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Investigation into the Container loss of the Container Vessel MSC Zoe in the North Sea on 01 and 02 January 2019

Ordered by:
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(Federal Bureau of Maritime Casualty Investigation)

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1 Summary

On behalf of the German Federal Bureau for Maritime Casualty Investigations, the loss of Containers on board the Container Vessel MSC ZOE is to be analyzed.

Our analysis has come to the following conclusions:

The root cause of the container loss is a very high stability in combination with low damping. The roll damping of the hull is not sufficient for very large values of initial stability. As the roll damping is speed dependent, it was further reduced due to the low ship speed. The ship speed of 10 knots led to a situation where the ship was rolling permanently with 5-10 degree amplitude. Under these circumstances, the transversal accelerations were not large enough to cause a cargo loss. Our calculation has shown that the ship must have been hit by a group of waves which caused roll angles between 17 and 18 degree. During this events, transversal accelerations occurred which led to the first losses of the cargo.

Had the ship speed been larger than 10 knots, this would have prevented the cargo loss. At 14 knots ship speed, the cargo loss could have been avoided definitively, at 12 knots most probably.

Consequently, the speed reduction after the first losses of containers led to further losses, because due to further reduced roll damping, large transversal accelerations have become more probable.

Most probably, the crew was not aware of the fact that their hull did not produce sufficient roll damping at 10 knots ship speed.

Shallow water effects have a small, but probably negligible effect on the roll motion, as the roll angle is slightly increased only. The major effect of the shallow water is on the steering of the vessel.

Conclusions and some recommendations are given in section 13 of this report.

2 Facts

The following facts result from the documents and data provided by the BSU:

At the 1st of January 2019 the 18,400 TEU Containership MSC ZOE was sailing through the North Sea coming from Sines. The payload was 118291.4 t and the (corrected) metacentric height (GM) was about 9 m. The drafts of MSC ZOE were abt. 12.03 m fore and abt. 12.47 m aft. The water depth was between 20 and 30 m. The weather condition was rough with NNW winds of abt. BFT 8-10, in gales the wind was stronger. The sea state was also rough with waves of abt. 5.5 m significant height and abt. 12-13 s period. MV ZOE was sailing a course of 60 degree, which means that she was travelling in beam seas. The crew reported that the vessel was permanently rolling with amplitudes of abt. 5-10 degree. At about 23.00LT, the crew reported that the vessel was rolling heavily four to six times with amplitudes of abt. 30 degree. During this roll motion, some containers fell overboard. Fig. 1 summarizes the events during this first calculated container loss.

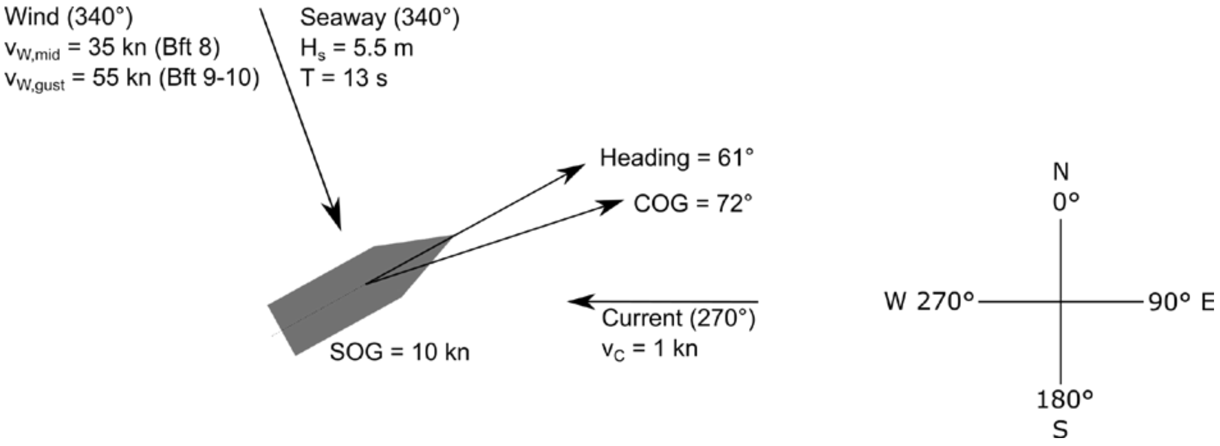


Figure 1: Course Angle, Heading and Speed of the MSC ZOE and environmental conditions, 01.01.2019 at 23:00 o'clock (1st calculated container loss).

The crew continued the voyage after an inspection of the damages. At abt. 1.30, the vessel was again rolling heavily with reported amplitudes of abt. 30 degree. Again, container stacks collapsed and containers fell overboard. The crew then decided to change course and turned the ship against the waves with a heading of 321 degree and continued the voyage. The scenario during the second calculated loss of containers is summarized in Fig. 2, and the situation after the course has been altered is shown in Fig. 3.

Later investigations have shown that there have been probably more than the above mentioned two container losses which were reported by the crew. As the weather was quite stable this night on one hand and the above mentioned losses were stated by the crew on the other, in the following, we concentrate on the two events which took place at 23.00 and 1.30LT, respectively.

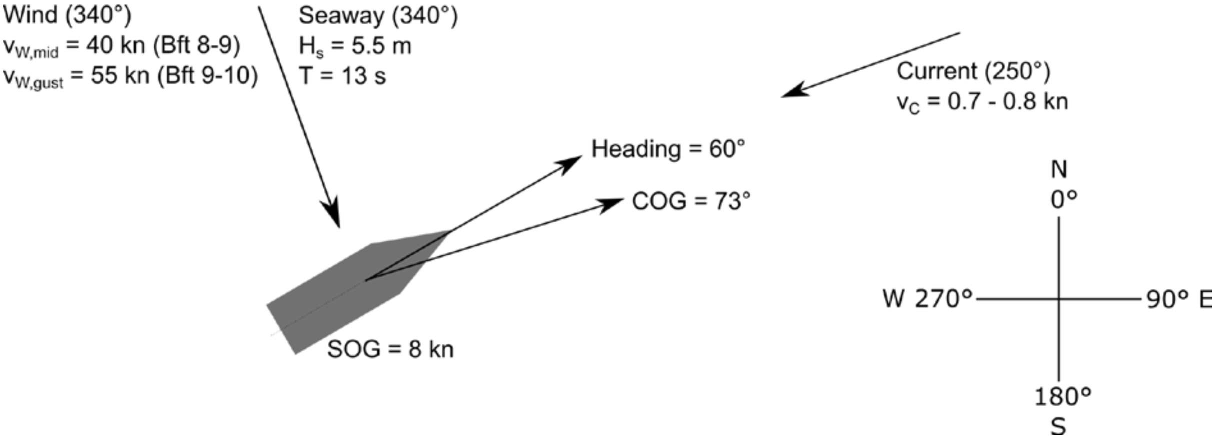


Figure 2: Course Angle, Heading and Speed of the MSC ZOE and environmental conditions, 01.01.2019 at 01.30 o'clock (2nd calculated container loss).

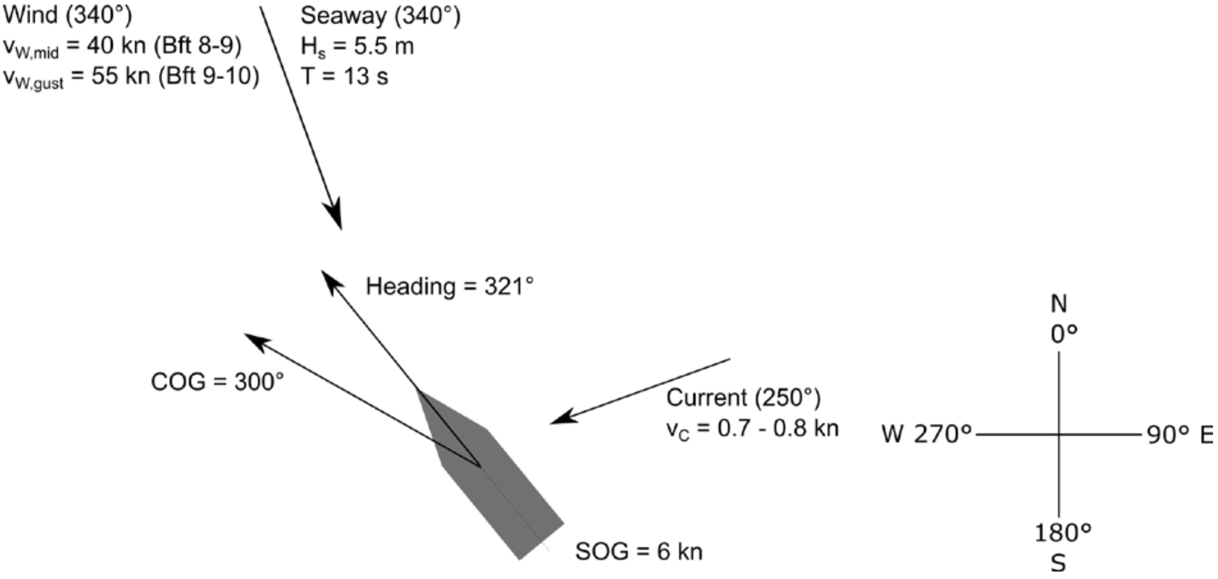


Figure 3: Course Angle, Heading and Speed of the MSC ZOE and environmental conditions, 02.01.2019 at 02:34 after the losses of containers at the new heading.

3 Additional data from the Voyage Data Recorders of the MSC ZOE

The VDR data from MSC ZOE has been handed over to us by the BSU. Unfortunately, the VDR did not record the heel of the ship. For the present investigation this is very unfortunate as rolling angles of abt. 30 degree as stated by the crew are not very likely: During the time of the container loss, the water depth was abt. 22-23 m. MSC ZOE had a beam of 59 m, and she was sailing with a mean draft of 12.25 m. Consequently, the ship would have touched the seabed if the heeling angle was larger than 19.2 degree. A diver inspection of MSC ZOE was carried out later, and no deformations of the steel structure were recorded which indicate that a ground contact has taken place. This fact makes roll angles of more than 19 degree not probable.

At the same time, the VDR data indicated a significant rudder action through the whole time. The crew switched to manual steering, and from the VDR data it becomes obvious that they must have had problems to maintain the ship's course.

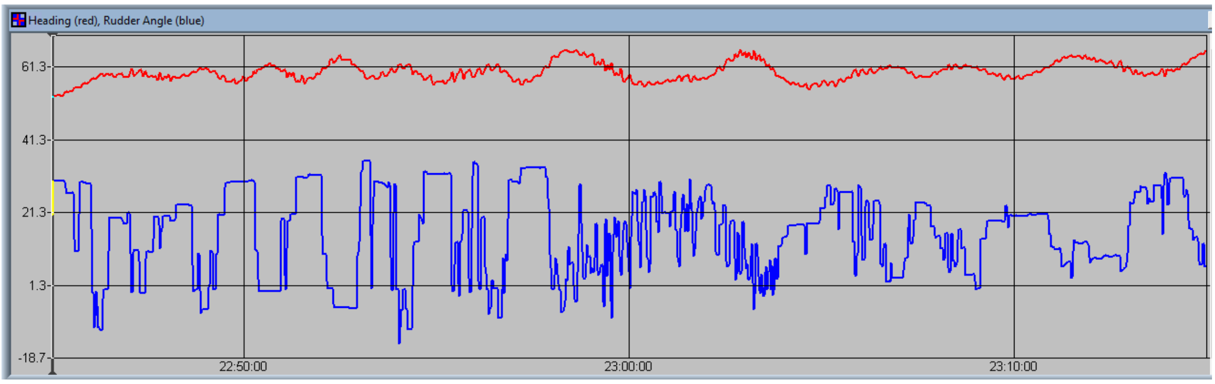


Figure 4: Heading and Rudder angle of MSC ZOE as obtained from the VDR.

Fig. 4 shows that a significant rudder action is required to maintain the ships course. The rudder command is several times to full port, the time averaged rudder angle is abt. 16-18 degree port rudder.

4 Questions that have to be answered by the present report

The following questions were put forward by the BSU which are to be clarified by our investigation:

- What is the probable root cause of the container loss and which roll angles did probably occur?

- How large were the lateral accelerations on the cargo and are they sufficiently large to explain the container loss?

- In how far do shallow water effects play a role for the container loss?

- Are they any general conclusions which can be drawn from this particular accident with respect to the loss of containers?

These questions will be dealt with in the following sections.

5 Ship Data and Loading Condition

MSC ZOE is a 18,400 TEU container ship. The ship was built by DAEWOO SHIPBUILING & MARINE ENGINEERING CO., LTD (DSME) Shipyard as Yard No. 4279 and she was delivered in June 2015. MSC ZOE is classified by DNV GL according to GL Rules, the class notation is GL 100 A5 Container Ship. MSC ZOE flies Panama flag. The IMO-number is 9703318. The main engine is a two-stroke engine designated as MAN B&W 11S90ME-C10.2 with a power of 62,500 kW MCR at 82.2 RPM. The fixed pitch propeller is directly driven by the main engine. The design speed is 22.8 kn, guaranteed at the design draft of 14.5 m.

The main dimensions of the ship are the following:

Length over all	: 395.40 m
Length between Perpendiculars	: 379.40 m
Breadth moulded	: 59.00 m
Depth	: 30.30 m
Design Draft	: 14.50 m
Draft summer freeboard	: 16.00 m

The BSU provided the General Arrangement, Docking Plan and Trim & Stability Booklet. The data was used for the creation of a ship model in our ship design system E4. This model is used for further calculations and it is shown in figure 5. The frame plan is shown in Fig. 6.

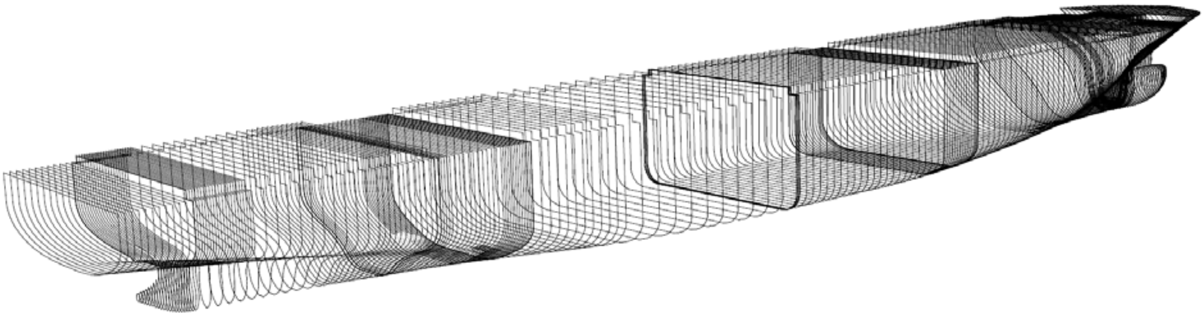


Figure 5: Hydrostatic Calculation Model of MSC ZOE

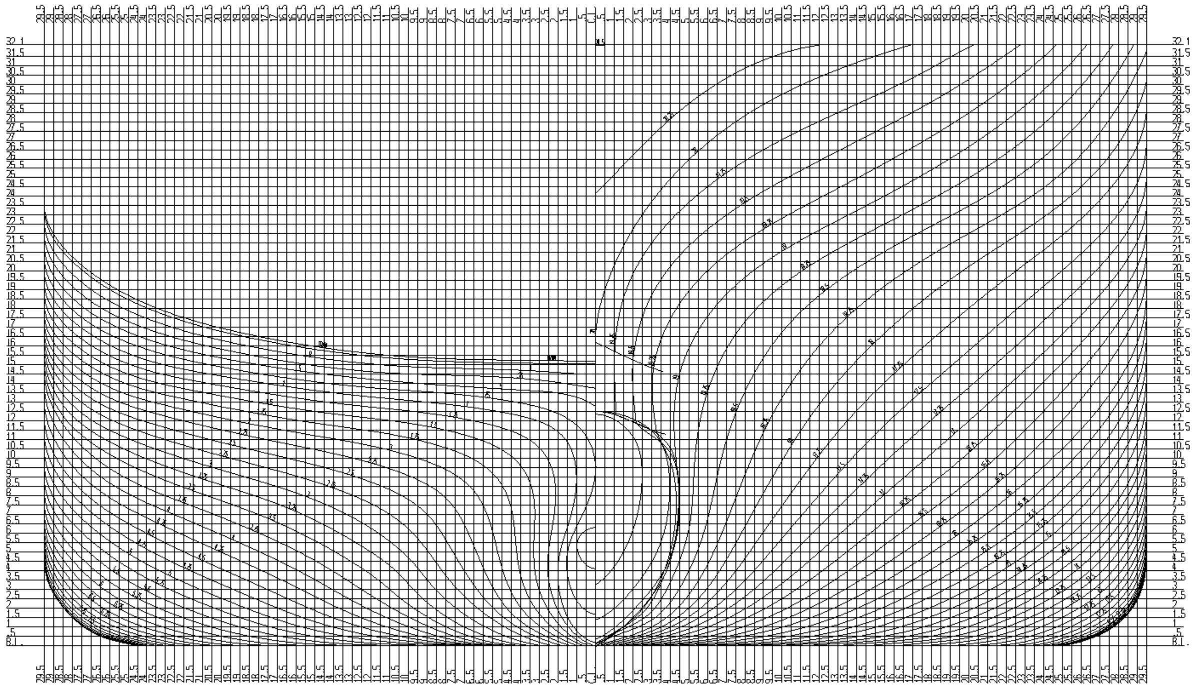


Figure 6: Frame Plan of the MSC ZOE as developed from the Docking Plan Information.

We have checked the accuracy of our model by comparing our computation of hydrostatic particulars against the approved trim and stability booklet of the shipyard. For the draft of 14.525 m, we obtain the following data:

	Displacement in tons	XCB m f. A.P.	KM m a. BL.	KB m a. BL.
Stabi-Book	223200	188.59	30.38	7.87
Our Calc.	224456	188.81	30.26	7.87

The values match quite well and they are within the typical tolerances of such kind of calculations. The comparison demonstrates that the hull form was captured with sufficient accuracy.

The loading condition of MSC ZOE during the accident is stated on the following pages:

```
Loading Condition: ACCIDENT CONDITION
-------------------------------------------------------------------
Light Ship Weight                  : 59087.301 t
Longitudinal Centre of Gravity     :   175.553 m fr. AP
Transversal  Centre of Gravity     :     0.012 m fr. CL
Vertical     Centre of Gravity     :    18.543 m fr. BL
-------------------------------------------------------------------
Deadweight                         :126453.812 t
Longitudinal Centre of Gravity     :   196.413 m fr. AP
Transversal  Centre of Gravity     :     0.012 m fr. CL
Vertical     Centre of Gravity     :    22.500 m fr. BL
-------------------------------------------------------------------
Total weight                       :185541.109 t
Longitudinal Centre of Gravity     :   189.770 m fr. AP
Transversal  Centre of Gravity     :     0.012 m fr. CL
Vertical     Centre of Gravity     :    21.240 m fr. BL
-------------------------------------------------------------------

Equilibrium Floating Condition of Case: ACCIDENT CONDITION

Shell Plating Factor:   1.003   |Density of Sea Water:   1.025 t/m3
-------------------------------------------------------------------

For the determination of each floating condition, the VCG is
corrected for all partly filled tanks according to the initial
free surface moment as stated in the Loading Condition item
tables below.

-------------------------------------------------------------------

Equilibrium Floating Condition :

Ships Weight                            : 185541.109 t
Longit. Centre of Gravity               :    189.770 m.b.AP
Transv. Centre of Gravity               :      0.012 m.f.CL
Vertic. Centre of Gravity (Solid)       :     21.240 m.a.BL
Free Surface Correction of V.C.G.       :      0.000 m
Vertic. Centre of Gravity (Corrected)   :     21.240 m.a.BL
Draft at A.P    (moulded)               :     12.437 m
Draft at LBP/2  (moulded)               :     12.185 m
Draft at F.P    (moulded)               :     11.934 m
Trim (pos. fwd)                         :     -0.503 m
Heel (pos. stbd)                        :     -0.067 Deg.
Volume (incl. Shell Plating)            : 181015.703 m3
Longit. Centre of Buoyancy              :    189.751 m.b.AP
Transv. Centre of Buoyancy              :      0.029 m.f.CL
Vertic. Centre of Buoyancy              :      6.578 m.a.BL
Area of Waterline                       :  17882.398 m2
Longit. Centre of Waterline             :    184.011 m.b.AP
Transv. Centre of Waterline             :      0.027 m.f.CL
Metacentric Height                      :     10.814 m
Metacentric Height required GMreq       :      0.000 m
```

Calculation of righting levers:

Trim chosen from Equilibrium condition. Draft at LbP/2 from A.P.
Non wt openings considered for freeboard calculations only

For the determination of each floating condition, the VCG is corrected for all partly filled tanks according to the initial free surface moment as stated in the Loading Condition item tables below.

Port side of righting lever curve calculated.

Maximum Leverarm : 5.890 m
Downflooding Angle : 70.000 Deg
Range : 69.933 Deg

Draft m.a.BL	Trim m	Heel Degree	GZ m
12.185	-0.503	0.000	-0.013
12.101	-0.375	5.000	0.935
11.849	-0.015	10.000	1.906
11.428	0.530	15.000	2.911
10.829	1.174	20.000	3.909
10.021	1.796	25.000	4.781
8.957	2.348	30.000	5.395
7.639	2.823	35.000	5.786
6.166	3.387	40.000	5.890
4.603	3.882	45.000	5.706
2.986	4.439	50.000	5.261
1.347	5.023	55.000	4.572
-0.312	5.646	60.000	3.692
-1.977	6.271	65.000	2.677
-3.634	6.881	70.000	1.564

The loading instrument of MV ZOE has calculated a draft at AP of 12.47 m, mid 12.25 m and 12.03 m at FP. The trim is then 0.44 m down by stern. Our values are again in quite good agreement with the data from the loading instrument.

From the printout of the on board loading instrument, the fact becomes obvious that many ballast water tanks were indeed partly filled. The ballast water tanks #3DBBWT to #9DBBWT were partly filled with fillings between 2.5 % and 12 %. In total, this results in a free surface correction of the initial metacentric height of 1.24 m.

From previous investigations we have carried out on behalf of the BSU (BSU report 391/09) and for the ATSB (on behalf of the BSU, ATSB investigation 263-MO-2009-002) we know that partly filled tanks (unless specially designed as anti-roll tanks) have practically no influence on the ship motions in waves.

Although partly filled tanks may reduce the (initial) static stability of the ship, their influence on the ship motions is practically irrelevant, because the fluid only carries out local sloshing motions in the tank.

Therefore, it is common understanding that for seakeeping investigations, always the solid GM must be used. In the same way, the roll period must be calculated with the solid GM, too. The rolling period of the ship is stated as 12.279 s in the loading computer printout. We will show in the later sections that this roll period is not correct for the following reasons:

- The corrected GM of 9.50 m has been used instead of the solid GM of 10.81 m.
- The radius of gyration according to the assumptions of the IS Code is calculated as 0.32B, but our calculation resulted in a value of 0.44B. The roll period according to our calculation is 15.7 s.

It will be shown later that the assumptions of the current Intact Stability Code Weather Criterion are not correct for very large vessels. Fig. 7 shows our computed righting lever curve based on a solid GM of 10.81 m. It should be noted that the GM - despite the large size of the vessel - is actually very large.

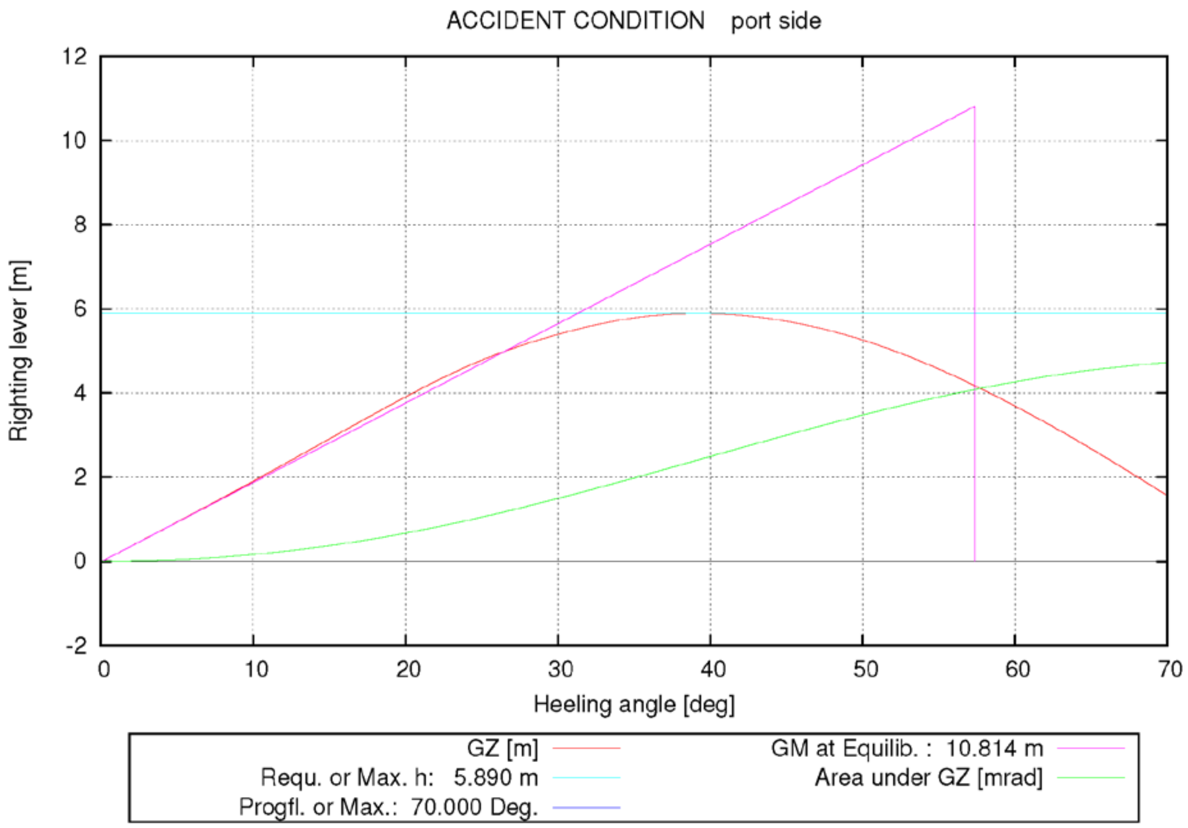


Figure 7: Righting lever curve of the MSC ZOE with GM_{SOLID} of 10.81 m.

6 Effects of Shallow Water on the Ship Motions

During the accident, MSC ZOE was travelling with abt. 10 knots in shallow water of abt. 22-23 m depth. The VDR data show that significant rudder action was required to maintain the course. We have shown above that the restricted water depth makes roll angles of more than 19-20 degree not plausible as there were no indications for a ground contact. We have good reasons to assume that shallow effects may have an influence on the accident and we will study in this section possible shallow water effects on the ship motions during the accident. To do so, we have made potential flow calculations with our in house flow solver KELVIN which includes a fully non-linear free surface boundary condition to study shallow water effects. We have assumed a heel of 15 degree, speed 10 knots and a water depth of 22 m. The results of the flow computations are shown in Fig. 8.

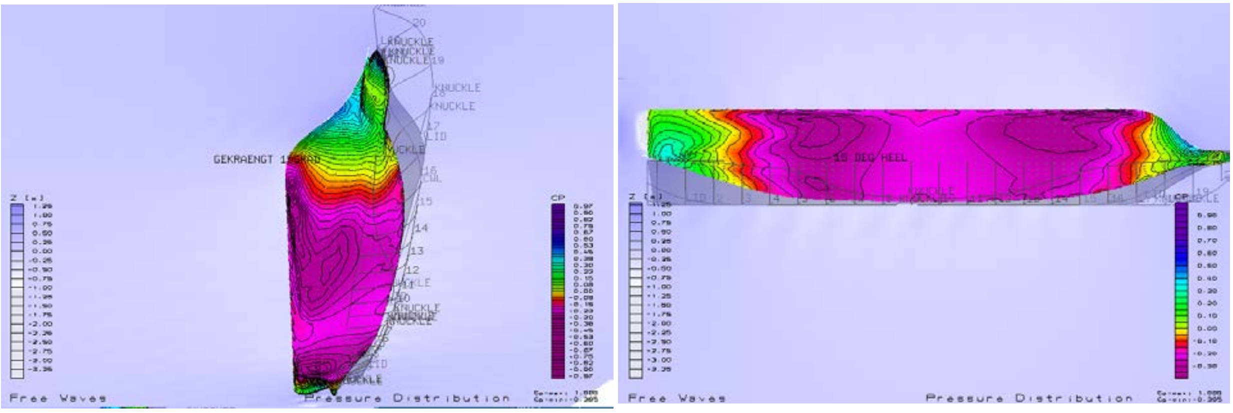


Figure 8: Pressure distribution along the hull of MSC ZOE. 15 Deg. STBD Heel, 22 m water depth, speed 10 knots.

From Fig. 8 it can be seen that due to the heel combined with the restricted water depth, the pressure distribution along the hull becomes strongly asymmetric. On the starboard side, there is a strong low pressure region at the bottom of both fore and aft body. These low pressure regions can also be seen at the ship sides, and they cause a suction force. This suction force causes a yawing moment as well as a heeling moment. The heeling moment will increase the static heeling angle, and the yawing moment will force the ship into a turning circle into the direction of the heel.

The suction force depends on the square of the ship speed, on the heel and on the water depth. For 10 knots speed, 15 Deg. heel and 22 m water depth, we have calculated an additional heel of abt. 0.2 degree and a yawing moment (to starboard side) of 19881 mt. The additional heel angle is relatively small, which is due to the fact that the ship speed is very low with abt. 10 knots on one hand and the restoring moment is very large due to the high GM.

Compared to the dimensions of the ship, the yawing moment is also not very large (due to the low ship speed), but it must be taken into account that also the rudder forces depend roughly on the square of the ship speed, and they are very small, too. From the GA plan, we have estimated the rudder area (movable part) to 95 m^2, the aspect ratio Λ of the rudder was measured to abt. 1.25. If we assume that the pivoting point of the ship in shallow water is abt. 0.5L, then the computed yawing moment results in a rudder force of abt. 100 t to compensate this yawing moment. A simple estimation of the rudder lift according to formulae presented in Brix, Manoeuvring Technical Manual, give the result that abt. 22 degree rudder angle result in abt. 100 t rudder cross force if the inflow velocity into the rudder is assumed to be 10 knots. Although our calculations are based on a very simplified approach, this value is principally in line with the recorded rudder angles.

Therefore, we can draw the following conclusions on the shallow water effects on the ship motions: The additional heeling moment due to the asymmetric pressure on the hull seems to be negligible due to the combination of low ship speed and high restoring moment. More important is this effect on steering: Whenever the ship heels, it is forced into a turning circle which must be compensated by the action of the rudder. We have computed a rudder angle of abt. 22 degree for 15 degree heel. The VDR printout presented in Fig. 4 shows that our calculation is plausible: The crew reported that the vessel was permanently rolling with roll angles of 5-10 degree due to the combined action of wind and waves. The plots of the heading and of the rudder angle shown in Fig. 4 exactly reflect this behavior of the ship.

When the heel induced yaw moment forces the ship into a turning circle, this turning motion will also increase the heeling angle. Other than the additional heeling angle we have computed from the asymmetric flow around the ship hull, the nature of this additional heeling angle is purely dynamic. We have good reasons to assume that this additional dynamic heeling angle may not be very large, as the ship speed is very low. As the main focus of the later investigations is not on heeling angles, but on lateral accelerations, this effect influences the lateral accelerations only via the increase of the heeling angle, as the dynamic contribution of this turning motion is probably small.

Therefore, it is according to our opinion justified to assume that the shallow water effects have a negligible influence on the heeling angles and transversal accelerations, but mainly an effect on the course keeping performance of the ship. But it must also be concluded that the shallow water effects mentioned do in fact increase the heeling angles and lateral accelerations compared to deep water, but they are by far not large enough that they can be regarded as the root cause of the container loss.

7 A brief introduction into the seakeeping method E4ROLLS

For roll motion computations, we use the sea keeping code E4ROLLS which was originally developed by Söding and Kröger for the investigation of the E.L.M.A. Tres capsizing accident in 1986. E4ROLLS simulates all six degrees of freedom in time domain. The concept is that those degrees of freedom which are governed by hydrodynamic effects are computed by using linear RAOs (e.g. from a strip theory or panel code). These degrees of freedom are heave, pitch, sway and yaw. A nonlinear treatment is foreseen for those degrees of freedom where the nonlinearities are the governing effects. These degrees of freedom are roll and surge. The equation used for the roll motion reads as follow:

$$\ddot{\varphi} = \frac{M_{wind} + M_{sy} + M_{wave} + M_{Tank} - M_d - m(g-\ddot{\zeta})h_s - I_{xz}\left[\left(\ddot{\vartheta}+\vartheta\dot{\varphi}^2\right)\sin\varphi - \left(\ddot{\psi}+\psi\dot{\varphi}^2\right)\cos\varphi\right]}{I_{xx} - I_{xz}\left(\psi\sin\varphi + \vartheta\cos\varphi\right)}$$

Here, M_{wave} denotes the direct roll moment obtained from the roll RAO, and h is the righting lever in waves computed by the concept of Grim's equivalent wave (Grim 1960), see Fig.9. The latter makes the computation extremely fast and at the same time reliable. M_{wind} and M_{Tank} are external moments from wind action or moving fluids, M_D is the (nonlinear) roll damping moment, where roll damping is accounted for according to Blume.

I_{xx} and I_{xz} denote the mass moments of inertia including section added masses, m is the ship's mass. E4ROLLS was intensively validated by model tests during German BMBF-funded research programs from 1998-2006.

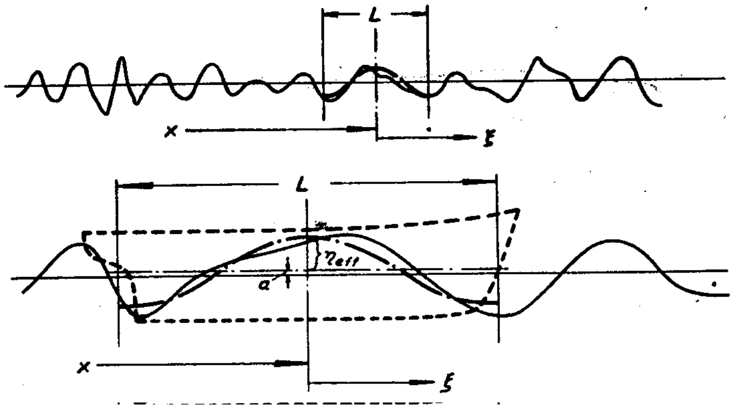


Figure 9: Principle of Grim's equivalent wave

8 Selected Results of the linear Strip Method

Fig. 10 shows the computational model for the linear strip method. It shows the frame setup for the calculation of section added mass as well as the cuboid for the mass representation, which is generated from the input of the light ship and the loading condition.

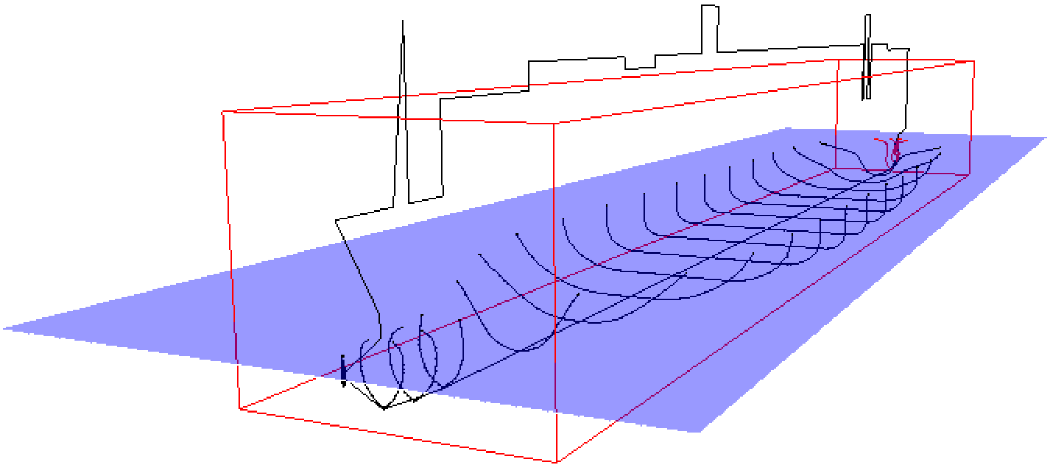


Fig. 10: Calculation model for the linear strip method

The linear strip theory has computed the natural roll period of the ship as 15.7 s. This calculation is based on a roll radius of gyration which amounts to 0.44B including the contribution of the section added mass. The "dry" part of the radius of gyration amounts to 0.37B, and it is equivalent to the cuboid shown in Fig. 10. The roll period stated in the loading instrument is 12.28 s. We have checked this calculation, and we found that this roll period is based on the GM including free surface corrections (which is not correct, as shown above) and it is at the same time based on a roll radius of gyration of 0.32B. This value is computed according to the standard procedure of the IS Code, and it is by far too small. According to the IS Code formula, the radius of gyration, denoted by *C* is to be calculated as follows:

$$C = 0.373 + 0.023(B/D) - 0.043(L_{WL}/100)$$

Where B is the breadth of the ship, D is the draft and L_{WL} the waterline length of the ship. This formula was in use when at the same time, the ship length was restricted to 100m in the IS Code, and for these ships the formula might have been correct. For the present investigation, the length correction amounts to -1.63 which results in the unrealistically small value of 0.32. Consequently, the roll period based on this value is by far too small. It is not known to us whether the crew considered the roll period for their decision making, but if they had done so, their decision would have been based on a wrong value.

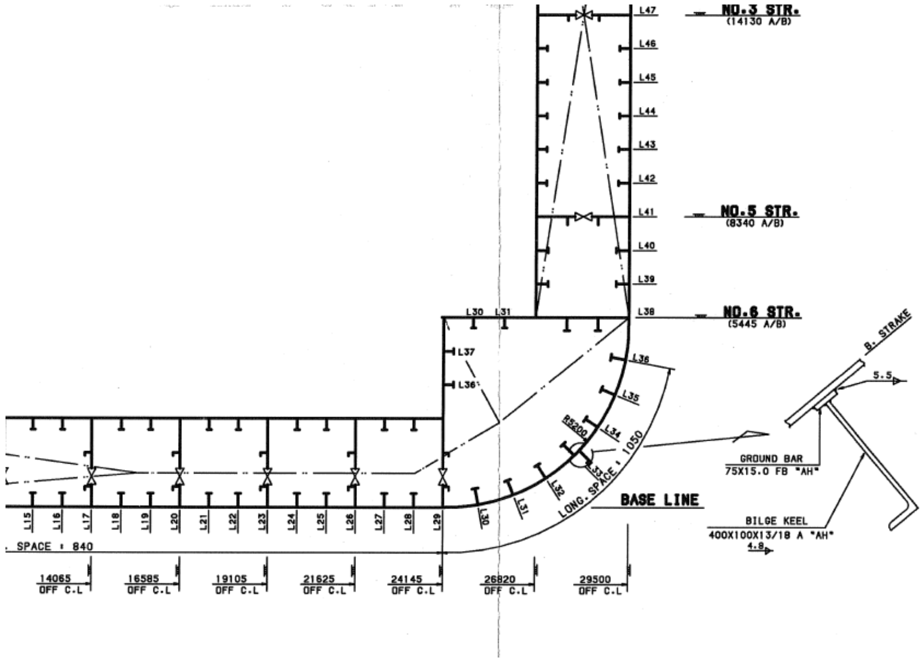


Fig. 11: Bilge keel details, taken from the Docking Plan.

Interesting to note are further the details of the bilge keel. The bilge keel consists of an L-Bar with 400 mm height (see Fig. 11). From the shell expansion plan the length of the bilge keels could be determined as 104.30 m, resulting in a total bilge keel area of 83.44 m^2. Compared to the overall size of the ship, the bilge keel area which provides the major part of the roll damping is quite small. Therefore, it is to be expected that especially at lower ship speeds, there is not sufficient roll damping. This general trend has already been observed during the investigation of the CHICAGO EXPRESS accident, see BSU report 510/08.

The following figures show the computed RAOs for a ship speed of 10 knots. According to our experience, the RAOs are quite normal.

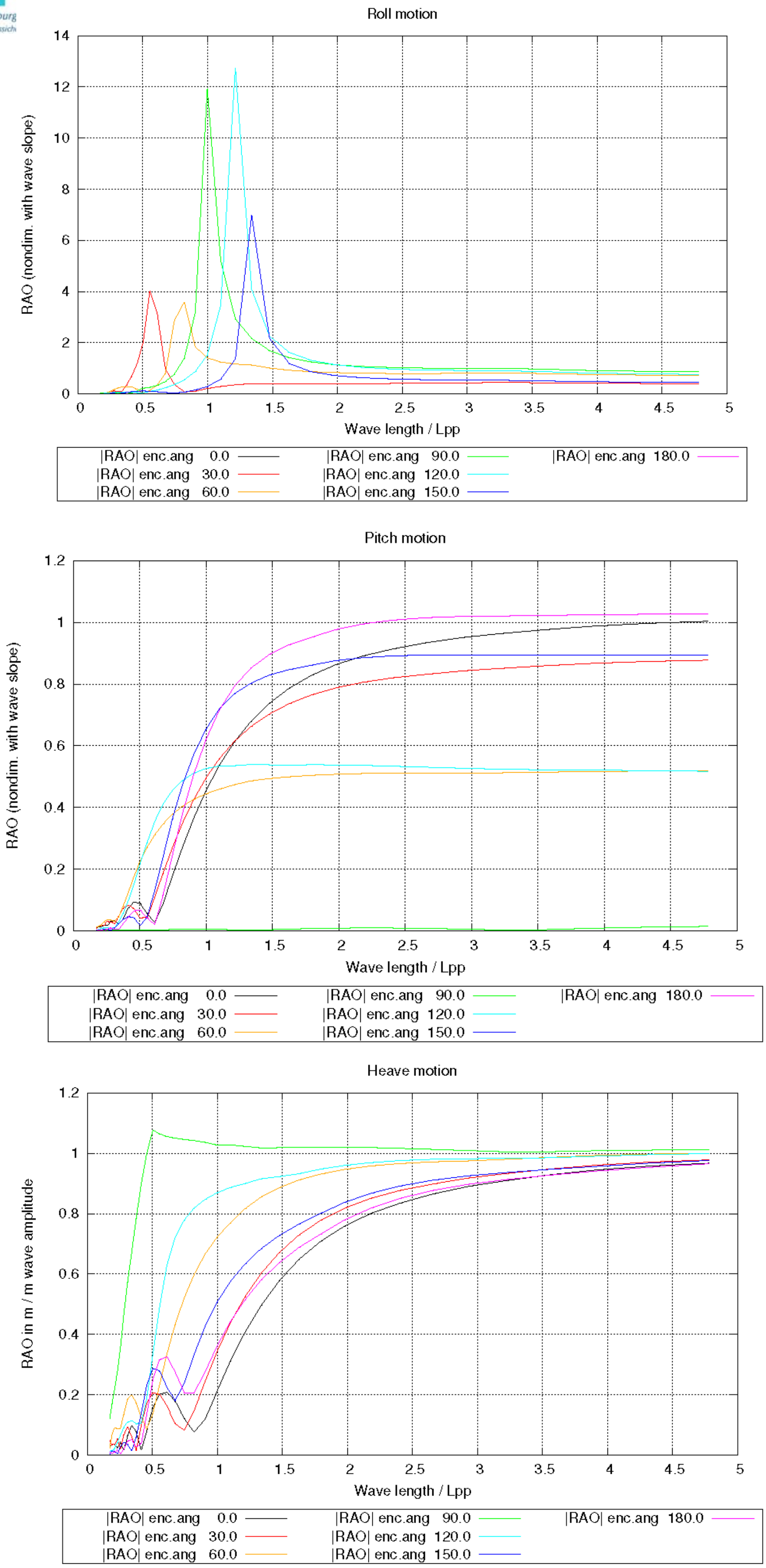


Fig. 12: RAOS for the roll (top), pitch(middle) and heave motion (bottom).

9 Results of the Nonlinear Seakeeping Investigation

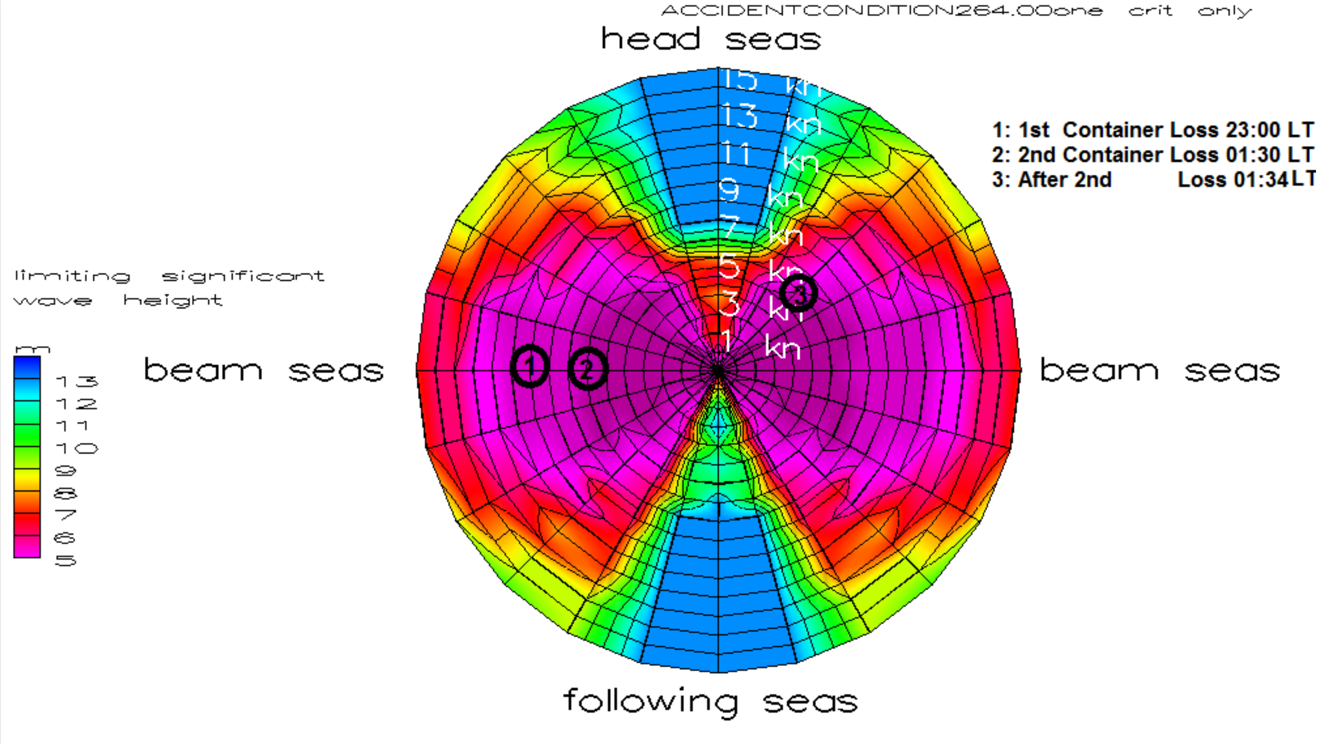


Fig. 13: Computed Polar Diagram for MSC ZOE, Accident Condition, wave period 13 s, roll angle 15 degree, 50.000 s simulation time.

We have started our seakeeping investigation by calculating the limiting significant wave height for a roll angle of 15 degree in waves of 13 s period. The results are presented in Fig. 13. The ship is assumed to be in the centre of the polar plot. The radial rings represent the ship speed, the sectors indicate the encounter angle of the waves. Wind is not included in the calculation. It becomes obvious that 15 degree roll angle is reached in beam seas in all speeds for significant wave heights of abt. 5 m. For all other courses, much larger wave heights are required. The loss on the containers took place in beam sea scenarios (see Fig. 1-3). This is in line with the results presented in Fig. 13. Fig. 13 also underlines the fact that the ship does not have much roll damping. It further shows that also in bow quartering seas, comparable roll angles are possible for encounter angles slightly beyond 30 degree and slow speed. We have analysed the loss of containers at 23.00LT more in detail, and the plot of the time series is presented in Fig. 14.

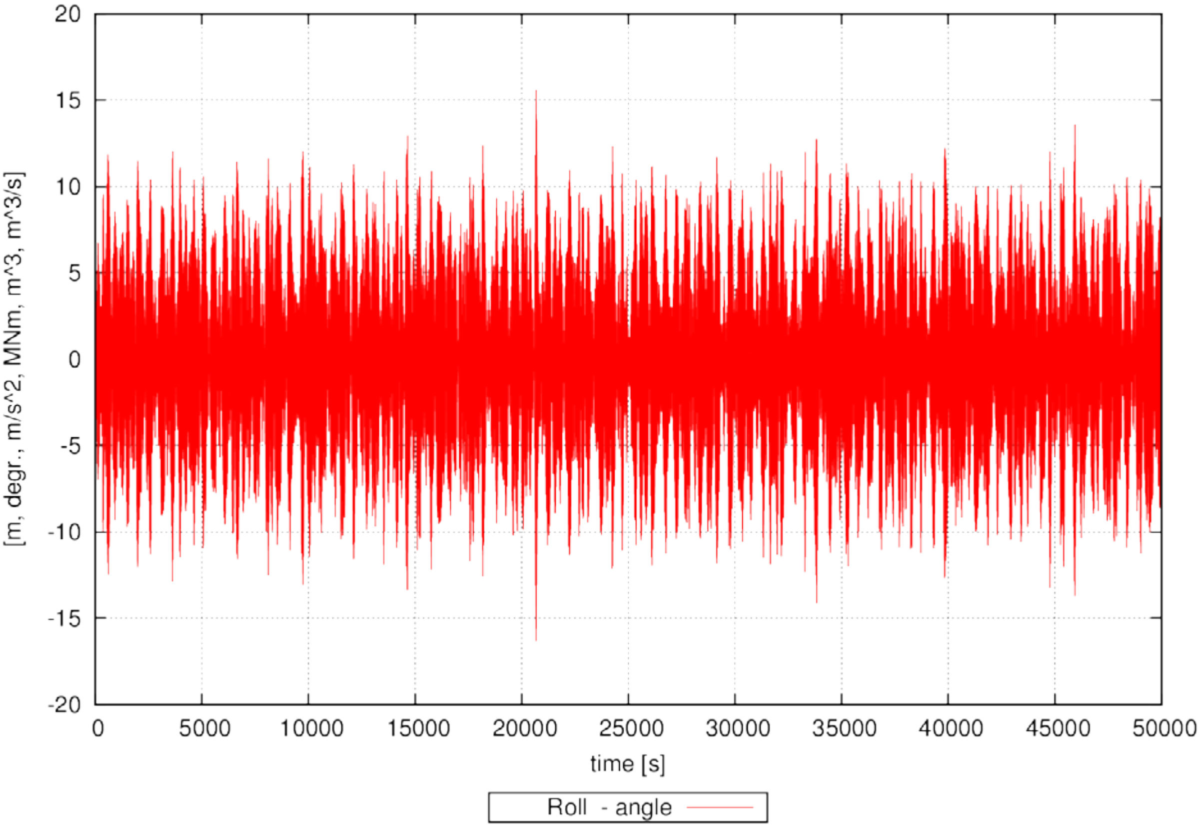


Fig. 14: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 10 knots, encounter angle 93 degree, 50000 s simulation time.

Fig. 14 shows that the vessel is permanently rolling with amplitudes between 5 and 10 degree. This is exactly in line with the statements of the crew. Fig. 14 also shows that one time (at abt. 20670 s), a roll angle of 16 Deg. occurs. We have plotted the roll angle and the wave elevation at mid ship in Fig. 15. There, it becomes immediately obvious that this roll angle is only possible if the ship is hit by a group of larger waves. Otherwise, the roll motion declines and the roll angle is abt. 10 degree.

From Fig. 13-15, the principal nature of the accident becomes obvious: The ship travels in beam seas, and she is rolling moderately up to 10 degree. During this roll motion, she becomes unstable in course and permanent rudder action is required to keep her course. Suddenly she is hit by a group of higher waves which results in a larger roll motion. This roll motion was certainly not 30 degree, as reported by the crew, as the ship would have grounded then. The roll angle was probably more than 15 degree and certainly less than 19 degree. We do believe that the crew overestimated the magnitude of the roll angle due to the very high accelerations, which are a consequence of the large initial GM.

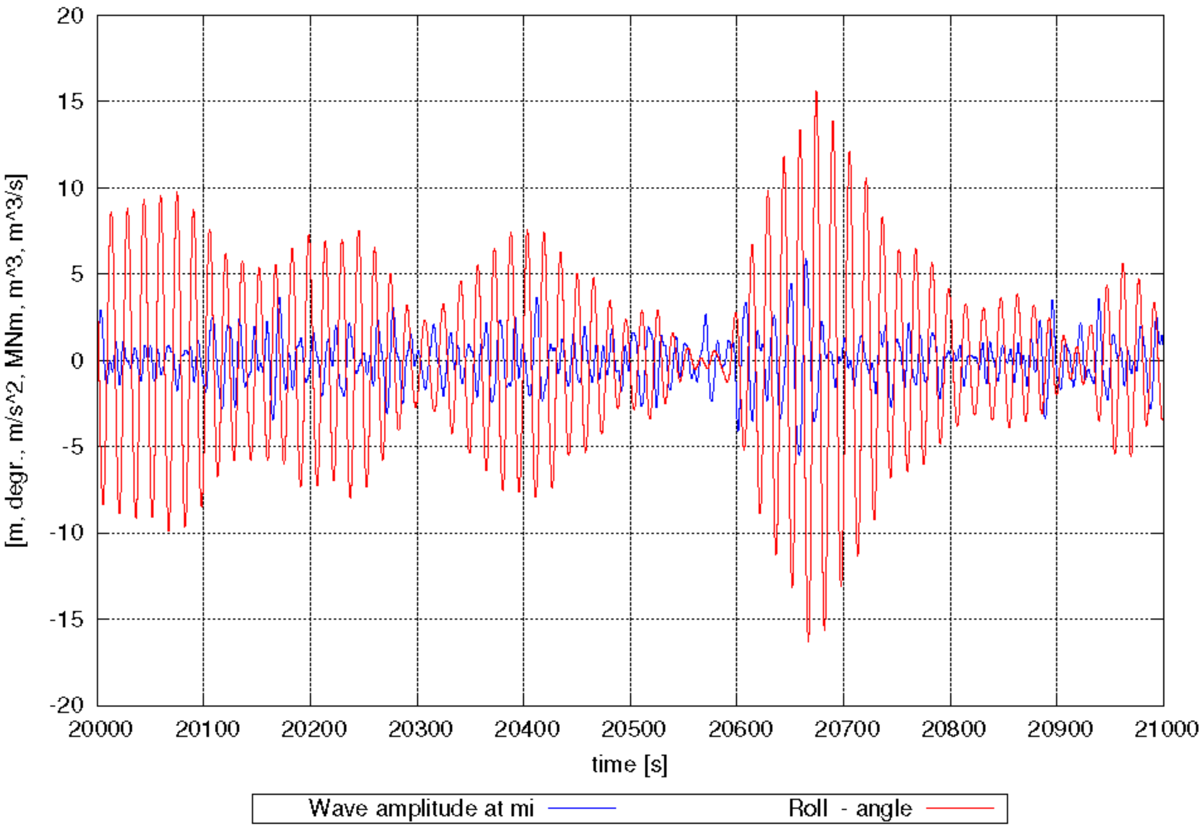


Fig. 15: Computed time series of the roll angle and wave elevation at mid ships of MSC ZOE. Accident condition, speed 10 knots, encounter angle 93 degree without the effect of beam wind.

Until now, we have not studied the effect of the beam wind on the roll motion during the first calculated container loss. The ship was exposed to a wind force of approx. 10 Bft, the encounter angle was abt. 93 degree. As the stability of the ship is very high, it is not to be expected that the wind force will lead to a significant increase of the roll angle. We have repeated the calculation including the wind heeling moment and it turned out that the maximum heel at abt. 20670 s increases from -16.3 to -16.9 degree. In section 6 we have computed the additional heeling angle from the shallow water effects to abt. 0.2 degree, which means that our computed total heel is still below the limiting heeling angle for a possible grounding of the vessel. Fig. 16 shows the same time series as Fig. 15, but now including beam wind of BFT 10 and consequently a slightly larger maximum roll angle.

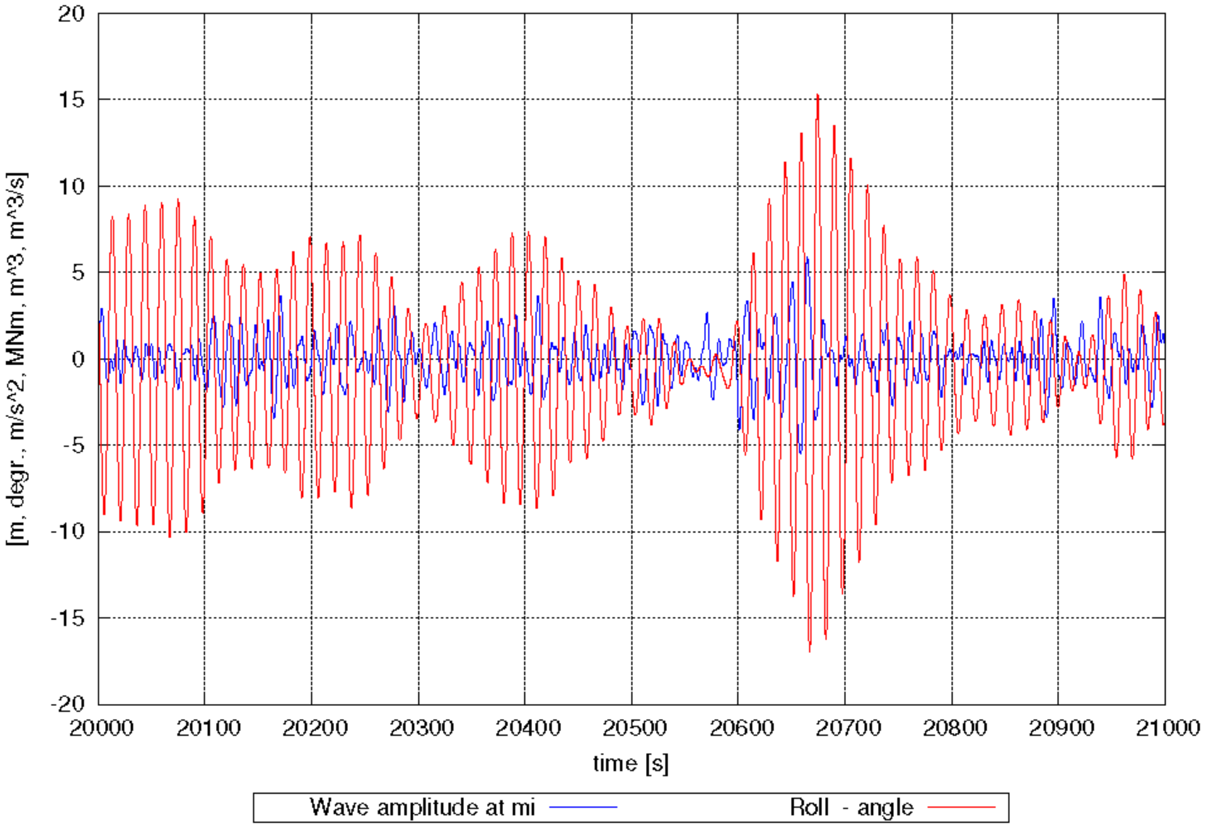
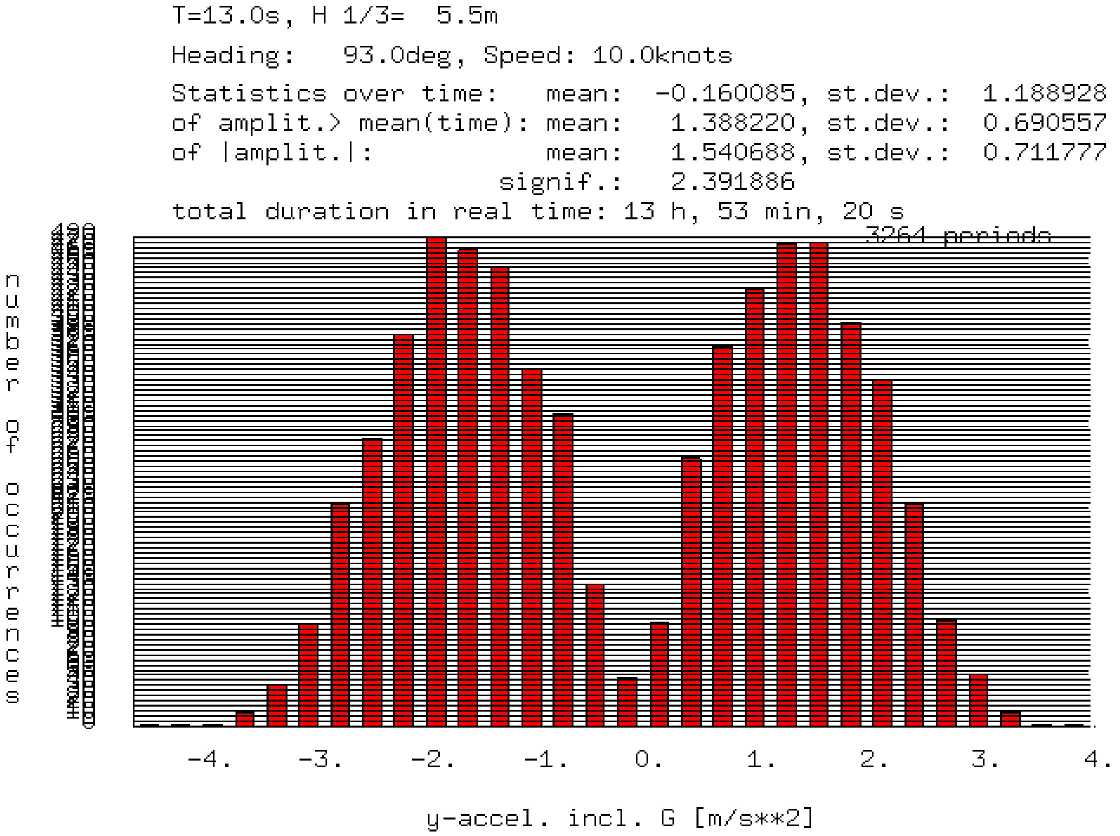


Fig. 16: Computed time series of the roll angle and wave elevation at mid ships of MSC ZOE. Accident condition, speed 10 knots, encounter angle 93 degree including the effect of beam wind.

10 Transversal accelerations

Containers were actually lost from Bays 10,26 and 42-58. In total, 8 tiers were stowed on deck. This last tier is approx. 53 m above the base line. The most forward point where containers were lost is 332m from A.P., the point located most aft is abt. 134 m from A.P. Therefore we calculated lateral accelerations for the two points (X,Y,Z) = (134,0,53) and (332,0,53). Our calculation includes wind. The results have shown that the resulting transversal accelerations do not significantly depend on the longitudinal position, therefore we show the results only for the point located most aft.



```
T=13.0s, H 1/3=  5.5m
Heading:   93.0deg, Speed: 10.0knots
Statistics over time:   mean:  -0.160085, st.dev.:  1.188928
of amplit.> mean(time): mean:   1.388220, st.dev.:  0.690557
of |amplit.|:           mean:   1.540688, st.dev.:  0.711777
                     signif.:   2.391886
total duration in real time: 13 h, 53 min, 20 s
```

Fig. 17: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 10 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 50000 s.

Fig. 17 shows that during the accident condition, a maximum transversal acceleration of -4.6 m/s^2 is reached when the maximum roll angle of -16.9 degree occurs. Typically, container lashing equipment is designed for a lateral acceleration 0f 0.5g, which is 4.9 m/s^2. Our computed maximum acceleration is quite close to this value. It must be noted that this acceleration occurs only one time in 50000 s (see Fig. 14). If we now restrict the simulation time to 10000 s, we obtain the following scatter diagram for the lateral accelerations:

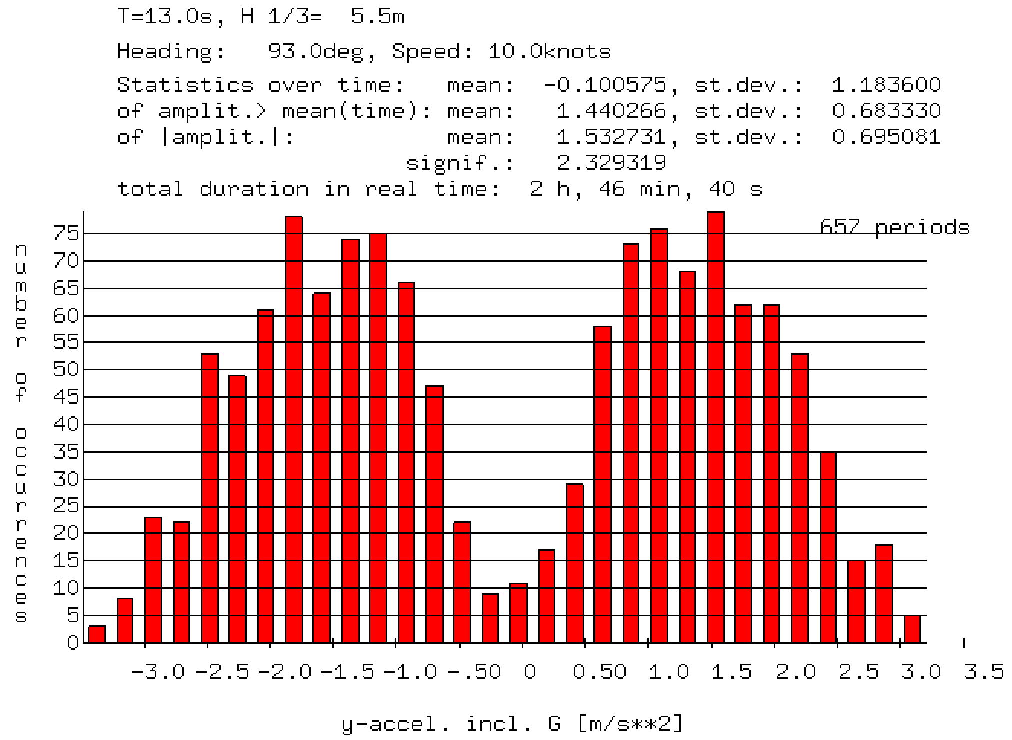


Fig. 18: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 10 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 10000 s.

Fig. 18 shows that the lateral accelerations are well below the threshold of 0.5g. This explains why the crew did not see a reason to alter course or speed: The vessel was rolling between 5 and 10 degree, see Fig. 14, and the accelerations were not large enough to cause a cargo loss. From the fact that the containers did not fall overboard during this phase one can conclude that they were probably correctly lashed. When the ship was hit by a higher wave group, the rolling increased and the accelerations were severe enough that the lashing failed and the cargo fell overboard.

It is well possible that in our calculation, we have underestimated the significant wave height which we have assumed as 5.5 m. Therefore, we have repeated the calculation with a significant wave height of 6m. The maximum roll amplitude at 20670 seconds is now -18.35 degree, and the maximum transversal acceleration is now -4.8 m/s^2. Assuming a maximum wave height of 6.50 m leads to a maximum roll angle of -19.6 degree and -5.2 m/s^2. Under these conditions, the vessel would have just hit the ground during the heeling motion.

Fig. 19: Photo of the inclinometer at the Bridge of the MSC Zoe after the container loss.

A photo of the inclinometer, which is installed at the bridge of the MSC Zoe, is shown in Fig. 19. The inclinometer reading suggests that a roll angle of 30 degree has appeared when the ship rolled to the starboard side. But it was shown before that a heel angle of more than 19 degree is hardly possible as the ship would then have had ground contact.

It should be noted in this context that the inclinometer works only for static situations (see further explanations in the report of CHICAGO EXPRESS (BSU 510/08)). If the ships rolls dynamically, the inclinometer actually measures the transversal accelerations due to the mass of the pendulum. A measured static heel angle of 30 degree (which was physically not possible) is equivalent to a (dynamic) lateral acceleration of 0.5g. So our computations are in line with the readings of the ship's inclinometer in this respect.

Our calculation clearly shows that in the accident condition, it is possible that the lateral accelerations become larger than the design values of the lashing equipment. This is confirmed by the inclinometer reading. The crew could not be aware of a potential cargo loss as the accelerations were not large enough to initiate a cargo loss except during the event that the ship was hit by a higher wave group. We will show in the following that the root cause of the container loss is in fact insufficient roll damping, which is a combination of the ship design and the low ship speed.

After the first few cargo losses, the crew must have decided to reduce the speed. The second calculated loss of containers took place at a ship speed of abt. 8 knots at abt. 1.30LT. For this, we have again calculated the time series of the roll angle. The results are shown in Fig. 20.

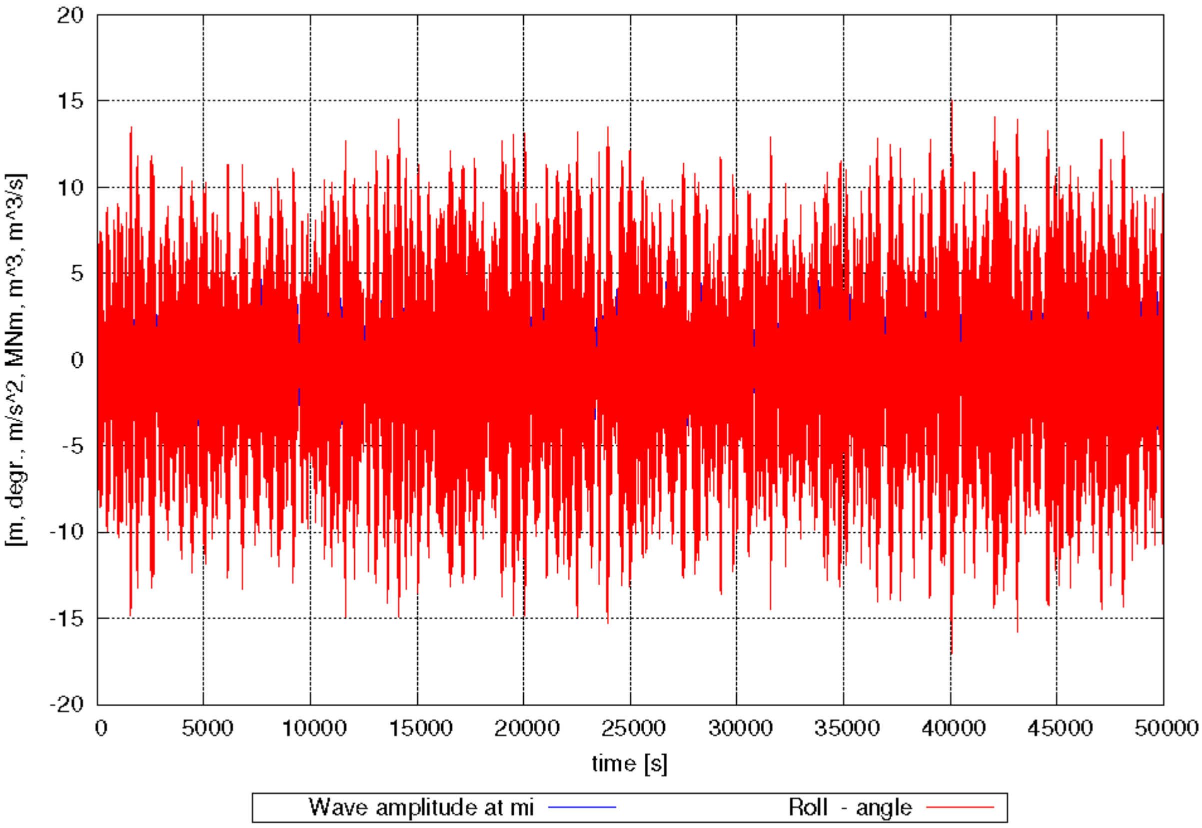


Fig. 20: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 8 knots, encounter angle 93 degree, 50000 s simulation time.

The maximum roll angle is again about -17 degree (at abt. 40000 s), but the comparison of Fig. 20 and Fig. 14 clearly shows that larger roll angles about 15 degree now have become much more probable. This is also reflected in the scatter diagram presented in Fig. 21 for the speed of 8 knots. The maximum transversal acceleration has not changed significantly, but larger acceleration values have become more probable. At the same time, the statistical mean value of the accelerations has increased, which is in line with the expectation. So our calculation has shown that the reduced ship speed has made the container loss more probable.

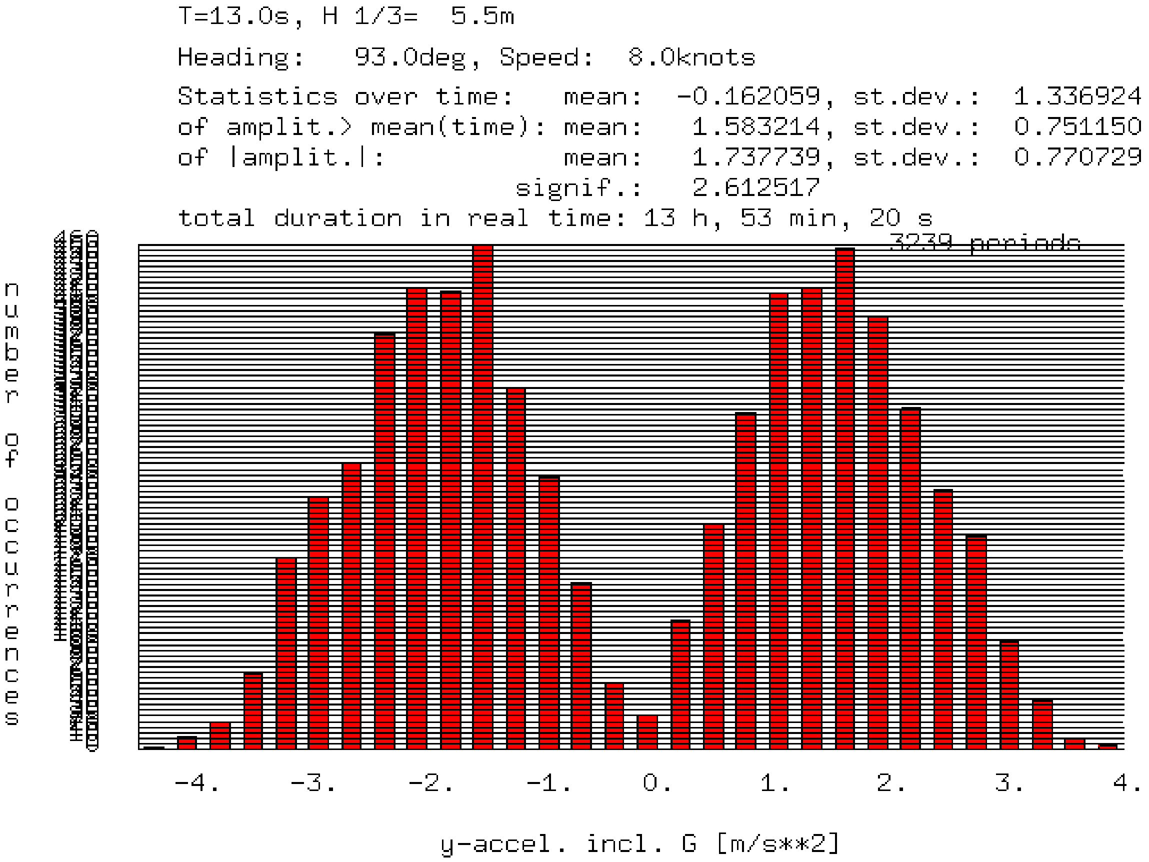


Fig. 21: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 8 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 50000 s.

Consequently, we have then analysed what would have happened if the ship speed had been larger than 10 knots and how that affects the transversal accelerations. We have studied two further ship speeds, namely 12 and 14 knots. The results for 12 and 14 knots ship are shown in Figs. 22-25.

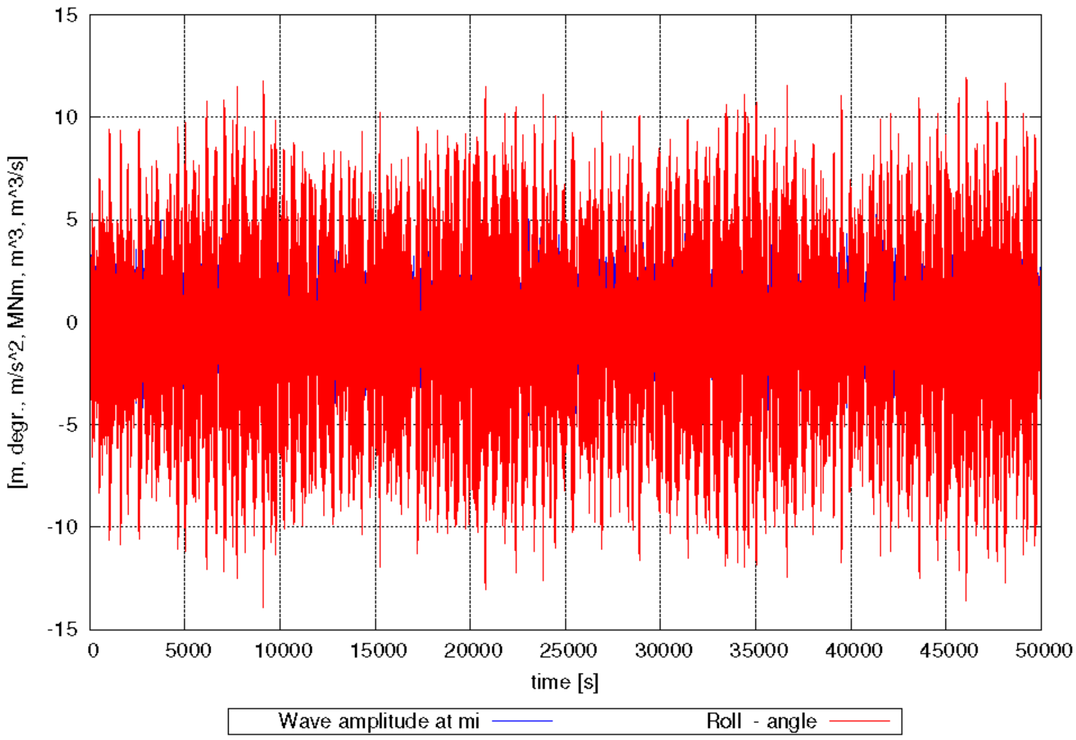


Fig. 22: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 12 knots, encounter angle 93 degree, 50000 s simulation time

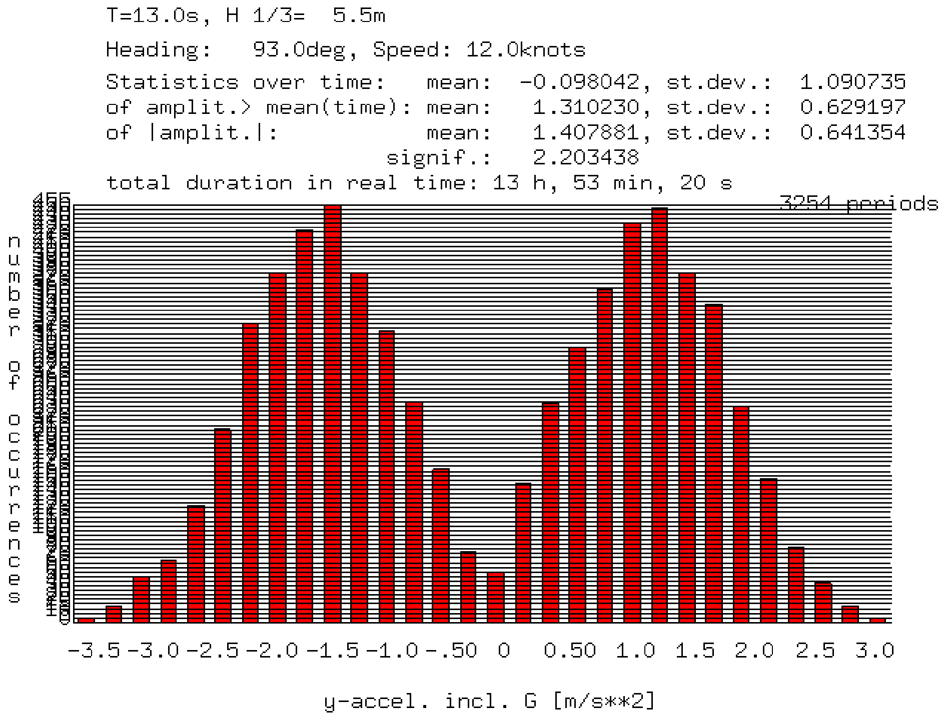


Fig. 23: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 12 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 50000 s.

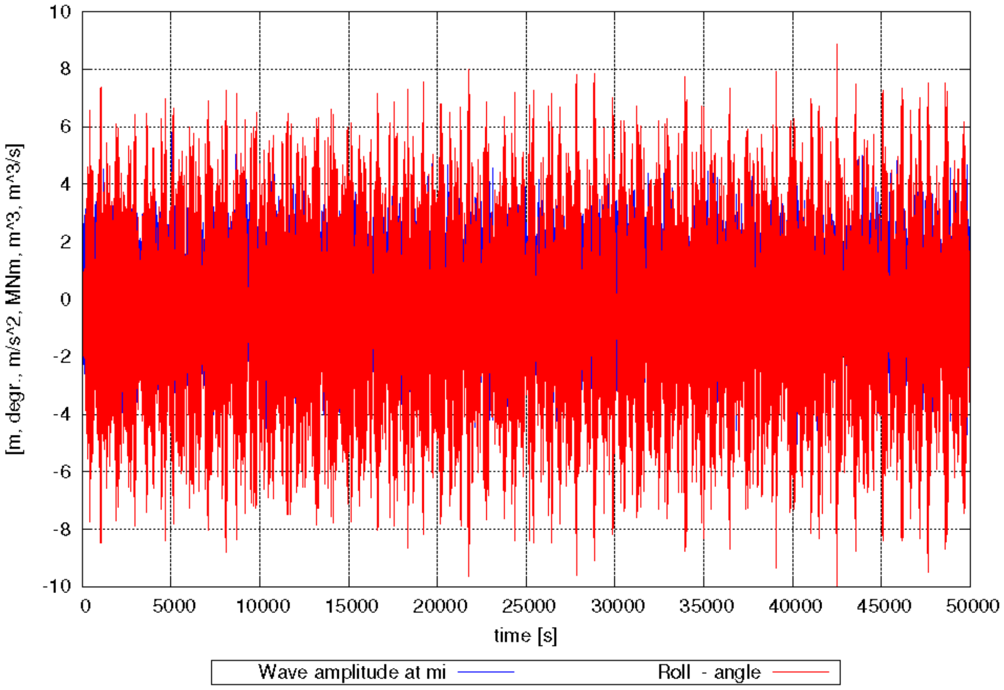
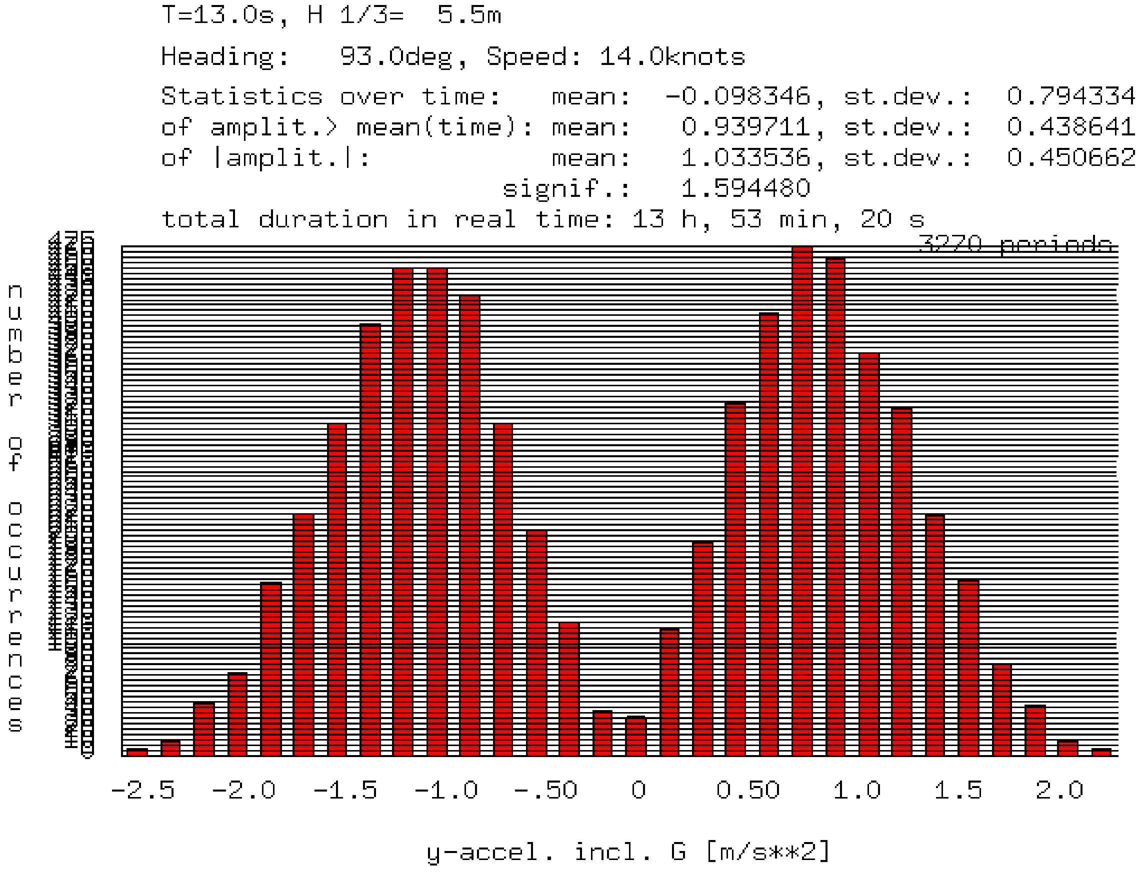


Fig. 24: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 14 knots, encounter angle 93 degree, 50000 s simulation time.



```
T=13.0s, H 1/3=  5.5m
Heading:   93.0deg, Speed: 14.0knots
Statistics over time:   mean:  -0.098346, st.dev.:  0.794334
of amplit.> mean(time): mean:   0.939711, st.dev.:  0.438641
of |amplit.|:           mean:   1.033536, st.dev.:  0.450662
                      signif.:   1.594480
total duration in real time: 13 h, 53 min, 20 s
```

Fig. 25: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 14 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 50000 s.

The results are clear: At a ship speed of 12 knots, the maximum accelerations are about -3.5 m^2, which means that most probably the containers would not have fallen overboard. At 14 knots ship speed, the maximum acceleration is about -2.5 m/s^2. The containers would not have fallen over board at that ship speed, provided, they were properly lashed. These calculations confirm that the root cause of the container loss is insufficient roll damping, caused by the low ship speed combined with the large stability of the ship. This is also underlined by the results presented in Fig. 13: For beam seas, the roll angle is reduced if the ship speed is above 12 knots.

Most probably, the crew was not aware of the fact that their hull did not produce sufficient roll damping and that the selection of the low ship speed would favour roll angles which lead to the cargo loss.

11 On the relation between high stability and roll damping

We have analysed the loading conditions in the stability booklet of MSC ZOE with respect to their stability. The results are shown in Fig. 26. It becomes obvious that a loading condition with a very high initial GM of 10.81 m is not an unusual loading condition for MSC ZOE. At maximum draft of 16.00 m, the ship can operate (theoretically) with a GM-value of abt. 1.30 m. At the partial draft of 13.00 m, the ship can be operated with a minimum GM of 1.50 m. Both limiting values come from the damage stability requirements. At the lightest seagoing condition, the minimum GM comes from the intact stability requirements, and this GM is about 16 m.

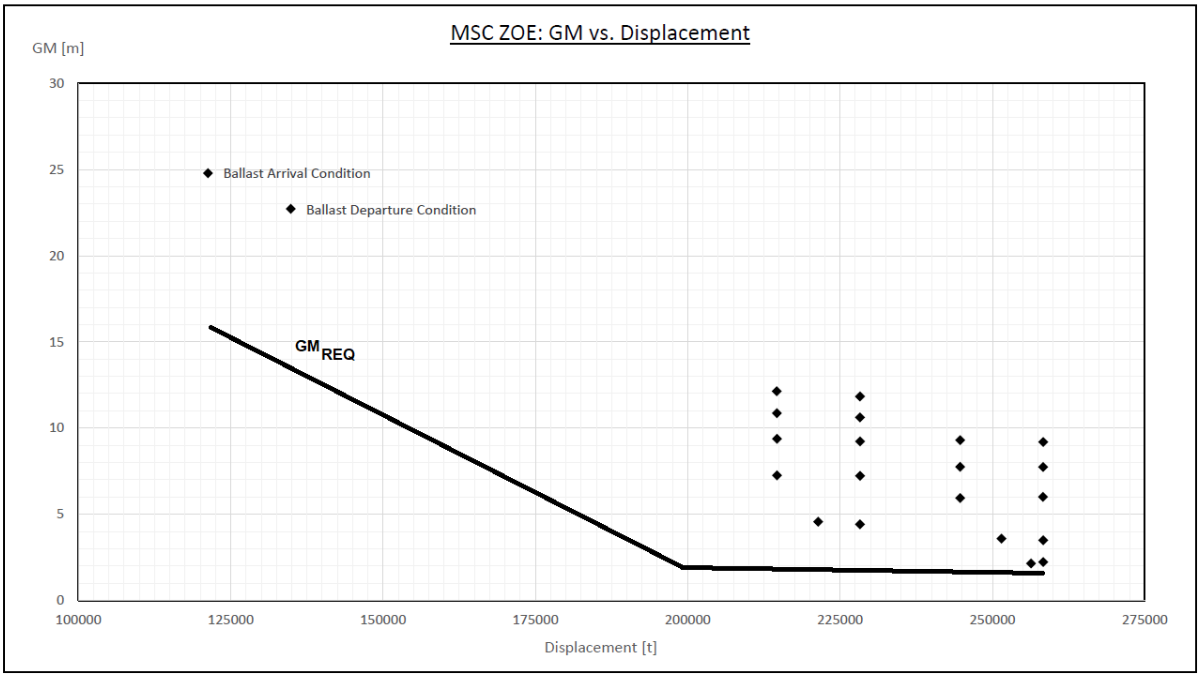


Fig. 26: Summary of Stability Booklet Loading Conditions of MSC ZOE in relation to the GM_{REQ}- Curve.

From Fig. 26 it becomes immediately obvious that there are many loading conditions where the GM is one order of magnitude larger than the prescribed minimum values. From this, the conclusion can be drawn that the design range of stability differs significantly from the operational stability range. Secondly, the conclusion can be drawn that the operational range of stability covers a very large span of stability (i.e. from 1.30 m to 26 m).

Our calculations above have shown that the root cause of the container loss of the MSC ZOE is a very large (excessive) stability combined with insufficient roll damping in the accident condition due to the low ship speed. For large container ships like the ZOE, the operation with excessively high GM now appears to be a typical loading condition, if we consider the stability of the ZOE in the accident condition as excessive. So the conclusion which can be drawn from the ZOE accident investigation is that situations with excessive stability seem to be quite normal operating conditions for large container vessels.

The container loss of the ZOE happened in beam seas, see Fig. 13. In beam seas, the dominant roll mode is rolling due to the excitation of the direct wave moment. The ship is rolling with the encounter period, which is approx. 13 s. As the vessel travels (more or less exactly) in beam waves, the encounter period becomes (nearly) independent from the ship speed. The roll period was abt. 16 s, which is sufficiently far away from the encounter period. Consequently, resonance effects do not play a role for the container loss.

The resulting transversal accelerations in the accident situation (where the exiting moment is given) are now a balance between exciting, restoring and damping forces. As soon as the course is not altered, the exciting forces do also not alter. The restoring forces (for a given ship hull) depend solely on the stability, which is also given.

The damping forces depend on the ship hull and the bilge keel layout and further, on the ship speed. If we assume for a moment that the course is not altered, then the ship speed is the only variable which the crew can influence.

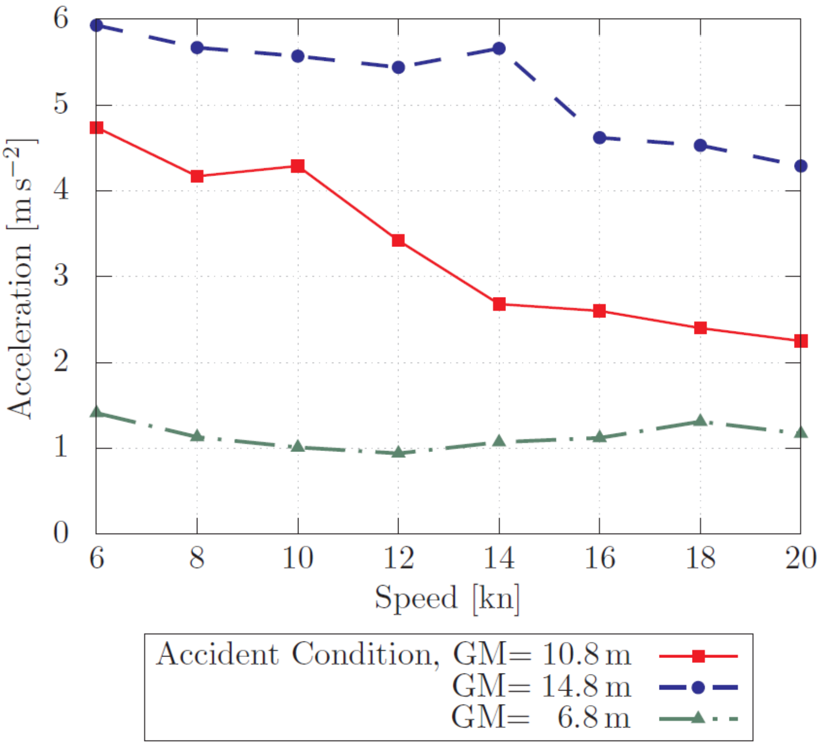


Fig. 27: Dependency of Maximum Transversal Acceleration of MSC ZOE in the Accident Condition Seastate on the ship speed for three different values of GM.

To demonstrate the effect of ship speed on the roll angle and to demonstrate the interaction between damping and restoring forces, we have computed the maximum transversal acceleration as a function of the ship speed and the initial GM. The results are plotted in Fig. 27. As we have not taken into account the beam wind and the shallow water effect, the accelerations stated in Fig. 27 are a little smaller compared to those in Fig. 21-25.

The red curve shows the maximum transversal accelerations for the GM of the accident condition. Due to the high stability, the large restoring moments lead to substantial accelerations. The fact that the accelerations decrease significantly with increasing ship speed has its cause in the increased damping forces. Because roll damping depends on the ship speed, and it is the only force which counteracts the restoring forces.

The blue curve shows the same situation, but we have assumed an initial GM-value which is 4 m larger. Due to the larger restoring forces, the maximum transversal acceleration increases accordingly, as the damping and exciting forces remain the same (for each ship speed). The effect of the speed increase on the accelerations is still present, but the total reduction of the transversal acceleration is smaller due to the fact that the restoring forces are larger. Beyond a certain ship speed, the damping will remain nearly constant, and this then also holds for the transversal accelerations.

If the GM is reduced by 4 m to a value of 6.80 m, the accelerations do decrease significantly as the restoring forces do also decrease (see green curve in Fig. 27). For this value of GM, also a certain dependency of the transversal accelerations on the ship speed can be noted, especially for the lower speed values. But the effect is much less than for the two higher GMs, as the accelerations are low.

This underlines the fact that for large stability values beyond about 10.80m, the restoring forces are too large for the damping the hull provides.

It should again be noted that the damping is speed dependent and that lower ship speeds will result in larger transversal accelerations for the large values of GM.

It should also be noted that many operational stability conditions of the MSC ZOE do differ significantly from the stability values the ship was designed for (GM_{REQ}- limit of the stability booklet).

12 Effect of Roll Damping on the Container Loss

Fig. 28: Original Length of the bilge keel (red) of MSC ZOE and investigated extension (blue).

As the probable root cause of the container loss was the large stability combined with the low roll damping due to the low ship speed, BSU has requested us to study alterative bilge keel sizes and their effect on the roll damping and the resulting lateral accelerations. Fig. 28 shows the shell expansion of MSC ZOE, and we have marked in red the bilge keel as built. The height of the bilge keel is 400 mm, and the length as built is 104.30 m. We have elongated the bilge keel to a still reasonable length of 186.20 m and analysed a bilge keel height 750 mm. The results are shown in the following figures.

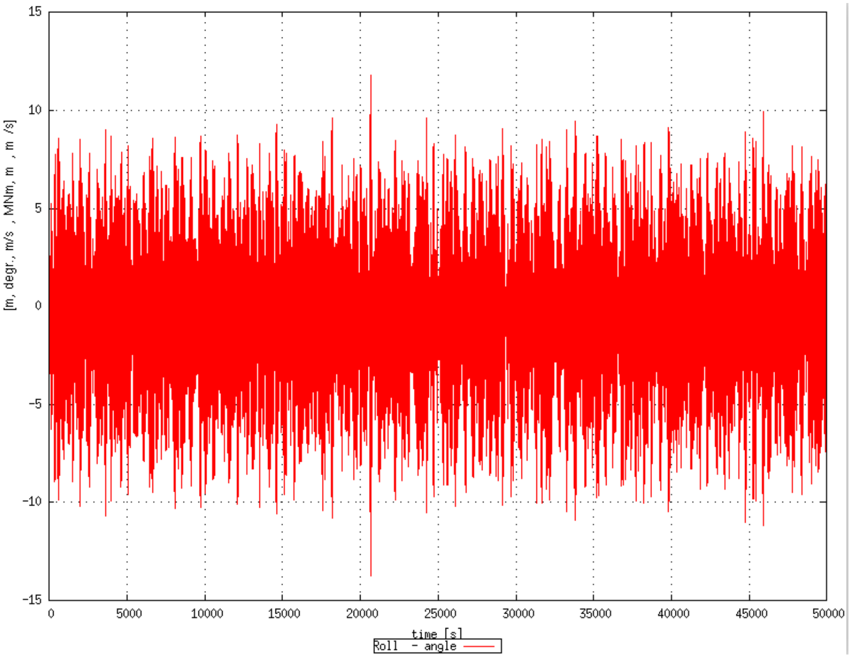


Fig. 29: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 8 knots, encounter angle 93 degree, including beam wind of BFT 10. 50000 s simulation time, bilge keel length 186.20 m, height 750 mm.

With this assumed bilge keel size, the maximum roll angle (including beam wind of 10 BFT) reduces from -16.9 to -13.8 degree in the accident scenario.

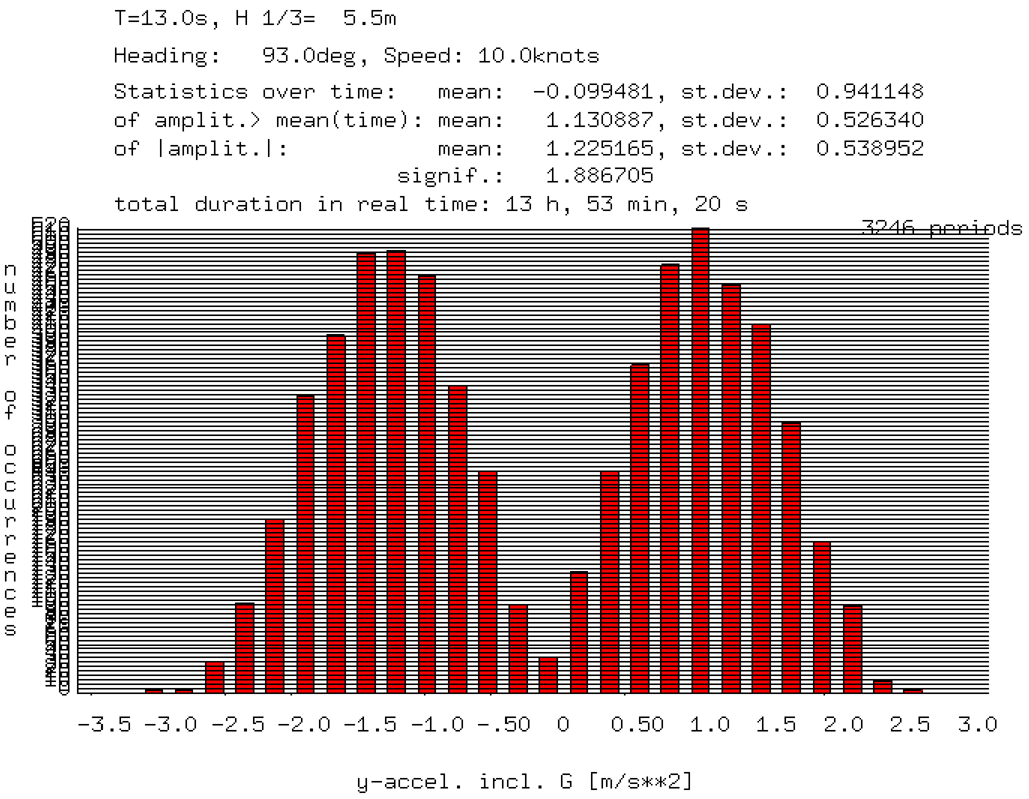


Fig. 30: Computed scatter diagram of the transversal acceleration at (134,0,53). MSC ZOE. Accident condition, speed 8 knots, encounter angle 93 degree including beam wind of BFT 10. Simulation time 50000 s, bilge keel length 186.20 m, height 750 mm.

The maximum lateral accelerations are reduced to abt. -3.5 m/s^2, this is roughly equivalent to a ship speed increase from 10 to 12 knots as shown above. Probably, the assumed larger bilge keel would have avoided the container loss in the same way as it could also have been avoided with a ship speed of 12 knots (see Fig. 23).

Despite the fact that the major cause of the container loss was the large stability, our calculations show that it could be useful to reconsider bilge keel layouts for very large ships. Because it was demonstrated that the hull does not provide sufficient damping if the ship is operated with GM-values that are far higher that the design values of stability.

13 Recommendations for Ship Safety

The root cause for the container loss of MSC ZOE is a combination of high stability and insufficient roll damping. From our accident investigations, the following conclusions can be drawn which might be put forward as safety recommendations:

- It should be made clear that large container vessels are often operated with stability conditions that are far above their design stability values. In such situations, the large restoring forces can result in significant transversal accelerations.

- It should be made clear that especially larger container ships might have insufficient roll damping in situations with large stability. This is again a consequence of the fact that the operating conditions of these ships differ significantly from the design conditions.

- It should be made clear that roll damping is speed dependent. It may happen that in situations with large stability, the roll damping at lower ship speeds may be insufficient. Then, large transversal accelerations may occur. To avoid these large accelerations, a (moderate) increase of the ship speed is an effective option.

- Large ships may have a much higher roll radius of gyration than according to the simple formulae in the IS Code. If the roll period of the ship is calculated on the basis of these formulae, the result may be wrong and the crew could be potentially misguided. Only roll periods should appear in the printout of stability documents which are roughly correct.

- It should be made clear that free surfaces only affect the static stability of the ship unless a tank is specially designed as anti-roll tank. Free surface effects have limited to no influence on the roll motion and on the roll period.

- It could be useful to monitor the transversal accelerations on board of ships and to give an alarm if some threshold (e.g. 0.4g) is exceeded.

- Although we could not find in our analysis that shallow water effects have played a major role in the present accident, we would like to note that the effect of shallow water on the seakeeping performance of a (large) ship is not commonly understood and further research into this topic is found to be necessary.