failures and for a number of ship speeds, relative wave headings and environmental conditions as determined by Administration.]

6.6.6 A comparison should be made ~~at each level of partial or total stability failure~~ between the extrapolation and the "true value" for each data set. The comparison should be considered successful if the extrapolation confidence interval and the confidence interval of "true value" overlap.

6.6.7 Validation for each level of partial stability failure or total stability failure should be considered successful if [84%] of individual data set comparisons were successful.

6.6.8. Number of successful levels of partial stability failure and conditions to consider the validation successful should be specified by Administration].

APPENDIX

BACKGROUND INFORMATION TO DRAFT INTERIM GUIDELINES FOR DIRECT STABILITY ASSESSMENT

1 Nomenclature

B_{wl}, m	waterline breadth of ship
d, m	mean draught of ship
$Fr=v_s(gL_{pp})^{0.5}$	Froude number
GM, m	metacentric height of ship
h_r, m	height of considered location above assumed roll axis
h_s, m	significant wave height
k_{xx}, m	dry roll radius of inertia with respect to centre of gravity
k_{yy}, m	dry pitch radius of inertia with respect to centre of gravity
k_{zz}, m	dry yaw radius of inertia with respect to centre of gravity
L_{pp}, m	length of ship between perpendiculars
N	number of simulations
f_s, $(m\cdot s)^{-1}$	joint probability density of sea state, i.e. probability of sea states per unit range of significant wave heights and mean zero-upcrossing wave periods
r, 1/s	mean rate of stability failures (mean number of stability failures per time)
T, s	mean time until stability failure
T_r, s	linear natural roll period of ship in calm water
T_z, s	mean zero-upcrossing wave period
v_s, m/s	ship forward speed
φ, degree	roll angle (positive for starboard down)
φ_{3h}	mean 3 hour maximum roll amplitude
μ, degree	wave direction (0 degree for following waves, 90 for waves from steering board and 180 for head waves)
ω_r, rad/s	linear natural roll frequency of ship

2 Definition of stability failure

2.1 Exceedance of a threshold roll angle and a threshold lateral acceleration are used as stability failures; namely, unless stricter requirements are deemed to be necessary for particular ships or ship types, the following definitions seem appropriate:

.1 *exceedance of roll angle* defined as the minimum of 40 degrees, angle of vanishing stability in calm water and angle of submergence of unprotected openings in calm water; or

.2 *exceedance of lateral acceleration* of 9.81 m/s^2.

2.2 To simplify the evaluation of motion criteria, instead of the requirement in paragraph 2.1.2, an equivalent maximum acceptable roll angle, defined as $57.3/(1+h_r\omega_r^2/9.81)$, in degree, can be used. For this calculation, the roll axis can be assumed at the midpoint between the waterline and the centre of gravity of the ship.

2.3 Thus, in numerical simulations, only one stability failure event will need to be tracked: exceedance of the minimum of the three roll angles defined in 2.1.1 and 2.2.

3 Introduction

3.1 In a probabilistic direct stability assessment, probability of stability failure is used directly as a safety measure (criterion), therefore, such assessment requires some form of counting of stability failures, which hence need to be encountered in the simulations. This leads to the problem of rarity, because very long simulations are required for the relevant ships and loading conditions. Besides, reliable estimation of the mean stability failure probability requires simulation of a sufficiently large number of stability failures, which further increases the required simulation time.

3.2 At the same time, direct stability assessment should enable most accurate assessment within SGISC, taking into account as much relevant physics as possible in the most accurate way. This means that the simulation tools employed are slow and require much more computational time than tools used in level 1 and level 2 vulnerability assessment. Therefore, some simplifications are required regarding probabilistic procedures. Here, three such simplification methods are exploited.

4 Ships and loading conditions used in tests

4.1 Five ships were used: a cruise and a RoPax vessels and three container ships of 1700, 8400 and 14000 TEU capacity. For each ship, 5 loading conditions were selected: three loading conditions with small GM values, relevant for parametric roll, pure loss of stability and stability in dead ship condition, and two loading conditions with big GM values, relevant for excessive accelerations, Table 1. To fine-tune the ranges of the tested GM values, level 1 and level 2 vulnerability assessments regarding all stability failure modes were conducted.

Table 1. Ships and loading conditions used in study

Ship	L_{pp}, m	B_{wl},m	Loading condition:	01	02	03	04	05
Cruise vessel	230.9	32.2	d, m	6.9				
			GM, m	1.5	2.0	2.5	3.25	3.75
RoPax vessel	175.0	29.5	d, m	5.5				
			GM, m	3.7	4.5	5.2	5.9	6.6
1700 TEU container ship	159.6	28.1	d, m	9.5			5.5	
			GM, m	0.5	1.2	1.9	5.75	6.75
8400 TEU container ship	317.2	43.2	d, m	13.93	14.44	14.48	11.36	
			GM, m	0.89	1.26	2.01	5.0	6.93
14000 TEU container ship	349.5	51.2	d, m	14.5			8.5	
			GM, m	1.0	2.0	3.0	9.0	12.0

5 Database of results of direct simulations

5.1 For each ship and each loading condition, full probabilistic assessment was performed using numerical simulations of ship motions in waves to provide validation database for simplified procedures. The simulations were performed for six forward speeds, Table 2, for the mean zero-upcrossing wave periods T_z and significant wave heights h_s covering all entries in the North Atlantic wave scatter table, IACS Rec. 34, and for wave directions μ from 0 to 180 degrees every 10 degrees.

Table 2. Non-dimensional forward speeds used in analysis

Ship	L_{pp}, m	Froude numbers					
Cruise	230.9	0.0	0.0454	0.0908	0.1362	0.1816	0.2270
RoPax	175.0	0.0	0.0546	0.1093	0.1639	0.2185	0.2732
CV1700	159.6	0.0	0.0481	0.0962	0.1443	0.1924	0.2405
CV8400	317.2	0.0	0.0452	0.0904	0.1356	0.1808	0.2259

CV14000	349.5	0.0	0.0427	0.0854	0.1281	0.1708	0.2135

5.2 For each combination of forward speed, wave period, significant wave height and wave direction, numerical simulations of ship motions in 200 realisations of the same sea state were performed by random variation of frequencies, directions and phases of wave components composing sea state. Each simulation was conducted for the simulation time $1.7 \cdot 10^4$ hours or until the first exceedance event, after which it was repeated in another realisation of the same seaway.

5.3 From each simulation, the time until stability failure T_i was defined; the estimate of the mean time until stability failure T was calculated by averaging over N=200 failures as

$$T = \sum_{i=1}^{N} T_i \Big/ N \tag{1}$$

5.4 The maximum likelihood estimate for the rate r, 1/s, of stability failures is

$$r = 1/T \tag{2}$$

5.5 Note other useful relationships:

.1 probability that at least one failure happens during time t is

$$p = 1 - \exp(-rt) = 1 - \exp(-t/T) \tag{3}$$

.2 standard deviation of time until stability failure is

$$\sigma_T = 1/r = T \tag{4}$$

.3 variance of time until stability failure is

$$\mathrm{Var}_T = 1/r^2 = T^2 \tag{5}$$

5.6 The studied ships demonstrated stability failures due to principal parametric resonance in bow waves, principal and fundamental parametric resonance in stern waves and synchronous roll in beam waves (relevant for dead ship and excessive acceleration stability failures). Some of loading conditions indicated big heel angles in following waves at large forward speeds, although their maximum speeds, while sufficient for vulnerability to the pure loss of stability, were not high enough for strong pure loss failures. Surf-riding/broaching was not found relevant for any of the tested ships.

5.7 To test and validate simplified probabilistic procedures, including extrapolation of the stability failure rate over wave height, design situations and non-probabilistic assessment, it was necessary to separate the stability failure events identified in the direct simulations with respect to stability failure modes. Although the extrapolation of stability failure rate over wave height does not assume any specific stability failure mechanism and is applicable to any stability failure mode, it was interesting to check how much its accuracy and robustness differ between different stability failure modes. On the other hand, in the document SDC 3/INF.12 it was found that the same design situations cannot be used for different stability failure modes, therefore, different failure modes require different design situations, which requires the definition of the failure mode-specific stability failure rate in the full probabilistic assessment for validation and calibration of the failure mode-specific desing situations.

5.8 In the full probabilistic assessment, parametric roll (specifically, principal parametric resonance) in bow waves was detected in mean wave directions from head up to about 70 degree off-bow; nevertheless, in all cases where principal parametric resonance in bow waves occurred, head waves led to largest roll motions, Figure 1 (top left and top middle plots). Therefore, for parametric roll in bow waves, assessment in head waves will always detect the worst situations and, moreover, include most relevant stability failure events. Therefore, to select the relevant simulation results from the full database for validation and calibration of simplified methods for parametric resonance in bow waves, three sets of reference data were generated, for wave directions from 170 to 180, 160 to 180 and 150 to 180 degree.

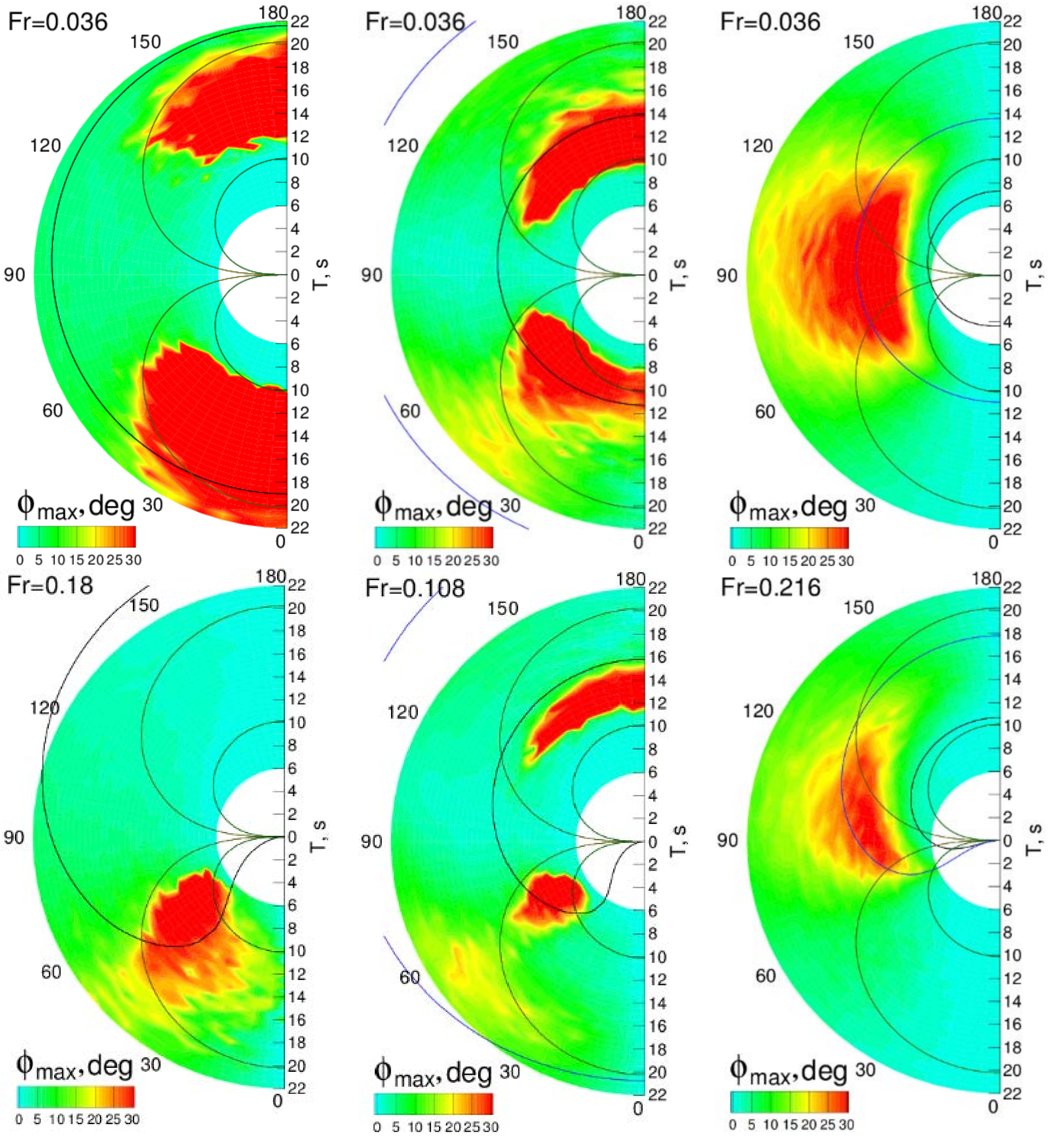

Figure 1. Colour plots of mean three-hour maximum roll amplitude depending on mean wave period (in s, radial coordinate) and mean wave direction (circumferential coordinate, waves from top, bottom and right correspond to 180, 0 and 90 degree, respectively) for principal parametric resonance at low (left) and medium (middle) GM and synchronous roll at high GM (right) at low (top) and high (bottom) forward speed

5.9 Parametric resonance (principal and, much less, fundamental) in stern waves was detected in the full probabilistic assessment in wave directions from following up to about 80 degree off-stern. Unlike for parametric roll in bow waves, for which head waves always represent the worst case, following waves were not always worst (over all stern wave directions) for parametric roll in stern waves. Moreover, for some loading conditions at certain forward speeds, parametric roll did not occur in following waves while being very strong in stern-quartering waves, Figure 1 (bottom left and middle); see a detailed discussion in Shigunov (2009)[2]. This means that for some ships in some loading conditions, assessment in following waves may not detect the possibility of severe parametric roll in stern waves.

5.10 This is unpleasant since the need to address parametric roll in stern-quartering wave directions in simplified assessment procedures can lead to the following problems:

.1 since level 1 and level 2 vulnerability assessment do not consider parametric resonance in stern-quartering waves, direct stability assessment including stern-quartering wave directions may lead to inconsistency;

.2 number of required design situations will significantly increase if assessment of parametric roll in stern waves will require all wave directions from following to 90 degree off-stern; moreover, this means significantly more expensive model tests and much more advanced model testing facilities required.

5.11 To check whether addressing parametric roll specifically in stern-quartering waves is essential for direct assessment, the results of the full assessment are plotted in Figure 2 in the following way: y-axis corresponds to the total stability failure rate over all wave directions, whereas x-axis corresponds to the sum of stability failure rates over parametric roll in bow and stern waves (sectors from 150 to 180 and 0 to 30 degree, respectively) and synchronous roll in beam waves (60 to 120 degree) for all ships and loading conditions (differentiated by symbol type and colour) and forward speeds; thus, x-axis variable neglects parametric roll in stern-quartering waves, included in the y-axis variable.

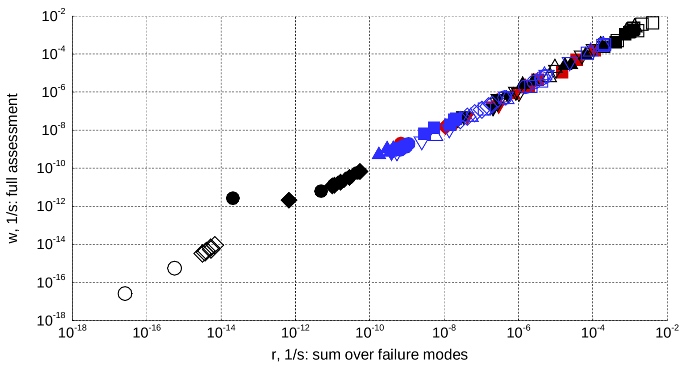

Figure 2. Total stability failure rate in all wave directions vs. sum of stability failure rates due to parametric roll in bow and stern waves and synchronous roll in beam waves; symbol type and colour differentiate ships and loading conditions

5.12 Since the dependency in Figure 2 is monotonous and rather sharp, contributions from parametric resonance in stern-quartering waves do not need to be additionally addressed in the direct stability assessment (unlike in operational measures): taking into account parametric resonance in following waves is sufficient to represent the contributions of parametric resonance in all stern wave directions. The reason is that parametric resonance in stern-quartering waves becomes important with increasing forward speed, when parametric roll decreases, whereas much larger contributions occur in following waves at low forward speeds.

5.13 Therefore, for validation and testing of the simplified procedures for parametric resonance in stern wave directions, three comparative sets of data were generated from the

2 *Shigunov, V. el Moctar, O., and Rathje, H.* (2009) Conditions of parametric rolling, *Proc. 10th Int. Conf. on Stability of Ships and Ocean Vehicles*.

full database of assessment results, corresponding to wave directions from 0 to 10, 0 to 20 and 0 to 30 degree.

5.14 For synchronous roll in beam waves, the relevant wave directions in the full probabilistic assessment were found from about 40 degree off-bow to about 40 degree off-stern, depending on the forward speed, Figure 1 (top right and bottom right). However, at low forward speeds, wave directions close to beam are sufficient to assess synchronous roll. Therefore, to select relevant cases for validation for synchronous roll in beam waves from the full database of assessment results, three comparative sets of reference data were generated: for wave directions from 80 to 100, 70 to 110 and 60 to 120 degree.

5.15 Reference data for pure loss of stability were also generated, although this stability failure was especially difficult to identify, since none of the selected ships was expected to undergo severe pure loss, due to low (although in the region of vulnerability) maximum speeds. Three simple conditions were used: following waves, encounter period (corresponding to peak wave period) exceeding 30 s and wave length, corresponding to the peak wave period, close to the ship length.

6 Extrapolation of failure rate over wave height

6.1 In SDC 4/5/8 and SDC 4/INF.8, extrapolation of stability failure rate over significant wave height in the form suggested by Tonguc & Söding (1986)[3] was validated for synchronous roll in beam waves (relevant for dead ship and excessive acceleration failure modes),

$$\ln T = A + B / h_s^2 \tag{6}$$

6.2 In eq. (6), T means the expected time to stability failure, h_s the significant wave height and A and B constants, independent from the significant wave height but depending on the ship, loading condition, forward speed and wave period and direction.

6.3 Here eq. (6) is applied also to parametric roll in bow and stern waves. To quantify the accuracy of the extrapolation, several variants of extrapolation were tested by varying the number of extrapolation points. Namely, 4, 5, …, 11 wave heights were selected, starting from the minimum wave height for which the results could be obtained by direct simulations and for which $\ln T > 6$, i.e. $T > 400\ \mathrm{s}$, see document SDC 4/INF.8. All of these points excepting one (corresponding to the minimum significant wave height) were used to perform extrapolation (6) using 3, 4, …, 10 points, respectively, whereas the results of the direct simulation at the minimum significant wave height was used to find the deviation between the extrapolated and directly computed mean time to failure.

6.4 Figure 3 shows the results as histograms of the ratio of the extrapolated to directly computed estimate of the mean time to failure: y-axis corresponds to the number of cases in bins (normed on 1) and x-axis shows the ratio of the extrapolated expected time to failure T_{extr} to the directly estimated one T.

6.5 To quantify the accuracy of extrapolation, the percentage of the extrapolated values was calculated, lying within the 95%-confidence interval of the directly computed estimate, Table 3 (if the extrapolation were exact, 95% of extrapolated values would have been within this interval). The results show that the extrapolation given by eq. (6) provides sufficiently accurate results and thus is a useful practical tool to accelerate direct assessment.

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3 *Tonguć, E. and Söding, H.* (1986) Computing capsizing frequencies of ships in seaway, *Proc. 3rd Int. Conf. on Stability of Ships and Ocean Vehicles*.

7 Design situations

7.1 The full probabilistic assessment requires summation of short-term stability failure rates over all sea states of a relevant wave climate and all seaway directions and thus large computational time. The document SDC 3/INF.12 proposed to reduce the assessment to few combinations of sea state parameters (wave height, period and direction) and ship forward speed, referred to as design situations.

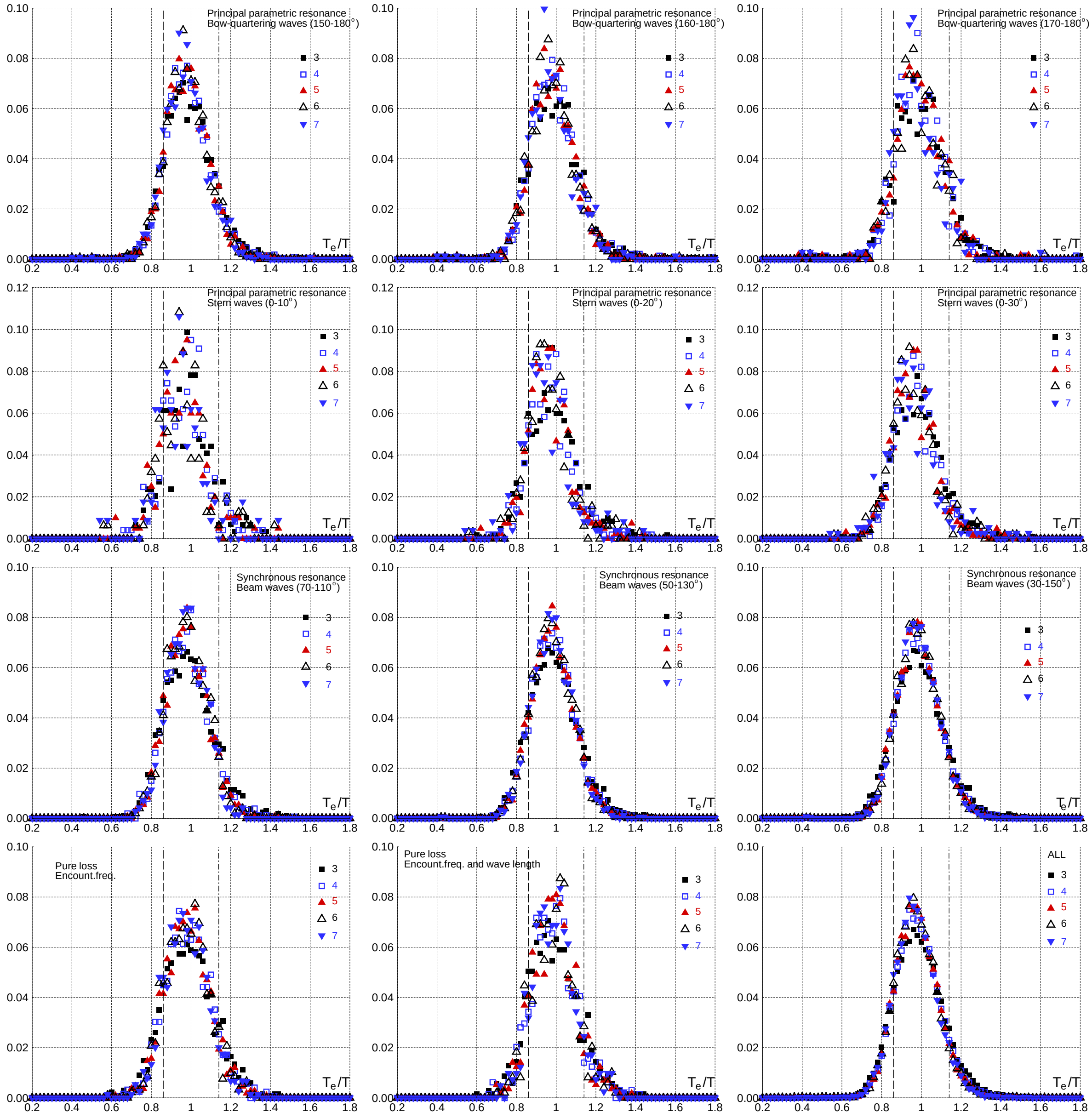


Figure 3. Histogram (number of cases normed on 1) of ratio T_{extr}/T and 95%-confidence interval of directly computed T (vertical lines) for (from top to bottom) parametric roll in bow waves, parametric roll in stern waves, synchronous roll in beam waves, pure loss of stability (bottom left and middle) and all cases together (bottom right); different symbols correspond to various number of points used in extrapolation over wave height

7.2 The idea is that a simplified safety criterion can be used for norming if the dependency of the true long-term probability of stability failure on this criterion (a) is monotonous and (b) shows little scatter between different ships, loading conditions and forward speeds. The standard for this simplified criterion (further referred to as threshold to differentiate it from the long-term standard) can be defined using a sufficient number of representative case studies, Figure 4. Thus the exact dependency w(s) does not matter in the practical approval and is not required, as long as it is proven that it satisfies conditions (a) and (b).

7.3 Document SDC 3/INF.12 proposed to use different design situations for different failure modes; in SDC 4/5/8 and SDC 4/INF.8, this method was verified for roll in beam sea (to address dead ship condition and excessive acceleration stability failure modes). Here, the verification is extended to other stability failure modes.

Table 3. Percentage of extrapolated values of time to stability failure within 95%-confidence interval of directly computed estimate

Number of wave heights used for extrapolation	3	4	5	6	7	8	9	10
Parametric resonance in bow waves								
Wave directions 150 to 180 degree	79	83	85	84	83	81	78	81
Wave directions 160 to 180 degree	79	82	84	82	81	79	77	79
Wave directions 170 to 180 degree	78	82	83	81	80	78	77	76
Parametric resonance in stern waves								
Wave directions 0 to 10 degree	79	82	80	76	73	75	71	62
Wave directions 0 to 20 degree	79	83	84	81	78	80	79	68
Wave directions 0 to 30 degree	79	82	81	79	76	78	76	68
Synchronous resonance in beam waves								
Wave directions 70 to 110 degree	77	83	85	87	88	88	85	77
Wave directions 50 to 130 degree	77	82	83	85	85	85	82	74
Wave directions 30 to 150 degree	77	82	83	84	84	84	82	78
Pure loss in following waves	77	82	83	84	84	86	87	88
All above cases	**77**	**81**	**82**	**83**	**82**	**81**	**79**	**75**

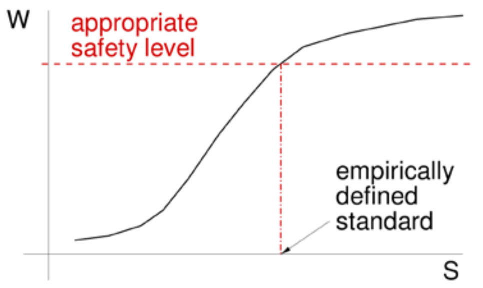


Figure 4. Idea of simplified safety criterion s; w is the "true" safety measure, e.g. mean long-term probability of stability failure

7.4 To verify conditions (a) and (b) in 7.1, the mean long-term rate of stability failures was computed using the results of the full probabilistic assessment as

$$w(\text{ship},\text{LC},v_s)=\sum_s\sum_\mu f_s(h_s,T_1,\mu;\text{ship},\text{LC},v_s)\cdot r(h_s,T_1,\mu;\text{ship},\text{LC},v_s)\cdot\Delta h_s\Delta T_z \qquad (7)$$

7.5 In eq. (7), v_s is the ship forward speed, μ is the wave direction and $s=(h_s,T_1)$ denotes all sea states in the scatter table. Different forward speeds were applied and evaluated separately, because the selection of a suitable speed to be used in design situations was one of the tasks of this investigation.

7.6 As the first step, wave directions for design situations were selected: 180 degree for parametric roll in bow waves, 0 degree for parametric roll in stern waves, 90 degree for synchronous roll in beam waves and 0 degree for pure loss of stability.

7.7 The second step was the selection of wave height (aiming at using only one significant wave height per wave period). Several approaches to the selection of sea states in design situations were compared in SDC 4/5/8 and SDC 4/INF.8, including sea states according to the steepness table from MSC.1/Circ.1200, sea states along constant steepness lines $h_s=\text{const}\cdot 0.5gT_1^2/\pi$, along lines of constant density of sea state occurrence probability and along lines of constant normed and not normed quantiles of sea state occurrence probability.

7.8 Results shown in SDC 4/5/8 and SDC 4/INF.8, confirmed here, indicate that sea states selected along the lines of constant density of sea state occurrence probability, Figure 5, provide the best correlation between w and s; therefore, results are shown here only for such design sea states. Note that using design sea states along the lines of constant normed and not normed quantiles of sea state occurrence probability (the latter mean lines of constant conditional exceedance probability of various significant wave heights) results in comparable quality of results. Also note that the lines of constant probability density or constant quantiles of probability were defined using logarithmic interpolation for probabilities.

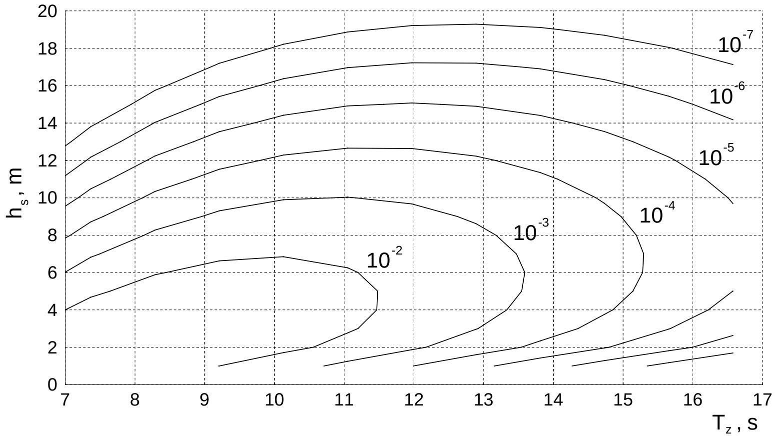


Figure 5. Lines of constant density of sea state occurrence probability f_s, $(m \cdot s)^{-1}$, for North-Atlantic wave scatter table

7.9 As the simplified criterion in these sea states, maximum (over all design sea states) stability failure rate r was used, following recommendations in SDC 4/5/8 and SDC 4/INF.8.

7.10 Figures 6 to 9 show the mean long-term stability failure rate w vs. maximum (over design sea states) mean short-term failure rate for design sea states with probability densities of 10^{-7}, 10^{-6}, …, 10^{-2} $(m \cdot s)^{-1}$ for all failure modes. Each point corresponds to one ship, loading condition and forward speed.

7.11 The sharp monotonous dependencies in Figure 2, concerning selection of wave directions for design situations, and in Figure 6, Figure 7, Figure 8 and Figure 9 (at f_s of 10^{-4} $(m \cdot s)^{-1}$ and less), concerning selection of wave heights for design situations for parametric roll in bow and stern waves, synchronous roll in beam waves and pure loss of stability, respectively, indicate that the accuracy of the simplified criterion is satisfactory and improves with increasing wave steepness. Note that the required model testing or numerical simulation time quickly reduces with the increasing wave height, therefore, it is better to use design sea states of larger steepness; however, sea states of too large steepnesses may be difficult to realise in model tests or numerical simulations.

7.12 To check whether parametric roll in stern waves can be related to assessment results in design sea states in head waves, which would allow skipping assessment for parametric roll in stern waves, Figure 10 shows the mean long-term stability failure rate due to parametric roll in stern waves vs. the maximum mean short-term stability failure rate in design sea states in head waves; however, the correlation is very poor.

7.13 Results presented so far allow reducing the number of assessment cases due to using one wave direction per failure mode (reduction factor of about 19) and one wave height per wave period (reduction factor of several orders of magnitude, because assessment at low wave heights requires very long simulations, if feasible at all). Another reduction possibility is the selection of a suitable forward speed: if, for example, only one speed needs to be used per failure mode, this will lead to a reduction of the number of test cases by about one order of magnitude for some stability failure modes, as well as will allow significant simplifications in numerical simulations or model test setup.

7.14 For dead ship condition and excessive accelerations, only zero forward speed is applied in the full assessment anyway; for pure loss of stability, the rate of stability failures increases monotonously with increasing speed (for the considered ships), therefore, the maximum possible speed should be used. To select the forward speed for design situations for parametric roll, Figure 11 (left) shows failure rate for parametric roll in head waves along the $f_s=10^{-5}$ $(m{\cdot}s)^{-1}$ line (maximum over all wave periods) as a function of Froude number. Each plot corresponds to one ship, and each line corresponds to one loading condition.

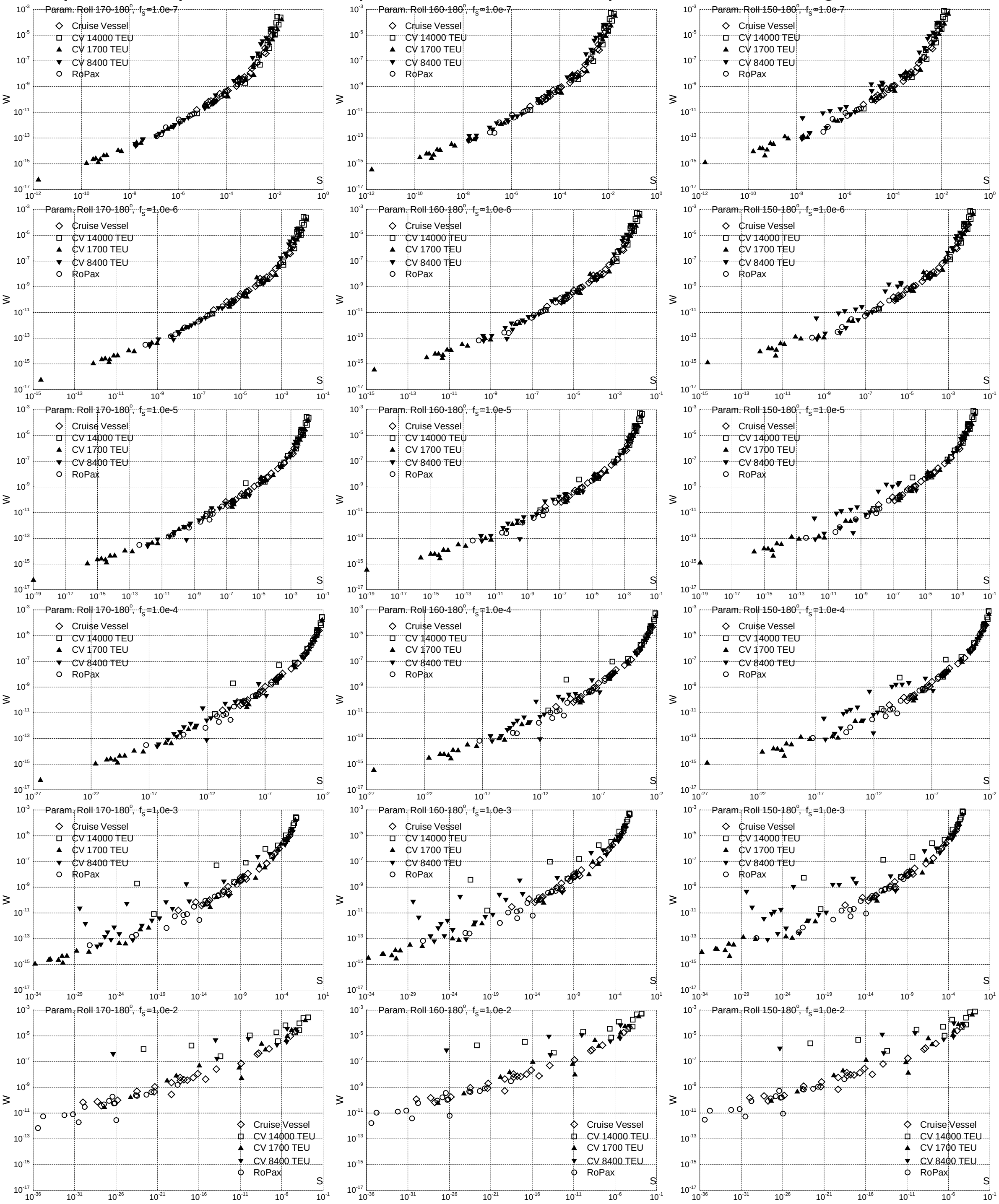


Figure 6. Dependency w(s) for design situations for parametric roll in bow waves: mean long-term stability failure rate w(ship,LC,v_S), 1/s, y axis, in wave directions from 170 to 180 degree (left), 160 to 180 degree (middle) and 150 to 180 degree (right) vs. simplified criterion, 1/s, x axis – short-term mean stability failure rate in head waves, maximum over design sea states along lines with sea state probability density f_s of (top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$

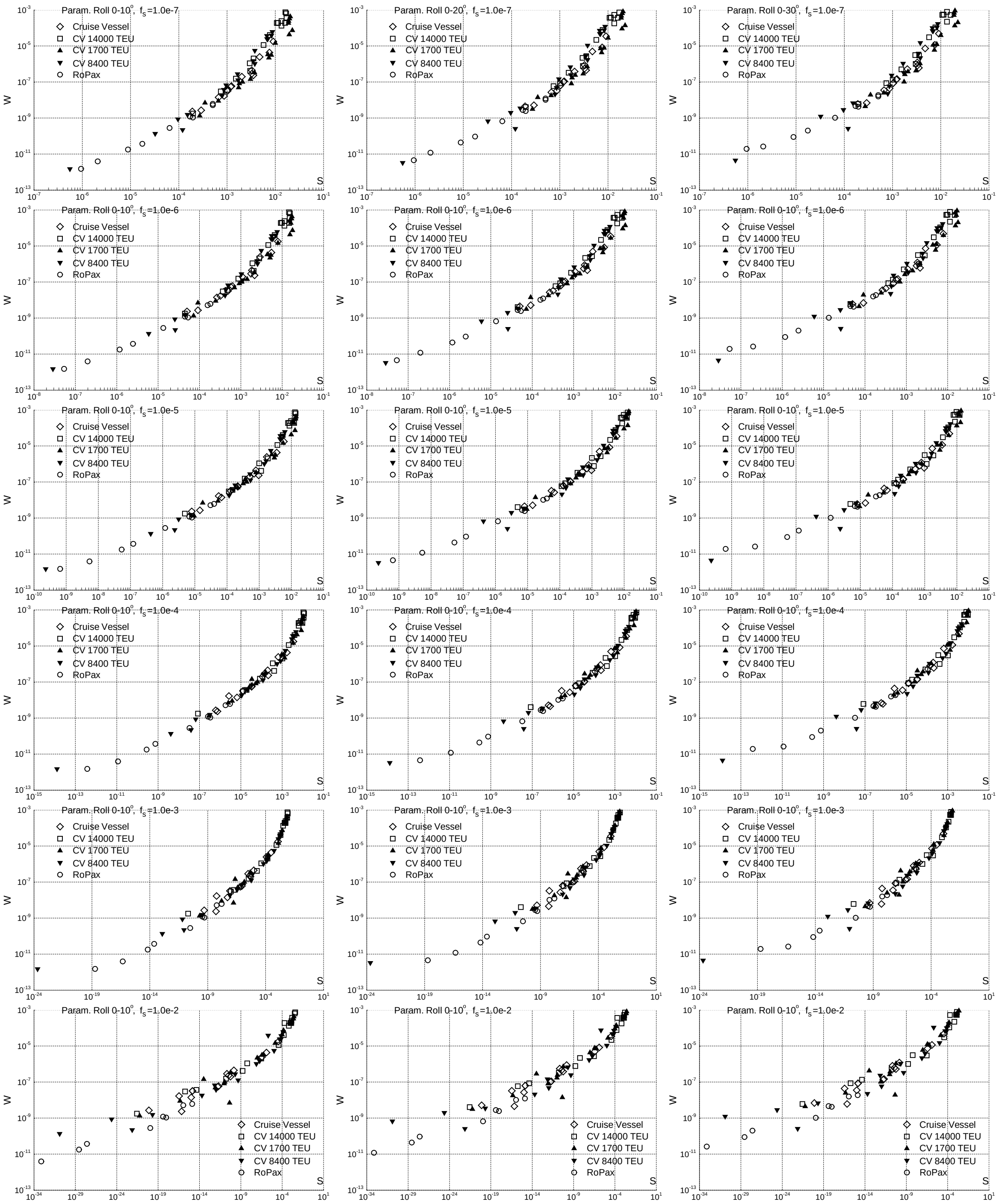


Figure 7. Dependencies w(s) for design situations for parametric roll in stern waves: mean long-term stability failure rate w(ship,LC,v_S), 1/s, y axis, in wave directions 0 to 10 degree (left), 0 to 20 degree (middle) and 0 to 30 degree (right) vs. simplified criterion, 1/s, x axis – short-term mean stability failure rate in following waves, maximum over design sea states

along lines with sea state probability density f_s of (top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} (m·s)$^{-1}$

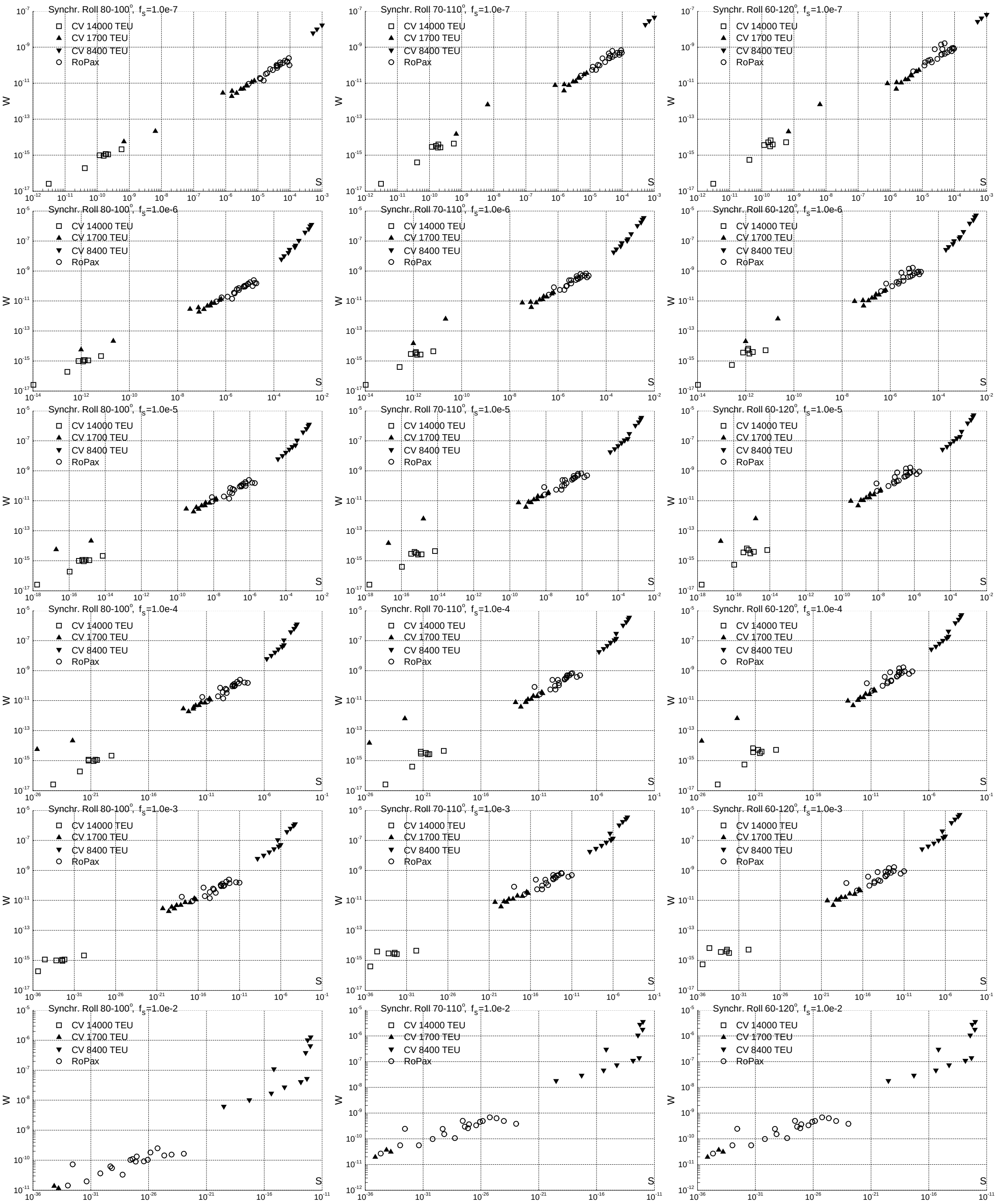


Figure 8. Dependency w(s) for synchronous roll in beam waves: mean long-term stability failure rate w(ship,LC,v_s), 1/s, y axis, in wave directions from 80 to 100 degree (left), 70 to 110 degree (middle) and 60 to 120 degree (right) vs. simplified criterion, 1/s, x axis – short-term mean stability failure rate at μ=90 degree, maximum over design sea states along lines with sea state probability density f_s equal to (from top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} (m·s)$^{-1}$

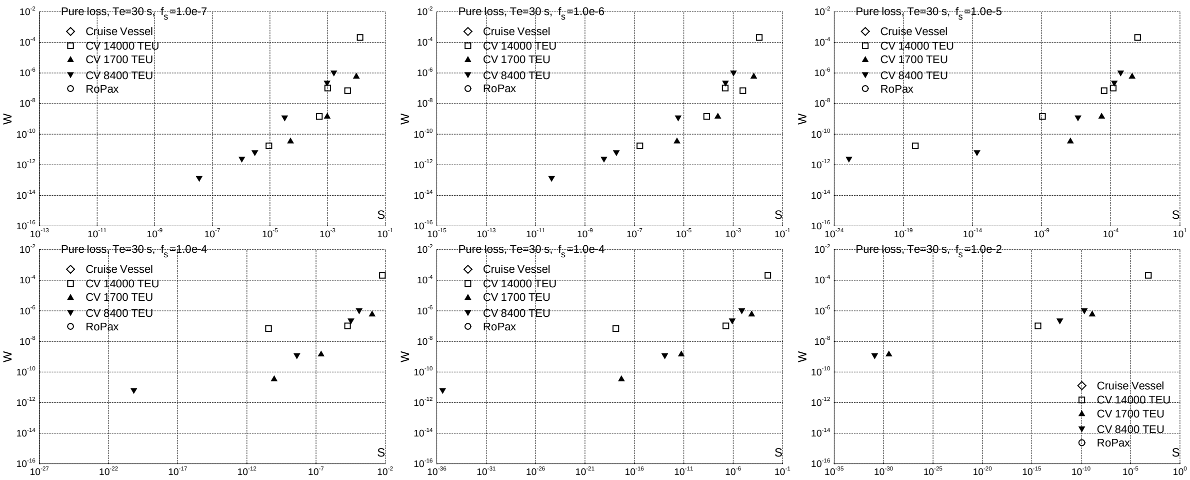


Figure 9. Dependency w(s) for pure loss of stability: mean long-term stability failure rate w(ship,LC,v_s), 1/s, y axis, vs. simplified criterion, 1/s, x axis – short-term mean stability failure rate in following waves, maximum over design sea states with occurrence probability density f_s of (left to right, then top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$

7.15 The results show that for all loading conditions with high failure rate, the failure rate decreases with increasing forward speed. This is due to, first, broadening of the encounter wave spectrum with increasing forward speed in bow waves and, second, due to increasing roll damping with increasing forward speed. Note also that according to operational experience, parametric roll accidents in bow waves always happen at low forward speed. For RoPax vessel in all loading conditions and cruise vessel in two loading conditions with the largest GM, the stability failure rate increases with increasing forward speed; however, the stability failure rate for these cases is very small anyway. Therefore, it seems appropriate to use only zero forward speed in design situations for parametric roll in bow waves. Note that if zero speed is difficult to implement in model tests (e.g. due to wave reflections) or in simulations, as low as practicable forward speed can be applied.

7.16 Concerning parametric roll in stern waves, Figure 11 (right) shows a more complex dependency of the failure rate on the Froude number in design sea states in following waves. This is due to the more complex relationship between the wave frequency and the encounter frequency in stern waves and thus more complex behaviour of the encounter wave spectrum. It appears, however, that in all cases with big stability failure rate, simplified assessment only at zero forward speed will either not introduce any non-conservative error or will be conservative, thus zero (or as low as practicable) forward speed appears appropriate also for parametric roll in following waves.

7.17 Note that zero forward speed in high head or following waves is impossible in reality because of the inability of a ship (with a usual steering system) to keep course at zero speed; here, however, this assumption is acceptable as a practical simplification of the roll motion assessment procedure (which, however, will require some adjustment of the setup).

7.18 Reducing assessment of parametric roll to zero forward speed case has also the following effect: Figure 12 (left) shows stability failure rate due to parametric resonance at zero forward speed in design situations in following (y axis) vs. head (x axis) wave directions: obviously, in the relevant region, these two stability failure rates are well correlated. Note that the full probabilistic assessment with respect to parametric resonance shows the same at zero forward speed, Figure 12 (right), unlike when all forward speeds were taken into account in Figure 10. Therefore, assessment with respect to parametric resonance in following waves at zero forward speed can be omitted in the design situations approach.

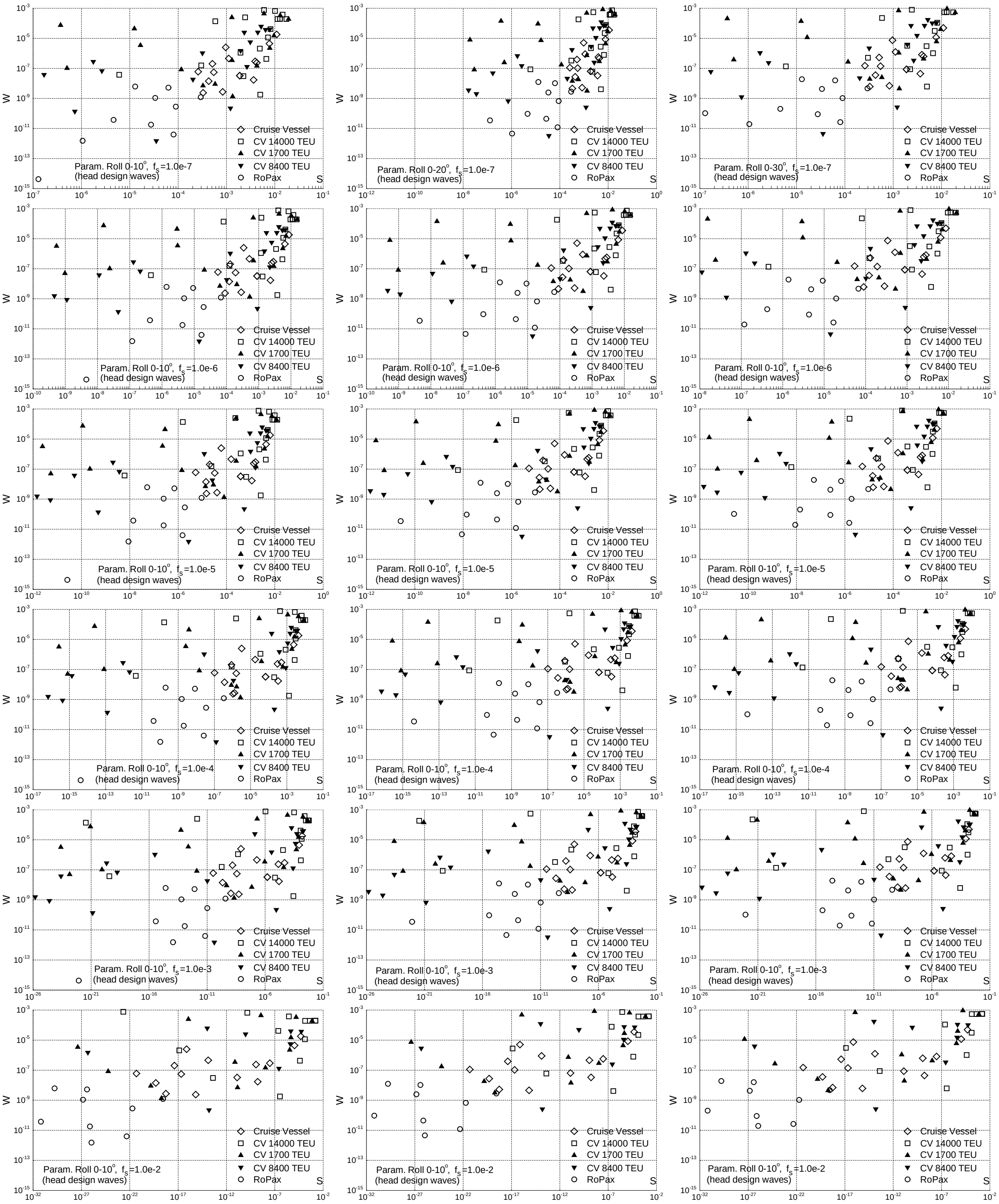


Figure 10. Dependency w(s) for design situations for parametric roll in stern waves: mean long-term stability failure rate w(ship,LC,v_s), 1/s, y axis, in wave directions from 0 to 10 degree (left), 0 to 20 degree (middle) and 0 to 30 degree (right) vs. simplified criterion, 1/s, x-axis – short-term mean stability failure rate in head waves, maximum over design sea states along lines with sea state probability density f_s of (top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$; unlike in Figure 7, where simplified criterion is calculated in following waves, here simplified criterion is calculated in head waves

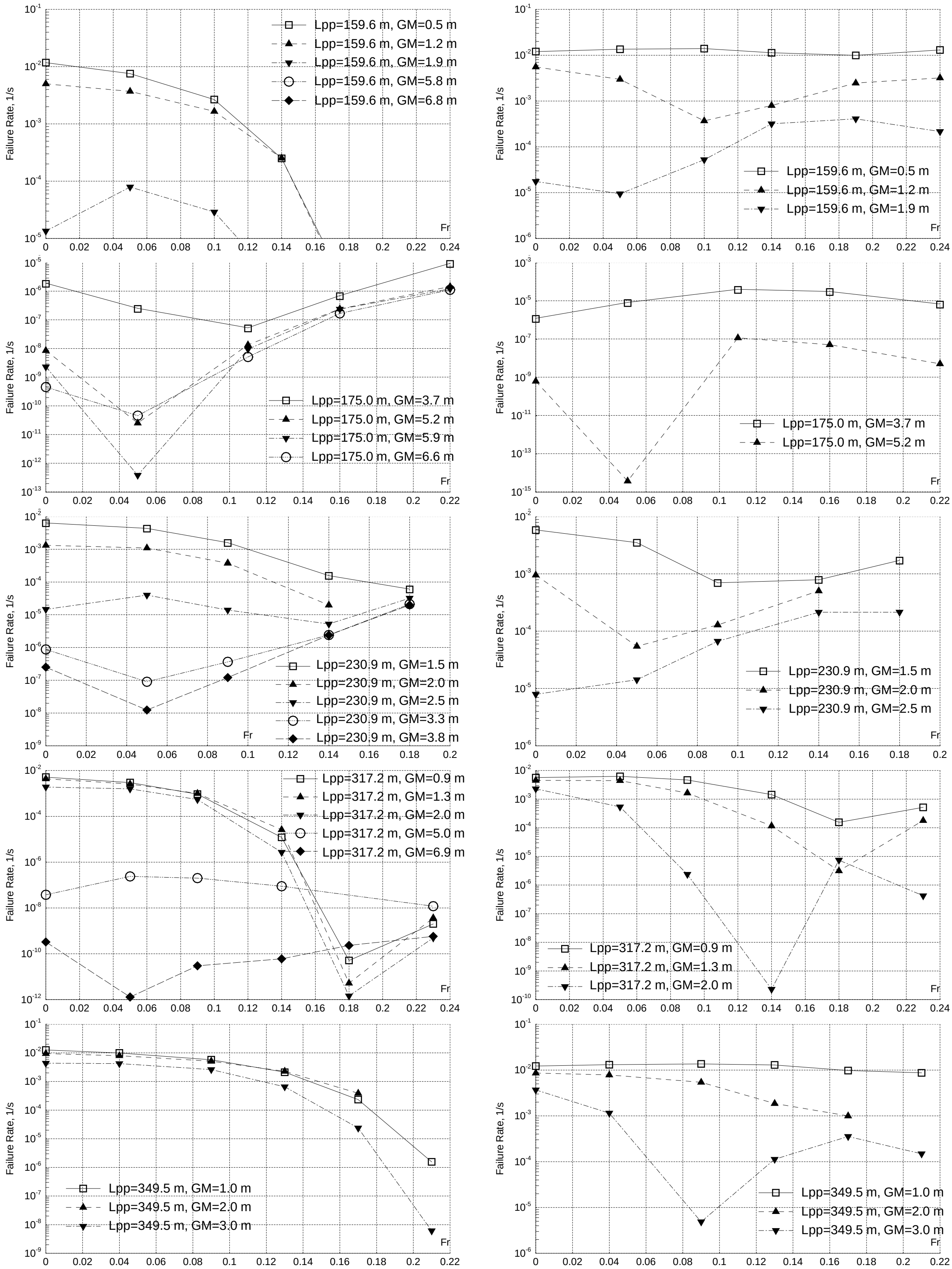


Figure 11. Maximum (over all wave periods) mean short-term stability failure rate, 1/s, at wave height corresponding to sea state probability density $f_s=10^{-5}$ (in $(m\cdot s)^{-1}$, y axis) vs. Froude number (x axis) in head (left) and following (right) waves for (from top to bottom) 1700 TEU container ship, RoPax, cruise vessel and 8400 and 14000 TEU container ships; each line corresponds to one loading condition

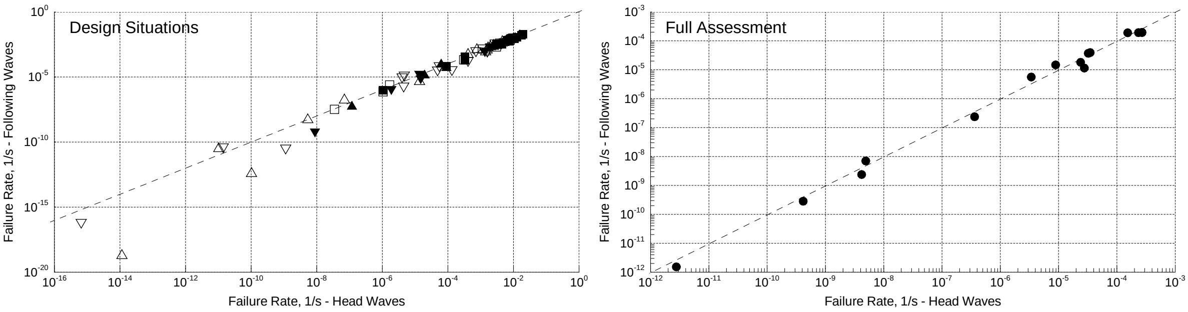
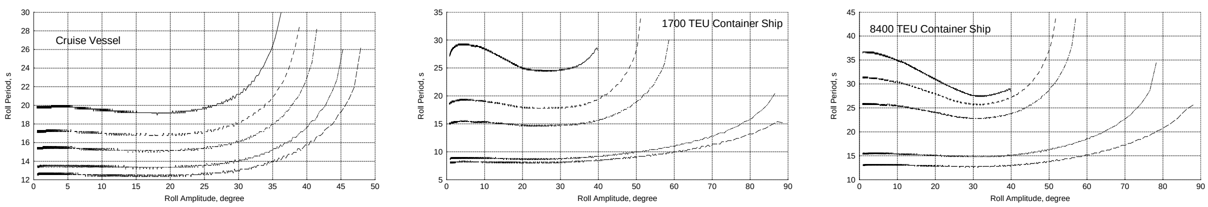


Figure 12. Stability failure rate due to parametric resonance in design situations at zero forward speed (left, symbols differentiate sea state probability density) and in full probabilistic assessment at zero forward speed (right) in following (y axis) vs. head (x axis) waves for all ships and loading conditions

7.19 One more possibility to reduce the number of design situations is to specify the wave period (or at least limit the relevant range of wave periods) before performing seakeeping tests or simulations, e.g. based on the natural roll period from a linear estimation or from roll decay simulations or roll decay model tests (which are performed before seakeeping tests anyway).

7.20 The difficulty is that the natural roll period strongly depends on the roll amplitude: Figure 13 shows the natural roll period estimated from roll decay simulations as a function of the roll amplitude. The dependencies indicate a non-monotonous behaviour, e.g. a decrease of the natural roll period with increasing roll amplitude at small to moderate roll amplitudes, due to nonlinearity of GZ curve, followed by an infinite growth of the natural roll period when roll amplitude approaches the angle of vanishing stability. The other difficulty is that in irregular waves, there is no perfect characteristic of the excitation frequency.



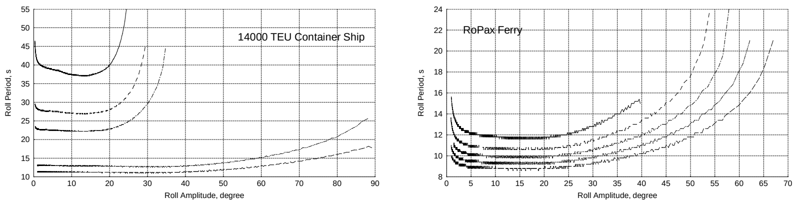


Figure 13. Natural roll period vs. roll amplitude from roll decay for five test ships; lines differentiate loading conditions

7.21 From the results of numerical simulations for those conditions of design situations that are already defined above (namely, wave direction 180 degree for parametric roll in bow waves, 0 degree for parametric roll in stern waves and 90 degree for synchronous roll in beam waves and zero forward speed in all cases), the zero-upcrossing wave period leading to the maximum failure rate over all design sea states was identified, Table 4. According to these results, the range of the encounter wave periods (calculated using the mean zero-upcrossing wave period) leading to maximum failure rate can be localised between 0.3 and 0.5 of the linear natural roll period for principal parametric resonance in bow and stern waves and between 0.7 and 1.3 of the linear natural roll period for synchronous roll in beam waves.

7.22 The simplifications considered so far reduce the total number of assessment cases (i.e. number of combinations of wave height, period and direction and ship forward speed) from about 200 (number of sea states with non-zero probabilities in a scatter table) times 19 (number of wave directions) times 7 (number of forward speeds), i.e. about 25000 altogether, to about 10 (the number of wave periods covering the ranges defined in paragraph 7.20).

Table 4. Ratio of wave encounter period (corresponding to mean zero-upcrossing period) leading to maximum failure rate to natural roll period at 0 and 40 degree roll amplitudes

Ship	GM, m	T_r, s, IS Code	T_r, s, from roll decay at roll amplitude of		$\frac{T_{ez}}{T_r^0}$	$\frac{T_{ez}}{T_r^{40}}$
			0^o	40^o		
Parametric Roll in Bow Waves						
1700 TEU Container Ship	0.50	30.3	29.3		0.346	
	1.20	19.6	19.4	19.4	0.427	0.427
Cruise Vessel	1.50	20.0	19.8		0.465	
	2.00	17.4	17.2	36.9	0.481	0.225
8400 TEU Container Ship	0.89	36.7	36.7	28.8	0.301	0.384
	1.26	31.4	31.3	27.2	0.353	0.406
	2.01	25.9	25.7	23.8	0.358	0.387
14000 TEU Container Ship	1.00	39.0	38.8		0.308	
	2.00	27.6	27.6		0.400	
	3.00	22.5	22.6		0.407	
Parametric Roll in Stern Waves						
1700 TEU Container Ship	0.50	30.3	29.3		0.314	
	1.20	19.6	19.4	19.4	0.427	0.427
Cruise Vessel	1.50	20.0	19.8		0.465	
8400 TEU Container Ship	0.89	36.7	36.7	28.8	0.301	0.384
	1.26	31.4	31.3	27.2	0.353	0.406
	2.01	25.9	25.7	23.8	0.358	0.387
14000 TEU Container Ship	1.00	39.0	38.8		0.308	
	2.00	27.6	27.6		0.400	
	3.00	22.5	22.6		0.448	
Synchronous Roll in Beam Waves						
1700 TEU Container Ship	5.75	8.9	8.8	9.2	0.941	0.901
	6.75	8.2	8.2	8.5	1.234	1.187
RoPax Vessel	3.70	11.7	11.8	15.5	0.780	0.594
	5.20	9.9	9.8	12.1	0.939	0.762
	5.90	9.3	9.4	11.0	0.979	0.837
	6.60	8.8	9.0	10.2	1.022	0.903
8400 TEU Container Ship	5.00	15.5	15.4	15.1	0.776	0.795
	6.93	13.1	13.2	13.0	0.767	0.781
14000 TEU Container Ship	9.00	13.0	13.0	12.9	0.849	0.854
	12.00	11.3	11.4	11.2	0.888	0.905

7.23 For a given number of the required assessment cases, simulation (or model testing) time can also be reduced. For example, the extrapolation of failure rate over wave height can be used to reduce simulation time not only in the full probabilistic assessment but also in the design situations approach, when the required simulation time becomes too large.

7.24 One more possibility to reduce the computational or model testing time is to stop further realisations of the design sea state in numerical simulations or model tests once it is obvious that further realisations are not going to change the final conclusion, i.e. when the estimate of the lower boundary of, for example, a 95%-confidence interval of the mean time to failure exceeds the specified threshold (thus, the loading condition can be considered as allowed) or when the estimate of the upper boundary of the 95%-confidence interval of the mean time to failure is less than the specified threshold (thus, the loading condition can be considered as not allowed). Figure 14 shows simulation results for the 14000 TEU container ship in three loading conditions in a design sea state corresponding to parametric roll in bow waves: if the acceptance threshold for the mean time to stability failure is set to (only as an example) 10^2 s, the loading condition with GM=1.0 m can be considered as not allowed already after 80 simulations, the other one with GM=2.0 m will require 200 realisations, and the loading condition with GM=3.0 m can be considered as allowed already after about 20 simulations.

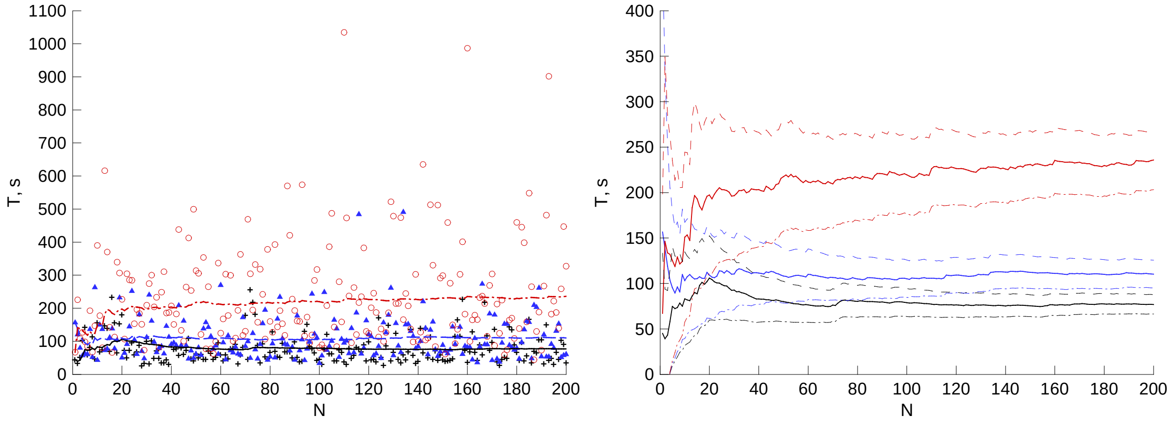


Figure 14. Simulation results for 14000 TEU container ship in design situation corresponding to parametric roll in bow waves. Left: time to stability failure from individual realisations for GM of 1.0 (+), 2.0 (▲) and 3.0 (○) m and estimates of mean time to failure (—, - - - and - · -, respectively). Right: estimates of mean time to failure (solid lines) and upper (- - -) and lower (- · -) boundaries of their 95%-confidence intervals for loading conditions with GM=1.0 m (black), 2.0 m (blue) and 3.0 m (red).

8 Non-probabilistic direct stability assessment

8.1 A drawback of a probabilistic assessment is the need to encounter stability failure events in simulations or in model tests, which requires long durations of simulations or model tests for relevant cases. An appealing idea is to combine design situations with non-probabilistic criteria, e.g. mean maximum roll amplitude per given exposure time, mean roll amplitude etc., which require much less simulation or model testing time for their definition.

8.2 The idea is the same as was shown in Figure 4: as long as the selected non-probabilistic criterion is monotonously related to the true safety measure (e.g. long-term safety failure probability) and scatter between ships, loading conditions and forward speeds is not excessive, the simplified criterion can be directly used for norming, and its acceptance threshold can be defined directly using results of a non-probabilistic assessment for a sufficient number of representative sample cases.

8.3 In the documents SDC 4/5/8 and SDC 4/INF.8, this method was verified for roll in beam sea to address dead ship condition and excessive acceleration stability failures. Two non-probabilistic short-term criteria (mean roll amplitude and mean 3 hour maximum roll amplitude) were tested for different ships, loading conditions and forward speeds in irregular beam seaways. The latter criterion has shown significantly better results than the former one, therefore, it was used here in combination with design situations to develop a non-probabilistic direct assessment concept for parametric and synchronous roll.

8.4 The ships and loading conditions used are the same as listed in Table 1. In the first step, different forward speeds were evaluated separately. One wave direction per failure mode was used for design situations: 180, 0, 90 and 0 degree for parametric roll in bow and stern waves, synchronous roll in beam waves and pure loss of stability, respectively.

8.5 As in the previous section, sea states selected along the lines of constant density of seaway occurrence probability f_s, Figure 5, were used as possible design sea states; as the simplified criterion s, maximum (over design sea states) of the mean 3 hour maximum roll amplitude was used.

8.6 To compute the mean 3 hour maximum roll amplitude, numerical simulations were performed in 50 realisations of each sea state by random variation of frequencies, directions and phases of components modelling seaway.
8.7 Evaluation of the mean 3 hour maximum roll amplitude is impossible in cases with capsizings, since then the roll amplitude is not defined. To distinguish such cases in plots, the mean 3 hour maximum roll amplitude is shown for them as 60 degree for ease of identification, since mean 3 hour maximum roll amplitude never achieved 60 degree in simulations where capsizings did not happen (for the considered ships).

8.8 Figure 15 to Figure 18 show the mean long-term stability failure rate w vs. the mean 3 hour maximum roll amplitude for parametric roll in bow (Figure 15) and stern (Figure 16) waves, synchronous roll in beam waves (Figure 17) and pure loss of stability (Figure 18). The shown mean 3 hour maximum roll amplitude is defined as maximum over all wave periods in design sea states with the density f_s of occurrence probability of 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$ for wave directions 180 degree (for parametric roll in bow waves), 0 degree (parametric roll in stern waves) and 90 degree (synchronous roll in beam waves), and for combined conditions of wave direction 0 degree, encounter peak wave period more than 30 s and wave length equal to ship length (for pure loss of stability). Each point corresponds to one ship in one loading condition at one forward speed.

8.9 Correlation between the mean long-term stability failure rate and mean 3 hour maximum roll amplitude in design sea states is very poor, especially in cases with small roll motions. Although increasing roll motions significantly improve this correlation, they also lead to capsizings which make the evaluation of non-probabilistic criteria impossible.

8.10 To select forward speeds to be used in the assessment, the mean 3-hour maximum roll amplitude in head and following (for parametric roll), beam (synchronous roll) and following (pure loss of stability) waves in sea states with probability density 10^{-5} $(m{\cdot}s)^{-1}$ is plotted vs. forward speed in Figure 19 to Figure 22. The results are similar to the speed dependency of the probabilistic criterion: for parametric roll in head waves and for synchronous roll, decreasing forward speed maximizes 3-hour maximum roll, whereas for pure loss of stability, the greatest roll responses correspond to the maximum forward speed. For parametric roll in following waves, maximum roll may both decrease or increase with increasing forward speed; however, for the most critical loading conditions, low forward speeds lead to maximum roll response. Therefore, similar recommendations can be given for the selection of forward speed as those in the probabilistic design situations approach.

9 Influence of propulsion, steering and seakeeping

9.1 For some stability failure modes, neglecting propulsion and steering abilities of a ship, as well as such seakeeping problems as excessive vertical motions and accelerations and excessive loads at high forward speeds in bow waves, can lead to non-conservative errors in design assessment or misleading operational recommendations. In particular,

.1 For pure loss of stability and surf-riding/broaching stability failures, which are relevant in stern waves, neglecting speed limitations does not lead to non-conservative errors, thus is not critical for dynamic stability.

.2 Dead ship condition stability failure is relevant only at zero forward speed in beam seaway, therefore these problems are also not critical.

.3 For excessive acceleration stability failure, achievable forward speed in beam seaway rather moderately influences roll motion (due to decreasing roll damping with decreasing forward speed) and does not influence the design assessment (which is performed at zero forward speed).

.4 For parametric roll in bow waves, neglecting propulsion, steering and seakeeping abilities can lead to over-estimation of ship's safety in the design assessment, when safe but unattainable combinations of the ship's speed and course are weighted as possible.

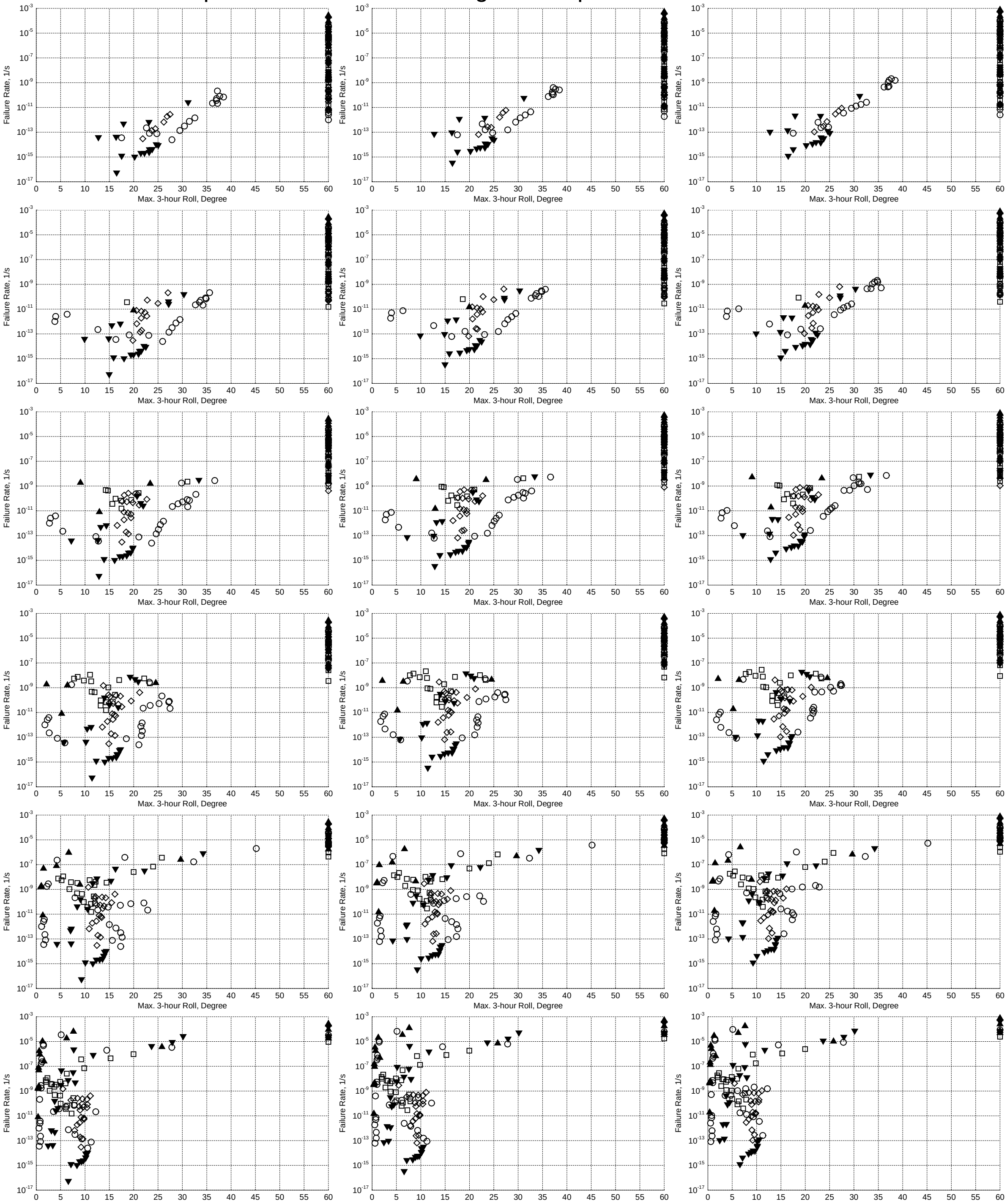


Figure 15. Parametric roll in bow waves: mean long-term failure rate w(ship,LC,v_s), 1/s, y axis, in wave directions from 170 to 180 degree (left), 160 to 180 degree (middle) and 150 to 180 degree (right) vs. non-probabilistic criterion, degree, x axis – mean 3-hour maximum roll amplitude in head waves, maximum over design sea states along lines with sea state occurrence probability density f_s equal to (from top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$. Each point corresponds to one ship (different symbols), one loading condition

and one forward speed. Points with mean 3-hour maximum roll amplitude equal to 60 degree indicate cases with capsizings.

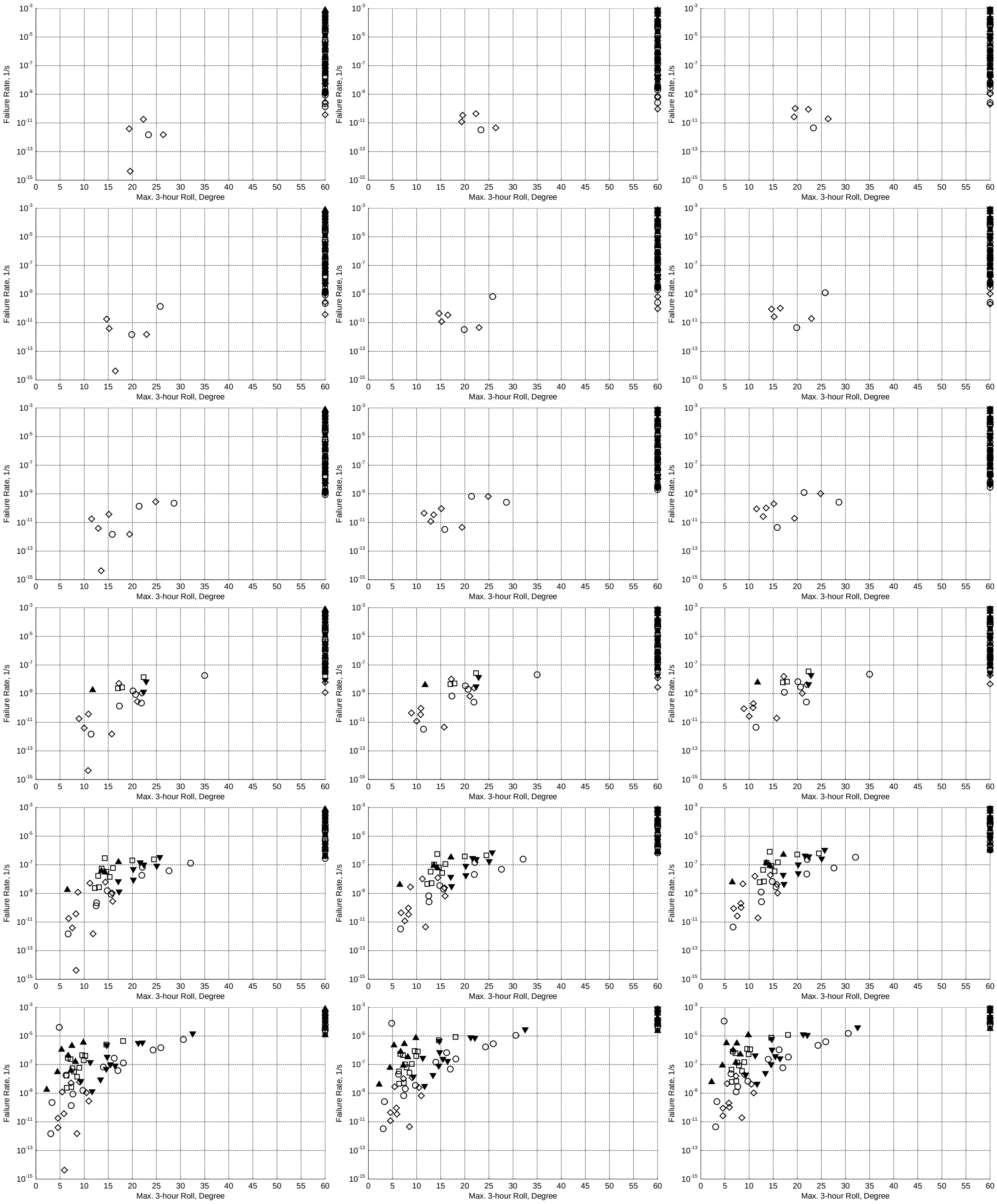


Figure 16. Parametric roll in stern waves: mean long-term stability failure rate w(ship,LC,v_s), 1/s, y axis, in wave directions from 0 to 10 degree (left), 0 to 20 degree (middle) and 0 to 30 degree (right) vs. non-probabilistic criterion, degree, x axis – mean 3-hour maximum roll amplitude in following waves, maximum over design sea states along lines with sea state occurrence probability density f_s equal to (from top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$. Each point corresponds to one ship (different symbols), one loading condition and one forward speed. Points with mean 3-hour maximum roll amplitude equal to 60 degree indicate cases with capsizings.

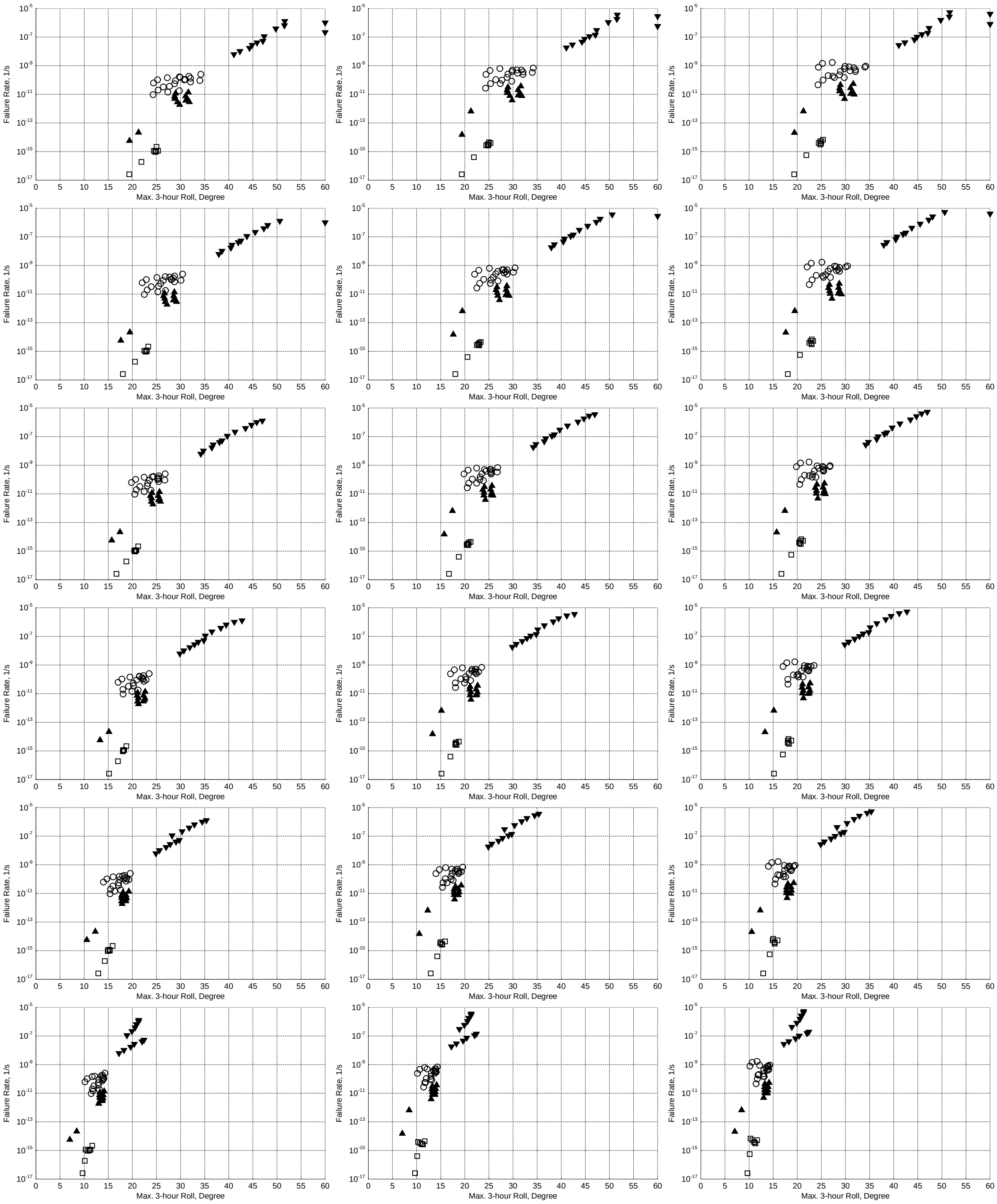


Figure 17. Synchronous roll in beam waves: mean long-term stability failure rate $w(ship, LC, v_s)$, 1/s, y axis, in wave directions from 80 to 100 degree (left), 70 to 110 degree (middle) and 60 to 120 degree (right) vs. non-probabilistic criterion, degree, x axis – mean 3-hour maximum roll amplitude at μ=90 degree, maximum over design sea states along lines with sea state occurrence probability density f_s equal to (from top to bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m \cdot s)^{-1}$. Each point corresponds to one ship (different symbols), one loading condition and one forward speed. Points with mean 3-hour maximum roll amplitude equal to 60 degree indicate cases with capsizings.

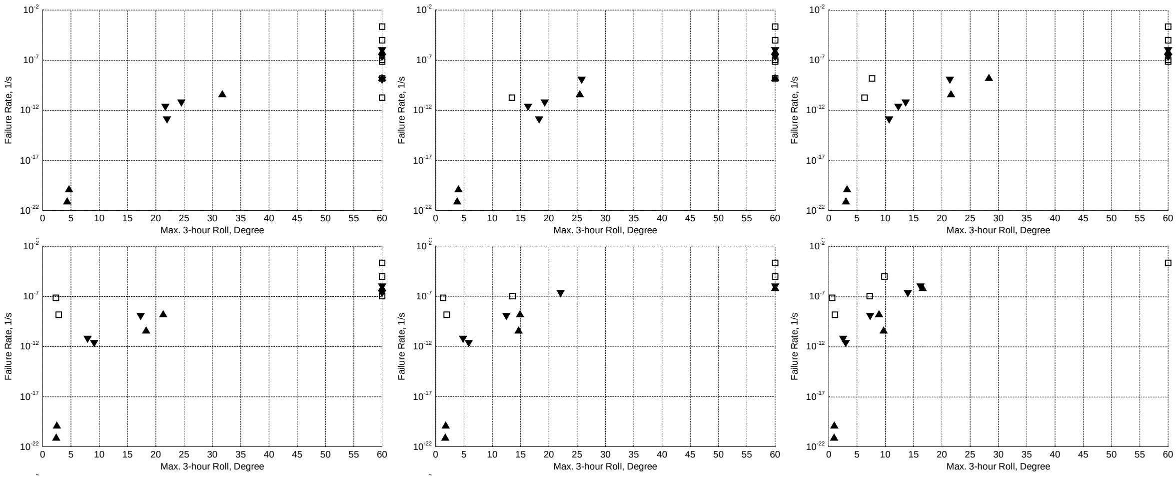


Figure 18. Pure loss of stability in following waves: mean long-term stability failure rate w(ship,LC,v_s), 1/s, y axis, vs. non-probabilistic criterion, degree, x axis – mean 3-hour maximum roll amplitude in following waves, maximum over design sea states along lines with sea state occurrence probability density f_s equal to (from left to right, top then bottom) 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} and 10^{-2} $(m{\cdot}s)^{-1}$. Each point corresponds to one ship (different symbols), one loading condition and one forward speed. Points with mean 3-hour maximum roll amplitude equal to 60 degree indicate cases with capsizings.

9.2 To estimate the influence of propulsion ability on parametric roll in head waves, average (over all significant wave heights and wave periods) rate of parametric roll stability failures in head waves was calculated with and without considering maximum attainable speed in head waves. In both cases, the forward speed was applied that minimises the stability failure rate, but in the calculations considering propulsion ability, the range of speeds was restricted by the condition that the required engine power should not exceed the available power. Figure 23 shows the result as the rate of stability failures considering speed limit plotted depending on the rate of stability failures without considering speed limit.

9.3 The results show that the rate of stability failures increases by several orders of magnitude if propulsion ability is considered. This means that assessment at zero forward speed in head waves (already proposed in the design situations method using other considerations) is a conservative but realistic assumption.

10 Definition of standard and thresholds

10.1 To distinguish allowed and not allowed loading conditions, an acceptance standard should be defined for the mean long-term stability failure rate w, as well as coherent short-term acceptance thresholds for the criteria used in the simplified assessment procedures (i.e. for the mean short-term stability failure rate r and for the mean three-hour maximum roll amplitude φ_{3h} in design situations) for all stability failure modes.

10.2 The relationship between the long-term probabilistic criterion w, on the one hand, and the short-term design-situation criteria r (Figure 6, Figure 7, Figure 8 and Figure 9) and φ_{3h} (Figure 15, Figure 16, Figure 17 and Figure 18), on the other hand, are universal as pure statistical relationships and do not depend on the code; besides, the dependencies between w and r are sharp, thus they are not subject to stochastic noise. Thus, short-term acceptance thresholds for r and φ_{3h} can be defined directly from case studies in design situations, without the need for a full probabilistic assessment, and the standard for w for the full probabilistic assessment can be derived from the short-term design-situation thresholds for r and φ_{3h}.

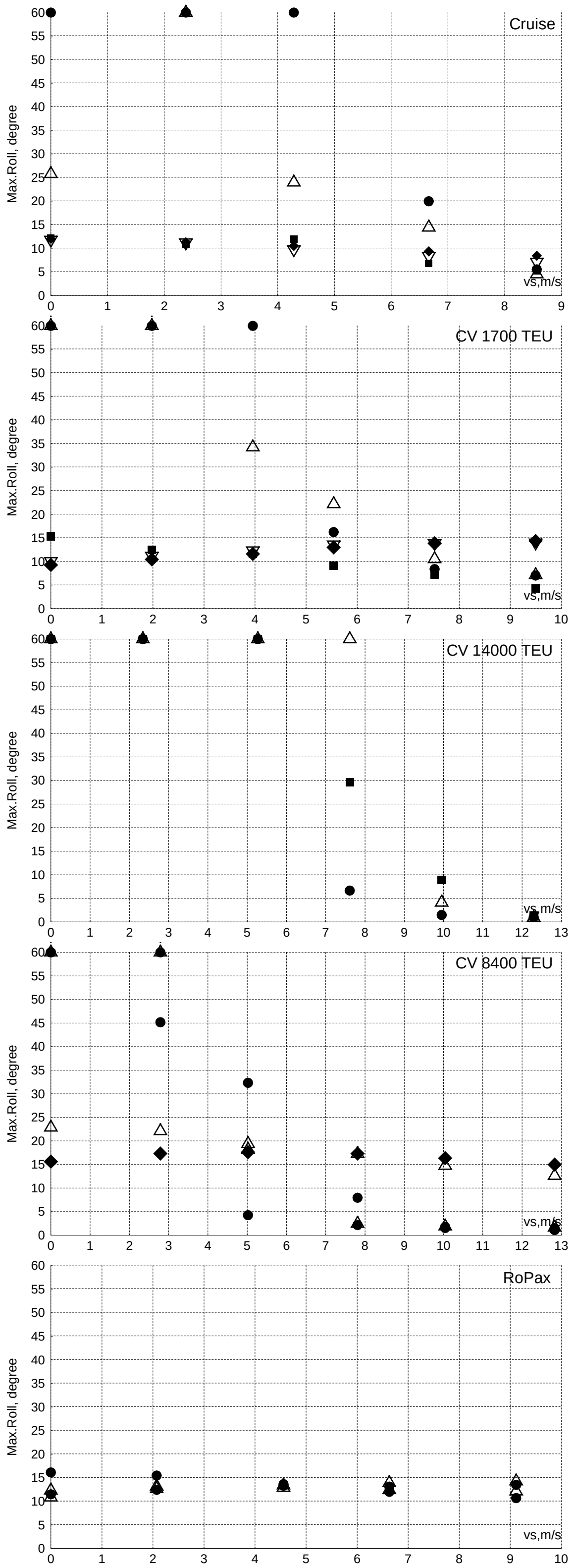


Figure 19. Mean 3-hour maximum roll amplitude due to parametric roll in head waves in sea states with $f_s=10^{-5}$ (m·s)$^{-1}$ vs. forward speed. Each plot corresponds to one ship; different symbols correspond to different loading conditions.

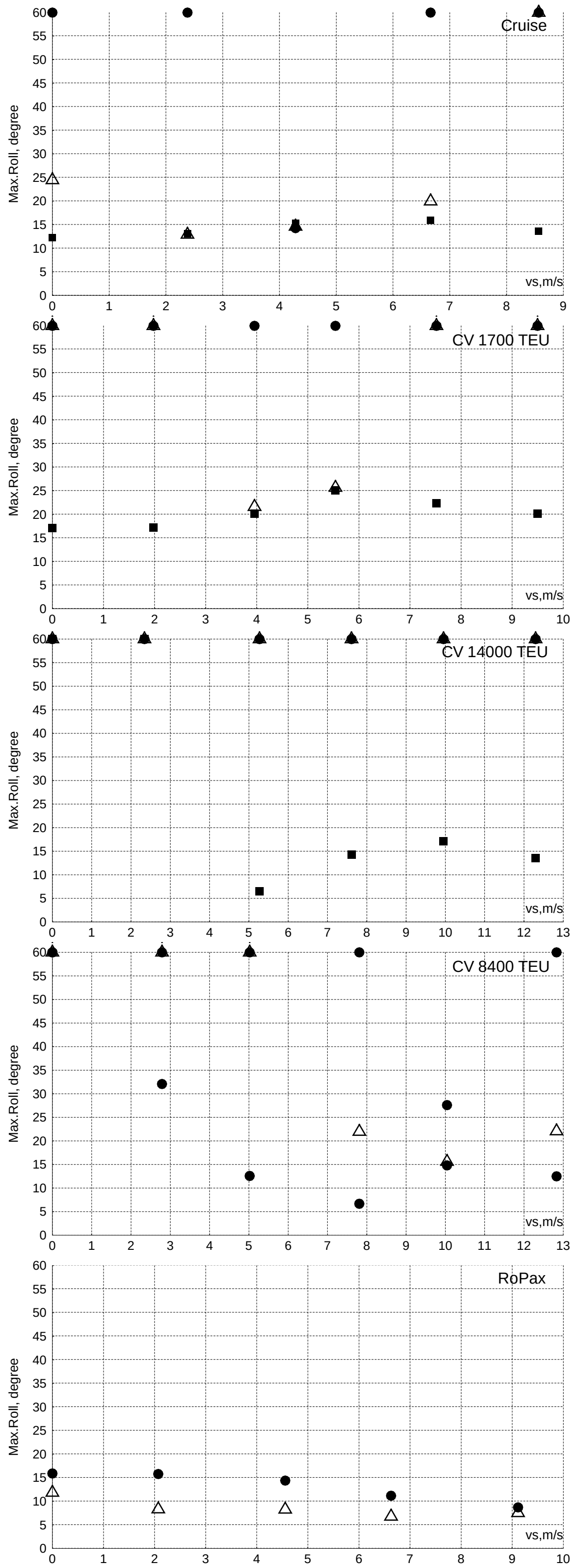


Figure 20. Mean 3-hour maximum roll amplitude due to parametric roll in following waves in sea states with $f_s=10^{-5}$ (m·s)$^{-1}$ vs. forward speed. Each plot corresponds to one ship; different symbols correspond to different loading conditions.

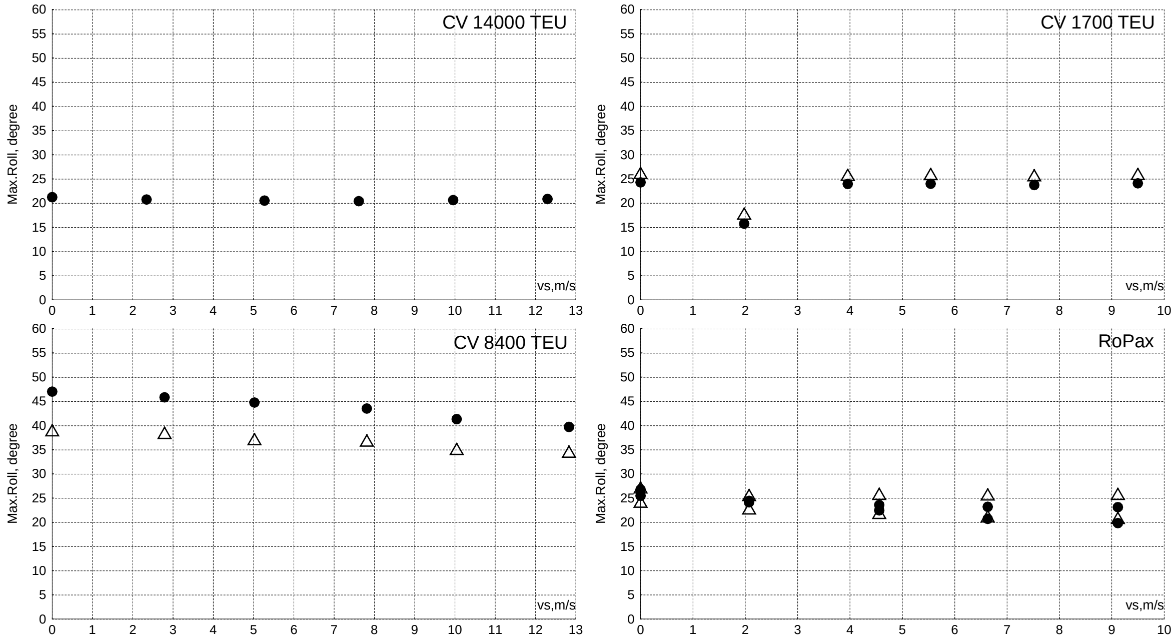


Figure 21. Mean 3-hour maximum roll amplitude due to synchronous roll in beam waves in sea states with $f_s=10^{-5}$ $(m\cdot s)^{-1}$ vs. forward speed; each plot corresponds to one ship; different symbols correspond to different loading conditions

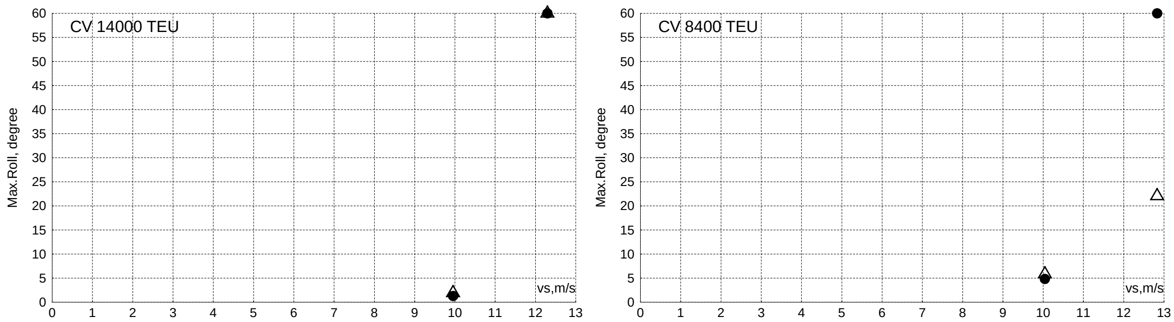


Figure 22. Mean 3-hour maximum roll amplitude due to pure loss of stability in following waves in sea states with $f_s=10^{-5}$ $(m\cdot s)^{-1}$ vs. forward speed. Each plot corresponds to one ship; different symbols correspond to different loading conditions.

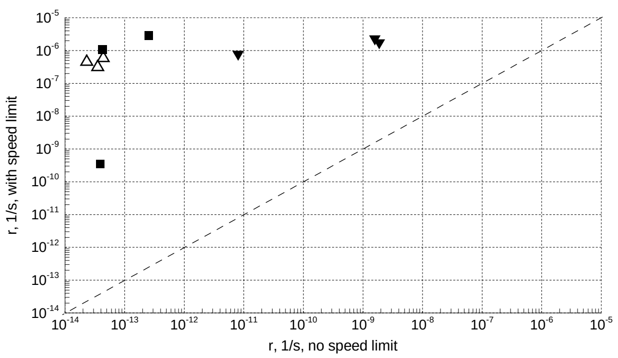


Figure 23. Rate of parametric roll stability failures in head waves considering (y axis) and not considering (x axis) attainable forward speed for three container ships (different symbols) in three loading conditions each

10.3 However, the missing link is the relationship between the standard for the mean long-term stability failure rate in the full probabilistic assessment and the mean stability failure rate in the real operation, i.e. the actual safety level: this relationship is uncertain, whereas the stability failure rate in the full probabilistic assessment may differ from the failure rate in real operation by few orders of magnitude due to several factors:

.1 full probabilistic assessment is conducted in the rather severe North Atlantic wave climate and the mean safety level relates to the world-wide operation;

.2 routing and heavy-weather avoidance are not considered;

.3 assessment is performed separately for each loading condition, thus the worst loading condition (which may never occur in practice) has the dominating effect on the results;

.4 unsafe forward speeds and courses, avoided in reality in heavy weather, produce dominating (by few orders of magnitude) contributions to the long-term failure rate. For example, principal parametric resonance in following waves, especially at low speeds, provides dominating contributions to failure rate for loading conditions with low GM, Figure 24, whereas in reality such situations are avoided (stern slamming, low free board) or impossible (inability to keep course).

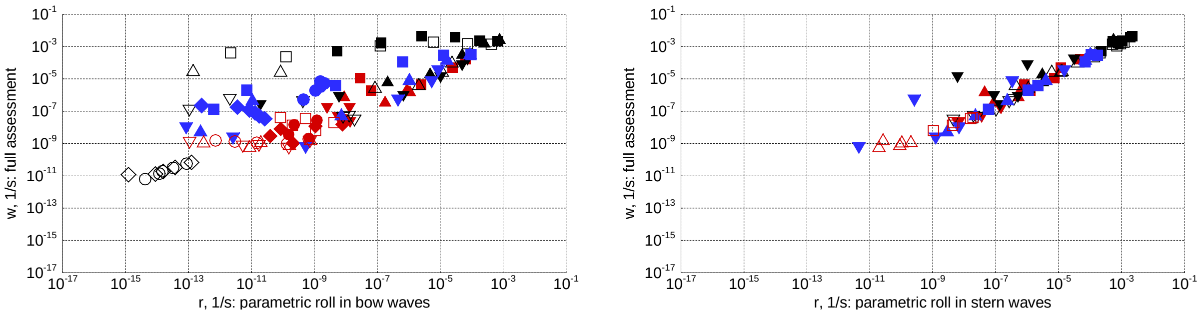


Figure 24. Contributions to mean long-term stability failure rate w (1/s, y-axis) from principal parametric resonance in bow (left) and stern (right) waves (1/s, x-axis); symbol types and colours differentiate ships and loading conditions

10.4 To estimate the lower and upper bounds for the standard for the mean long-term stability failure rate w in the full probabilistic assessment and the short-term threshold for the stability failure rate r in design situations, the following considerations were applied:

.1 In the Appendix to the proposal for the Guidelines for operational measures, the value $2.64 \cdot 10^{-3}$ accidents per ship per year was proposed as the required safety level, based on FSA studies for container vessels, LNG carriers, crude oil tankers, cruise ships, RoPax and general cargo vessels (ref. documents MSC 83/INF.8, MSC 83/INF.3, MEPC 58/INF.2, MSC 85/INF.2, MSC 85/INF.3 and MSC 88/INF.8, respectively). From this figure, a conservative estimate of the standard for the full probabilistic assessment in the North Atlantic wave climate was defined as $2.6 \cdot 10^{-8}$ 1/s considering factors mentioned in paragraphs 10.3.1 to 10.3.4, which is used here as one of estimates for the lower bound of the standard for w;

.2 It is useful to note that a similar study on setting standards for the vertical bending moment[4] has shown that the definition of the standard for results of numerical assessment as once per design life in the North Atlantic wave climate leads to too conservative results compared to the existing fleet

[4] Derbanne, Q., Storhaug, G., Shigunov, V., Xie, G., and Zheng, G. (2016) Rule formulation of vertical hull girder wave loads based on direct computation, Proc. PRADS 2016, 4th-8th September, Copenhagen, Denmark

(known to be sufficiently safe) and requirements of classification societies; to harmonise the results of direct assessment with classification rules, a “routing factor” 0.85 was proposed, with which wave heights should be multiplied. For comparison, the present results of the full probabilistic assessment were reevaluated with 0.85-scaled wave heights, which leads to the standard for w of $1.4{\cdot}10^{-8}$ 1/s; since this value is close to the estimate of the standard in paragraph 10.4.1, it was not used;

.3 The results of assessment with respect to the dead ship stability failure mode in design situations were sorted, suggesting that loading conditions satisfying the Weather Criterion of the 2008 Intact Stability Code should also satisfy the direct stability assessment with respect to the dead ship stability failure mode, whereas loading conditions failing the Weather Criterion should also fail the direct assessment with respect to the dead ship condition stability failure mode; this led to the upper and lower estimates for the short-term design-situation threshold for r shown in Table 5.

.4 Stability failure rate defined from numerical simulations or, especially, model tests cannot be too high or too low: in the former case, it will be difficult to minimize the influence of the initial conditions (thus, it is proposed to limit the mean stability failure rate in design situations as $r \le 10^{-3}$ 1/s, i.e. one failure in 10^3 s), and in the latter case, required testing or simulation time will be too large (thus, it is proposed to limit the mean stability failure rate in design situations as $r \ge 10^{-4}$ 1/s, i.e. one failure in 3 hours).

Table 5. Estimates of lower and upper boundaries for short-term design-situation r-threshold from comparison with Weather Criterion

f_s, $(m{\cdot}s)^{-1}$	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
lower	$1.8{\cdot}10^{-34}$	$1.0{\cdot}10^{-15}$	$2.8{\cdot}10^{-10}$	$7.5{\cdot}10^{-8}$	$1.8{\cdot}10^{-6}$	$1.4{\cdot}10^{-5}$
upper	$1.7{\cdot}10^{-9}$	$2.8{\cdot}10^{-5}$	$4.7{\cdot}10^{-4}$	$1.7{\cdot}10^{-3}$	$3.5{\cdot}10^{-3}$	$5.6{\cdot}10^{-3}$

10.5 Figure 25 plots together the w(r) dependencies of the mean long-term stability failure rate w on the mean short-term stability failure rate in design situations r for all stability failure modes from Figure 6, Figure 7, Figure 8 and Figure 9 for $f_s=10^{-2}$ to 10^{-7} $(m{\cdot}s)^{-1}$ together with the estimates for the bounds for w-standard and r-threshold according to the considerations in paragraphs 10.4.1, 10.4.3 and 10.4.4; the bounds for w-standard are transferred into bounds for r-threshold and the other way around using the w(r) dependencies. The colours of the resulting rectangles indicate:

.1 red: requirements according to FSA studies, paragraph 10.4.1;

.2 green: Weather Criterion results, paragraph 10.4.3 and Table 5;

.3 blue: practical considerations in paragraph 10.4.4.

10.6 Overlapping areas, indicated with arrows in Figure 25 and shown in increased resolution in Figure 26, mean the possibility of non-contradicting combination of all estimates and show that the direct assessment using design situations is possible in design sea states with probability density $f_s=10^{-5}$, 10^{-6} and, marginally, 10^{-7} $(m{\cdot}s)^{-1}$, as well as for all intermediate values of f_s. For greater or lower values of f_s, the areas corresponding to various estimates do not overlap, note, however, that for design sea states with the probability density 10^{-4} (m·s)$^{-1}$, the limitation is long simulation time, which is not a crucial problem for some numerical methods and, besides, that the required simulation time reduces if the standard for the mean long-term stability failure rate w increases.

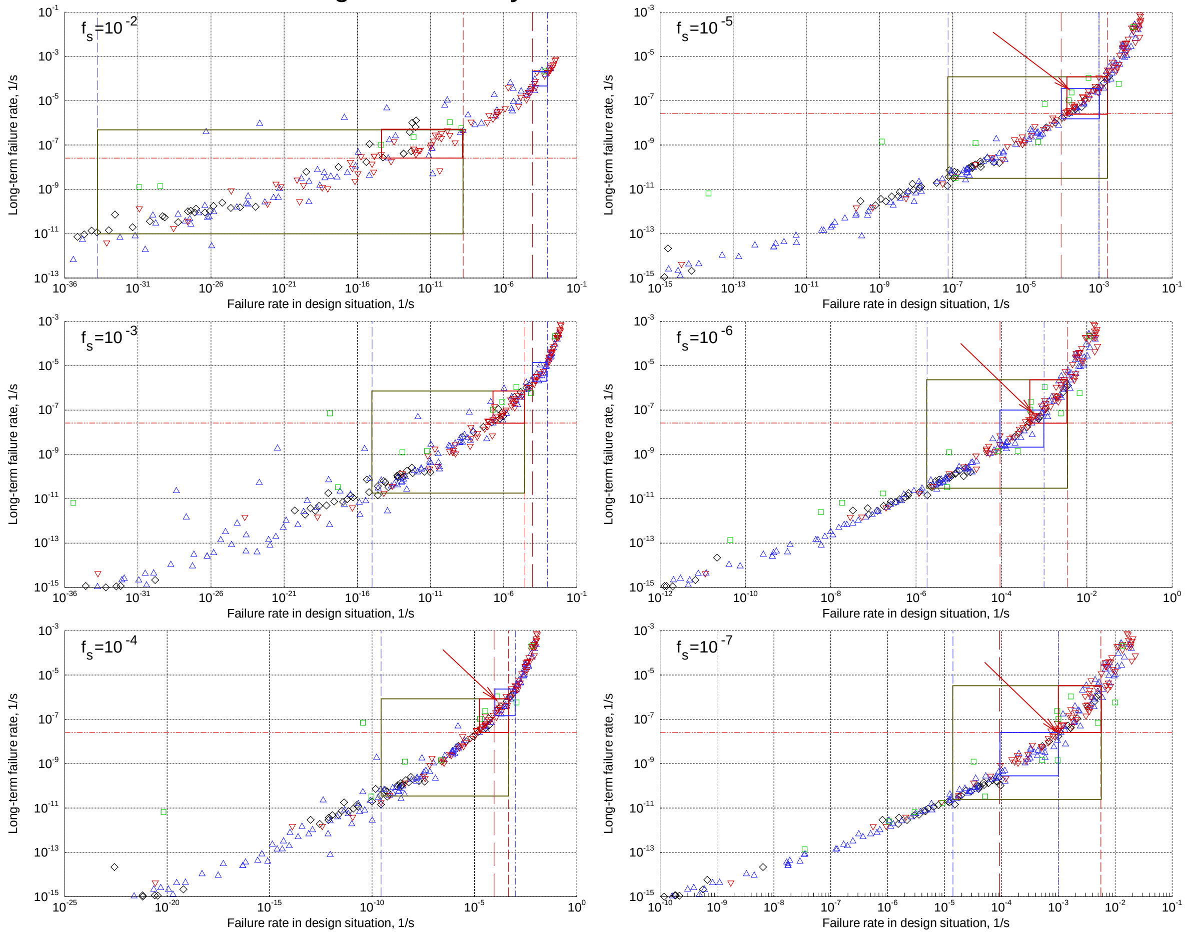


Figure 25. Combined dependencies w(r) of mean long-term stability failure rate w on mean short-term design-situation stability failure rate r for all stability failure modes from Figure 6, Figure 7, Figure 8 and Figure 9 for f_s of (from top left to bottom right) 10^{-2} to 10^{-7} (m·s)$^{-1}$ together with estimates according to paragraphs 10.4.1, 10.4.3 and 10.4.4; arrows indicate overlapping areas, where non-contradicting combination of estimates is possible

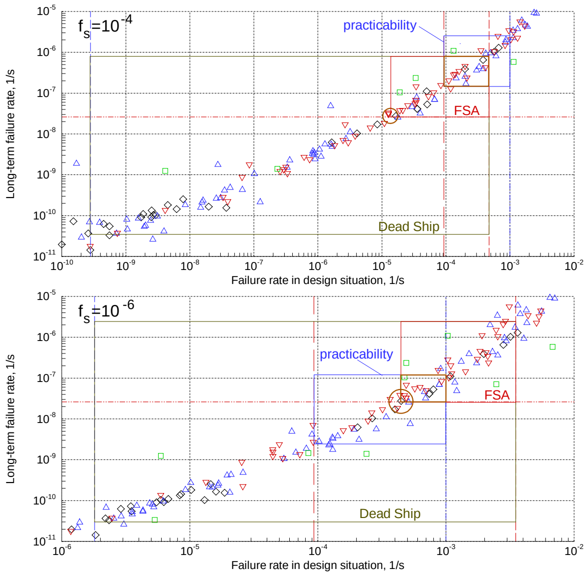


Figure 26. Definition of standard and threshold (increased resolution plots from Figure 25); thick line rectangle indicates overlapping area, circle indicates selection

10.7 According to the analysis in Figure 25 and Figure 26, the value $2.6\cdot10^{-8}$ 1/s seems suitable as a conservative estimate for the standard for the mean long-term stability failure rate w in the full probabilistic assessment. As thresholds for the mean short-term stability failure rate r in design situations, the following values are suitable:

.1 one stability failure in 20 hours in design sea states with $f_s=10^{-4}$ $(m\cdot s)^{-1}$;

.2 one stability failure in 3 hours (slightly conservative) to one stability failure in 2 hours in design sea states with $f_s=10^{-5}$ $(m\cdot s)^{-1}$;

.3 one stability failure in one hour (rather conservative) to one stability failure in 40 minutes in design sea states with $f_s=10^{-6}$ $(m\cdot s)^{-1}$;

.4 one stability failure in 15 minutes in design sea states with $f_s=10^{-7}$ $(m\cdot s)^{-1}$; however, such a high failure rate may lead to a significant influence of initial conditions, and, besides, sea states corresponding to $f_s=10^{-7}$ $(m\cdot s)^{-1}$ may be too steep for model tests.

10.8 Table 6 shows the significant wave height vs. the mean zero-upcrossing wave period at $f_s=10^{-5}$ and 10^{-6} $(m\cdot s)^{-1}$ for unrestricted service, i.e. wave scatter table from IACS Rec. 34.

Table 6. Significant wave height depending on mean zero-upcrossing wave period for sea states with density of occurrence probability of 10^{-5} and 10^{-6} $(m\cdot s)^{-1}$

f_s, $(ms)^{-1}$	T_z, s													
	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
10^{-5}	2.8	5.5	8.2	10.6	12.5	13.8	14.6	15.1	15.1	14.8	14.1	12.9	10.9	-
10^{-6}	3.7	6.8	9.8	12.3	14.3	15.7	16.6	17.1	17.3	17.2	16.7	15.9	14.7	12.9

10.9 Whereas the threshold for the mean 3-hour maximum roll amplitude φ_{3h} for non-probabilistic assessment in design situations can be defined in a similar way, a slightly different approach was used:

.1 the threshold for φ_{3h} was set to half of the heel angle in the definition of the stability failure to avoid capsizings in the relevant model tests or numerical simulations;

.2 the maximum value of the mean long-term stability failure rate w, computed in the full probabilistic assessment, was found over all ships, loading conditions and forward speeds satisfying the chosen φ_{3h}-threshold in design situations;

.3 in this way, the maximum value of the mean long-term stability failure rate w becomes a function of the probability density f_s defining design sea states, in which the non-probabilistic assessment is performed.

10.10 Figure 27 plots the resulting mean long-term stability failure rate w (y-axis) as a function of the probability density f_s defining design sea states (x axis). To satisfy the selected standard for the mean long-term stability failure rate $2.6{\cdot}10^{-8}$ 1/s (dashed line), the design sea states with the probability density $f_s=7{\cdot}10^{-5}$ $(m{\cdot}s)^{-1}$ (circle) should be used.

10.11 Table 7 shows the significant wave height vs. the mean zero-upcrossing wave period for $f_s=7{\cdot}10^{-5}$ $(m{\cdot}s)^{-1}$ for unrestricted service (IACS Rec. 34 wave scatter table).

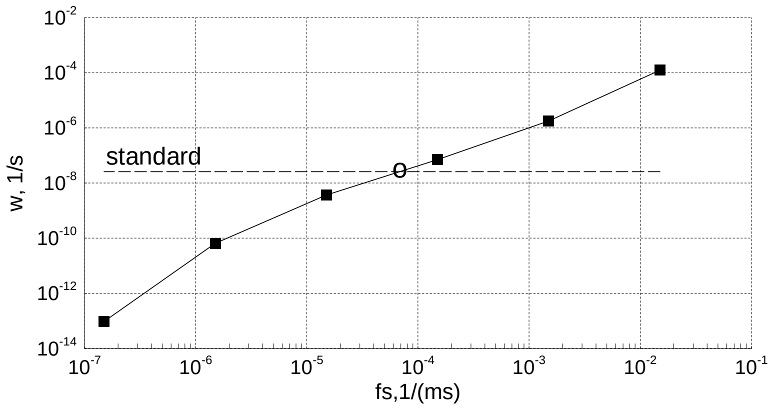


Figure 27. Definition of design sea states for non-probabilistic assessment

Table 7. Significant wave height vs. mean zero-upcrossing wave period for sea state probability density of $7{\cdot}10^{-5}$ $(m{\cdot}s)^{-1}$ in North Atlantic wave climate

T_z,s	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
h_s,m	2.0	4.4	6.9	9.1	10.9	12.1	12.8	13.1	13.0	12.5	11.3	9.0

10.12 The proposed standard for the mean long-term stability failure rate w and thresholds for mean short-term failure rate r and mean 3 hour maximum roll amplitude φ_{3h} in design situations can be fine-tuned using either the full probabilistic assessment or assessment in design situations for accidental ships in accidental loading conditions and applying Figure 25, Figure 26 and Figure 27 to scale the long-term standard into short-term threshold or vice versa.