Using Full-Scale Capsizing Accidents for the Validation of Numerical Seakeeping Simulations

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ABSTRACT

It has become obvious that modern ships suffer from problems related to their seakeeping-behaviour, which is mainly related to large amplitude roll motion in head and following seas. An state-of-the-art tool to address the phenomena connected to these stability accidents are numerical seakeeping simulations. The present document analyses a number of real capsizing accidents, which are related to poor stability in rough weather, showing that numerical simulations are suitable to identify safe and un-safe conditions clearly for specific ships. For this purpose various criteria assessing the intact stability of ships are applied, including a new one, which was developed at Hamburg University of Technology in the recent years.

KEYWORDS

Ship safety; parametric rolling; intact stability; capsizing; stability criteria; seakeeping performance;

INTRODUCTION

The last years have seen several intact-stability-accidents of ships, ranging from the loss of several containers to the total loss of the whole vessel due to capsizing. The causes often appeared to be related to poor seakeeping behaviour resulting in large amplitude roll motion. This generates the need for improved methods and tools, capable of predicting the seakeeping behaviour of ships sufficiently accurate in order to identify potential risks.

Numerical seakeeping simulations in the time domain are state-of-the-art tools to address the above mentioned needs. Hamburg University of Technology (TUHH) uses the code E4-ROLLS, which has been extensively validated by model tests within several BMBF (German Federal Ministry of Education and Research) funded projects. However, the possibilities in a towing tank are limited, for example due to the tank geometry (long crested waves only) and the limited duration of the test runs.

Therefore TUHH additionally follows a second, different approach to validate its seakeeping simulations. The basis for this methodology are real, full-scale accidents. A characteristic set of such accidents, all of them closely connected with the occurrence of large heeling angles in intact conditions, has been investigated for this purpose, including relevant effects such as cargo shift, extra heeling moments and water ingress.

The main aim of this analysis is to show whether the simulation code is capable to address the relevant hazards which lead to the above mentioned accident scenarios.

In the second stage of our investigations the intact stability of the ships was assessed in order to evaluate our new approach for a intact stability criterion, the Insufficient Stability Event Index (ISEI).

THE E4-ROLLS SIMULATION TOOL

The simulation code E4-ROLLS, based on the code developed by Kroeger (1987) and Petey (1988), was chosen to serve as basis for the evaluation of seakeeping related problems. The code was validated and further enhanced by Cramer and Krueger (2005). The code considers all six degrees of freedom, whereas only two of them are treated non-linearly. Namely these are the roll motion and surge. All others are calculated by transfer functions, which makes the code extremely fast. This enables us to calculate relatively long time series for a vast number of variations. The roll motions is simulated using equation [1].

$$\ddot{\varphi} = \left\{ \begin{array}{l} \sum M_{wind} + M_{sy} + M_{wave} + M_{Tank} - M_d - \\ m(g - \ddot{\zeta})h_s - I_{xz}\left[\left(\ddot{\vartheta} + \vartheta\dot{\varphi}^2\right)\sin\varphi - \left(\ddot{\psi} + \psi\dot{\varphi}^2\right)\cos\varphi\right] \end{array} \right\} / \\ I_{xx} - I_{xz}\left(\psi\sin\varphi + \vartheta\cos\varphi\right) \quad [1]$$

with

M_{wind}	Moment due to wind
M_{sy}	Moment due to sway and yaw motion
M_{wave}	Moments from radiation, diffraction and Froude-Krylow forces
M_{Tank}	Fluid shifting moment
M_d	Non-linear damping moment
φ, ϑ, ψ	Roll, pitch and yaw angle
m	Ship's mass
$\ddot{\zeta}$	Heave acceleration
h_s	Righting lever
I_{xx}, I_{xz}	Roll moment of inertia and mixed part

The current righting levers are determined by applying Grim's equivalent-wave concept as modified by Soeding (1982). This approach replaces the exact wave contour along the ship's hull by a simplified wave profile, which delivers similar righting levers as the exact solution. The coefficients of the equivalent wave are determined using a least squares approach.

Leaks and tanks can be taken into account as well for more detailed investigations. For this method the geometry of the respective tanks needs to be modelled. Once the geometry is known, the fluid movement within the tank can be calculated, using either a deep-water model or a shallow-water model depending on the tank's eigenfrequency. The deep-water model treats the water as a point mass concentrated in its current centre of gravity, assuming that the water surface is always an even plane. The shallow-water water model is implemented according to Petey (1985) .

THE INSUFFICIENT STABILITY EVENT INDEX (ISEI)

In the last years Hamburg University of Technology has developed a new probabilistic method, assessing the intact stability of ships in heavy seas. The methodology is based on the assessment of ship motions in heavy seas calculated by means of numerical seakeeping simulations in the time domain. All simulations are carried out in irregular, short crested waves, where the energy distribution is based on JONSWAP spectra.

In contradiction to existing criteria, it was decided to assess all possible scenarios that may lead to a dangerous situation with appropriate granularity. The new concept distinguishes between a ship being safe(0) or unsafe(1) in a specific operating condition, but it does not take into consideration the calculated up-crossing rates. This procedure was chosen due to two reasons: First it is relatively difficult to calculate up-crossing rates with sufficient reliability as extrapolation methods suffer from relatively large scatter and therefore are not well suited to serve as basis for a minimum stability requirement. Secondly real capsizing events are usually the result of very complex event chains which can not be taken fully into consideration for an intact stability criterion. Thus counting up-crossing rates would feign a precision of the criterion which is not met in reality.

Given an methodology, which is able to distinguish clearly between safe and unsafe conditions the total probability for a dangerous situation happening can be quantified by the insufficient stability event index (ISEI), which is defined by the following equation (see also Krueger and Kluwe (2006)):

$$ISEI = \int_{T_1=0}^{\infty} \int_{H_{1/3}=0}^{\infty} \int_{\mu=0}^{2\pi} \int_{v_s=v_{\min}}^{v_{\max}} p_{sea}(H_{1/3},T_1) \cdot p_{dang}(H_{1/3},T_1,\mu,v_s)\ dv_s\ d\mu\ dH_{1/3}\ dT_1 \qquad [2]$$

Here p_{sea} denotes the probability of occurrence of a specific seastate defined by the significant wave height $H_{1/3}$ and the characteristic (peak) period T_1, whereas p_{dang} represents the probability for the actual loading condition leading to a dangerous situation under the condition of a specific seastate. The two-dimensional probability density function for the seastate is calculated from a scatter table presented by Soeding (2001). The failure probability p_{dang} is governed by the following relationship:

$$p_{dang}(H_{1/3},T_1,\mu,v_s) = p_{fail}(H_{1/3},T_1,\mu,v_s) \cdot p_\mu(\mu) \cdot p_v(v_s | H_{1/3},T_1,\mu) \qquad [3]$$

In this equation, $p_\mu(\mu)$ denotes the probability the ship is travelling at a course of μ-degrees relative to the dominating wave propagation. It is assumed that $p_\mu(\mu)$ is independent from the actual values of $H_{1/3}$ and T_1. $p_\mu(\mu)$ can be taken from full scale observations (see Krueger, Hinrichs, Kluwe and Billerbeck (2006)). Then $p_v(v_s | H_{1/3},T_1,\mu)$ denotes the conditional probability that the ship is travelling at a speed of v_s knots. Not all speeds are physically possible in a specific situation. Krueger, Hinrichs, Kluwe and Billerbeck (2006) determine the maximum possible ship speed in the given environmental conditions at full engine output and the minimum speed at engine idle speed from systematic propulsion calculations. Within the range of possible speeds $[v_{min},v_{max}]$ the probability of occurrence is assumed equally distributed as more accurate data are lacking.

The failure probability $p_{fail}(H_{1/3},T_1,\mu,v_s)$ is determined from the time series of the numerical simulation by applying the Blume-criterion. In cases where the Blume-criterion does not deliver suitable results, typically due to large angles of vanishing stability, the occurrence of a certain maximum roll angle (e.g. 50°) may be taken into account simultaneously. The Blume criterion considers a ship as save if the following condition is met:

$$\bar{E}_R - 3s > 0 \qquad [4]$$

Here $\bar{E}_R$ denotes the residual area below the lever arm curve, integrated from the largest roll angle observed during one simulation up to the point of vanishing stability, averaged over all runs. The symbol s represents the standard deviation of $\bar{E}_R$. Given the loading condition fulfills the Blume-Criterion in the actual situation, $p_{fail}(H_{1/3},T_1,\mu,v_s)$ is set to 0, otherwise it is set to 1.

The criterion is aimed to prevent large roll amplitudes related to periodic stability variations in waves. Therefore our method explicitly treats head sea and following sea cases only, and therefore we restrict the contributing courses to a 45-degree sector of encounter angles, port and starboard in head and following seas. Consequently, it is then useful to split the ISEI in a head sea and a following sea index. The criterion in practice is calculated for a discrete number of operating conditions, leading to the following formulation of the criterion:

$$ISEI = ISEI_{following} + ISEI_{head} = \sum_{f,h} \left\{ \sum_{i=1}^{N_{T_1}} \sum_{j=j_{Bl}}^{N_{H_{1/3}}} \sum_{k=1}^{N_\mu} \sum_{l=1}^{N_v} \left(\begin{array}{l} p_{sea}(H_{1/3}(j),T_1(i)) \cdot \\ p_\mu(\mu(k)) \cdot \\ p_v(v(l) | H_{1/3}(j),T_1(i),\mu(k)) \end{array} \right) \right\} \qquad [5]$$

In the formula, the summation on the limiting wave heights starts at j_{Bl}, which is the smallest significant wave height for the given significant period T_1 where p_{fail} equals 1.

INVESTIGATION OF REAL CAPSIZE ACCIDENTS

TUHH currently analyses real capsizing accidents for two main purposes: First it is a second method, besides the model tests, to validate our numerical code by reconstruction of the environmental conditions during the accident. Secondly the accidents clearly define ships in “un-safe” conditions, which helps us to define threshold values for the ISEI-concept.

The ships are each simulated with two different load cases: One representing the conditions during the accident and a second one assumed to represent a safe condition. Simulations are carried out for both conditions. The resulting ISEI's are calculated demonstrating whether the new concept is able to distinguish between safe and un-safe loading conditions.

Besides the ISEI also other stability criteria were calculated for comparison. As it is not possible to present all of them within the frame of this paper we refer to the original literature.

The Capsizing of SS Fidamus (1950)

On January 31st, 1950, the 743 BRT vessel SS Fidamus capsized in heavy weather bound

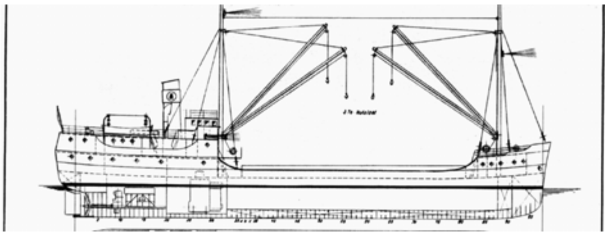

Fig.1: General Arrangement of SS Fidamus

from Wismar to Antwerp close to Langeoog, 54° N, 7° E. The vessel was loaded with ca. 900t potash (angle of repose ca. 35 Deg.). The vessel was travelling in following seas of ca. 40 m significant wave-length, $H_{1/3}$ was ca. 2.0 m and the vessel's speed was ca. 9.5 knots. The vessel suddenly heeled to more than 30 degrees and remained there with a steady list of ca. 35 to 40 degrees. Water ingress then lead to capsizing within 10 minutes according to Seeamt Bremerhaven (1950).

The floating condition prior to the accident could be reconstructed approximately as follows: The ship had a total displacement of ca. 1541 tons, resulting in a draft of 4.69m at the aft perpendicular (a.p.). The trim was 1.12m by stern. Interestingly enough the ship did not carry any ballast water, although this was strongly recommended in the stability booklet. The resulting righting levers are shown in Fig.2. The initial GM in still water conditions amounts ca. 0.30 m. Based on these lever arm curves we can conclude that, without any external heeling moment, the vessel would immediately heel to about 30 Degree if it stays long enough on the wave crest.

In an expertise made on behalf of Seeamt Bremerhaven, Kempf (1950) concluded that the vessel was travelling in a 1:1 following sea resonance, where the rolling period of the vessel (for small angles) was determined to 11.8 s by Kempf at an encounter period of 11.1s.

The numerical simulations, carried out with

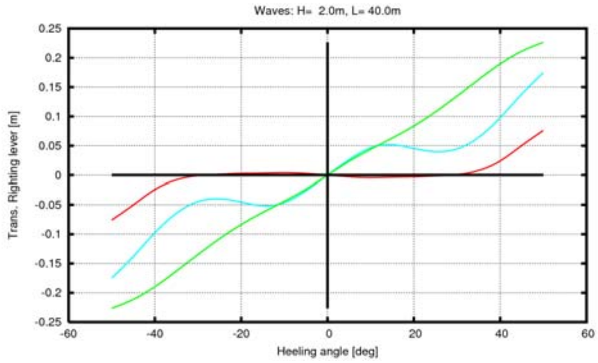

Fig.2: Lever arm curves for SS Fidamus (cyan: still water, green: wave trough, red: wave crest)

E4-ROLLS show that the vessel is permanently rolling with a maximum angle of ca. 45 degree.

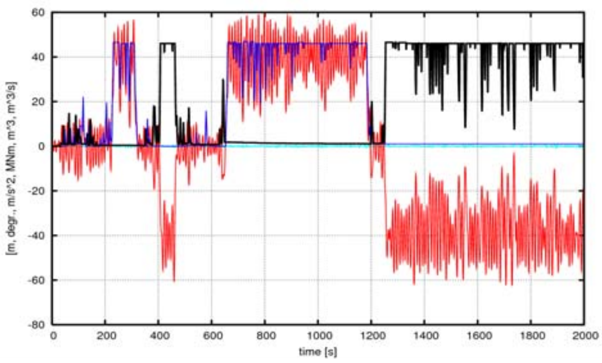

Fig.3: Simulated time series of SS Fidamus including entrapped water (blue: starboard side, black: port side). The red curve shows the roll angle (positive starboard)

As the static angle of vanishing stability in still-water conditions is beyond 90 degree, it is theoretically not possible to capsize the vessel without any additional heeling moment. For the dynamically rolling vessel, additional water ingress is not necessary for the final capsizing. Another important aspect discussed already during the original investigations is, that a significant amount of water is entrapped between hatchway coaming and bulwark, which produces a sufficient heeling moment to keep the ship at a steady list at around 40 degrees, as the time series in Fig.3 demonstrates clearly.

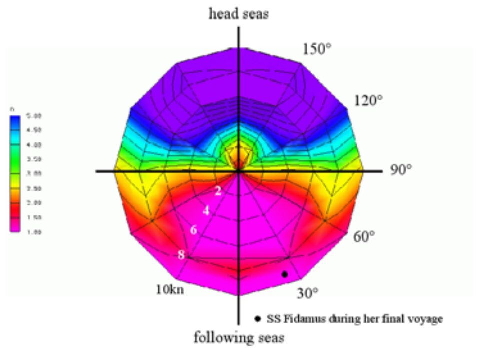

Fig.4: Polar diagram showing limiting wave heights with respect to a maximum roll angle of 40 degree. Significant wave length is 40 m

For nearly all situations the ship is travelling in following seas large heeling angles beyond 40° can be observed, as shown in Fig.4. It can be shown that the water between hatchway coaming and bulwark is sufficient to cause the final capsizing of the vessel.

Table 1: Results for different criteria in “safe” and “unsafe” loading condition for SS Fidamus

Criterion	**GM=0.30 m**	**GM=0.50 m**
Kastner/Roden Capsizing time [s]	487	2386618
Soeding Capsize Probability	0.25/Roll Cycle	0.1 - 0.7E-6 /year
Blume (Modified) E_R - 3 S	E_R = S = 0	1.772 mmRad
ISEI (direct)	0.20078	0.0008
Empirical Criteria		
Crest lever	< 0.05	> 0.05
Crest range	< 16 Deg	> 16 Deg.
Blume c- factor	none fulfilled	all fulfilled

Comparing the results for different intact stability criteria as presented in Table 1, it can clearly be seen that all criteria consider the case where the vessel did actually capsize as dangerous, whereas all criteria consider the 0.50m GM case as determined by the Kastner-Roden-criterion as clearly save. Additionally, it can be stated that a direct ISEI of 0.2 represents a condition, which has clearly proven to be unsafe, whereas an ISEI of 0.0008 represents a condition considered to be safe by all other criteria.

The Capsizing of MV Lohengrin (1963)

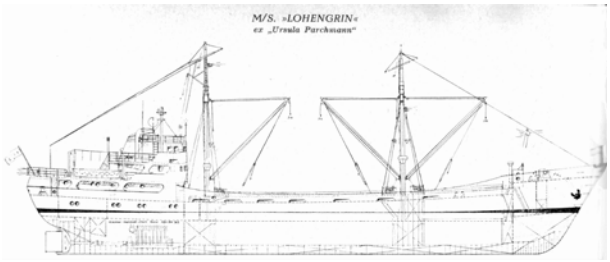

Fig.5: General Arrangement of MV Lohengrin (taken from Die deutsche Handelsflotte (1963))

On January 14th, 1950 the 955 BRT vessel MV Lohengrin capsized in heavy weather bound from Iggesund/Sweden to Kiel. The vessel was loaded with ca. 1195 t cellulose in bales. Half a year before the accident, the vessel was converted, which resulted in higher hatch coamings and an increased VCG of the cargo hold volume. Based on the information obtained from the Seeamt Flensburg (1964) the most probable floating condition at the time of the accident shows a draft of 4.69m at a.p. with a total displacement of ca. 2000 tons and an initial GM of 0.13 m. The resulting lever arm curves are shown in Fig.6. At the day of the accident the vessel entered the Kiel Fjord at about 14.00 hrs. The waves encountered the vessel from abaft. Significant wave period was ca. 6 seconds, the wave height was reported to be about 2 metres. At about 14.15 hrs the vessel heeled to 40-45 degree starboard side and remained there with a steady list of the same size. The ship finally capsized and sank ca. 1.5 hrs later.

Table 2: Results for different criteria in “safe” and “unsafe” loading condition for MV Lohengrin

Criterion	**GM=0.131 m**	**GM=0.305 m**
Kastner/Roden Capsizing time [s]	6024	-
Soeding Capsize Probability	-	0.4E-7/year
Blume (Modified) E_R - 3 S	-3.509 mmRad	51.9 mmRad
ISEI (direct)	0.18911	0.002
Empirical Criteria		
Crest lever	< 0.05	> 0.05
Crest range	< 16 Deg	> 16 Deg.
Blume c- factor	none fulfilled	all fulfilled

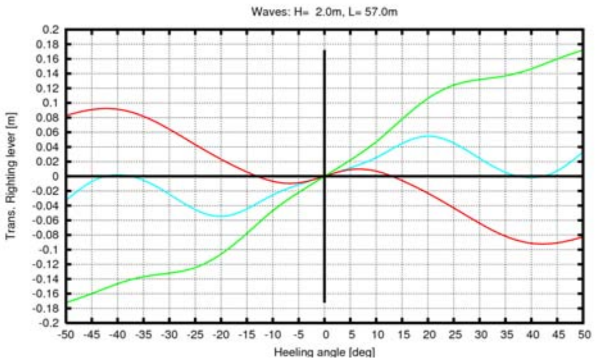

Fig.6: Lever arm curves for MV Lohengrin (cyan: Stillwater, green: wave trough, red: wave crest)

The numerical simulations clearly show that the reason for the loss of MV Lohengrin can be consistently explained by insufficient stability and a pure loss on the crest situation. The stability at the time of the accident was even be low the recommended Rahola-criteria. As the deckhouse was weathertight the vessel could find an intermediate equilibrium while resting on the superstructures. This intermediate equilibrium is possible only if an additional heeling moment acts on the ship, for example due to cargo shift. Our investigations show that a shift of TCG of the cargo by 4cm would be enough to keep the vessel in the listed position. In general, in the given loading condition the vessel was theoretically unsafe in all following sea situations.

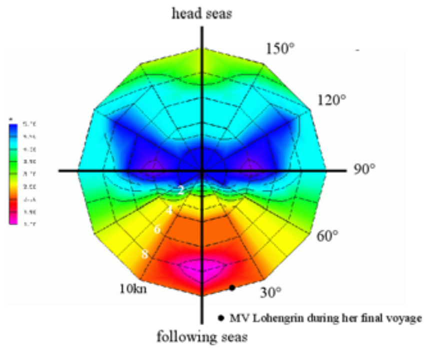

Fig.7: Polar diagram showing limiting wave heights with respect to the Blume-criterion. Significant wave length is 60 m

Again, comparing all criteria, the results are unique. All criteria consider the case where the vessel did actually capsize as dangerous. For the GM-value of 0.305m, which was selected from the simulations in artificially amplified waves, all criteria consider this case as safe.

Additionally, it can be stated that a direct ISEI of 0.189 represents a condition, which has clearly proven to be unsafe, whereas an ISEI of 0.002 represents a condition, which is considered to be safe by all criteria.

The Capsizing of SS Irene Oldendorff (1951)

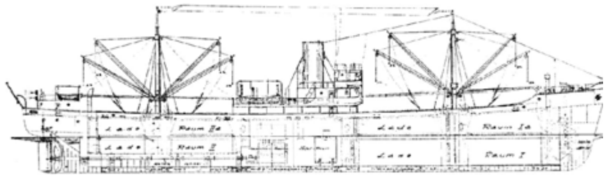

Fig.8: Side view of SS Irene Oldendorff

On December 31st, 1951, the vessel SS Irene Oldendorff capsized in heavy weather bound from Emden to Ystad in the Hubert Gat. The vessel was carrying ca. 2750 tons of coke, of which ca. 440 t has been carried on deck. The last known position of the vessel was close to buoy J/E 1 in the Hubert Gat. According to our findings based on data of the Seeamt Bremerhaven (1952) the vessel had a draft of 5.4 m a.p., trimmed 0.108 m by head at the beginning of the voyage (Emden Lock). This equals a displacement of 4575t.

Table 3: Results for different criteria in "safe" and "unsafe" loading condition for SS Irene Oldendorff

Criterion	**GM=0.14 m**	**GM=0.39 m**
Kastner/Roden Capsizing time [s]	13800	No capsize found
Soeding Capsize Probability	-	0.3E-6 for h>9m none for h<9m
Blume (Modified) E_R - 3 S	-64.0 mmRad	181.5 mmRad
ISEI (direct)	0.158	0.0011
Empirical Criteria		
Crest lever	0.008 < 0.05	> 0.05
Crest range	10 < 16 Deg	> 16 Deg.
Blume c- factor	none fulfilled	all fulfilled

The simulation-based analysis shows that the reason for the loss of SS Irene Oldendorff can be consistently explained as an intact stability accident due to the loss of stability in extreme weather conditions. The loss of stability in the particular situation can be clearly related to water entrapped in the coke deck cargo, which could not drain off fast enough through the freeing ports. The capsizing sequence most

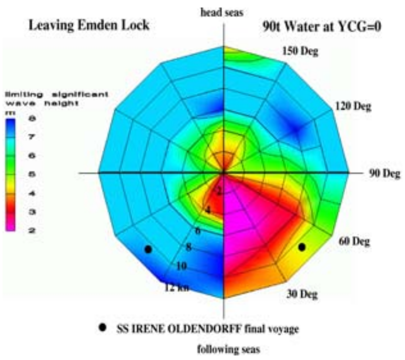

Fig.9: Polar Diagram showing limiting wave heights according to Blume criterion

likely was as follows: Due to the low stability in wave crest conditions a large heeling angle must have occurred, shifting the vessel to an intermediate equilibrium at ca. 45°. Water ingress, cargo shift or both must then have lead to the final capsize.

The simulations have shown that capsizing is hardly possible for the stability the ship had, when she left Emden lock. This is clearly stated in the polar-diagram (Fig.9, left side) for the Emden Lock situation, where significant wave heights of ca. 7-8m are required to endanger the vessel. These extreme (significant) wave heights are hardly possible in the Hubert Gat. Assuming an amount of 90 tons water, entrapped in the coke, the polar-diagram changes significantly (Fig.9, right side). Now, the limiting wave height is shifted to much lower values of about 4-5 meters for the operating condition of the vessel.

Table 3 shows that all investigated criteria consider the case as dangerous, where the vessel did actually capsize. On the other hand all criteria consider the 0.39m-GM case as clearly save. Therefore the direct ISEI of 0.158 represents a condition, which has clearly proven to be unsafe, whereas an ISEI of 0.0011 represents a condition, which is considered to be safe by all criteria. All criteria except the C-factor and the Blume-criterion do not consider the situation at Emden lock as sufficiently safe where GM was ca. 0.20 m. This condition is related to an ISEI of 0.0139. The C-factor concept may suffer from the fact that the vessel is actually a Shelter Decker, which has large freeboard and may not be covered by the concept. Taking all findings into account, the SS Irene Oldendorff -accident can be regarded as a case, which did occur close to the limit that distinguishes a ship from being safe or unsafe.

The Capsizing of MV FINNBIRCH (2006)

On Wednesday, 1st of November 2006, the 8500 dwt RoRo-Ferry M/V FINNBIRCH (call sign SLNK) capsized in heavy weather in the Baltic Sea between the islands Gothland and Olland. At the time of the accident, the vessel was travelling south at an estimated course of abt. 190- 200 Degree. The vessel was loaded with trailers, of which a significant amount was stowed on the top deck (see Figure 10). At the time of the accident, the weather wind was about 20-25m/s or BF9-10. The sea was rough with significant wave heights of abt. 5-6m, significant period about 8-8.5s. These data are obtained from hindcast sources.

Figure 10: MV Finrnbirch in intermediate floating condition

According to the observations of the master of M/V MARNEBORG, the vessel closest to the MV FINNBIRCH, who later coordinated the rescue operations the vessel was rolling significantly. At about 16:15 she heeled to about 50 degree. The vessel remained in that intermediate equilibrium floating condition for a while (see Figure 10), until she finally capsized at about 19:37.

M/V FINNBIRCH was built in 1978. In 1979 the vessel was additionally equipped with side sponsons and in 1986 an additional weather deck was added. Both conversions have significantly affected the stability of the vessel. The official accident investigation has not been finished yet, why no investigation report is available so far. Therefore, some assumptions have to be made with respect to the loading condition prior to the accident:

- The additional steel weight of the retrofitted top deck is ca. 250 tons.
- The top deck was fully loaded with 36 trailers according to Figure 10. From this fact we conclude that also the other decks were almost fully loaded.
- The average trailer weight is assumed to be ca. 23.5 tons.

When M/V FINNBIRCH was delivered in 1979, no damage stability regulations were in force, which means that the stability of the vessel was governed by the relevant intact criteria.

The limiting intact stability criterion is most likely $h_{\min}(30°) \geq 0.20m$ for the vessel including the sponsons and the top deck. Our investigations show that, in case the top deck is fully loaded, the ship operates close to the intact stability limit. Taking all assumptions into account we obtain the following floating condition:

Table 4: Intact floating condition

Total Weight :	13686.000 t
Draft at A.P (moulded) :	6.843 m
Trim (pos. fwd) :	-0.078 m
Metacentric Height :	1.704 m

The computed righting levers in waves show practically no stability on the wave crest for a wave which comes close to the accident seastate (see Figure 11).

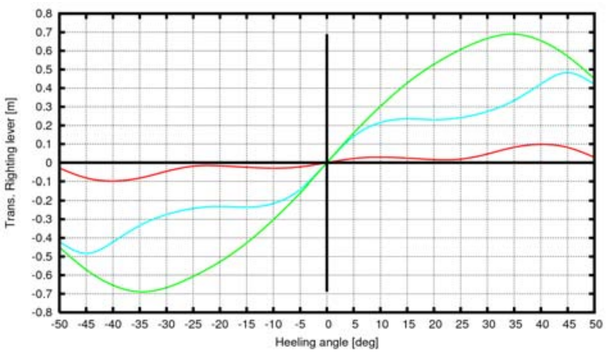

Figure 11: Lever arm curve of M/V Finnbirch

It is also important to underline the fact that the alterations of the initial GM in the sea state are substantial, which means that a lot of energy is introduced into the vessel by the sea state.

The speed of the vessel is assumed with 16 knots at an encounter angle of 30 degree. The results of the numerical simulation show that roll angles up to 40 Degree occur for situations when the wave height exceeds some threshold value and is at the same time in phase with the roll motion (Figure 12).

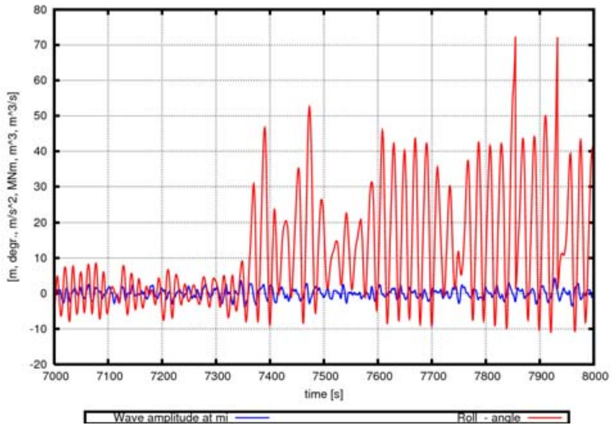

Figure 12: Simulated time series of the accident

Figure 10 shows a intermediate equilibrium floating condition of abt. 45-50 degree, which is only possible in case cargo has significantly shifted. Introducing this cargo shift into the simulation results in an intermediate equilibrium there as well (Figure 12, 7350s onwards). In this phase, an additional cargo shift may have taken place or water may have entered the vessel, which has then lead to the final loss.

Our analysis indicates that the vessel was most probably travelling close to a 1:1 resonance condition at the time of the accident. In this context, it is interesting to note that the actual scenarios which lead to critical resonances could not be determined from the stillwater rolling period for small roll angles as the nonlinearity of the lever arm curve shifts the natural roll period significantly.

Concluded, it can be stated that the dynamic analysis has clearly shown that the reason for the loss of MV FINNBIRCH was most probably insufficient stability in a following sea scenario.

CONCLUSIONS

A selection of real capsizing accidents is investigated to follow two main goals. First these are used to further evaluate our numerical simulation code E4-ROLLS with respect to its capability to reproduce dangerous situations for ships in waves and its capability to predict the ship response in those situations with satisfying accuracy. Also more complex failure scenarios like cargo shift and entrapped water on deck are modelled for this purpose.

Secondly we use these accidents to assess the limiting boundaries, which separate the save and the un-save operating conditions of ships.

For this purpose TUHH has developed a new probabilistic intact stability criterion, called Insufficient Stability Event Index (ISEI).

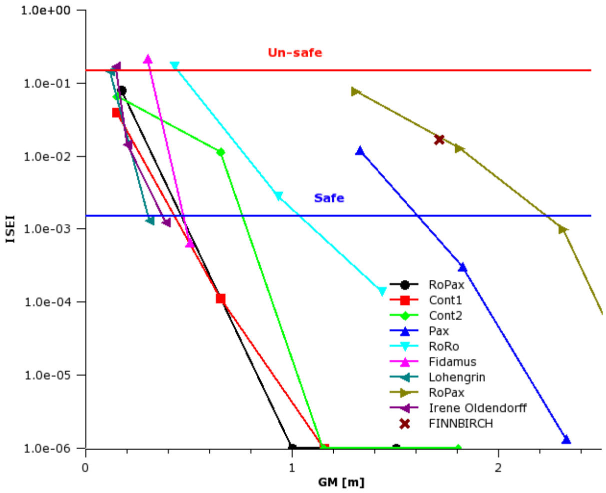

Figure 13: ISEI values for different ships

The new probabilistic concept takes into account the occurrence probabilities of seastate, course and ship-speed. The actual failure criterion for the ship in a specific operating condition is implemented via a “safe”/”unsafe”-decision based on the Blume-criterion and the maximum roll angle observed during the simulation.

In order to benchmark the new criterion, two loadcases were analysed for each of the investigated ships, one representing the failure condition and one assumed to be in the “safe” domain.

The results show that the concept is able to distinguish between safe and un-safe operating conditions clearly. Figure 13 shows the calculated ISEI-values for the investigated ships and a selection of modern vessels of different type. The “safe” and “un-safe”-boundaries are estimated values based on our findings. The picture demonstrates very clearly that typical modern ships, complying with all intact stability requirements in force, are critical, or even unsafe with respect to their stability. Therefore we can conclude that the current intact stability criteria are neither sufficient nor suitable to avoid accidents related to stability alterations in waves.

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