Possible Simplifications of Direct Stability Assessment

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ABSTRACT

The second generation intact stability criteria, presently developed at IMO, are based on three alternative assessment procedures: level 1, level 2 and a direct stability assessment (DSA). DSA is the most accurate assessment available in SGISC, however, it requires significant computational effort. To reduce it, three simplifications are considered to enable using DSA in practical design approval: extrapolation of the average time to stability failure over wave height, reduction of the assessment to few selected design situations and use of deterministic safety criteria in design situations.

Keywords: *Second-Generation Intact Stability Criteria, Direct Stability Assessment, Probabilistic Assessment.*

1. INTRODUCTION

The framework of the second generation intact stability criteria (SGISC) [1] relies on three alternative assessment procedures: level 1 (L1), level 2 (L2) and direct stability assessment (DSA). Compliance with any of these assessments is sufficient to fulfil SGISC. Alternatively, ship-specific operational limitations (OL) or operational guidance (OG) can be developed for loading conditions failing to fulfil the criteria.

Assessment of a loading condition is done by comparing a *criterion* (measure that quantifies ship safety in seaway) with a *standard* (threshold value that separates safe and unsafe values of the criterion). In a *probabilistic DSA*, the probability of stability failure (or a similar measure, such as rate of stability failures per time) is used as a criterion, thus a probabilistic DSA requires some form of counting of stability failure events per given time, which means that such events need to be encountered in the simulations. This leads to the *problem of rarity*, because for the cases where DSA will be relevant in practice, stability failure events are very rare. Moreover, a reliable estimate of stability failure probability requires simulation of a sufficiently large number of stability failure events, which further increases required simulation time.

On the other hand, DSA is intended to be the most accurate procedure available in SGISC, which considers all relevant physics in the most accurate way. Thus, simulation tools employed in DSA are rather slow and require much more computational time than those in L1 and L2, i.e. simplifications are required in *probabilistic procedures* to enable the use of DSA in practical design approval. Several probabilistic procedures have been proposed so far reducing the required simulation time or number of simulations or both. Here, two of such probabilistic procedures are studied: extrapolation of the average time to stability failure over wave height and reduction of the number of cases considered in the assessment to few selected *design situations* defined by the specified ship speed and wave height, direction and period.

The advantage of the extrapolation of time to stability failure over wave height is that it provides, in feasible computational time, probability of stability failure for all combinations of wave height, period and direction encountered during a design life of a ship, and the results of such DSA can be directly used as an OG.

In the *design situations* method, the assessment is performed for few selected combinations of ship speed and wave height, direction and period, referred to as design situations, which significantly reduces the number of required simulations. The drawback of this approach is that the results of DSA cannot be directly used as OG, thus OG will have to be developed for loading conditions failing to fulfil DSA. On the other hand, such a quick DSA procedure will efficiently reduce the number of loading conditions requiring OG. Paper [2] shows that this method reduces the required computational time by an order of magnitude compared to the extrapolation method. On the other hand, significant scatter of the dependencies of the stability failure probability computed over all sea states and all wave headings on the results of the procedure based on design situations was found between various ships and loading conditions. This paper tests the idea of using different design situations for different stability failure modes and considers, as the first step, dead ship stability failure in beam seaway.

The drawback of a probabilistic DSA is the need to directly simulate rare stability failure events, which requires long simulation times even when design situations are used; besides, probabilistic DSA is very difficult to do using model tests instead of numerical simulations. Therefore, another idea tested here to further simplify and accelerate DSA combines design situations with *non-probabilistic (deterministic) safety criteria*, such as the expected maximum roll amplitude during a specified time, mean roll amplitude etc. Evaluation of such criteria requires much less simulation time and is much easier to implement in model tests than evaluation of stability failure probability. Therefore, it appears worthwhile to check whether such simplified criteria are sufficiently accurate for practical use.

2. PROBABILISTIC ASSESSMENT

In a probabilistic DSA procedure, the probability of stability failure is used directly as a safety measure (criterion). Therefore, such DSA requires some form of counting of stability failure events. The probability of stability failure of a ship in a given loading condition during a given exposure time can be found by performing a sufficiently big number of simulations of a given duration, covering all relevant sea states, wave directions and ship speeds, and dividing the number of simulations in which a stability failure occurred by the total number of simulations. An alternative approach, based on the assumption of stability failure events as a Poisson process, can be used *if stability failure events are independent of each other*. This independence is obvious for the stability failure events in the reality; in numerical simulations, independence of stability failure events should be provided by the procedure. Here, each numerical simulation was performed (in a given sea state) only until the first stability failure event (here, exceedance of 40° roll angle). After that, the simulation was stopped and restarted, in the same sea state, with a different set of random phases, frequencies and directions of the wave components composing sea state.

For a Poisson process, the time to stability failure T is a random *exponentially distributed variable* with a constant *rate parameter* r and the following well-known characteristics:

1. Probability density function
$$f\left(T\right) = re^{-rT},\ T \geq 0,\ 0 \text{ otherwise} \tag{1}$$
2. Cumulative distribution function
$$f\left(T\right) = 1 - e^{-rT} \text{ for } T \geq 0,\ 0 \text{ otherwise} \tag{2}$$
3. Expected time until stability failure
$$E\left\{T\right\} \equiv \bar{T} = 1/r \tag{3}$$
4. Standard deviation of time until failure
$$\sigma\left\{T\right\} = 1/r = \bar{T} \tag{4}$$
5. Variance of time until stability failure
$$Var\left\{T\right\} = 1/r^2 = \bar{T}^2 \tag{5}$$
6. Probability of at least one failure during time t
$$p = 1 - e^{-rt} = 1 - e^{-t/\bar{T}} \tag{6}$$
7. Maximum likelihood estimate of rate r
$$\tilde{r} = N \Big/ \sum\nolimits_{i=1}^{N} T_i \tag{7}$$
where T_i are time intervals until stability failure from each of N realisations;
8. Maximum likelihood estimate of the expected time until stability failure
$$\tilde{T} = \frac{1}{N}\sum_{i=1}^{N} T_i \tag{8}$$
9. If T_1, …, T_L are independent exponentially distributed variables, $\min\left\{T_1, \ldots, T_L\right\}$ is also exponentially distributed with rate $r = r_1 + \cdots + r_L$; this is very convenient for combining stability failure modes.

Relation (4) allows estimating other statistical characteristics of an exponential distribution knowing only the estimated expected value $\tilde{T}$. To check this relation for exceedance of a given roll amplitude, Fig. 1 shows the ratio of the estimate of standard deviation of time to failure to the estimate of the expected time to failure as a function of the number of simulated stability failure events, whereas Fig. 2 shows the estimate of standard deviation $\sigma\{T\}$ vs. the expected value estimate $\tilde{T}$ after N=200 simulated stability failure events; the results confirm that equations (4) and (5) can be used to estimate the standard deviation and variance of the time until stability failure event (for a given loading condition, forward speed and course, and wave height, direction and period).

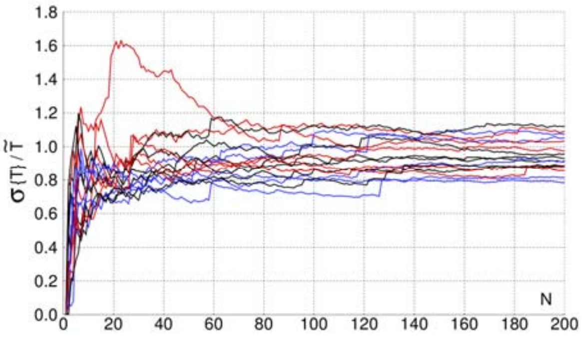

Fig. 1. Ratio of estimate of time to failure standard deviation to estimate of expected time to failure depending on number of simulated failures

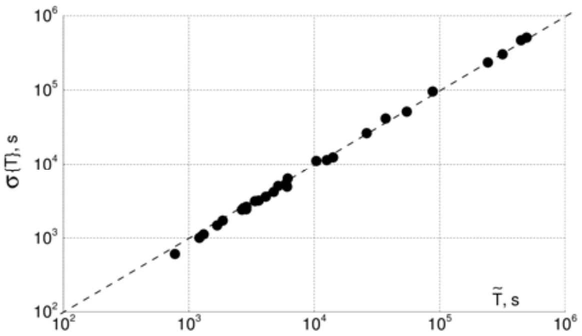

Fig. 2. Estimate of time to failure standard deviation vs. estimate of expected failure time for 200 simulated failure events

According to the central limit theorem, for a sufficiently large sample size N the expected time to failure can be assumed normally distributed with the standard deviation $\sigma\{\bar{T}\} = \sigma\{T\}/N^{0.5}$, where $\sigma\{T\}$ is the standard deviation of the time to stability failure and N is the sample size. Then, for example a 95%-confidence interval for the expected time to stability failure, $\bar{T} \pm 1.96 \cdot \sigma\{\bar{T}\}$, can be estimated as $\tilde{T} \pm 1.96 \cdot \tilde{T}/N^{0.5}$, or $\tilde{T}(1 \pm 0.14)$ for N=200. This can be used to estimate the required number of simulated stability failures to estimate the expected time to stability failure with a given accuracy $\Delta\tilde{T}/\tilde{T}$,

$$N = 1.96^2 / \left(\Delta\tilde{T}/\tilde{T}\right) \tag{9}$$

where $\Delta\tilde{T}$ is a 95%-confidence interval for the estimate of the expected time to failure. Figure 3 shows the estimate of the expected time to failure depending on the number N of simulated failure events from simulations together with the boundary of $\Delta\tilde{T}/\tilde{T}$ according to (9) and ±5% boundaries. The figure shows that 5%-accuracy requires about N=200 simulated failure events.

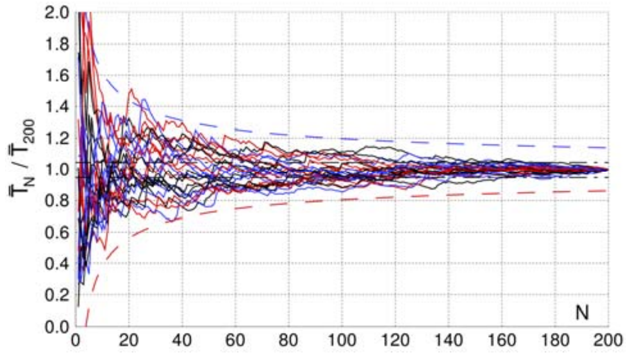

Fig. 3. Estimate of expected time to failure depending on the number of simulated failure events (solid lines) vs. estimate (9) (dashed lines) and 5%-tolerance boundaries (dash-dotted lines)

3. EXTRAPOLATION OVER H_S

The problem of rarity together with the problem of large number of stability failure events that need to be simulated need probabilistic procedures which can reduce required simulation time. This study considers the method of extrapolation of the expected time to stability failure $\bar{T}$ over significant wave height h_s (at a given wave period, wave direction and ship forward speed). The extrapolation method proposed in [3] is applied here in the following form:

$$\ln T = A + B/h_s^2 \tag{10}$$

where T means in this section the expected time to stability failure, h_s is the significant wave height and A and B are constant coefficients, independent from the significant wave height but dependent on the ship, loading condition, ship forward speed, wave period and wave direction.

This procedure efficiently calculates the rate of failure events for all sea states encountered during the design life of a ship, thus the results can be directly used as OG. In [2] it was shown that the procedure can provide accurate results; here the uncertainties of this procedure are quantified by comparison with direct simulations. The main particulars of ships and load cases used in testing are summarised in Table 1 (length between perpendiculars L_{pp}, waterline breadth B_{wl}, draught midships d and metacentric height GM).

In [2] it was recommended to use extrapolation (10) only for $\ln T > 6$ (i.e. for $T > 400\,\mathrm{s}$) to avoid possible concave portions of the dependencies of $\ln T$ on $1/h_s^2$, which would lead to non-conservative extrapolation (over-estimation of the expected time

Table 1. Main particulars of ships and loading conditions

Ship	L_{pp}, m	B_{wl}, m	d, m (GM, m)
Cruise vessel	230	32	6.9 (1.5, 2.0, 2.5, 3.25, 3.75, 4.0)
1700 TEU container ship	160	28	9.5 (0.5, 1.2, 1.9), 5.5 (5.75, 6.75, 7.75)
8400 TEU container ship	317	43	13.93 (0.89), 14.44 (1.26), 14.48 (2.01), 11.36 (5.0, 6.93, 9.0)
14000 TEU container ship	350	51	8.5 (1.0, 2.0, 3.0), 14.5 (9.0, 12.0, 15.0)
RoPax	175	30	5.5 (3.7, 4.5, 5.2, 5.9 and 6.6)

to stability failure). Figure 4 shows all identified concave dependencies of $\ln T$ on $1/h_s^2$ and dependencies which are concave when $\ln T > 6$. Obviously, excluding portions with $\ln T < 6$ drastically reduces the possibility of non-conservative extrapolation, and even for the remaining curves, accurate extrapolation can be done using their portions at large $1/h_s^2$.

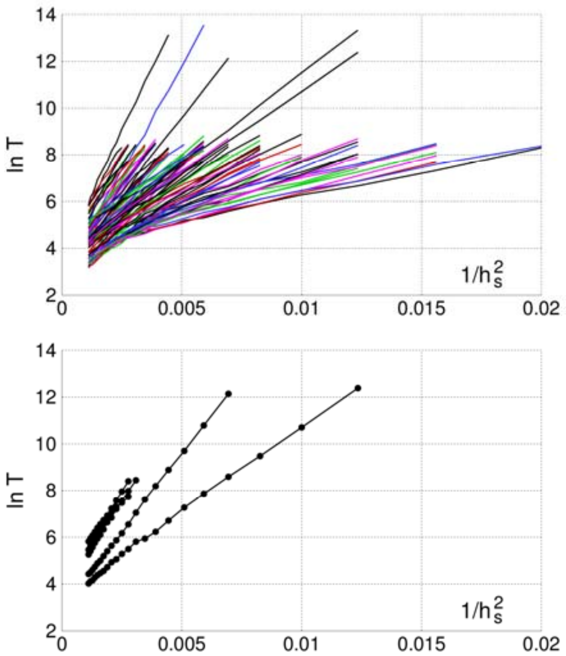

Fig. 4. Cases with concave dependency of $\ln T$ on $1/h_s^2$ taking (top) and not taking (bottom) into account results with $\ln T < 6$

To quantify the accuracy of extrapolation (10), 4, 5 and 6 points were selected starting from the minimum wave height for which the results were available from direct simulations. Correspondingly, extrapolation (10) was performed using 3, 4 or 5 points, respectively, and the deviation was defined between the extrapolated and directly computed expected time to failure at the minimum significant wave height for which direct simulation results were available. The percentage was calculated of the extrapolated values lying within the 95%-confidence interval of the directly computed estimate of the expected time to stability failure, which was defined as $\tilde{T}(1 \pm 0.14)$ using N=200.

In [2] it was suggested that if extrapolation (10) of time to failure over wave height is used, the required number of simulated failure events can be reduced due to the smoothing action of the linear fit with regard to the random oscillations of $\tilde{T}$ estimates. Therefore, the procedure was repeated using N=20 simulated stability failure events.

Figure 5 shows the results as a histogram of the ratio of the extrapolated to directly computed estimate of the expected time to failure; the y-axis corresponds to the number of cases (normed on 1) and the x-axis corresponds to the ratio of the extrapolated expected time to failure $\tilde{T}_{extr}$ to the directly estimated one $\tilde{T}$. The top and bottom plots correspond to N=200 and 20 simulated stability failure events, respectively.

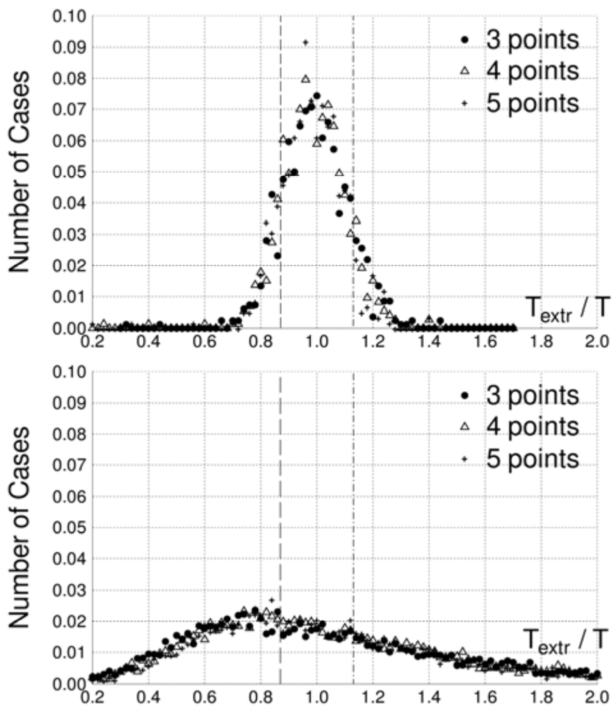

Fig. 5. Histogram (number of cases normed on 1) of ratio $\tilde{T}_{extr}/\tilde{T}$ and 95%-confidence interval of directly computed $\tilde{T}$ (vertical lines) for N=200 (left) and 20 (right) simulated stability failure events

The results indicate that N=20 simulated failure events is not enough, whereas 200 simulated stability failure events lead to sufficiently accurate results. In particular, when 200 failure events are simulated and 3 points are used for extrapolation, over 77% of the extrapolated values of time to failure are within the 95% confidence interval of the directly computed estimate of the expected time to failure. This means a loss of accuracy due to extrapolation of about 20% (if 95% of extrapolated values were within the 95% confidence interval of the directly computed ones, the extrapolation would have been exact in a statistical sense). When 4 or 5 points are used for extrapolation, over 80% of the extrapolated values of time to failure lie within the 95% confidence interval of the directly computed estimate, which means a loss of accuracy due to extrapolation of about 16%. However, the results demonstrate presence of some outliers which require manual check (note that these outliers are not always related to extrapolation problems, but sometimes to directly computed estimates of time to failure). Figure 6 shows examples of non-conservative (over-estimation of the time to stability failure) and conservative (under-estimation of the time to stability failure) outliers, whereas Fig. 7 shows examples of accurate extrapolation.

Another series of comparisons of the extrapolated with directly computed time to failure used 3, 4, …, 10 points for extrapolation starting with the maximum significant wave height for which $\ln T > 6$ and using all remaining available directly computed values of time to failure to estimate the ratio $\tilde{T}_{\text{extr}}/\tilde{T}$. Minimum and maximum (left- and right-hand plots, respectively, in Fig. 8) values were separately evaluated over all significant wave heights for the same wave period and direction. Figure 8 shows histograms of the ratio $\tilde{T}_{\text{extr}}/\tilde{T}$ for (from top to bottom) 3, 4, …, 10 extrapolation points. The width of the band of the values $\tilde{T}_{\text{extr}}/\tilde{T}$ decreases with the increasing number of points used for extrapolation; however, even using 10 points still can lead to both conservative and non-conservative outliers which require manual corrections, Fig. 9.

Linear extrapolation (10) of $\ln T$ over $1/h_s^2$ is a useful practical tool to estimate the time to stability failure for cases where it cannot be estimated otherwise. The results of testing show that the method cannot be used fully automatically to compute time to stability failure for all sea states in a given wave climate and may require manual adjustment (i.e. removal of outliers) for some cases. On the other hand, the method can be efficiently used if the number of situations used in the DSA is not too large.

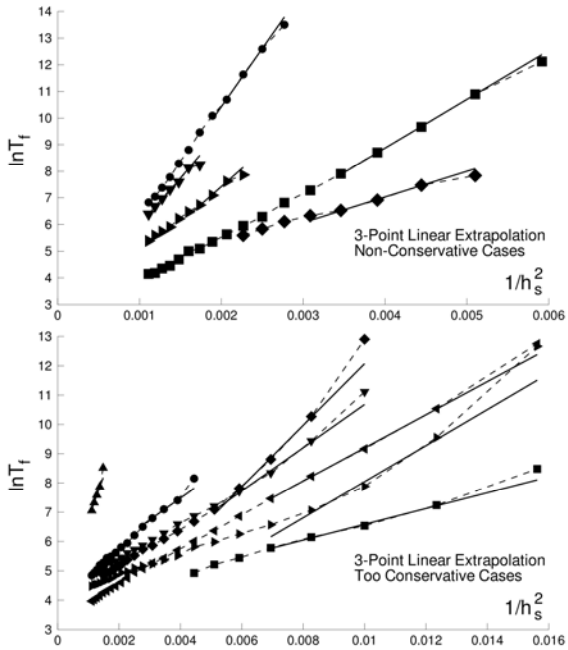

Fig. 6. Examples of non-conservative (top) and conservative (bottom) cases using 3 points for extrapolation

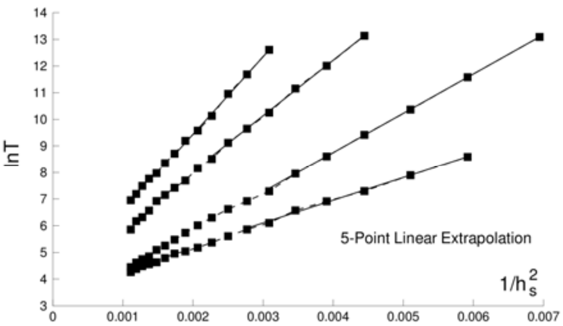

Fig. 7. Examples of accurate extrapolation cases using 5 points for extrapolation

4. DESIGN SITUATIONS

A probabilistic DSA requires, in principle, summation of short-term stability failure probabilities over all contributing sea states of the relevant wave climate and all seaway directions.

For example, North-Atlantic scatter table [4] contains 197 sea states with non-zero probabilities; if DSA is done for every 10° seaway directions, the number of short-term conditions is 1970 for each forward speed and each assessed loading condition.

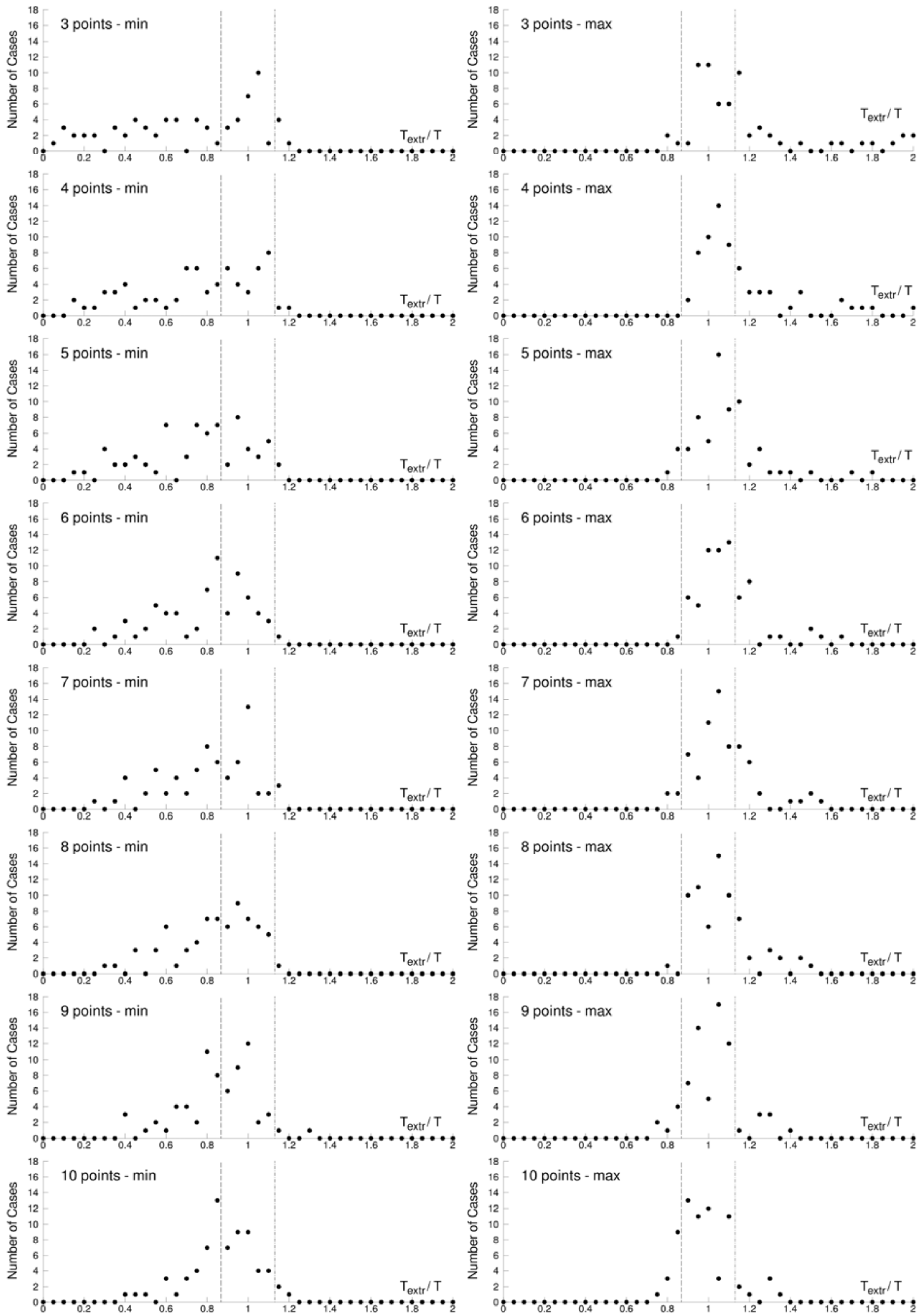

Fig. 8. Histograms of minimum (left) and maximum (right) ratio of $\tilde{T}_{\text{extr}}/\tilde{T}$ over all available results using (from top to bottom) 3, 4, …, 10 points for extrapolation of $\ln \tilde{T}$ over wave height

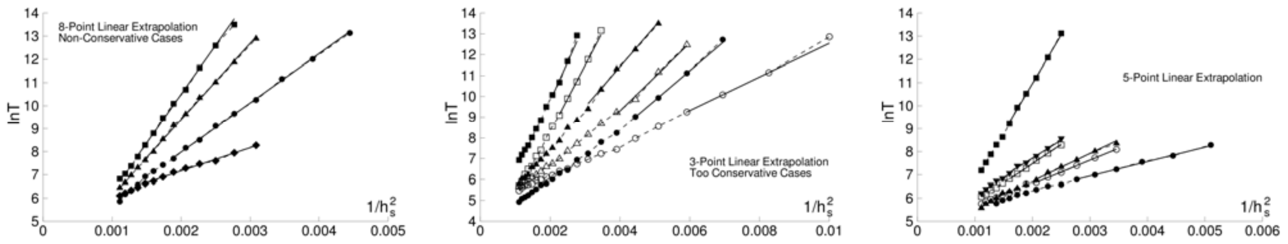

Fig. 9. Examples of non-conservative (left), conservative (middle) and accurate (right) extrapolations

This requires a robust and efficient procedure able to efficiently calculate failure probabilities in all relevant short-term conditions; besides, such assessment is impossible to do using model tests. Paper [2] discussed another possibility, based on reducing DSA to the assessment for few combinations of sea state parameters (wave height, period and direction) and ship forward speed, referred here as *design situations*.

The idea of this simplification is that a safety criterion S, based on the assessment in few selected conditions, can be used to norm stability if its relation to the "true" long-term probability of failure W is monotonous and does not show significant scatter between ships, loading conditi-ons and forward speeds, Fig. 10; the standard for this simplified criterion can be defined using a sufficient number of representative case studies.

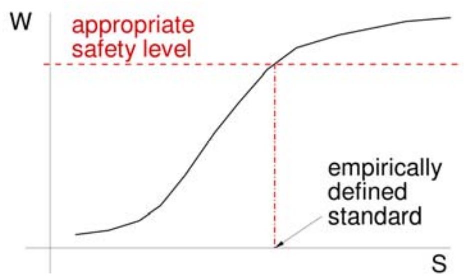

Fig. 10. Idea of simplified safety criterion *S*; *W* is safety measure, e.g. long-term probability of stability failure

Note that the exact dependency $W(S)$ does not matter in the practical approval and is not required, as long as it is known that such dependency, in principle, exists, is monotonous and does not show significant scatter between different ships.

A drawback of this approach is that DSA is separated from OG: results of DSA cannot be directly used as OG. On the other hand, such simplified DSA procedure allows efficient identification of those loading conditions which require OG, thus reducing the number of cases requiring more time-consuming simulations. Paper [2] showed significant scatter of relation $W(S)$ between different ships, loading conditions and forward speeds. To improve this method, it is proposed to use different "dedicated" design situations (i.e. combinations of sea state, ship speed, wave direction and wave period) for different failure modes. Here, roll in beam sea is considered to address the dead ship condition stability failure mode, assuming exceedance of 40° roll angle as a stability failure event (in principle, the conclusions will also be valid for the excessive accelerations stability failure mode).

Ships and loading conditions listed in Table 1 were used. Different forward speeds were applied and evaluated separately: even though dead ship condition corresponds to zero forward speed, the influence of forward speed on roll motion in beam seas manifests itself mostly through roll damping, therefore, non-zero speeds were also used in this study to ensure that the dependency $W(S)$ does not show significant scatter between cases with different roll damping characteristics.

Several ways to select design sea states were used; in all cases, a range of mean wave periods T_1 was applied and only one significant wave height h_s per wave period, selected according to (Fig. 11)

1. Steepness table from [5]; simplified criteria: sum and maximum of the short-term weighted failure rate $p_s{\cdot}r$ over design sea states; p_s is the occurrence frequency of a sea state and r=1/T is the stability failure rate in a sea state, Fig. 12.
2. Constant steepness $h_s = \mathrm{const} \cdot 0.5 g T_1^2 / \pi$, with const=0.02, 0.04, …, 0.1; the same simplified criteria as in 1 were used.
3. Lines of constant density of seaway probability p_s, corresponding to sea state duration of one month, one week and one day per year, one day in ten years and one hour in ten years; simplified criteria: sum and maximum of the short-term failure rate over all design sea states.
4. Constant normed quantiles p_s^*, defined for each T_1 as cumulative p_s value from the maximum to current h_s, at levels 0.2, 0.02, …, $2 \cdot 10^{-5}$, with the same simplified criteria as in 3.

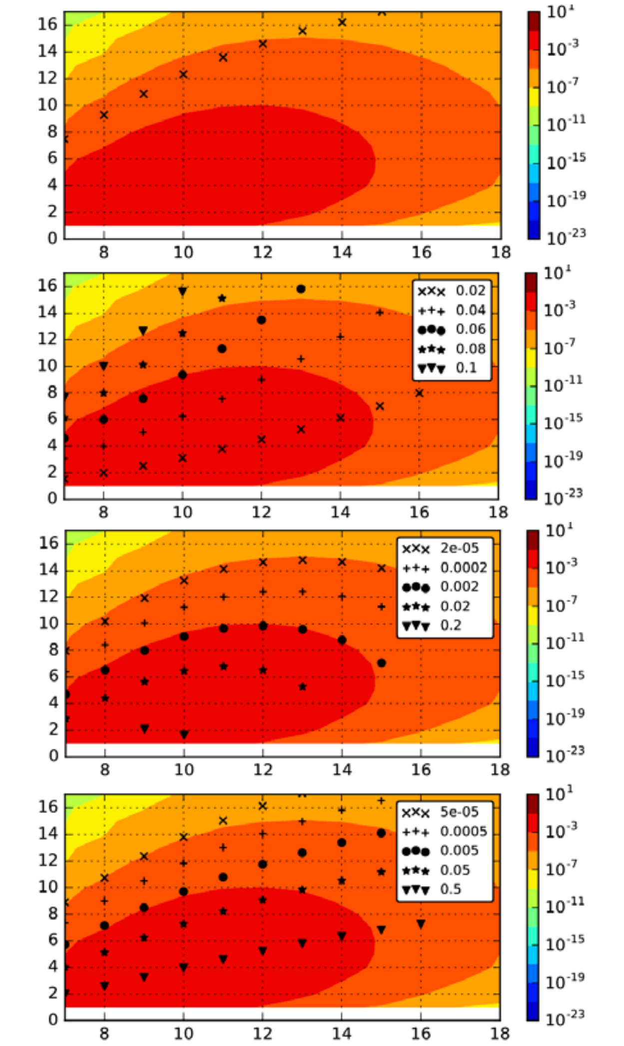

Fig. 11. Design sea states (symbols) vs. mean wave period T_1, s, (x axis) – significant wave height h_s, m, (y axis) using (from top to bottom) steepness table from [5], constant steepness lines, normed and not normed quantiles; colours show constant density of seaway occurrence probability p_s

5. Constant not normed quantiles p_s^{**}, defined as p_s^* values divided by the occurrence probability of each sea state wave period T_1 (i.e. quantiles not taking into account differences in the occurrence probability of different wave periods), at levels 0.5, 0.05, …, $5\cdot10^{-5}$, with the same simplified criteria as in 3.

The long-term rate of stability failure $W=\sum_s p_s\left(h_s,T_1;\text{ship},\text{LC},v\right)r\left(h_s,T_1;\text{ship},\text{LC},v\right)$ was directly computed; here v is the ship forward speed and $s=(h_s,T_1)$ denotes all sea states of the North Atlantic scatter table. Figures 13 to 17 plot the simplified criteria evaluated in the design sea states (y axis) vs. criterion W (x axis).

The best correlation of a simplified criterion with the long-term stability failure rate is achieved using lines of constant probability of occurrence of sea states, followed by the very similar lines of constant normed quantiles and then by lines of constant quantiles. The next are criteria defined along the steepness line from [5]; worst suitable are the criteria defined along the lines of constant steepness. In all cases, criteria defined by the sum over all design sea states are very similar to criteria defined as the maximum value over all sea states. For the criteria defined along the lines of constant occurrence probability of sea states and constant quantiles, the performance of the criteria improves with increasing steepness.

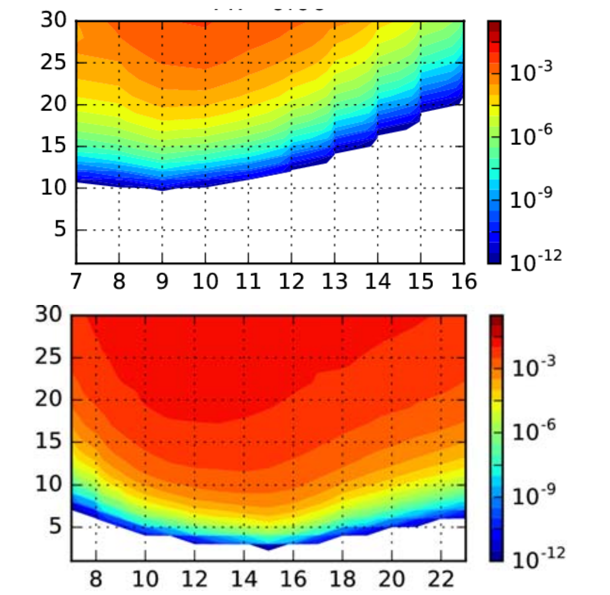

Fig. 12. Short-term stability failure rate r=1/T of RoPax vessel, GM=4.5 (top) and 14000 TEU container vessel at GM=1.0 (bottom) at zero forward speed in beam seaway vs. mean wave period T_1, s, (x axis) and significant wave height h_s, m, (y axis)

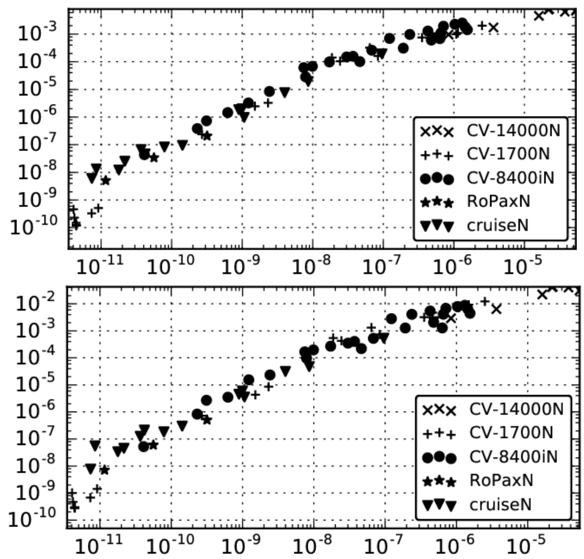

Fig. 13. Simplified criteria: maximum (top) and sum (bottom) of $p_s{\cdot}r$, 1/s, (y axis) vs. long-term stability failure rate W, 1/s, (x axis) for design sea states according to steepness table from [5]

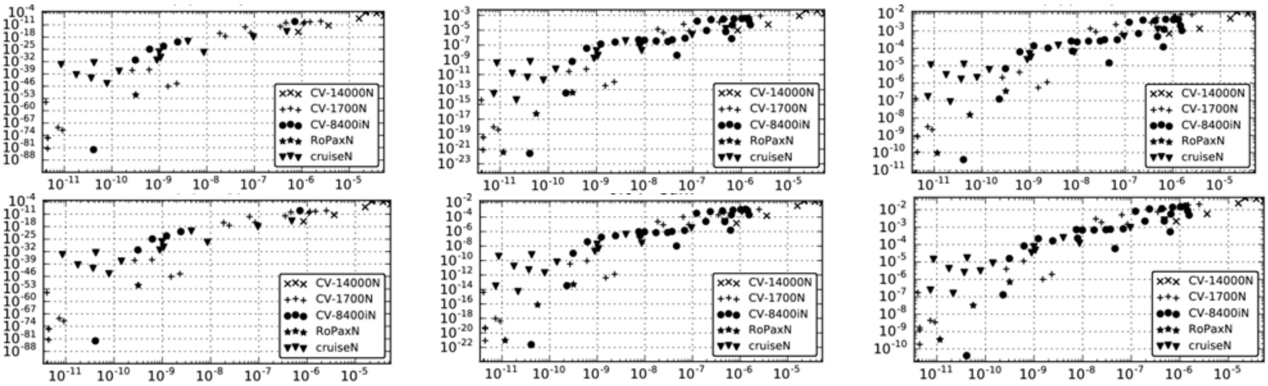

Fig. 14. Simplified criteria: maximum (top) and sum (bottom) of $p_s \cdot r$, 1/s, (y axis) vs. long-term stability failure rate W, 1/s, (x axis) in design sea states along lines of constant steepness $h_s = \text{const} \cdot 0.5 g T_1^2 / \pi$, const=0.02, 0.04 and 0.06 (from left to right)

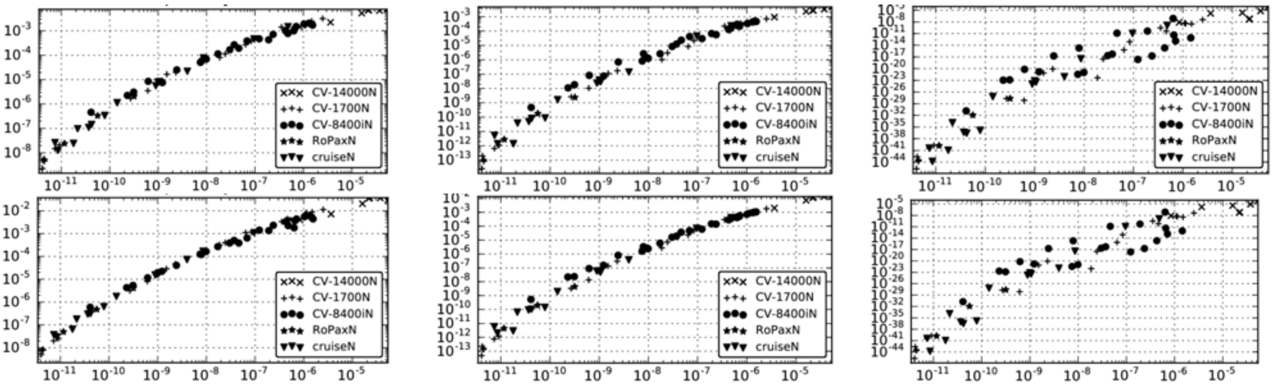

Fig. 15. Simplified criteria: maximum (top) and sum (bottom) of short-term failure rate r, 1/s, (y axis) vs. long-term stability failure rate W, 1/s, (x axis) in design sea states with constant seaway occurrence probability density of (from left to right) 1 hour per 10 years, 1 day per 10 years and 1 week per year

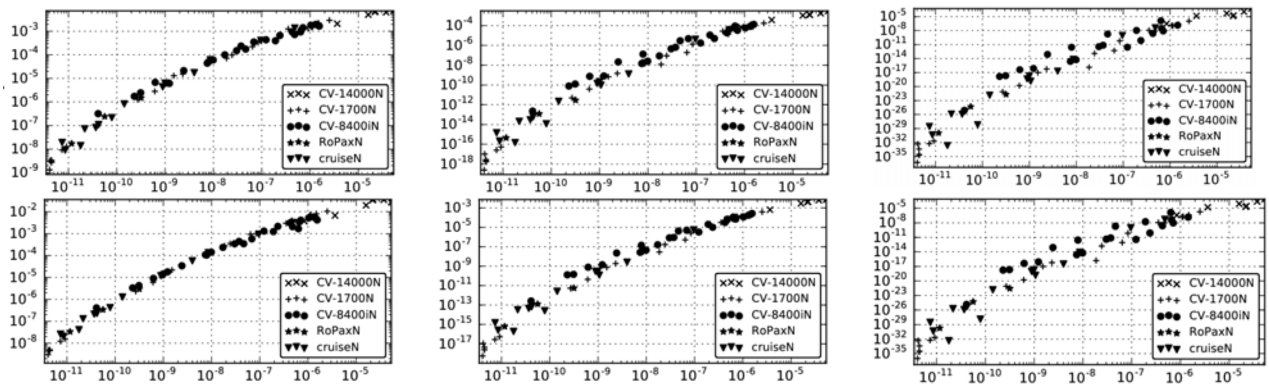

Fig. 16. Simplified criteria: maximum (top) and sum (bottom) of short-term failure rate r, 1/s, (y axis) vs. long-term stability failure rate W, 1/s, (x axis) in design sea states with constant normed quantiles of (from left to right) $2 \cdot 10^{-5}$, $2 \cdot 10^{-3}$ and 0.02

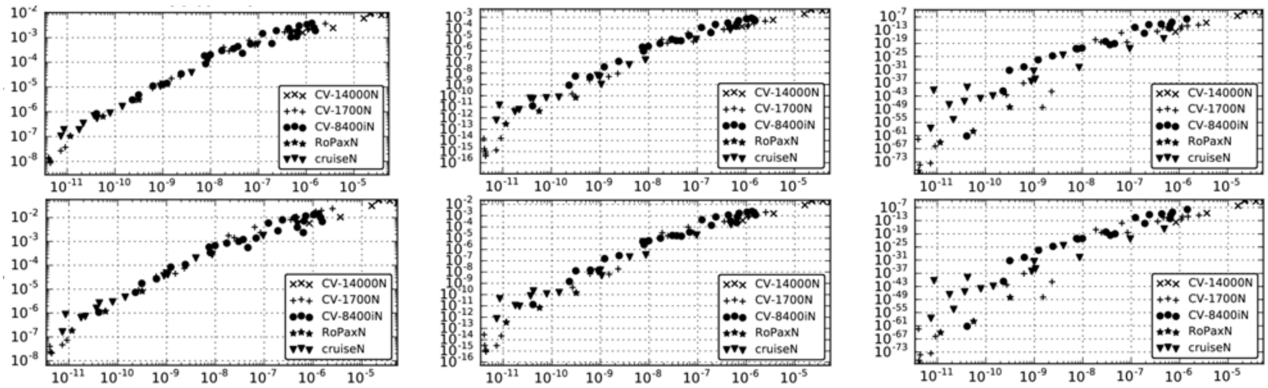

Fig. 17. Simplified criteria – maximum (top) and sum (bottom) – of short-term failure rate r, 1/s, (y axis) vs. long-term stability failure rate W, 1/s, (x axis) in design sea states with constant quantiles of (from left to right) $5 \cdot 10^{-5}$, $5 \cdot 10^{-3}$ and 0.5

5. NON-PROBABILISTIC DSA

A drawback of a probabilistic DSA is the need to encounter stability failure events in simulations (or in model tests), which requires long simulation times or big model test durations. This means, for example, that model tests can be used only for the validation of numerical simulations for few selected situations, and it is impossible to provide DSA based on only model tests. An appealing idea is to combine the design situations method with non-probabilistic (deterministic) criteria, e.g. expected maximum roll amplitude per given exposure time, mean roll amplitude etc. Such non-probabilistic measures require much less simulation or model testing time for their definition.

The idea is the same as shown in Fig. 10: if the selected non-probabilistic criterion is monotonously related to the true safety measure (e.g. long-term failure probability), and scatter between ships, loading conditions and forward speeds is small, the simplified criterion can be directly used for norming; its standard should be fine-tuned using a representative ship sample. Two simplified non-probabilistic short-term criteria, average and expected 3-hour maximum roll amplitude, defined in the same design sea states as described in the previous section, are compared between different ships, loading conditions and forward speeds in irregular beam seaways to assess their correlation with the long-term rate of of stability failure W. Results in Fig. 18 to 20 show significant scatter of the dependencies $W(S)$ between different ships, loading conditions and forward speeds, as well as non-monotonous dependencies.

6. CONCLUSIONS

Probabilistic DSA uses directly stability failure probability as a safety measure (criterion), thus some form of counting of stability failure events is required. Because stability failure events are very rare for the cases practically relevant for DSA, very long simulations are necessary. Because simulation tools employed in a DSA are rather slow compared to methods used L1 and L2, some simplifications are needed in the probabilistic assessment methods to make DSA feasible in design and approval.

Several possibilities to simplify probabilistic assessment are studied: *extrapolation* of the time to stability failure over wave height, reduction of the number of considered situations to few selected *design situations* (combinations of ship speed and wave height, direction and period) and use of *non-probabilistic (deterministic)* safety criteria.

The *extrapolation* of time to stability failure over wave height provides, in acceptable computational time, average time to stability failure for all combinations of wave height, period and direction encountered during a design life of a ship, i.e. results of such DSA can be directly used as OG. The procedure leads to sufficiently accurate results in most cases, however, some outliers are present, which require manual control; therefore, it is easy to use when the number of considered situations is not large. It is important to do such studies for other available statistical extrapolation methods to address their accuracy, robustness and feasibility with respect to practical design and approval.

In the *design situations* method, the assessment is performed for few selected situations, which significantly reduces required simulation time. A drawback of this approach is that DSA results cannot be used directly as OG, thus OG will have to be additionally developed for loading conditions failing to fulfil DSA requirements. Several ways for the selection of design sea states were tested: based on the wave steepness table from [5], constant wave steepness, constant occurrence frequency of the sea state, and constant quantiles of significant wave height exceedance. The results were compared with the long-term stability failure probability obtained by the direct summation over all sea states in the scatter table. The best simplified criterion is the sum of the short-term failure rate along the lines of constant occurrence probability of sea states; the performance of the simplified criteria improves with increasing steepness of the design sea states.

A further possibility to simplify and accelerate a DSA is to combine design situations with *non-probabilistic (deterministic)* safety criteria, such as the expected maximum roll amplitude per specified time, mean roll amplitude etc. Evaluation of such criteria requires much less simulation time and is much easier to implement in model tests compared to the evaluation of stability failure probability. The results show, however, significant scatter of the dependencies of the long-term failure rate on the non-probabilistic criteria between ships, loading cases and forward speeds and multiple instances of non-monotonous dependencies, thus the tested non-probabilistic criteria cannot be used in DSA.

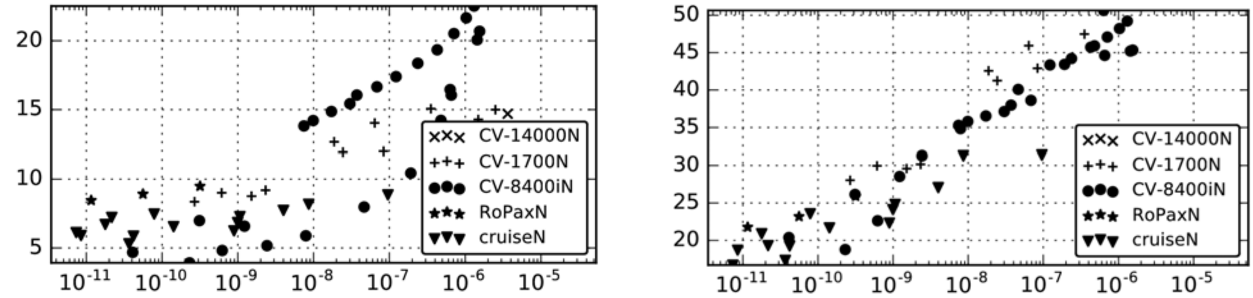

Fig. 18. Maximum short-term average roll amplitude (left) and expected 3-hour maximum roll amplitude (right) in degree, *y*-axis, vs. long-term stability failure rate *W*, 1/s, (*x* axis) over design sea states according to [5]

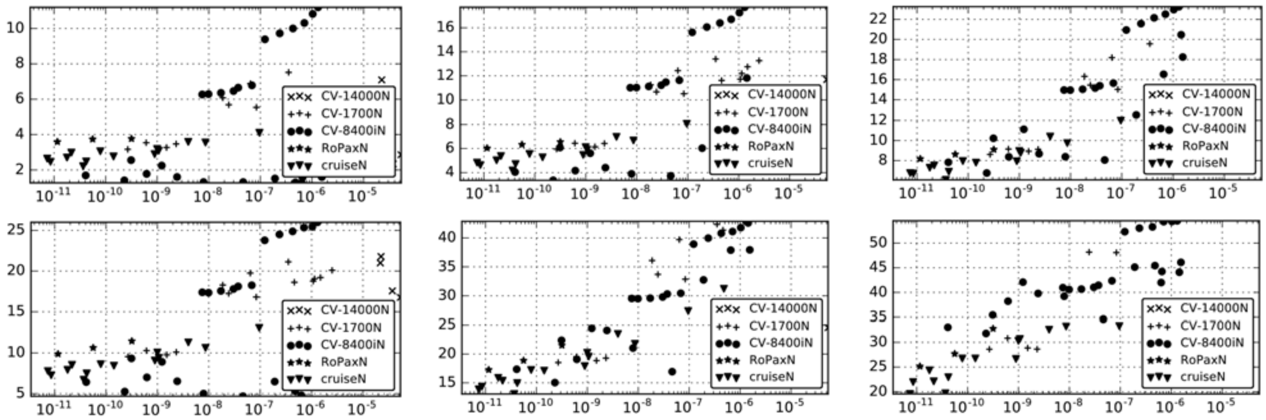

Fig. 19. Maximum short-term average (top) and expected 3 hour maximum (bottom) roll amplitude in degree over design sea states along lines of constant steepness (0.02, 0.04 and 0.06 from left to right) (*y* axis) vs. long-term stability failure rate *W* in 1/s, (*x* axis)

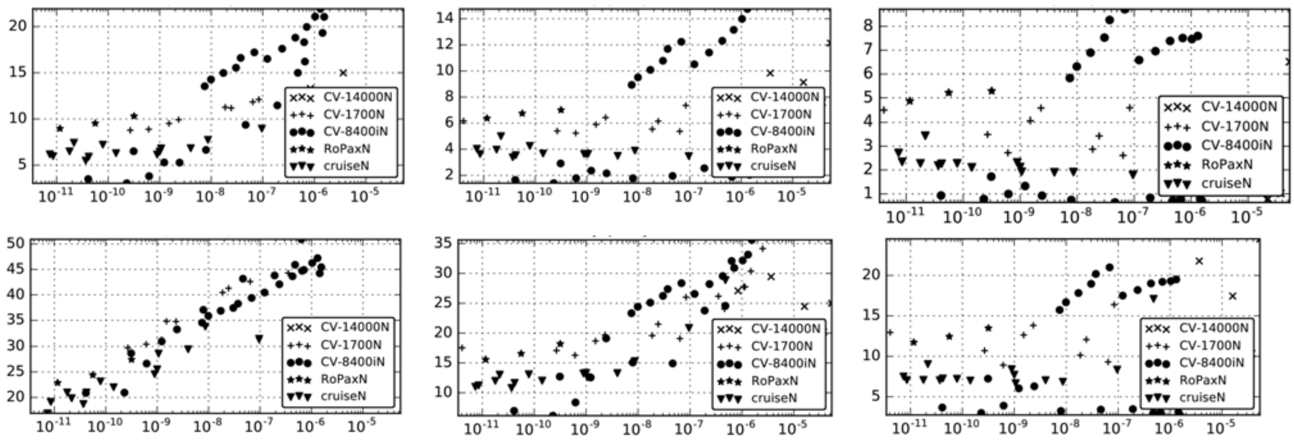

Fig. 20. Short-term average (top) and expected 3 hour maximum (bottom) roll amplitude, degree, (*y*-axis), maximum over design sea states with constant seaway occurrence probability density of (from left to right) 1 hour per 10 years, 1 day per year and 1 week per year vs. long-term stability failure rate *W*, 1/s, (*x* axis)

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