



DMAIB

DANISH MARITIME ACCIDENT
INVESTIGATION BOARD



MAERSK ESSEN

Marine accident report on loss of cargo

16 JANUARY 2021

**MARINE ACCIDENT REPORT ON MAERSK ESSEN'S
LOSS OF CARGO ON 16 JANUARY 2021**

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Photo: Collapsed containers on MAERSK ESSEN
Source: Maersk A/S

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Introduction

Start of the investigation

On 16 January 2021 at 2226 (UTC+1), the Danish Maritime Accident Investigation Board was notified by Maersk A/S that the Danish container ship MAERSK ESSEN had lost containers overboard due to heavy rolling. The containers were lost approximately 450 nm off Hawaii, while the ship was en route from Xiamen, China, to Los Angeles, USA. The damage assessment was still ongoing, and the number of lost containers was unknown. In the days following, DMAIB received updates on the number of lost containers as the crew's damage assessment progressed. On 19 January, DMAIB received the result of the initial damage assessment. 732 containers were suspected to be lost overboard, but the crew were not able to verify the number before the ship reached port.

DMAIB decided to initiate an investigation to clarify the events and circumstances leading to loss of cargo because of the impact on the marine environment and the hazards such an event poses to the ship and crew.

After the containers were lost, MAERSK ESSEN was diverted to Lázaro Cárdenas, Mexico, where it berthed on 30 January 2021. Due to the COVID-19 pandemic, it was not possible to deploy DMAIB investigators to the ship. Instead, DMAIB interviewed the ship's navigational officers by video call. The crew and company representatives were also instructed to gather evidence for the investigation while the ship was at sea and after the ship berthed. The crew secured evidence from the moment the accident occurred and was thus able to provide the necessary information and documentation for the investigation.

By combining the crewmembers' witness accounts with VDR recordings, AIS information, logbooks and photos, it was possible for DMAIB to establish the sequence of events before, during and after the ship lost containers on 16 January 2021. The sequence of events forms the basis for the investigation into the circumstances that caused the containers to be lost.

Description of the ship

MAERSK ESSEN (Figure 1) was a container ship with a length overall of 366.45 m and a capacity of 13,600 TEU¹. At the time of the accident, MAERSK ESSEN was managed and operated by Maersk A/S and engaged in two combined service routes, AE1 (Asia Pacific-Europe) and TP6 (Asia Pacific-North America).

MAERSK ESSEN was built for the ship manager Rickmers Group along with seven sister ships and was delivered in 2010. All eight ships were chartered by Maersk A/S in 2010 on a 10-year contract.

In 2015, an analysis of the ships' operations concluded that the ships could be optimised by altering their design. As a result, Rickmers Group and Maersk modified MAERSK ESSEN and the seven sister ships to improve fuel-saving and cargo carrying capacities.

1 Twenty-foot Equivalent Unit



Figure 1: MAERSK ESSEN
Source: Maersk A/S

These improvements included re-design of the bulbous bow and propeller, upgrading reinforcement of the cargo hatches and increasing the height of the lashing bridges by an additional tier. The upgrade in lashing bridges allowed the carriage of an extra tier of containers on the cargo deck aft of the navigational bridge, corresponding to a stack height of ten containers (Figure 2). To accommodate the increased lashing bridge height and to afford the possibility for mixed stowage on the cargo deck, a new lashing system was also introduced.

The conversion of MAERSK ESSEN was commenced in 2016. Maersk A/S took over the ship management from Rickmers Group in 2019.

At the time of the accident, MAERSK ESSEN was manned with 25 crewmembers of various nationalities.

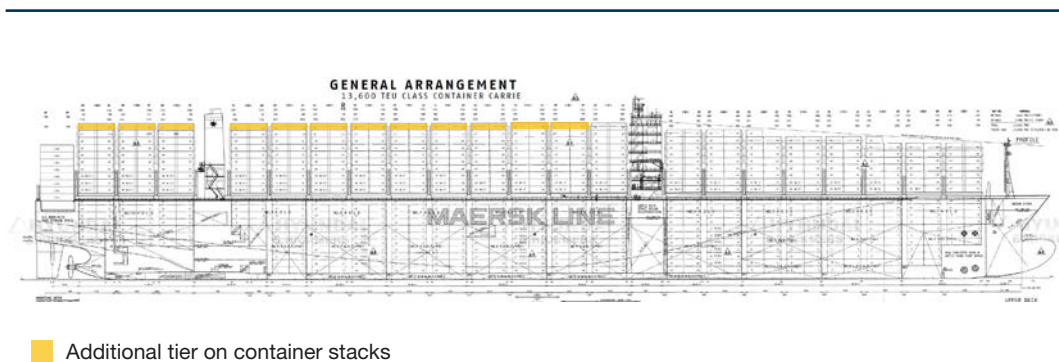


Figure 2: Increased stack height after conversion
Source: Maersk A/S, modified by DMAIB

Narrative

Sequence of events

Reconstruction of the course of events

The course of events is presented from the perspective of the involved persons on MAERSK ESSEN to give insights into how the events were perceived before, during and after the accident. The narrative is based on interviews with a selected group of crewmembers, VDR recordings, logbook records, emails and photo documentation taken before, during and after the accident.

The course of events covers the port stay in Xiamen and the entire voyage across the Pacific Ocean, from 25 December 2020 to 30 January 2021.

All times are the ship's local time.

Departure

On 25 December 2020, MAERSK ESSEN was alongside in Xiamen, China. Cargo operations had been completed, and the ship was ready for the scheduled departure the following day. The next port of call was Los Angeles, USA.

During the port stay, the 2nd officer had requested weather routing advice from the weather service company Weathernews Inc. (WNI). He had informed WNI that arrival in Los Angeles was scheduled for 20 January, and that the planned passage speed was 11 knots, which corresponded to the lowest possible engine rating (10%). While waiting for WNI's route recommendation, the navigational officers monitored the weather forecasts using the onboard software SPOS².

Later, MAERSK ESSEN received information that a berth in Los Angeles was not available until 22 January 2020. The master was concerned about arriving in Los Angeles before a berth was available, because if the ship had to anchor for a prolonged period, it would run critically low on fresh water. Additionally, the weather forecast predicted unfavourable weather conditions for the initial stretch of the voyage. With these factors in mind, the master decided to depart Xiamen as planned and let the ship drift south of the Japanese coast until the weather conditions improved. The 2nd officer informed WNI of the delayed arrival and the intention to drift south of Japan.

On 26 December, MAERSK ESSEN received an initial voyage plan from WNI approximately 45 minutes before departure. WNI suggested taking a more southerly route to avoid a low-pressure system developing in the northern part of the Pacific Ocean (Figure 3). MAERSK ESSEN's route was altered according to WNI's advice, and the ship departed Xiamen.

2 Ship Performance Optimization System

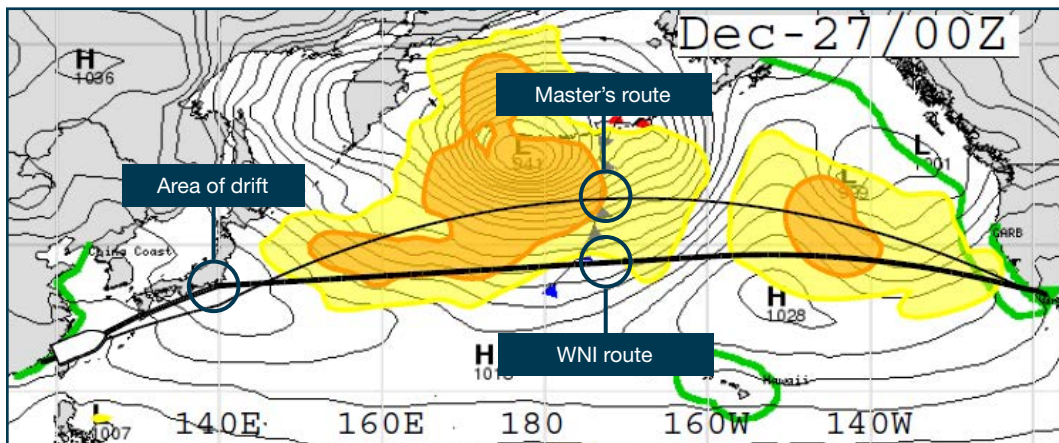


Figure 3: Master's initial route and WNI route plan
Source: WNI, modified by DMAIB

The voyage

Between 29 December and 3 January, MAERSK ESSEN drifted south of Japan. The ship then resumed the voyage in accordance with an updated voyage plan received by WNI. The master deemed the weather conditions to be reasonable, but expected them to deteriorate during the voyage which might require route adjustments later on.

On 8 January, the deck crew checked the cargo lashings, which they aimed to do weekly. All bays, except bay 1, were inspected. The wind had picked up, and it was not deemed safe to inspect the most forward bay. The following day, WNI recommended the ship's route be adjusted further to the south to avoid a forecasted low-pressure area in which wind speed and wave height were expected to increase. The master adjusted the route accordingly. During the following days, the weather deteriorated, and by the night of 12 January gale force winds and wave heights of 5-7 m were experienced. The ship was not significantly affected by the rough weather and moved easily through the sea, with only the occasional heavy roll.

On the 13 January, the master went through the Heavy Weather Check List to ensure that the ship was prepared for deteriorating sea conditions.

On 14 January, the weather improved, but MAERSK ESSEN received a recommendation from WNI to increase speed to 18 knots and adjust the course further south to stay clear of weather conditions that could be damaging to the ship. The ship was also advised to prepare for encountering 6 m sea and swell heights on 17 January. Accordingly, the master changed the ship's course, but he did not increase speed. By maintaining the current speed, the master expected to stay clear of the unfavourable weather conditions, while preventing the ship from arriving too early in Los Angeles. A berth in Los Angeles would now not be available until 28 January, and this was of concern to the master due to the problem with fresh water supplies.

On 15 January, the weather conditions continued to improve with the wind reducing to a fresh breeze throughout the day and evening.

Loss of containers

At 0400 on 16 January, MAERSK ESSEN was underway approximately 500 nm north of Hawaii (Figure 4).

At 0400, the chief officer came to the bridge and relieved the 2nd officer. During the handover, the 2nd officer informed the chief officer that increased wave heights were forecast later in the day. The chief officer could not see the sea surface due to darkness, but felt the ship moving comfortably in the sea. MAERSK ESSEN was following a heading of 087° on auto-pilot in port quartering seas. By now, the wind speed had increased to a strong breeze.

At approximately 0600, some of the crew were woken by the sound of cups and laptops sliding and falling off tables in their cabins as the ship took a few heavy, slow rolls. On the bridge, the chief officer saw from the inclinometer that the ship had rolled 15° to each side. The rolls stopped as quickly, as they had started. The chief officer observed nothing unusual out of the windows, and the sea state seemed not to have changed (Figure 5).

The chief officer thought nothing more of this, as it was normal for the ship to take an occasional heavier roll. Shortly after, an email with a weather warning was received from WNI advising that MAERSK ESSEN was expected to encounter deteriorating weather later that day. It also advised making heavy weather preparations, and that speed and course adjustments might be necessary to reduce the ship's motions. The chief officer planned to inform the master of the email after his meeting with the deck ratings at 0800.

At 0745, the 3rd officer came to the bridge to relieve the chief officer. They talked about the heavy rolling earlier in the morning and the swell always being high in that sea area. The chief officer also informed the 3rd officer that the sea conditions were expected to deteriorate later in the day.

The 3rd officer took over the bridge watch at 0800, and the chief officer went to the deck office to inform the deck ratings about the planned work of the day. A week had passed since the lashings had been checked and this was therefore on this day's work schedule.

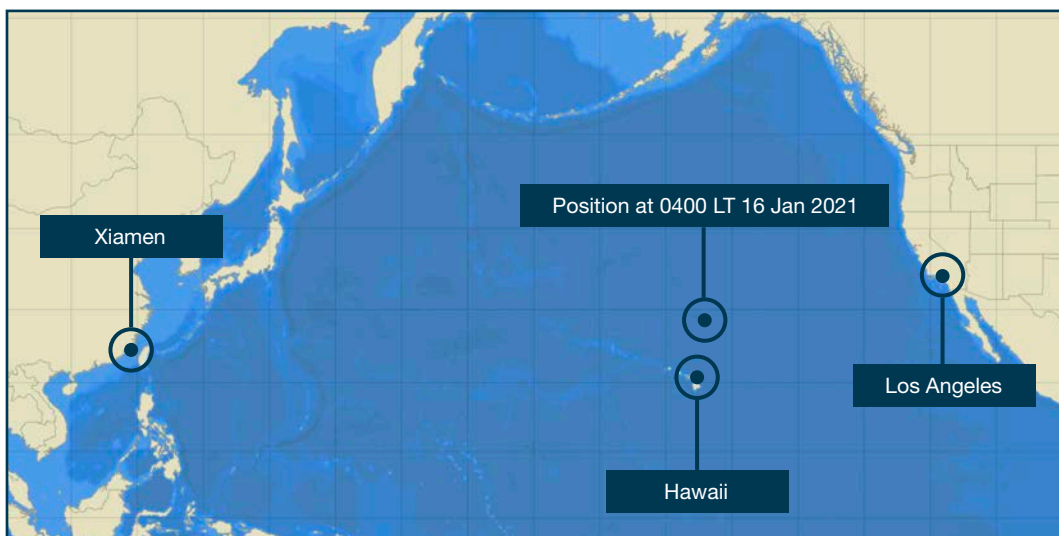


Figure 4: MAERSK ESSEN's position at 0400 LT on 16 January 2021
Source: © Made Smart Group BV 2021 © i4 Insiqth, modified by DMAIB



*Figure 5: Sea state in the morning on 16 January 2021
Source: Private photo*

At 0804, the ship suddenly rolled approximately 15° to each side. On the bridge, the 3rd officer immediately adjusted the course $2-3^{\circ}$ to starboard, although the vessel was already stabilising. He called the master, who was taking breakfast in the mess room, and asked him to come to the bridge. Meanwhile the deck ratings and the chief officer left the deck office and went to their cabins to secure them for heavy weather.

At 0807, MAERSK ESSEN again started to roll heavily. This time the angles of roll were greater than those previously experienced and increased with each roll cycle, resulting in the 3rd officer struggling to keep his balance and having to hold on to the bar on the conning station to stay upright. Loose items slid across the bridge, and alarms started to sound. Again, the 3rd officer altered course $2-3^{\circ}$ to starboard using the autopilot to stop the rolling. The heavy rolling stopped two minutes after it had started.

The master, who had rushed the flight of stairs from deck B to deck G, reached the bridge 15 seconds after the ship stabilised. He immediately took the hand steering and made a large course alteration to starboard from approximately 090° to 130° and increased speed. Meanwhile, the chief officer, 2nd officer and cadet came to the bridge. They started to clean the bridge, and the chief officer gave orders for the ratings to clean in the galley and mess rooms.

At 0815, the master detected an echo on the radar close astern of the ship (Figure 6).

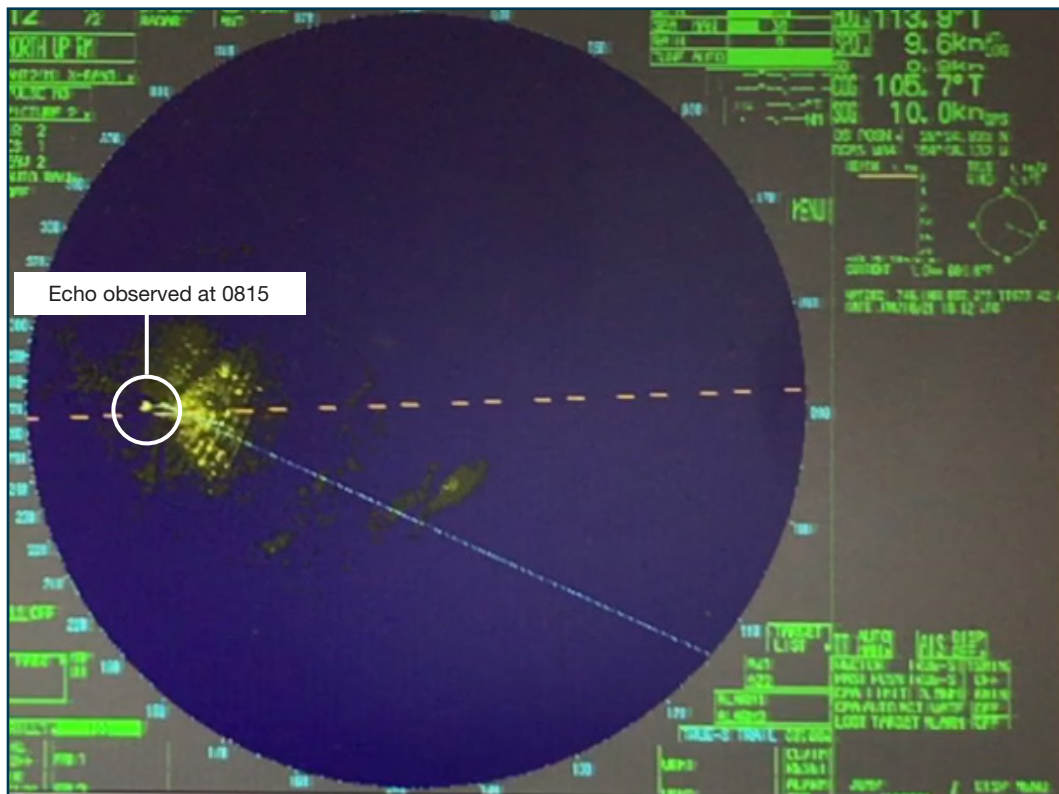


Figure 6: Echo observed on the radar at 0815
Source: Maersk A/S

He went to the bridge wing and looked aft and saw containers hanging over the ship's side and floating in the sea (Figure 7). He rushed back into the bridge and instructed the officers to fetch a camera to document the lost containers and to log the time and position. The heavy weather emergency response flowchart was put into use, and the 2nd and 3rd officer assisted the master in communicating with relevant authorities and the company.

Concerned if any crewmember might have been on deck during the rolls, the master sounded the general alarm to initiate a head count. The head count was conducted by the chief officer at the upper deck fire station, and none of the crew were identified as missing or injured. The master instructed the crew to stay away from the deck areas, but authorised the chief officer and the dayman to carry out an initial assessment of the damages and loss of cargo. They estimated that approximately 215 containers were missing. The following day, the chief officer and cadet carried out a systematic assessment of the damages at each bay as far as the damages allowed for. The result of the assessment was that 732 containers could not be accounted for.

Immediately after the loss of containers, the master contacted WNI for routing advice. He informed WNI that he had increased the speed to avoid further rolling, and he emphasised that the weather routing had to ensure minimum rolling for the remainder of the voyage due to the containers hanging over the ship's sides. The ship proceeded on a more southerly course and did not experience further rolling.

On 21 January 2021, MAERSK ESSEN was diverted to Lázaro Cárdenas, Mexico, for discharge of damaged cargo and emergency repairs. No further containers were lost, and the ship berthed in Lázaro Cárdenas on 30 January.



Figure 7: Lost containers floating in the water
Source: Maersk A/S

Damages

Damage assessments were made at sea and when the ship was alongside. The damage records show that the ship had sustained damages in the accommodation, the engine rooms and on deck.

On the cargo deck, the crew found that containers were damaged or lost overboard from eight bays. On some bays few containers were lost, while on others all containers were lost or damaged. During the discharge of the damaged cargo, it was concluded that a total of 689 containers were lost overboard and that 258 were damaged (Figure 8).

On bays where containers were lost overboard, the container stacks had collapsed and toppled over, causing damage to deck structures. On other bays, where container stacks had also collapsed, containers were hanging over the ship's side, blocking the deck passageways. Pedestal stools were bent, safety railings torn off, and the accommodation ladders on both port and starboard side were damaged (Figures 9 and 10). Several lashing bridges were deformed and fractured having being struck by falling containers, and the passageways on the lashing bridges were blocked and damaged (Figures 11 and 12).

In the accommodation, all compartments were affected. Items which had not been secured had been hurled around, and office equipment, furniture and galley machinery had fallen over. In the paint shop, barrels and cans had fallen to the floor from the shelves. In other storage rooms, entire racks were overturned, and their content hurled off the shelves (Figure 13). In the engine room, the compartment's heavy equipment, including a lifting device and a spare electrical motor, had loosened and slid across the floor (Figure 14 and 15).



Figure 8: MAERSK ESSEN at anchorage off Lázaro Cárdenas, Mexico
Source: Maersk A/S

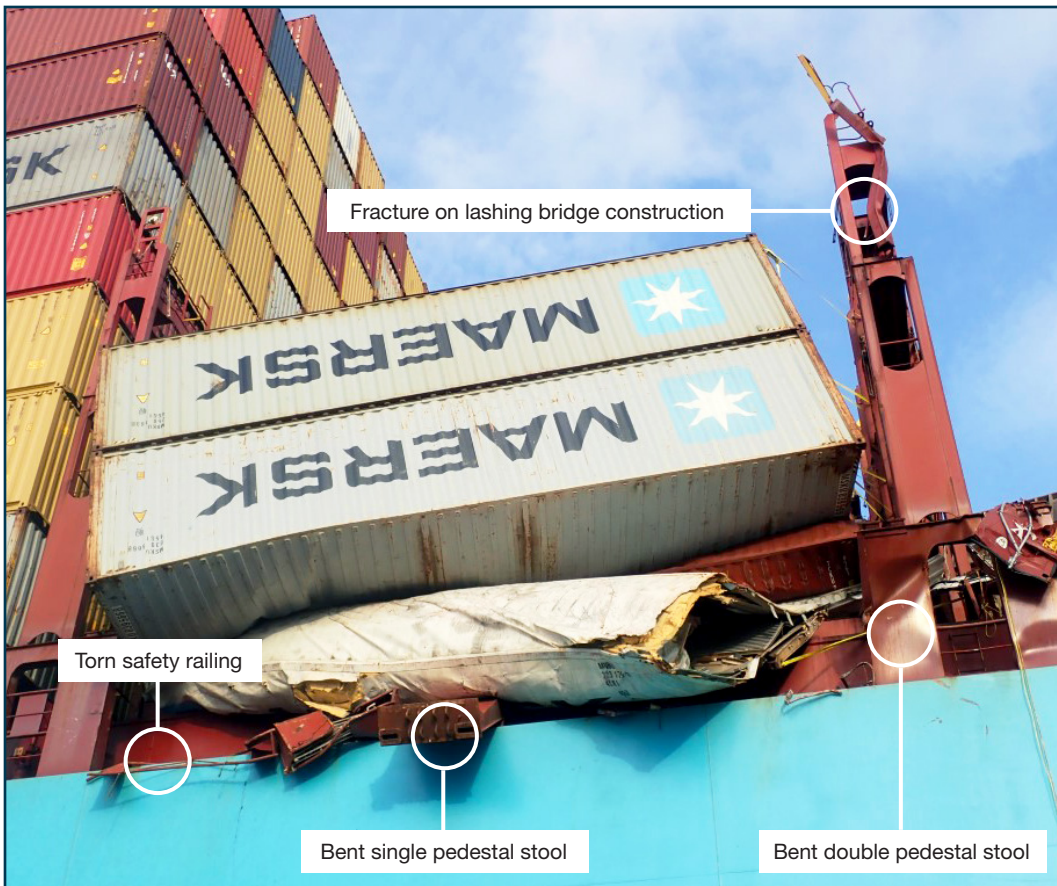


Figure 9: Example of damages on deck structures
Source: Maersk A/S, modified by DMAIB



Figure 10: Damage to port side accommodation ladder
 Source: Maersk A/S, modified by DMAIB

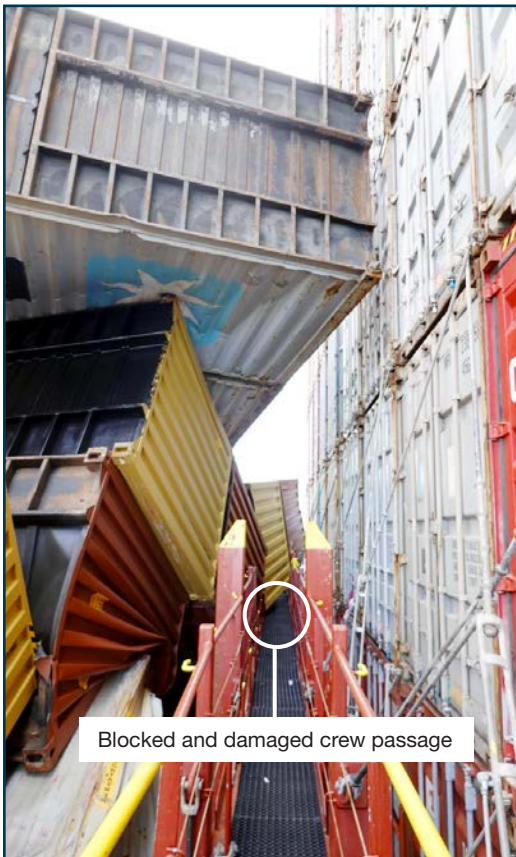


Figure 11: Example of lashing bridge damages
 Source: Maersk A/S, modified by DMAIB

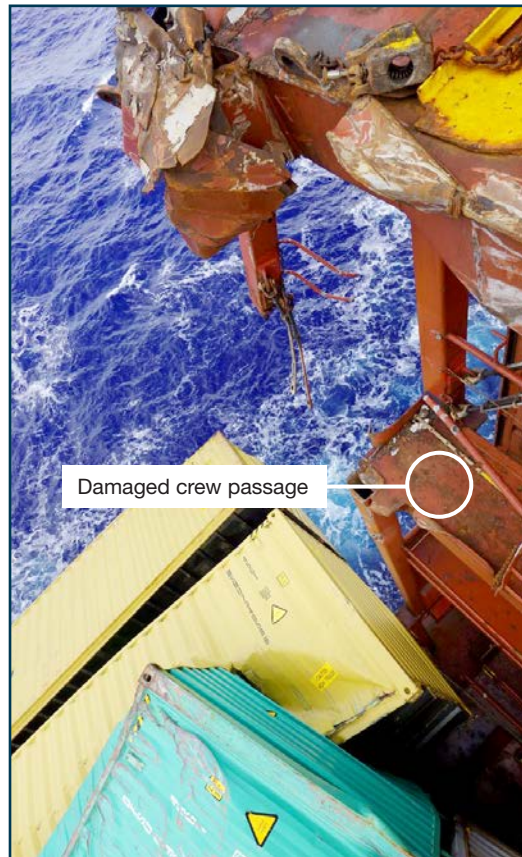


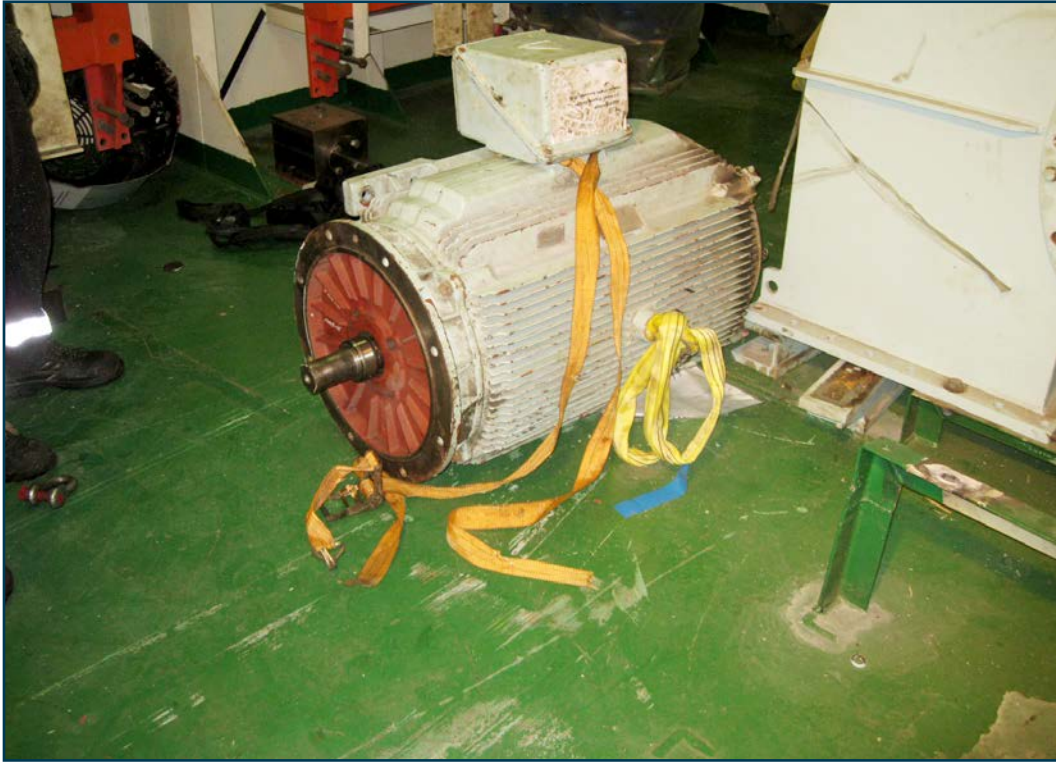
Figure 12: Example of lashing bridge damages
 Source: Maersk A/S, modified by DMAIB



Figure 13: Overturned storage racks
Source: Maersk A/S



Figure 14: Overturned and displaced lifting device near control panels in the engine control room
Source: Maersk A/S



*Figure 15: Electrical spare motor with broken lashings and damages from impact after having slid across the deck and hit other objects and structures.
Source: Maersk A/S*

Investigation

Scope and method description

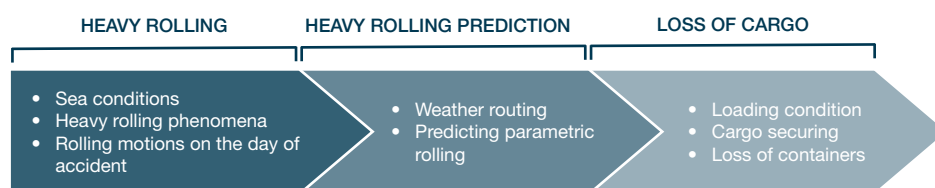
From the sequence of events, it was evident that MAERSK ESSEN experienced two episodes of heavy rolling within a 15-minute period in the morning of 16 January 2021, and that the second episode was more severe than the first. Each episode lasted only a few minutes and stopped as quickly as it had started. The heavy rolling was unexpected, because it occurred in a sea state which the crew considered to be nothing out of the ordinary, and in which the ship had been moving comfortably. That containers were seen in the water astern of MAERSK ESSEN immediately after the second episode of heavy rolling indicates they were lost overboard during the heavy rolling episodes.

The purpose of DMAIB's investigation was to establish the circumstances which caused MAERSK ESSEN to lose containers overboard. This investigation required the following questions to be answered:

- What caused the ship to roll heavily?
- Why was the heavy rolling unexpected?
- Why did the lashings fail to keep the cargo in place?

Therefore, the account of the investigation falls in three thematic sections.

The first section aims to establish the type of heavy rolling the ship experienced. The second section focuses on establishing the tools and information available to the crew on MAERSK ESSEN for predicting and avoiding the heavy rolling phenomena experienced. The final section focuses on cargo securing and stowage and aims to identify which factors were instrumental to the lashing failure during the heavy rolling.



Sea conditions

To gain an understanding of the sea conditions experienced by MAERSK ESSEN during the heavy rolling episodes on 16 January 2020, the crew's observations are compared to meteorological and sea condition data associated with the weather system influencing the area.

On board observations

During the hours prior to the heavy rolling episodes, observations of north-north-easterly (NNE) wind of Beaufort force 6 were recorded in the bridge logbook. This corresponded to a strong breeze of 10-14 m/s and moderate wind seas of approximately 2m. The Beaufort scale only refers to wind and wave, not swell. Hence, swell height was not recorded in the logbook. According to crew statements, the swell was about 5m with a long period coming on the ship's port quarter. Photographs taken 45 minutes before and 8 minutes after the loss of containers corresponds with the crew's observations (Figures 16 and 17).

The crew felt the ship moving comfortably and regarded the sea conditions to be better than those encountered on 13 January 2021, which had also appeared to have no significant effect on the ship's movement. The observed sea condition on 16 January 2021 was seen as normal for ocean voyages and was thus perceived to be unproblematic.



Figure 16: Sea state 45 minutes prior to the accident. Photo taken from the bridge wing.
Source: Maersk A/S



Figure 17: Sea state 8 minutes after the accident
Source: Maersk A/S

Meteorological analysis and hindcast data

DMAIB tasked the Danish Defence Joint GEOMETOC Support Center with analysing the sea conditions for the area at the time of MAERSK ESSEN's accident. The work was based on wave simulations and meteorological analysis, which were verified by measurements from various satellites and wave buoys.

The GEOMETOC analysis concluded that MAERSK ESSEN's container loss occurred when the ship was in an area of residual swell produced by a depression approximately 1,200 nm NW of the ship's position. From the depression, a long wind fetch developed between 13 and 15 January with wind forces reaching 24 m/s. On 14 January, the wind driven waves (windsea) reached a height of 14 m. As the low pressure's track deviated from the developed wind sea's direction, the waves continued as swell, and the swell height reduced as it fanned out. This residual swell reached MAERSK ESSEN on 16 January. The swell was from the WNW, with a significant height of 6 m, a period of 15 s and a length of 350 m.

Data from GEOMETOC's analysis of swell height and period together with hindcast data from MAERSK ESSEN's weather data suppliers WNI and SPOS are shown in Figure 18. Meteorological analyses are based on different modelling methods and the quality of the observed data is dependent on satellite and wave buoy locations. Thus, they provide a general image of the sea conditions in a wide sea area, but they cannot necessarily capture local or isolated wave phenomena. Slight discrepancies between the three hindcast analyses and the onboard observations are therefore to be expected. Nonetheless, the onboard observations made by the crew on MAERSK ESSEN and the hindcast data accord in that the sea condition was dominated by moderate wind sea and higher swell with a long period coming from a WNW'ly direction. Neither the sea condition analysis nor the onboard observation describes any extreme weather or sea phenomena. Indeed Figures 16 and 17 illustrate that the sea conditions before and after the accident were not out of the ordinary.

	<i>GEOMETOC (1800 UTC)</i>	<i>WNI (1800 UTC)</i>	<i>SPOS (1700 UTC)</i>	<i>Logbook (1800 UTC)</i>
<i>Wave direction</i>	-	<i>WNW</i>	-	-
<i>Wave height</i>	<i>4 m</i>	<i>0.7 m</i>	<i>1.5 m</i>	<i>2-3 m</i>
<i>Wave period</i>	-	<i>4 s</i>	-	-
<i>Swell length</i>	<i>350 m</i>	<i>519 m</i>	-	-
<i>Swell direction</i>	<i>300° (WNW)</i>	<i>WNW</i>	<i>WNW</i>	-
<i>Swell height</i>	<i>6.0 m</i>	<i>7.9 m</i>	<i>6.0 m</i>	-
<i>Swell period</i>	<i>15 s</i>	<i>18 s</i>	<i>15 s</i>	-

Figure 18: Matrix of observation and hindcast data

Source: GEOMETOC, WNI, SPOS, MAERSK ESSEN's bridge logbook

Findings: Sea conditions

- MAERSK ESSEN was situated in sea conditions dominated by residual swells coming from a WNW'ly direction with a period of 15-18 seconds and length of 350-519 m.
- MAERSK ESSEN had encountered similar or worse weather and sea conditions earlier in the voyage, on 12 and 13 January, without experiencing heavy rolling.
- The weather and sea conditions were not out of the ordinary for this sea area. No extreme weather phenomena were observed.

Heavy rolling on the day of the accident

Description of MAERSK ESSEN's heavy rolling motions

According to VDR recordings and weather hindcast data, the heavy rolling occurred as MAERSK ESSEN was on an easterly course (approximately 089°) with a speed varying between 10-12 knots. The ship was situated in an area of residual swell of approximately 6-7 m coming from a WNW'ly direction. This means that the vessel was sailing in port quartering seas. According to the crew, MAERSK ESSEN experienced two occurrences of heavy rolling in the morning of 16 Jan 2021 in the time frame between 08:00-08:10. The second heavy rolling occurrence was experienced as worse than the first. The crew reported that the rolling on each occurrence started suddenly, and the roll angle increased by every roll cycle and then suddenly stopped.

When DMAIB reviewed the ship's VDR, objects sliding across the bridge could be heard during the periods 08:04-08:05 and 08:07-08:10. The volume and number of noises from objects sliding from one side to the other gradually increased within these time frames, indicating more and heavier objects sliding around and increasing angles of roll. The VDR data also showed significant oscillation in the ship's heading (79-105°), indicating that the ship was heeling and yawing heavily.

A mechanical inclinometer on the bridge indicated the ship's heel angle and recorded the maximum heel angle. Photographs of the inclinometer taken after the heavy rolling episodes (Figure 19) show that the ship reached angles of 26° to port and starboard. The inclinometer had been reset by the chief officer before the 3rd officer took over the watch, and the 26° hence reflected the heavy rolling episode between 08:04-08:10.



Figure 19: Inclinometer after the heavy rolling occurrence on 16 January 2021

Source: Maersk A/S

HEAVY ROLLING ON THE DAY OF THE ACCIDENT

In another marine casualty investigation³, it has been questioned whether mechanical inclinometers accurately measure dynamic roll angles, as the pendulum can be sensitive to acceleration forces and inertia. Therefore, the inclinometer reading should be validated by calculation of the ship's motions.

On request from Maersk A/S, an investigation into MAERSK ESSEN's cargo loss was carried out by the Institute of Ship Design and Ship Safety at Technische Universität Hamburg (TUHH). By retrieving data from the VDR on the ship's course over ground and the ship's GPS antenna location, TUHH calculated the rolling angles experienced by MAERSK ESSEN between 08:00-08:12. The calculations concluded that the ship experienced roll angles up to 30° (Figure 20). As the inclinometer reading gives a lower value than the TUHH calculations, it suggests that it was not influenced by acceleration forces resulting in higher roll angle readings.

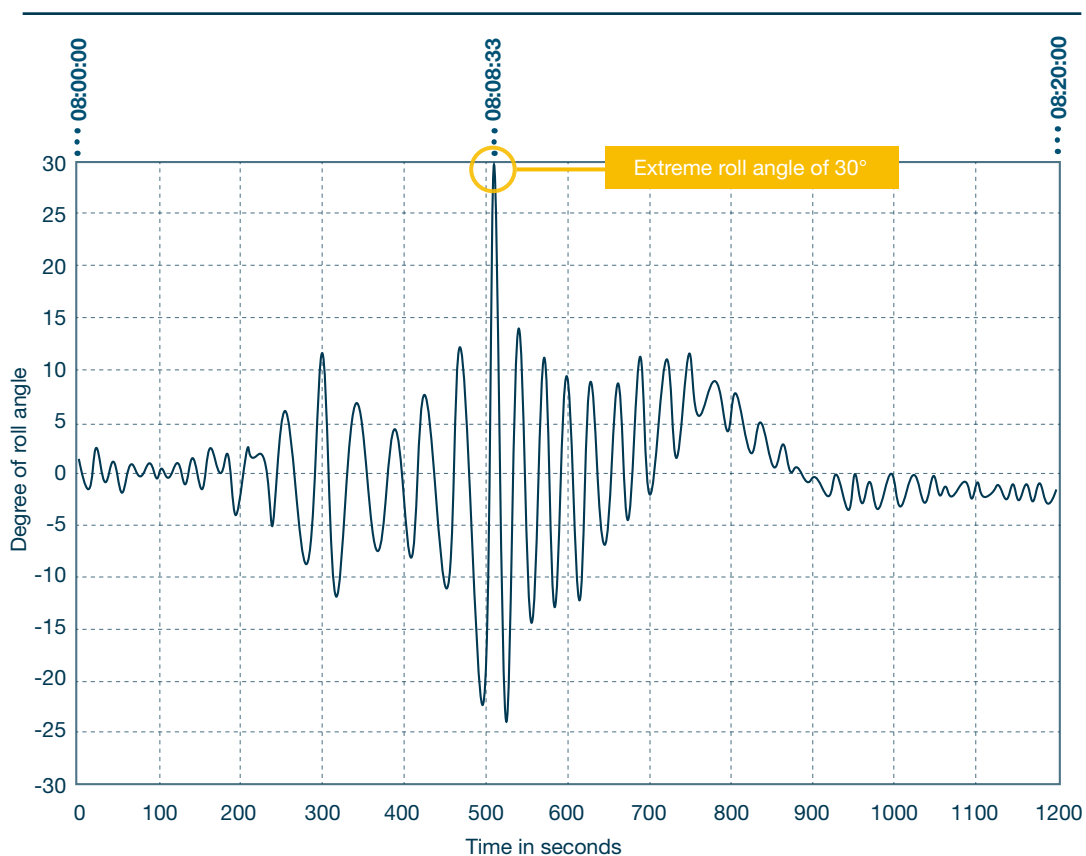


Figure 20: Graph of TUHH's roll angle calculations, modified by DMAIB
Source: Maersk A/S

Figure 21 shows TUHH's calculations of MAERSK ESSEN's roll cycles between 08:00 and 08:20. It can be seen that the roll angles before and after the episodes of heavy rolling were between 2-3° to each side, and that the stable period experienced by the 3rd officer was not a complete return to the ship's normal roll period and angle.

3 Bundesstelle für Seeunfalluntersuchung (BSU), et. al.: *Loss of containers overboard from MSC ZOE 1-2 January 2019* (2019)

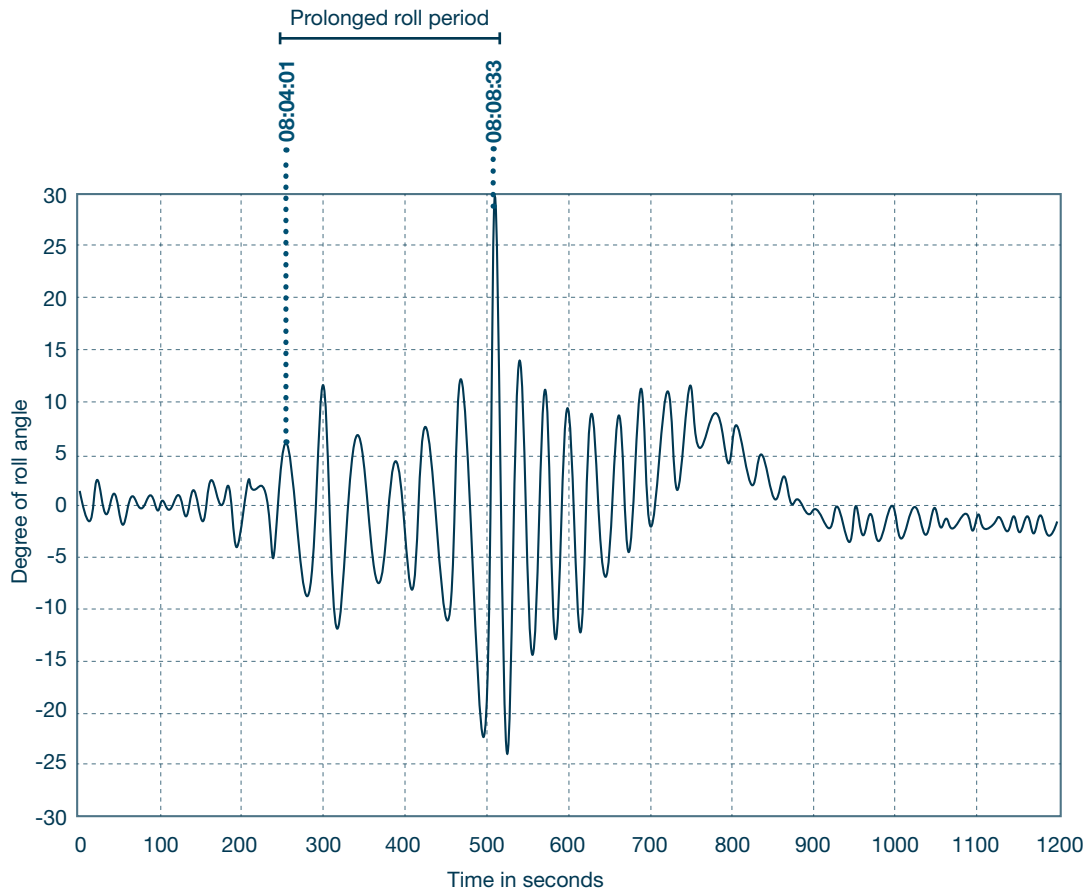


Figure 21: Graph of TUHH's roll angle calculations, modified by DMAIB
Source: Maersk A/S

Various phenomena with the potential to prompt the sudden heavy rolling experienced by MAERSK ESSEN, such as pure loss of stability on a wave crest, high wave attack and resonance effects, were examined by DMAIB to determine their likelihood in this case. High wave attack and synchronous roll resonance were ruled out as the conditions for these phenomena were not present at the time of the accident. It was found that the ship sailed in conditions with the potential to cause pure loss of stability on a wave crest and parametric roll resonance. Details of these findings will be elaborated in the following sections.

Pure loss of stability on wave crest

A ship's stability can be significantly reduced or lost when riding a wave crest amidships, as the submerged hull form changes. According to IMO MSC. 1/Circ. 1228, this stability reduction may become critical for wavelengths within the range of $0.6 L$ to $2.3 L$ (L = ship length in metres), depending on the wave height. Reduction of stability is particularly critical in following and quartering seas, because the period riding a wave crest is prolonged.

The weather hindcast data on the sea state on the day of the accident presents a spectrum of swell lengths ranging between 350-519 m (Figure 18). MAERSK ESSEN had a length of 350 m between perpendiculars, which means the critical range for wavelength was 210-805 m. The range of estimated wavelengths thus falls within the critical range for the ship. Based on the IMO criteria, the conditions for a possible reduction of stability on wave crest were likely to be present.

HEAVY ROLLING ON THE DAY OF THE ACCIDENT

In the TUHH investigation, MAERSK ESSEN's stability on a wave crest was calculated based on the ship's loading condition and wave height and length data retrieved from SPOS forecasts issued on 15 January 2021 at 1400 (UTC -10) (Figure 22).

The stability calculation indicates that while the GZ curve for calm sea was positive until a heeling angle of 55°, the initial stability was negative on a wave crest and would not find a stable equilibrium until an 18° heeling angle was reached. Based on this calculation, TUHH concludes that MAERSK ESSEN was exposed to a pure loss of stability which could potentially cause the ship to capsize. However, TUHH also concludes that this scenario would not be plausible for a container vessel, as the cargo will fall overboard and improve the stability.

As highlighted in the section on sea conditions on the day of the accident, there were discrepancies in the wave height and wave period values provided by the different weather information suppliers, and the forecast values did not necessarily reflect the actual swell influencing the ship's motions at the time of the accident. Therefore, TUHH's calculations do not with certainty prove that MAERSK ESSEN suffered a pure loss of stability in connection with the heavy rolling episodes on 16 January 2021. However, as the TUHH calculations are based on a wave height that lies within the spectrum of wave heights identified in the hindcasts, the risk of pure loss of stability was most likely to have been present.

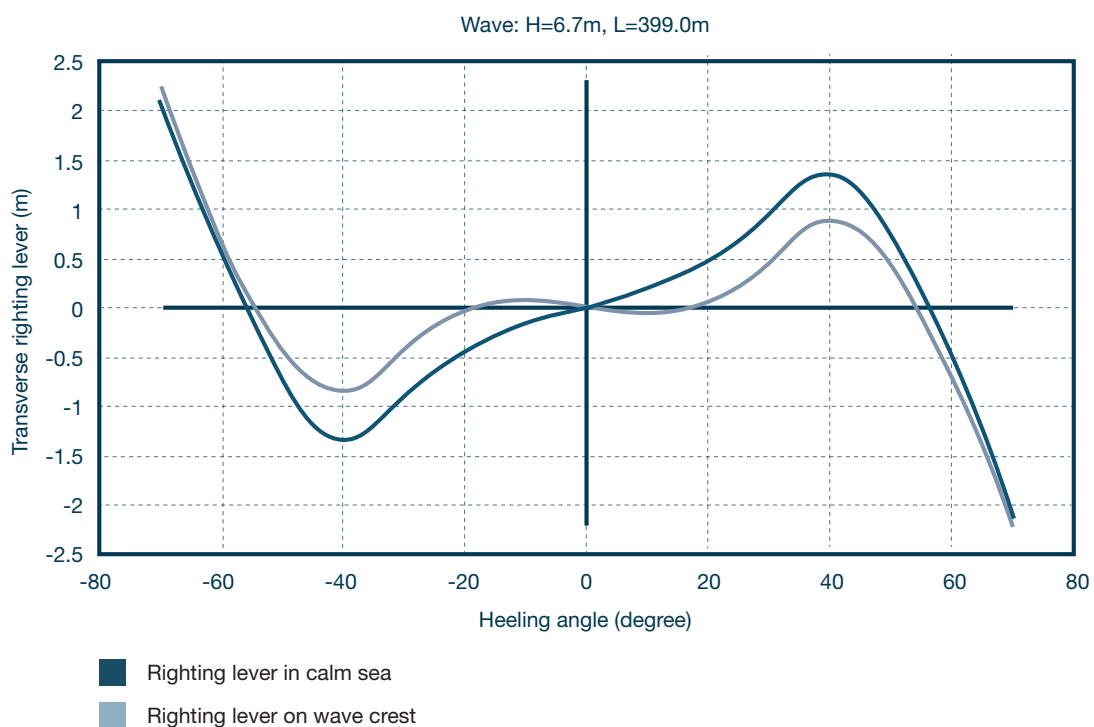
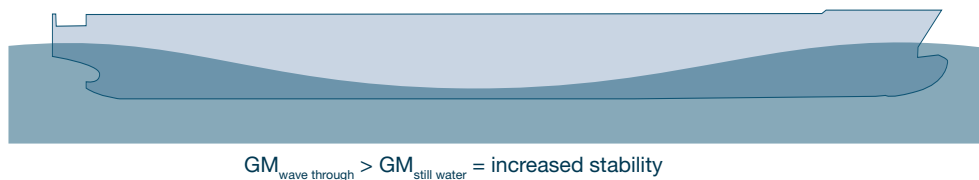


Figure 22: Stability graph for MAERSK ESSEN prepared by TUHH, modified by DMAIB
Source: Maersk A/S

Parametric roll resonance

Parametric roll is a phenomenon which can occur when a ship is proceeding in bow, stern or quartering seas, and can cause a ship to suffer sudden and large roll oscillations without being exposed to extreme excitation from high waves and wind forces. It is an auto-parametrically excited motion. This means that the main cause of extreme rolling lies within a ship's oscillating system. The phenomenon occurs as a result of the transverse stability alternating between being "stiff" and "tender" as the metacentric height (GM) fluctuates in response to a wave passing along the length of the hull, and leads to a rhythmical increase of any slight angle of heel that may have been initially present. When the ship is situated in a wave trough, the GM increases, so that the righting moment is larger than in still water. Conversely, the GM reduces below the GM in still water, when the ship is situated at a wave crest (Figure 23).

Stability at wave trough amidship:



Stability at wave crest amidship:

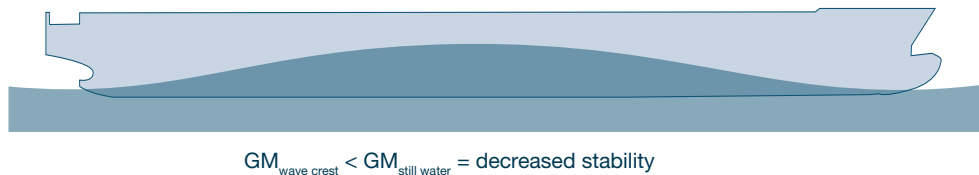


Figure 23: Stability at changing hull geometry at wave trough and wave crest
Source: DMAIB

When the ship is situated in wavelengths nearly equal to the ship's length and is met by longitudinal waves with an encounter period of half the ship's natural roll period, the alternating GM in wave trough and wave crest starts to resonate with the roll motion. When the ship's stability increases in the wave trough, the roll restoring moment pushes the ship back towards an upright position with increased force, and as the ship reaches the wave crest, the stability decreases so that the roll restoring moment cannot resist this energy and larger roll angles occur. This in turn leads to an even harder push back at the next wave trough, resulting in an additional increase in roll angle on the wave crest. Maximum roll to one side occurs at one wave crest, maximum to the other side occurs at the subsequent wave crest. Roll angles will hence continue to build up, until the conditions for resonance are no longer present (Figure 24).

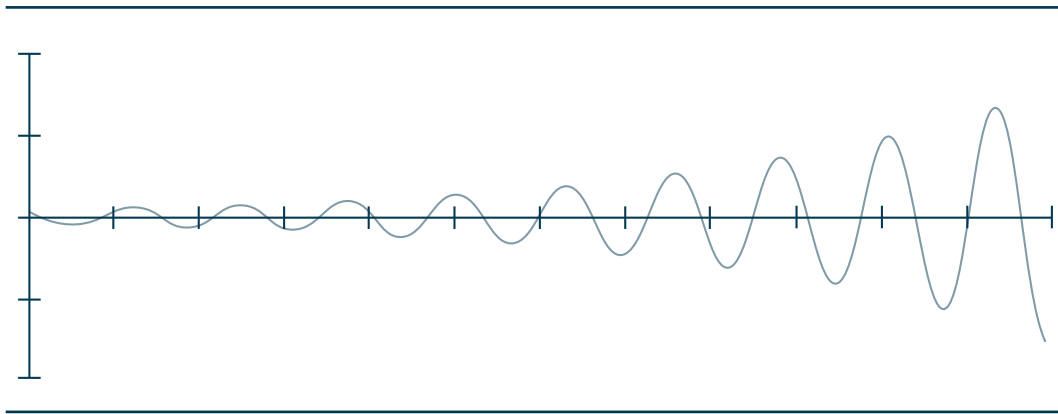


Figure 24: Development in heel angle amplitudes characteristic for parametric resonance
Source: ABS, modified by DMAIB

The condition for build-up of a parametric resonance is that the wave crest encounters are in phase with the roll maxima (to either side). This condition implies that a 1:0.5 ratio is maintained between roll period and wave crests over a number of roll periods. The resonance will stop being maintained when the phase angle between wave crests and roll motion gets out of synchronism. This can happen naturally by waves becoming more irregular or deliberately by change of ship's heading or speed. The phenomenon of resonance between wave crests and roll maxima will also be reflected in a resonance between motions in roll and motions in pitch and heave.

From previous investigations, DMAIB has found that parametric resonance effect is often considered a rare phenomenon by navigational officers. This is most likely a false assumption, as the triggering conditions are common. Parametric resonance is most likely experienced more frequently than reported, but only as an occasional deeper roll, because the resonance is stopped by a change in the ship's speed and course or by change in sea condition. Parametric resonance can hence be experienced as a single heavier roll.

The following factors contribute to triggering parametric roll resonance:

- Wavelength approximately equal to the ship's length. In this situation, the fluctuation in GM between wave trough and wave crest is most pronounced.
- The encounter period is equal to half the natural roll period. The encounter period is determined by the wave period and the ship's speed. When this condition is met, a frequency coupling between the ship's pitch motion and the natural roll occurs (Figure 25). One can describe this using nonlinear dynamics of coupled motions of the vessel, but the basic understanding of the phenomenon is the physics described above.
- Wave height needs to be above a certain threshold, depending on the ship's size and stability properties. There is no general rule of thumb for this threshold, but impact from waves is essential for the parametric resonance to occur.
- The ship has low roll damping.

The trigger conditions above relate to parametric roll in longitudinal waves. Parametric resonance can occur in other conditions and depend on a combination of the ship's stability and roll damping properties, hull design and the specific sea conditions. This also means that a ship can be exposed to the trigger conditions above without experiencing parametric rolling.

MAERSK ESSEN was most likely in a situation where the conditions for parametric resonance were present. According to the GEOMETOC hindcast data, the wavelength and ship's length were identical on the day of the accident, while WNI indicate the wavelengths were longer than the ship's length.

According to VDR recordings, the ship's speed fluctuated between 10-12 knots at the time of the onset of heavy rolling. The relationships between the ship's natural rolling period and the wave encounter period based on the various hindcast values are shown in the matrix below (Figure 25).

	<i>GEOMETOC</i>	<i>SPOS</i>	<i>WNI</i>
<i>Natural roll period (TUHH)</i>	42.8 s	42.8s	42.8 s
<i>Wave period</i>	15 s	15 s	18 s
<i>Encounter period (10-12 knots)</i>	18.5-19.4 s	18.5-19.4 s	21.4-22.2 s
<i>Ratio</i>	≈ 1-0:5	≈ 1-0:5	≈ 1-0:5

Figure 25: Ratio between natural roll period and encounter period depending on data source
Source: GEOMETOC, WNI, SPOS

The relationship between the ship's natural roll period and the encounter period based on the hindcast data was close to a 1:0.5 ratio and thereby within the risk of a coupling between the ship's natural roll period and encounter period, one of the conditions needed to trigger resonance.

The ship specific wave height threshold for triggering parametric resonance is unknown. However, the swell height did exceed the wave height limit decided in the voyage planning, and the sea was considered by the crew to be moderate/rough. MAERSK ESSEN was not equipped fin stabilisers or roll damping tanks to reinforce the ship's roll damping properties, and TUHH calculation concludes that the ship's bilge keel had low roll damping effect. Furthermore, due to the low speed of the vessel, no roll damping was achieved from the ship's forward motion and lifting.

The roll angle graph prepared by TUHH for the time of the container losses reflects parametric resonance. It can be seen that there are two episodes of increasing roll angles. After the first peak in roll angle, the roll angle starts to decrease while the roll period continues to be prolonged. This indicates that the resonance conditions diminished momentarily. This might have been due to alterations in frequency coupling linked to speed or wave period. However, the resonance effect swiftly returned. After the second extreme peak in roll angle, the roll angles decreased, and the roll period normalised (Figure 26). These episodes occurred without any observed changes in the sea conditions.

During these oscillations, the ship lost containers overboard resulting in significant change in GM. Information from the ship's stability calculation software indicated that the GM increased from 0.95 m to 2.44 m, which altered the ship's natural roll period so that the frequency coupling with the wave encounter ceased.

DMAIB finds it plausible that the heavy rolling motion on the day of the accident was a result of parametric resonance, because MAERSK ESSEN was situated in conditions equal or close to the trigger conditions described for this phenomenon, and because the roll angle graph shows the characteristics of parametric roll resonance.

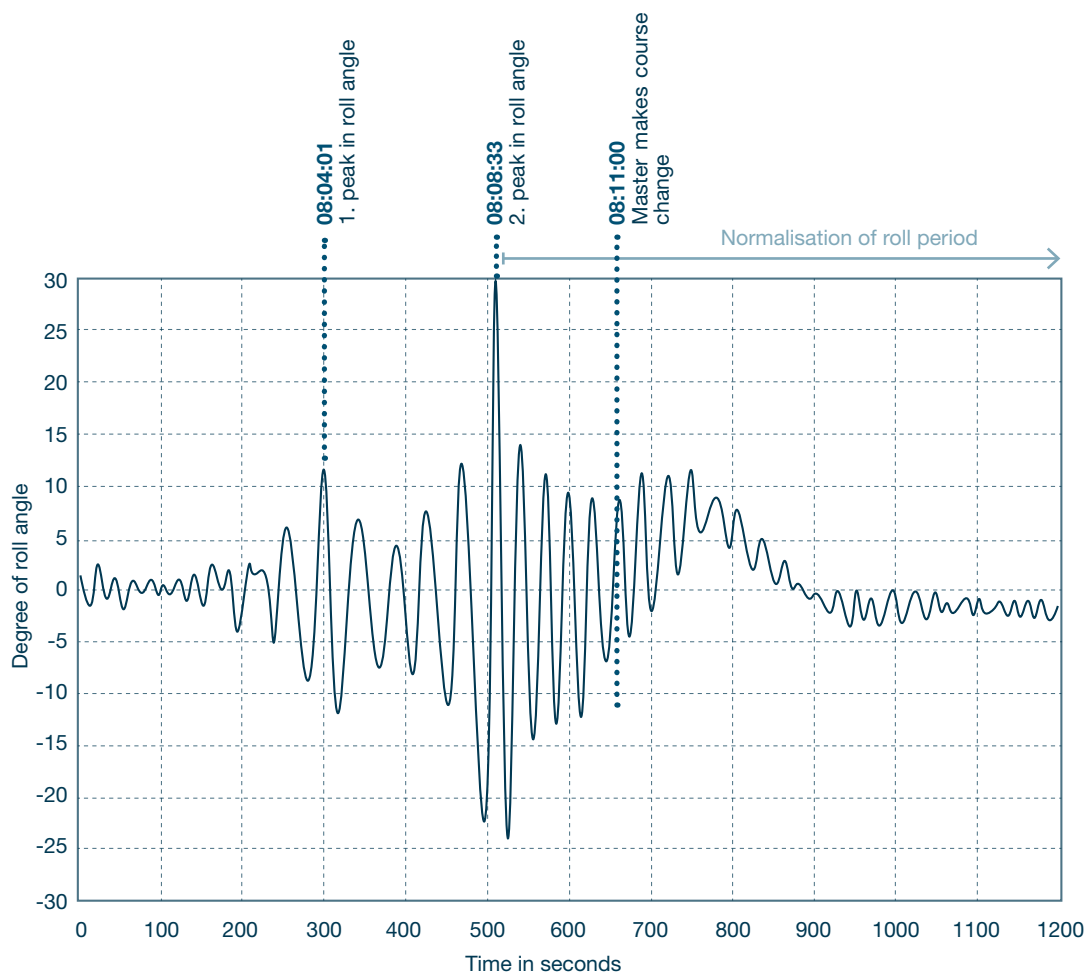


Figure 26: Graph MAERSK ESSEN's roll angles at time of the accident.
Source: TUHH, modified by DMAIB

Findings: Heavy rolling motions

- Parametric rolling is the result of a dynamic stability failure mode where the main cause of extreme rolling lies within the ship's oscillating system. Thus, heavy rolling can occur in wave and swell heights that are not perceived adverse to the ship.
- MAERSK ESSEN's heavy rolling motions was most likely caused by parametric roll resonance.
- MAERSK ESSEN was most likely operating in conditions with the risk of being exposed to pure loss of stability on a wave crest. This may have contributed to the onset of parametric roll resonance.

Weather routing

Weather routing for Xiamen to Los Angeles

On MAERSK ESSEN, the crew made use of several weather information services as an integrated part of the route planning and monitoring of the oncoming weather and sea conditions. The navigational officers used the route planning and weather information software SPOS for voyage planning and weather routing. SPOS supplied the crew with updated forecasts every 6 hours. The weather information presented in SPOS was for either 7 or 9-days forecasts, and the crew therefore requested routing advice from the weather service company WNI for ocean voyages exceeding SPOS' time range, as WNI had longer lead time forecasts available for their weather routing. WNI's routing service aimed to provide the optimal route based on weather limits, timely arrival and fuel consumption. Routing advice from WNI was usually accepted by the master, and route alterations were carried out in SPOS according to WNI's recommendations. In addition to WNI's recommendations, the crew monitored the route and forecasts in SPOS and local weather information from NAVTEX.

According to company procedure "P825 – Navigation in adverse weather", the crew was expected to use a template to request routing advice from WNI. A request sent to WNI on 23 December 2020 included the estimated times of departure and arrival, minimum and maximum speeds and engine rpm, draught, GM and limits for wind and significant wave height. The maximum wind was stated as 34 knots, and the maximum significant wave height was 5 m.

The wave height limit was a general threshold to be used by WNI when planning the ship's route. The crew's assessment of the acceptable wave height was more nuanced and considered combinations of several factors, e.g. the effect of encounter angle on the containers and their lashings. Wind sea and swell waves of up to 5 m were acceptable regardless of the encounter angle, as these did not have much impact on the ship's motion. For wave heights over 5 m, the master would assess the need for route changes based on the specific conditions. In head waves, the ship was susceptible to pitching, slamming and whipping which were undesirable because the lashings would be exposed to acceleration forces and vibrations. In quartering seas with a low GM, larger waves were acceptable, because the ship would roll slowly resulting in less stress on the lashings.

On 25 December, WNI were updated on MAERSK ESSEN's departure and arrival time, the ship's GM and the intention to maintain 10% engine load throughout the voyage, which resulted in a speed of between approximately 11-12 knots. WNI was also informed that the ship had problems making freshwater and needed to arrive in Los Angeles with full freshwater tanks due to the uncertainty over berth availability. This information was incorporated into the voyage plan received by the crew on 26 December 2020.

The routing advice from WNI focused mainly on avoiding areas with significant wave heights exceeding 5 m, taking timely arrival and fuel consumption into account. During the voyage, WNI issued three route diversion recommendations and one weather warning as the planned route passed areas with significant wave heights forecasted to exceed the threshold of 5 m.

The route diversion plan received on MAERSK ESSEN on 14 January 2021 and a damage mitigation message received on 16 January before the heavy rolling episodes will be examined in the following sections to increase understanding of the decisions made on board, and how the information was used.

Route diversion plan – 14 January 2021

On 14 January 2021 at 0645 MAERSK ESSEN received a route diversion plan by email from WNI with two PDF files enclosed: a four-day forecast of surface pressures and a voyage planning sheet with more detailed information on the route diversion. The message from the route advisor stated:

”++ The latest forecast indicates an enhanced threat to vessel safety periodically throughout the forecast period ++ Your vessel is expected to sail into an area of weather conditions that will likely cause stress on your vessel and/or cargo. If not already done so, please make all heavy weather preparations now in order to ensure safety of crew, vessel and cargo. Course and/or speed adjustments will be necessary at times in order to reduce vessel motion.”

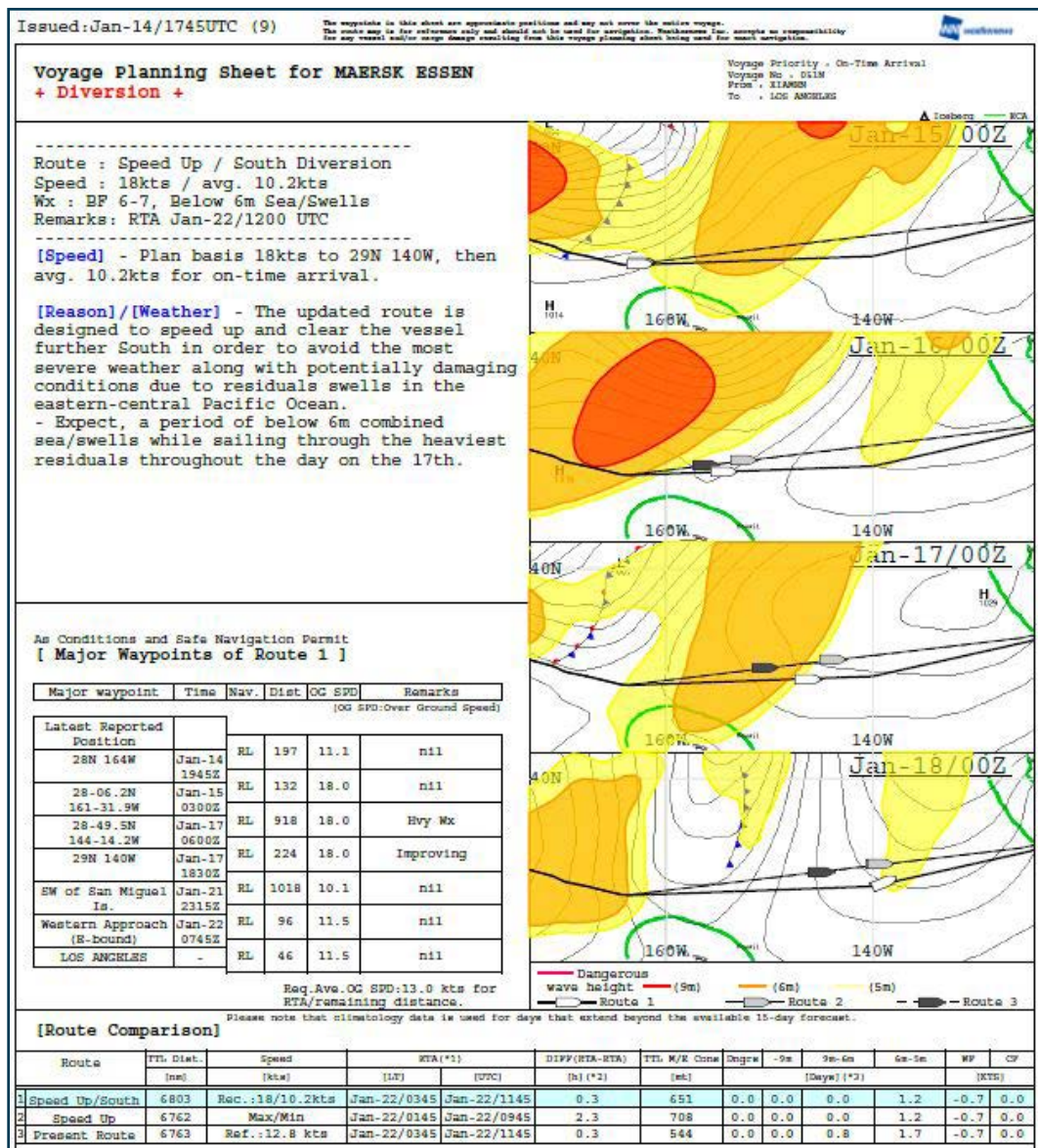


Figure 27: Voyage planning sheet issued 14 January 2021
Source: WNI

The voyage planning sheet from WNI consisted of text with advice and reasoning for the recommended route, four pressure surface maps with wave height indications, three route choices, a waypoint overview with weather remarks and speed advice, a route comparison scheme and graphs of speed and forecasted wind and wave height until arrival (Figure 27). MAERSK ESSEN was advised to increase speed and adjust course to the south to avoid a heavy weather area with significant wave heights exceeding 6 m. The three routes marked on the surface pressure maps represented WNI's recommendation of increasing speed and altering course further south (white ship), increasing speed only (grey ship) and the current route at a speed of 12.8 knots (black ship). Both WNI's recommended routes cleared a forecasted heavy weather area on 17 January 00 Zulu (00 GMT), corresponding to 16 January 2021, 14:00, ship's time.

In the waypoint scheme, the speed increase for the recommended route was stated as 18 knots followed by a decrease to 10.1 knots. In the route comparison scheme, there was no time difference between the recommended route and the route the ship was already following, which was based on a speed of 12.8 knots. Concerned about the early arrival in Los Angeles, the master wanted to maintain lowest possible speed of approximately 10-11 knots and therefore chose to acknowledge the WNI route diversion on course change, but not the speed increase. This was communicated to WNI, while also informing them that berth availability was postponed to 28 January. WNI did not respond to this email. The master had assessed the weather routing and forecasts in SPOS, from which the master concluded that the forecasted sea conditions on the recommended route were acceptable to the ship. Higher wind sea and swell had been encountered earlier during the voyage without significant impact on the ship's motions, and the wave encounter angle on the quarter was favourable with regards to the stress loading on the lashings.

Damage mitigation message – 16 January 2021

After MAERSK ESSEN received the route diversion plan from WNI on 14 January 2021, no further updates were received until 0645 on 16 January 2021 when a damage mitigation message was received by email, which stated:

“++ The latest forecast indicates an enhanced threat to vessel safety from late on the 16th through late on the 19th ++ Your vessel is expected to sail into an area of weather conditions that will likely cause stress on your vessel and/or cargo. If not already done so, please make all heavy weather preparations now in order to ensure safety of crew, vessel and cargo. Course and/or speed adjustments will be necessary at times in order to reduce vessel motion.

If you believe the possible stresses on your vessel/cargo caused by the forecast weather conditions cannot be handled effectively through course/speed adjustments, please advise and we will re-evaluate the route to try to further minimize the conditions.”

The email was received and read by the chief officer, who was on watch in the morning of 16 January. The chief officer decided to inform the master about the message at 0800 at the operational meeting. The damage mitigation message from WNI stated that WNI's suggested route remained valid.

A voyage planning sheet was attached to the email, which was based on a speed of 13.5 knots over the ground, not the ship's actual speed of between 10.5-11 knots as advised by the master.

Furthermore, although WNI were informed on 14 January that the ETA in Los Angeles had been delayed until 28 January, it remained as 22 January in the voyage planning sheet. It is thus evident that the voyage planning sheet had not been updated to incorporate the latest information received from MAERSK ESSEN.

WNI's voyage planning sheet contained a four-day forecast described in eight surface pressure charts starting at 16 January at 14:00 (Jan-17/00Z) (Figure 28) which indicated improving conditions with the ship clearing an area with significant wave heights between 6-9 m on 17 January at 02:00 ship time (Jan-17/12Z). The graph of forecasted wind, sea and swell heights combined indicated significant wave heights of 7.5 m on 16 January 14:00 LT (00 Zulu) and that the wave height was reducing (Figure 29).

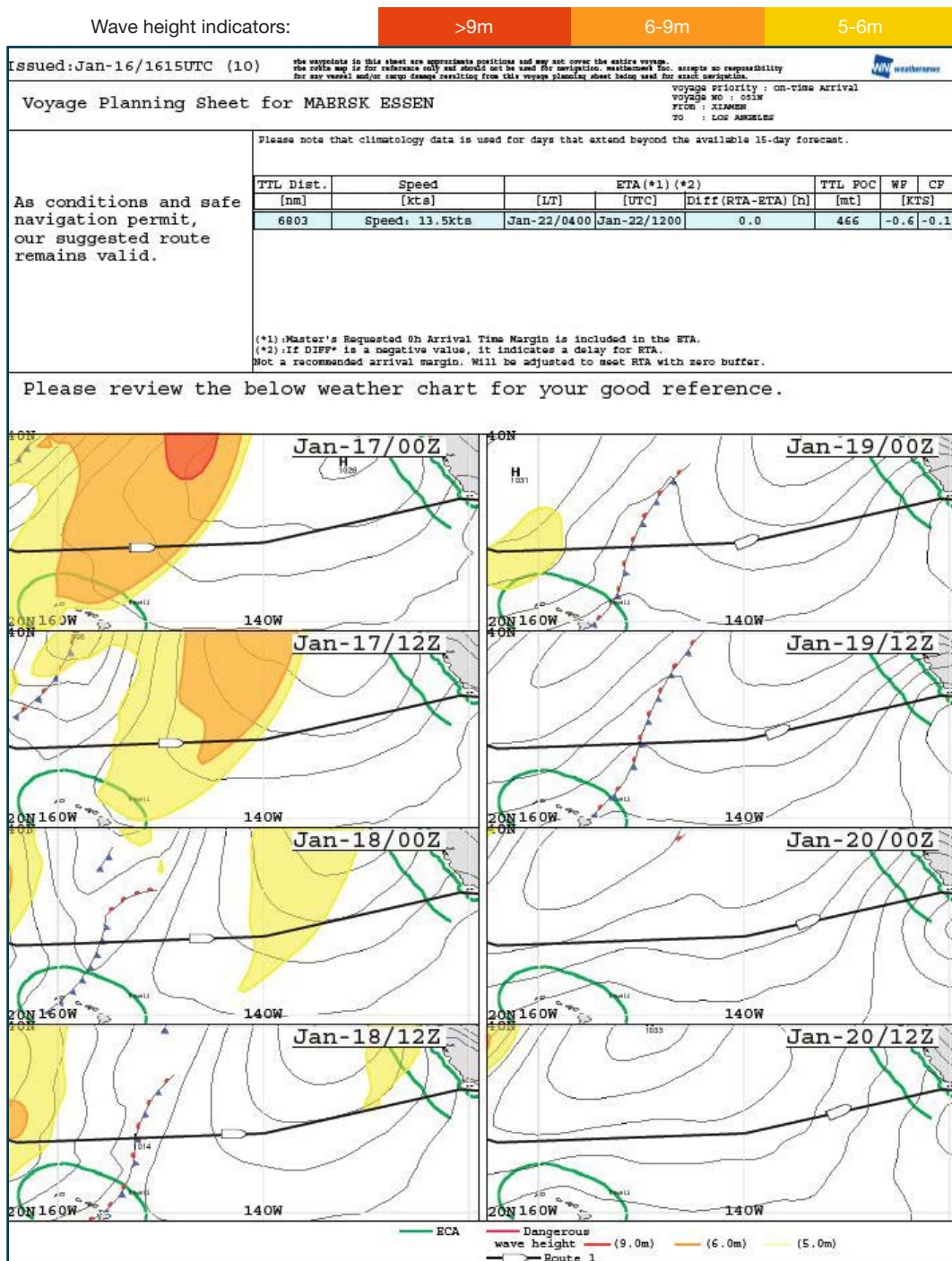


Figure 28: Voyage planning sheet issued on 16 January 2021
Source: WNI, modified by DMAIB

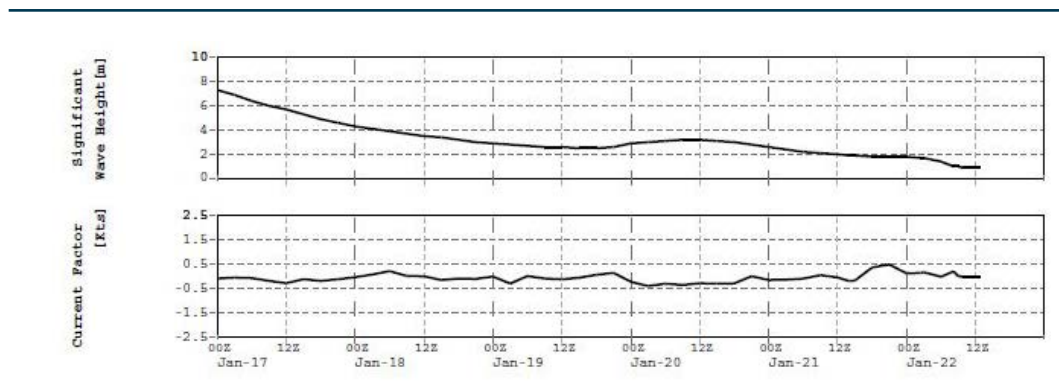


Figure 29: Voyage planning sheet issued on 16 January 2021
Source: WNI

The gradient of the significant wave height in the damage mitigation message indicates that the wave height was improving from 17 17 Jan/00Z (Figure 29). Arguably, when the message was received at 06:45 (ship's time), it could be extrapolated from the graph that the ship was already encountering worse sea conditions than those forecast in the damage mitigation message. In these circumstances, the message was not seen to be urgent which led to the chief officer's decision not to inform the master about the message until 08:00 at the operational meeting. In addition, as the damage mitigation message did not mention parametric rolling, it did not prompt the association of the heavy rolling at 06:00 with this phenomenon. It is noted that the heavy rolling that resulted in the loss of containers occurred at 08:00 on 16 January 2021, six hours earlier than the start of the period covered by the damage mitigation message from WNI.

As the ship was most likely already situated in worse conditions than forecast in the damage mitigation message, the message provided little or no possibility for the crew to react by means of heavy weather securing or route diversion. The heavy rolling accident occurred at 08:00 on 16 January 2021, six hours earlier than the time scope of the damage mitigation message. Neither of the route diversion recommendations or damage mitigations mentioned parametric rolling.

Findings: Weather routing

- The on board weather routing focused on direction and height of wave and swell. Risk of parametric rolling or pure loss of stability on a wave crest was not included in the on board template for weather routing request to WNI.
- The master followed WNI route diversion recommendation partly, as he assessed that MAERSK ESSEN was able to proceed safely in the 6 m combined wave and swell forecasted by WNI. This assessment was based on prior experience with the ship, and the ship had encountered worse sea state earlier during the voyage with little impact on the ship's motions.
- WNI's voyage planning sheets and damage mitigation warnings visually and in text highlighted areas exceeding a predefined wave/swell height threshold. Thus, the navigational officers did not perceive the message about potentially damaging conditions as a warning of risk of parametric rolling.

Instruments to predict parametric roll resonance

During DMAIB's investigations, the navigational officers expressed that they had knowledge of how to react to stop the heavy rolling caused by parametric resonance, and they had received on board computer based training on heavy weather damage, which included an approximately 30 minutes lecture on parametric rolling and resonance. However, they had no means or tools on board to monitor the risk of this phenomenon and pre-empt its onset. DMAIB found that procedure "P825 – Navigation in adverse weather" was the only procedure in the ship's safety management system that mentions parametric roll. Maersk A/S has confirmed that, besides this procedure, the crew had no tools for predicting parametric resonance, other than the IMO MSC.1 Circ. 1228, which the master was expected to be familiar with. In this section, DMAIB will examine the procedure and the IMO guidelines regarding their usability. The usability of a parametric calculator that was developed by Maersk A/S after the accident to aid crews in determining the risk of parametric resonance, along with other tools available within the company and to WNI, are also reviewed.

On board procedure

In Procedure "P825 – Navigation in adverse weather", parametric rolling is described as a "well-known phenomenon, which happens when the meeting frequency matches the double of vessel's own roll frequency and wavelength exceeds 0.8 vessel's length", and the crew is advised to mitigate parametric rolling by changing heading or speed. Hence, the procedure guides how to react, after the phenomenon has already started.

The procedure refers to the onboard training module for more guidance and neither references methods and/or tools for predicting the risk of parametric rolling, nor specifies how to determine the relationship between the ship's roll period and the wave encounter period. Therefore, the procedure could not be used by the crew to monitor the risk of parametric rolling.

IMO guideline

Maersk A/S has advised that "IMO MSC.1 Circ. 1228 – Revised guidance to the Master for avoiding dangerous situations in adverse weather and sea conditions" (2007) was the only instrument available to the crew for examining the risk of parametric rolling. The IMO guideline was not referred to in the procedure "Navigation in adverse weather".

The IMO guideline provides general guidance on avoiding dangerous phenomena in adverse weather and sea conditions, including parametric rolling. The IMO has since recognised that ships' stability is challenged in various ways and is currently working on developing performance-based criteria for various stability failure modes, including parametric rolling. Until these have been finalised, masters are still advised to follow the IMO MSC.1 Circ. 1228.

The guideline states that “For avoiding parametric rolling in following, quartering, head, bow or beam seas the course and speed of the ship should be selected in a way to avoid conditions for which the encounter period is close to the ship roll period or the encounter period is close to one half of the ship roll period”.

“Close to” is not defined by a spectrum or threshold and is hence left to masters’ discretion. Guidance is provided on how to obtain the values needed to determine the encounter period and ship’s roll period with a ship’s natural roll period being estimated by observing the rolling motion in calm sea. In practise, this is not possible as the ship will not roll in calm seas, and measuring the rolling motions in rough seas will not reflect a ship’s natural rolling motions. The variability of a ship’s roll period is demonstrated by the TUHH calculations which show that, in the case of MAERSK ESSEN, the roll period in waves before the heavy rolling episodes was considerably shorter than the natural roll period calculated by TUHH, while the roll period in waves during the parametric rolling motions is close to the calculated natural roll period (Figure 30).

As it is not possible to determine the actual natural roll period in calm seas, the natural roll period must be calculated. A calculation formula for roll period is provided in “IMO Res. MSC.267(85) – International Code on Intact Stability (2008)”. For container ships larger than 100 m this requires establishing a different roll radius of gyrations to the one preset in the general formula which is a complicated calculation requiring data that is not available to the crew and therefore not realistic to carry out on board.

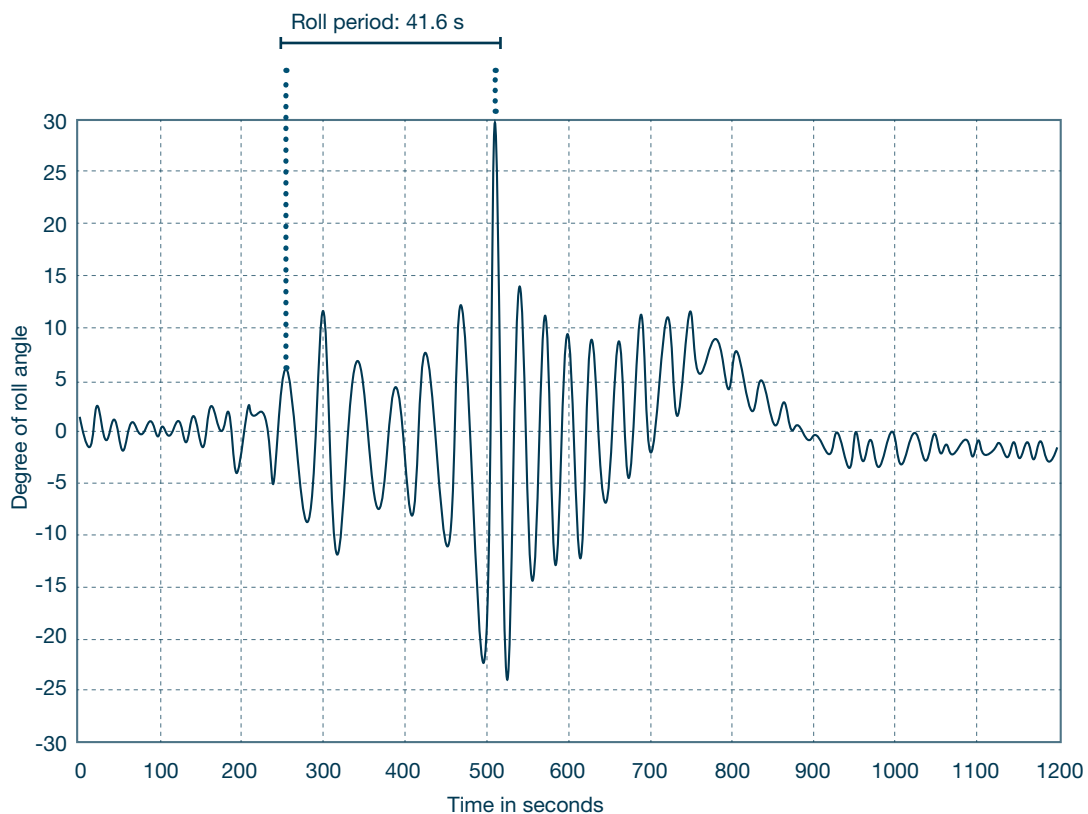


Figure 30: Graph MAERSK ESSEN’s roll angles at time of the accident.
Source: TUHH, modified by DMAIB

For determining the encounter period, data on wave period, encounter angle and ship's speed is needed. IMO MSC.1 Circ. 1228 details how the wave period can be measured visually and by radar. However, these methods are only valid at the time of measurement. To analyse future risk and to pre-empt the trigger conditions for parametric resonance from developing, crews must rely on forecast data. This is also the case for the wave encounter angle. As described in the section on sea conditions on the day of the accident, forecasts are generic for larger sea areas and depend on the calculation methods and models used. As a result, they might differ significantly from the actual sea conditions. Although accurate means are available onboard ships to measure speed, the speed will often fluctuate in waves. Therefore, the encounter period must be determined for a range of speeds.

The diagram below, which is provided in the IMO MSC.1 Circ. 1228, can be used to determine the encounter period (Figure 31). This is done by entering the wave period, wave encounter angle and ship speed.

This method requires crews to continuously update the input data and is therefore not a feasible method for monitoring the risk of parametric roll onboard ships. IMO MSC.1 Circ. 1228 conveys knowledge to be used when developing operational procedures; it is not an operational tool in itself. Consequently, MAERSK ESSEN's crew had no means available to predict the onset of parametric rolling.

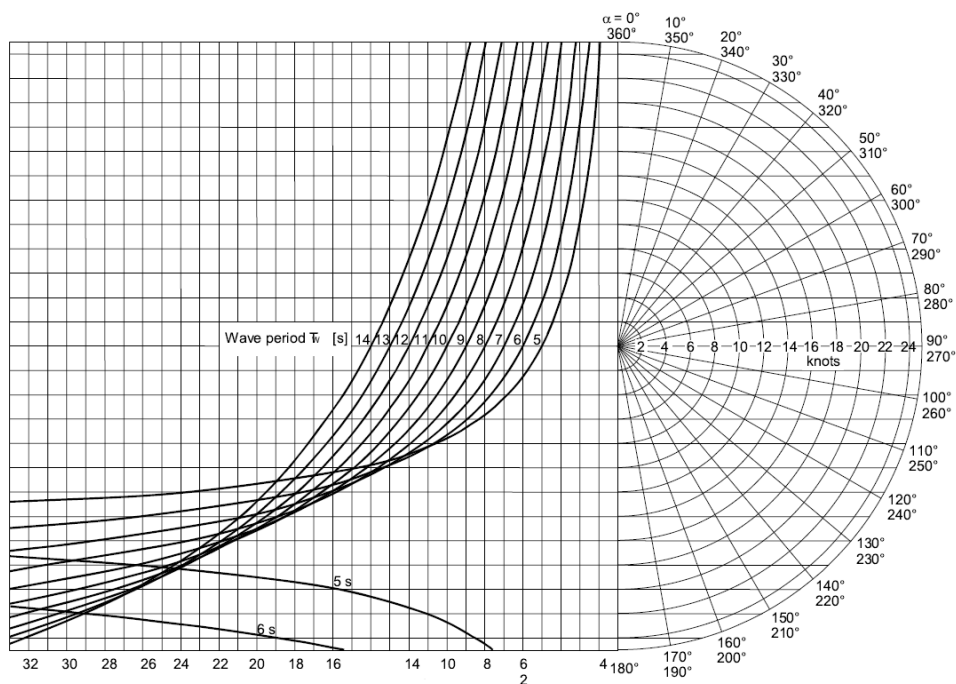


Figure 31: Encounter period graph issued in IMO MSC.1 Circ. 1228
Source: IMO

On board parametric roll calculator

Following the heavy rolling episodes, Maersk A/S provided MAERSK ESSEN with an “On Board Parametric Roll Calculator” in the format of an Excel spreadsheet based on the information contained in IMO MSC.1 Circ. 1228. According to the notes in the document, it is not feasible to use the calculator for continuously calculating the risk in real time, but the master and crew are encouraged to use the calculator to calculate the risk for voyage legs. This requires the use of forecast data to calculate the wave encounter period in combination with an automatically calculated natural roll period based on the GM.

The formula is adopted from “ABS Guide for certification of container securing systems” (2019) and uses a generic roll radius of gyrations for container ships. The natural roll period is therefore an estimate, since the roll radius of gyrations is not ship specific. This helps to explain why the natural roll period on the day of the accident derived from the onboard calculator (40.3 s) differs from the ship-specific calculation carried out by TUHH (42.8 s).

The onboard calculator is easy to use, as it only requires the crew to fill in five cells in the Excel document with values that are readily available on the loading computer and SPOS. The result of the calculation is displayed by highlighting a range of vessel speeds where the relation between roll period and encounter period will be close to 1:1 or 1:2 (Figure 32).

The calculator defines “close” to be within a margin of 10%. This means that the risk calculator is sensitive to variation and inaccuracies, which is a problem when calculations are based on forecast data, which are already prone to uncertainty and variation. A variation of one second to the wave period alters significantly the speeds identified with having risk.

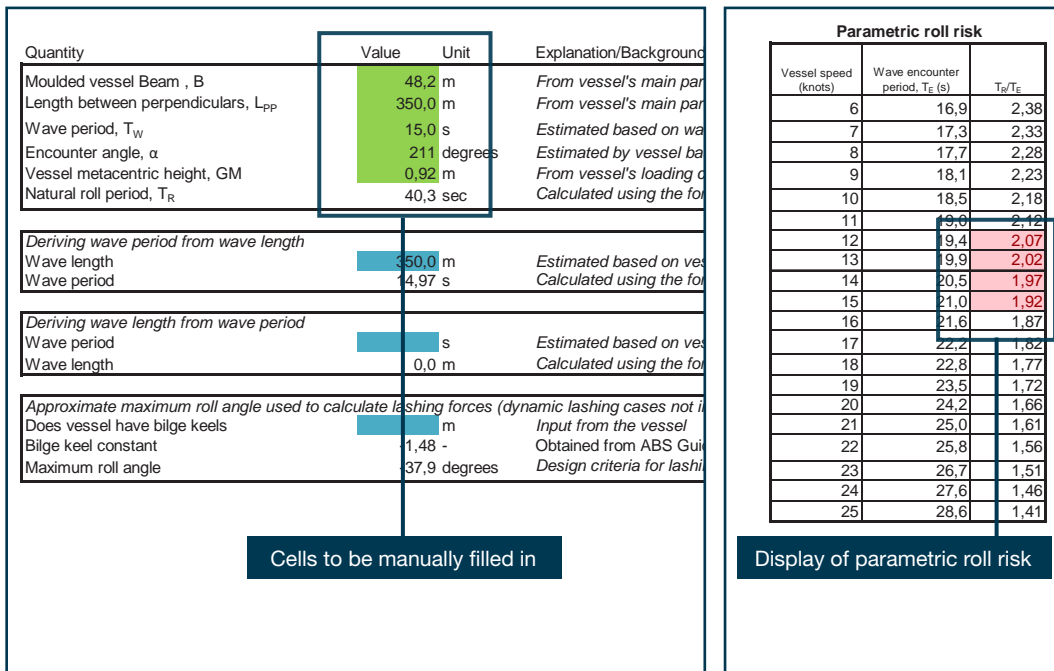


Figure 32: On board parametric roll calculator
 Source: Maersk A/S

While the onboard calculator operationalises the knowledge from the IMO MSC.1 Circ. 1228 and makes it easy to use for the crew, it still requires the crew to manually insert values into the calculator and is not suitable for monitoring the risk continuously in real time. The combination of the calculator's sensitivity, the generic calculation of natural roll period and the dependency of forecast data means that the risk calculation is a rough estimate. However, the numerical values and the sensitivity of the calculator give the impression of accuracy, which can be misleading to the crew.

SPOS Seakeeping

On board MAERSK ESSEN, the basic features of forecasts and route planning were available in SPOS. On other Maersk A/S ships, the software license also included the SPOS Seakeeping module. The Seakeeping module calculates a vessel's response to wind and wave, as well as resonance phenomena. The calculations are based on the criteria stated in IMO MSC.1 Circ. 1228.

The seakeeping module is fully integrated in the voyage planning and weather routing programme, which means that the risk of parametric rolling is automatically calculated based on forecast data and vessel information, and is readily available to the crew when planning the voyage and monitoring forecasted weather and sea conditions. The module can, inter alia, advise on safe speed for the given time, location and direction of travel, and displays real-time and predicted risk of resonance in a polar diagram (Figure 33). Furthermore, the module can automatically optimise the route according to motion limits.

To make use of the Seakeeping module, the software needs to be configured with ship particulars and roll damping parameters. This makes the calculation of parametric resonance more accurate than those provided by the onboard parametric roll calculator. However, the calculation is based on the same forecast data with the same uncertainty. Some of the navigational officers had experience from other ships with tools with similar functionalities as SPOS Seakeeping, and they found them to be useful tools for weather routing. However, the navigational officers on MAERSK ESSEN expressed concerns towards the tool's ability to foresee parametric rolling due to the differences between forecasted and observed wavelengths and wave periods.

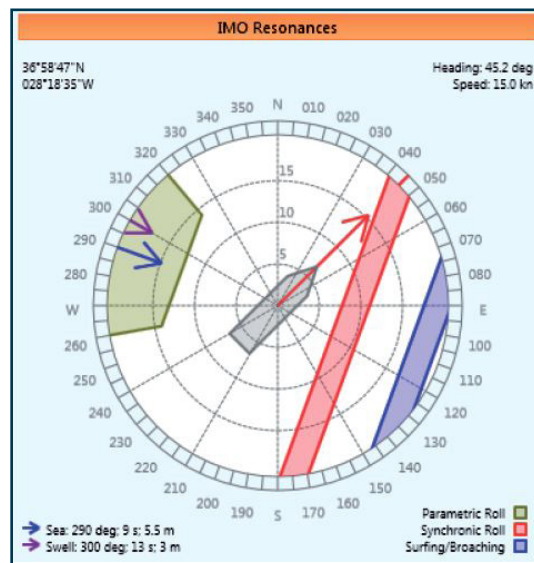


Figure 33: Example of polar diagram in SPOS Seakeeping module
Source: SPOS

WNI Motion Risk Forecast

Following the accident, WNI prepared a report on MAERSK ESSEN's heavy rolling. The report identifies that WNI had a software solution capable of motion risk forecasting, including the risk of parametric rolling. WNI's software is based entirely on IMO MSC.1 Circ. 1228. The WNI report concludes that the risk of parametric rolling was identified by its software to be high during MAERSK ESSEN's ocean voyage.

It is uncertain whether the risk analysis in the report was carried out by WNI route advisers during the voyage or carried out in response to the accident. However, WNI's communication to MAERSK ESSEN did not explicitly include information on parametric resonance to MAERSK ESSEN during the voyage.

DMAIB has reviewed WNI's report and found that WNI uses a roll period (28.4 s) that differs significantly from the roll period calculated by TUHH (42.8 s). It is not traceable in WNI's report how roll period is calculated. As the motion risk forecast references IMO MSC.1 Circ. 1228, DMAIB tested the generic formula for roll period calculation from the IMO Intact Stability Code which resulted in a value similar to WNI's. The generic formula in Intact Stability Code does not apply to container ships with lengths exceeding 100 m. According to the Intact Stability Code, container ships of this size require a different formula for calculating the ships roll radius of gyrations. If the general roll period calculation was used, then WNI's calculation of MAERSK ESSEN's parametric roll risk was based on an different value for roll period than the Maersk's On Board Parametric Roll Calculator and TUHH's calculation.

Prediction methods

The onboard calculator, the IMO MSC.1 Circ. 1228, SPOS Seakeeping and WNI motion risk forecast all share the same basic method for detecting risk of parametric rolling by examining the sea conditions in relation to the ship's stability. They differ in the degree and accuracy of ship specific information and definitions of risk threshold, but share the uncertainty embedded in forecasts and observed data. While some of the tools have more detailed ship specific data and are better integrated into the ship's operational procedures and software solutions, they are still prone to the uncertainty of accuracy in wave data and local variations. Therefore, a wide spectrum of unsafe speeds is necessary to compensate for this uncertainty.

The above method for predicting risk of parametric roll is the most common. DMAIB has been informed that alternative methods have been developed which monitor the ship's movements in real time using a combined 3-axis accelerometer and rate sensor, and analysing the data with an algorithm that can detect an onset of parametric roll and calculate the prevailing risk for parametric roll. DMAIB has not found any references to alternative detection methods within authoritative documents such as IMO guidelines, classification guidelines or marine technology textbooks.

Findings: Parametric roll prediction

- The crew did not have reliable information or tools readily available onboard to calculate and monitor risk of parametric roll resonance.
- Methods for prediction of risk of parametric rolling by comparing natural roll period with wave encounter period requires ship specific information and is sensitive towards small variations in ship's speed and wave data. This is problematic when risk calculation is based on forecasts and visual sea state observation characterised by uncertainty.

Loading condition

This section focuses on how MAERSK ESSEN's loading influenced the ship's stability and operational limits. The cargo plan is also compared against the ship's Cargo Securing Manual to examine the extent to which the cargo stowage complied with the manual.

Cargo Securing Manual

MAERSK ESSEN had a Cargo Securing Manual (CSM) as required by IMO's Code of Safe Practise for Stowage and Securing (CSS Code). The CSM was prepared by Maersk's Nautical Department in 2019 in accordance with IMO's MSC.1/Circ. 1353/Rev.1, Revised Guidelines for the Preparation of the Cargo Securing Manual and had been approved by Lloyd's Register. The purpose of the cargo securing manual was to provide guidance and instructions on stowage and cargo securing to mitigate excess forces acting on the containers with the risk of containers collapsing or tumbling. Other aspects of stowage, such as IMDG and reefer cargoes, was not included in the manual, but were covered elsewhere in the ship's safety management system.

The CSM guidance on stowage comprised bay plans, stack weight limits and a stowage rule for loading a heavier container onto a lighter container. It stipulated how different types of containers should be distributed over the ship on the individual bays. The stack weight limits concerned container stacks resting on hatch covers, pedestals and tank tops. For 20 ft containers the maximum permissible stack weight on all hatch covers was 100 t, while the limit was 170 t for 40 ft containers. The heavy over light stowage rule described that the maximum weight discrepancy for a heavier container being loaded on top of a lighter was 10 t. The rule is directed at the Cargo Coordinator ashore, not the ship's crew, but it is unclear whether this limit constitutes an actual rule to be followed as the CSM states that its purpose is only to improve stowage.

The CSM describes that the ship's stability and loading software had an integrated control function to warn of possible stowage errors, which comprised stack weight control, heavy over light control, lashing overload and a range of other requirements. In effect, the stability and loading computer collected and operationalised the requirements detailed in the CSM alongside other stowage requirements.

Loading and stability software

MAERSK ESSEN was equipped with a computer using Loadstar stability software designed for container freight purposes. Loadstar was type approved and met regulatory and classification society requirements as well as company specific requirements. The software was used by all stakeholders of the vessel's cargo operation onboard and ashore. Cargo coordinators and planners ashore prepared the cargo plan in Loadstar and forwarded the plan to the ship. The chief officer was responsible for evaluating the plan and verifying the ship was loaded in accordance with the plan.

Conflicts between stowage plans and classification society requirements were highlighted on Loadstar via a status bar. Green indicators in the status bar indicated compliance whereas red indicators in the status bar indicated non-compliance. Examination of the type of conflict that prompted a red indication on the status bar required an inquiry of information provided elsewhere in the program. However, not all conflicts displayed in the windows necessarily led to errors being displayed in the status bar. Although Loadstar checked for compliance with most of the limits and rules for cargo stowage, the crew manually checked the stowage plan for inexpedient placement of cargo, such as IMDG or reefer cargo in the outermost rows where they could be exposed to sea and sun.

Shifting or cancelling cargo had to be decided in collaboration with the cargo planners. As Loadstar was approved by the classification society, it was considered authoritative, and the crew was not expected to add a safety margin to the loading condition if all parameters were within the acceptable limits. Thus, the crew found it difficult to argue for taking less cargo on board or rearranging the stowage plan. For example, if the crew wanted to cancel cargo to ensure a buffer to the limits for shearing, bending and torsion, this would rarely be accepted by the cargo planners ashore unless limits were exceeded.

The software also included a lashing module that calculated the stress acting on lashings and containers based on cargo plan information (such as containers' type, location, weight etc.), the ship's stability data and operational limits concerning wind and roll angle (see also paragraph 4.6.2). On board MAERSK ESSEN, the roll angle limit for the container lashings was always set to 19.18°. This meant that Loadstar warned of lashing error, if the calculated acceleration forces at 19.18° exceeded the force limit of the lashings. Lashing error was a classification society defined rule and prompted a red indication on the status bar, which meant that the ship was not allowed to initiate a voyage, until the error had been resolved. In this sense, 19.18° was an operational threshold for MAERSK ESSEN. It was not intended for the ship to operate in conditions resulting in roll angles of 19.18° or greater. Weather routing was one method intended to avoid exceeding this threshold.

Loading condition at departure

On departure from Xiamen on 26 December 2020, MAERSK ESSEN was loaded with 6,643 containers, corresponding to 12,503 TEU, in total. The containers on board were ISO standard containers sizes (20, 40, 45 ft) and U.S/North American oversize containers (53 ft). The table below shows the number of different sizes on MAERSK ESSEN at departure (Figure 35):

<i>Size</i>	<i>Number</i>	<i>TEU</i>
<i>20 ft</i>	<i>783</i>	<i>783</i>
<i>40 ft</i>	<i>776</i>	<i>1552</i>
<i>40 ft</i>	<i>4824</i>	<i>9648</i>
<i>45 ft high cube</i>	<i>195</i>	<i>360</i>
<i>53 ft high cube</i>	<i>48</i>	<i>96</i>
<i>Total:</i>	<i>6,643</i>	<i>12,503</i>

Figure 35: Number of containers on board at departure from Xiamen
Source: Maersk A/S, modified by DMAIB

LOADING CONDITION

On some bays these occurrences exceeded 10 t. This did not activate an error indication in the status bar, because it was not a mandatory requirement, although the CSM mentioned 10 t as the limit for heavy over light containers. The settings in Loadstar were configured to display a warning for the individual bay, if a container was stowed on top of a container that was at least 5 t lighter. This meant that the user had to manually search for containers of concern. It also meant that the system did not highlight occurrences of heavy over light exceeding 10 t. The heavy over light error was not corrected by the crew on MAERSK ESSEN as this was considered up to the planners' discretion. Furthermore, the crew did not have time or resources to check for this error and potentially initiate cargo shifting.

As stated earlier, the limit for roll angle for which the stowage and lashing calculation was carried out was set to 19.18°. Simulation tests in Loadstar carried out by DMAIB determined that the lashing errors occurred at 19.50° roll angle at the departure condition.

Loading condition at time of the accident

During the voyage, the GM was continuously reduced due to fuel consumption from the bottom fuel oil tanks. By 16 January, the GM was 0.92, and the status bar still indicated that the loading condition parameters were within the classification society and company limits. Simulation carried out by DMAIB in Loadstar showed that the maximum roll angle to give no lashing errors had increased slightly to 19.80° roll angle. The simulation results thus support the crew's view that a lower GM reduced acceleration forces and hence reduced stress on the lashings.

The inclinometer and TUHH calculations concluded that roll angles experienced by MAERSK ESSEN during the loss of cargo was 26-30°. This is well above the ship's simulated maximum roll angle and the pre-set operational limit for the loading condition on this voyage.

Findings: Loading condition

- There were no errors in Loadstar conflicting with the mandatory loading requirements in the system
- Cargo planning and stowage introduced variabilities that the crew had little influence on or opportunity to react on.
- The lashing holding capacity formed an operational threshold at 19.18° roll angle. The ship's lashing system was not intended to withstand rolling motions exceeding this limit for this loading condition.
- Onboard weather routing was a means to avoid conditions leading to rolling motions exceeding the lashing roll angle.

Cargo securing

In this section, the lashing system on board MAERSK ESSEN will be described to understand how the containers were secured on deck and to understand the conditions influencing the holding capacity of the lashings.

Due to the COVID-19 situation, DMAIB was unable to carry out on-scene investigations when the MAERSK ESSEN was alongside in Lázaro Cárdenas. Therefore, it was not possible to examine the lashings or assess the condition of the lashing gear first-hand. Instead, DMAIB examined the photographic documentation obtained by the crew, damage records, crew statements and the cargo securing manual.

Lashing system

The cargo lashing system on MAERSK ESSEN was described in the CSM along with guidelines on how it was to be used and maintained.

Containers stowed on deck were secured with a lashing system comprising ISO container sockets fixed on hatch covers, base locks, semi-automatic twistlocks, knob lashing rods and turnbuckles. The lashing system consisted of various lashing patterns to be used on certain bays and container sizes. The dominant lashing pattern in use on MAERSK ESSEN was:

- Inboard stacks were secured with external lashings to the 2nd and 3rd tiers of the lashing bridges.
- The outboard stacks were secured to the 2nd and 3rd tier of the lashing bridge with internal lashings and one long windlash from 3rd tier.
- The containers on tiers five to ten were secured by semi-automatic twistlocks only, except the outermost rows where containers in tier 6 was lashed in one corner (Figure 38).

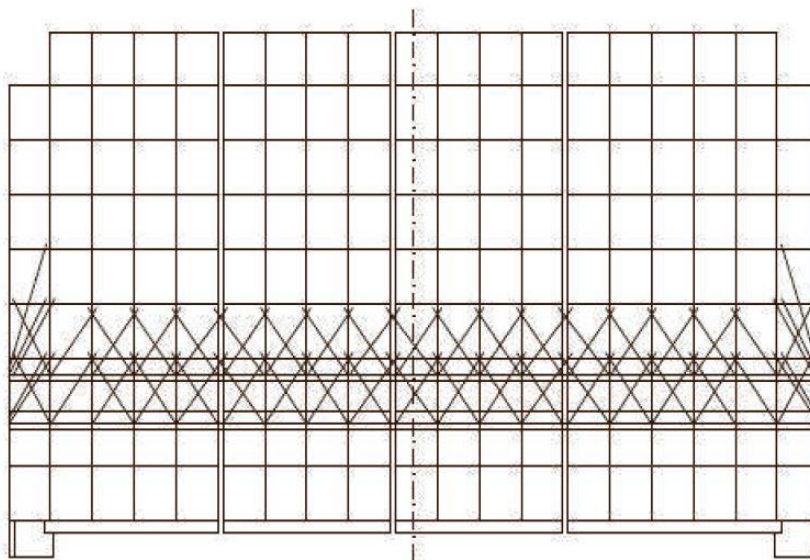


Figure 38: Lashing pattern for a nine high stack on MAERSK ESSEN
Source: Maersk A/S

The lashing system comprised of the following portable securing equipment:

- 1 type of baselock
- 1 type of semiautomatic twistlock
- 1 type of midlock
- 5 types of turnbuckles
- 5 types of short lashing rods
- 3 types of long lashing rods
- 2 types of extension rods

The turnbuckles and lashing were combined in four main variations of the lashing patterns designated for different bays. These were described in an installation guide consisting of a technical instruction drawing and boards that were intended to be mounted on each lashing bridge. The boards differed from the installation guide in that some of the turnbuckles were colour-coded whereas the installation guide had a disclaimer stating that the colours shown in the guide might be different from the colours on the turnbuckles. In reality, this meant that the colour codes on the general instruction boards offered no practical guidance or might even be misleading when posted on the lashing bridges. DMAIB has been informed that the general instruction boards were found to be missing from the lashing bridges.

The diagrams below, which are taken from the installation guide, are applicable to most of the bays on board MAERSK ESSEN (Figure 39). Note that four types of turnbuckles, four types of short lashing rods, one extension rod and one long lashing rod are to be applied in different combinations within the pattern. The various types of turnbuckles and lashing rods differed from each other in length.

The CSM required that the lashings be tightened equally and not too much. There was no mechanism or indication which specified when a lashing was correctly tightened. Hence, this was a subjective assessment by the persons applying and checking the lashings and therefore the tightness of each lashing was prone to variation.

According to the CSM, the portable and fixed lashing systems had to be visually inspected once a year and a function test must be carried out. The manual described what the visual inspection should focus on and how to test the equipment. Whether equipment was in a satisfactory condition was up to the crewmembers' assessments and subjective opinion, e.g. whether minor dents or bends on lashing rods were acceptable or not (Figure 40).

No maintenance records were kept on the individual lashing gear, so while the equipment might visually seem in working order, years of exposure to tension as well as general wear might have resulted in metal fatigue and reduced holding capacity to some degree. Furthermore, the crew did not perceive it to be possible to routinely assess the state of the ISO sockets fixed on the hatches and pedestals as they were in constant use, apart from when the ship was in dock. According to the company, some ISO sockets were renewed in dry-dock in February 2020.

INSTALLATION GUIDE -40'x 8'6" CONTAINER
BAY 82-14

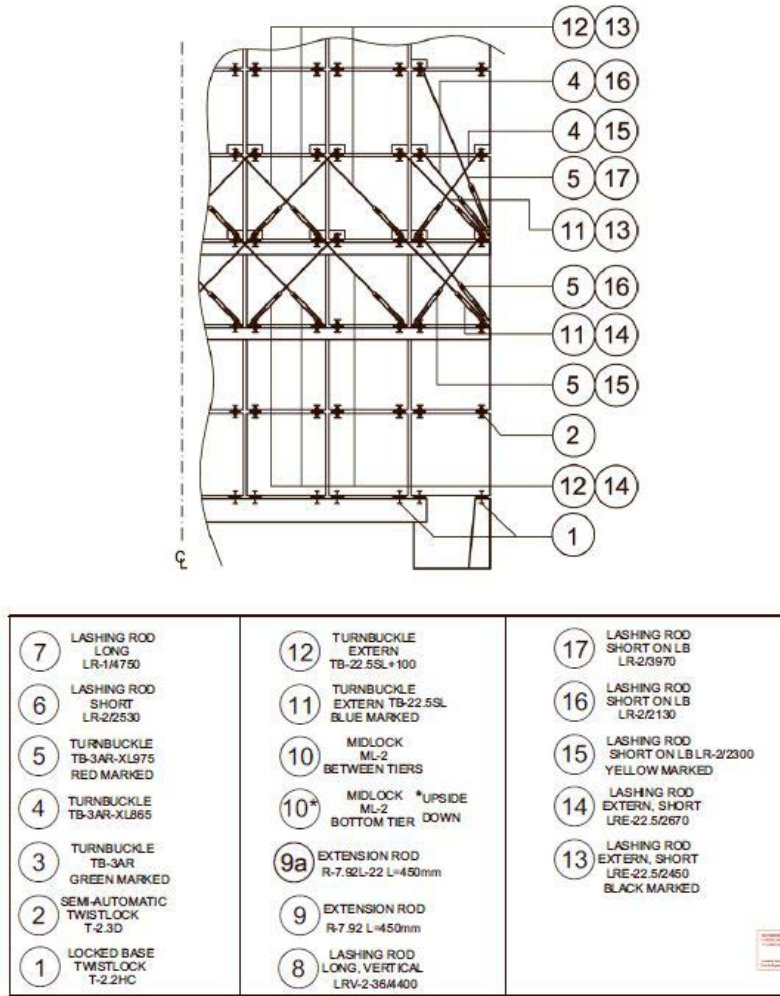


Figure 39: Lashing pattern on bay 82-14 for 40 ft x 8'6" containers.
Source: Maersk A/S

LASHING BAR

Inspect for any pittings or cracks which may weaken the lashing bar

A slight bend of the lashing rod is acceptable(1).
Sharply bent lashing rods must be discarded (2)

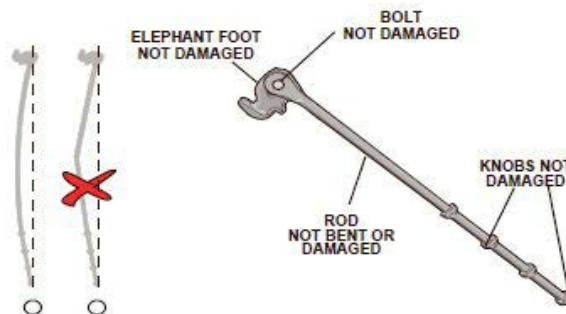


Figure 40: Inspection guide on lashing bar in CSM
Source: Maersk A/S

Lashing module in Loadstar

Loadstar contained a lashing module which calculated the stress on the lashing gear based on container size and location, the ship’s GM and roll angle. The lashing module calculated the acceleration forces acting on each container taking the longitudinal, vertical and transverse location of the container into consideration. The result was presented in Loadstar in a force table which was available for each bay (Figure 41).

Force Type	Row 18	Row 16	Row 14	Row 12	Row 10	Row 08	Row 06	Row 04	Row 02	Row 00	Row 01	Row 03	Row 05	Row 07	Row 09	Row 11	Row 13	Row 15	Row 17
Percentages																			
Corner Castings	47.76	50.73	62.66	70.15	67.58	77.79	76.96	75.73	79.37	72.92	78.41	77.16	75.20	68.06	70.93	70.26	61.72	52.61	48.29
Transverse Racking Forces	60.41	42.11	58.73	69.08	64.80	71.45	73.82	69.28	73.10	69.09	71.63	70.91	68.67	65.11	68.97	68.26	55.60	43.07	59.64
Longitudinal Racking Forces	37.07	40.07	47.87	53.24	53.85	61.30	61.88	61.68	62.56	60.62	64.87	64.52	62.64	56.17	57.41	53.38	46.68	40.49	37.25
Pull Out Forces	54.41	17.13	39.74	66.37	55.97	50.27	59.44	49.99	55.70	60.56	47.01	45.10	47.16	45.36	50.42	70.17	40.59	16.40	59.16
Corner Post Compressions	73.58	53.51	74.79	91.55	87.48	92.11	98.17	92.99	94.99	95.24	95.08	95.64	94.05	86.39	91.19	92.54	72.78	54.06	75.25
Corner Cast Compressions	72.96	54.76	71.91	85.42	81.97	82.35	88.27	84.59	84.83	88.03	87.80	89.40	87.14	81.36	85.03	85.91	70.53	56.37	73.06
Shear Forces	46.55	35.36	37.30	38.79	37.91	38.28	39.63	37.07	39.20	39.49	41.33	42.05	39.56	38.77	38.47	38.14	37.40	37.77	43.76
Lashing Rod Tensions	53.89	57.12	70.55	78.98	76.10	73.75	81.97	80.66	75.25	82.11	83.50	86.88	84.68	78.63	79.87	79.11	69.49	59.24	55.19
Actual Forces																			
Corner Castings	7.16	7.61	9.40	10.52	10.14	11.67	11.54	11.36	11.91	10.94	11.76	11.57	11.28	10.21	10.64	10.54	9.26	7.89	7.24
Transverse Racking Forces	9.06	6.32	8.81	10.36	9.72	10.72	11.07	10.39	10.97	10.36	10.74	10.64	10.30	9.77	10.34	10.24	8.34	6.46	8.95
Longitudinal Racking Forces	5.56	6.01	7.18	7.99	8.08	9.20	9.28	9.25	9.38	9.09	9.73	9.68	9.40	8.43	8.61	8.01	7.00	6.07	5.59
Pull Out Forces	13.60	4.28	9.94	16.59	13.99	12.57	14.86	12.50	13.93	15.14	11.75	11.28	11.79	11.34	12.61	17.54	10.15	4.10	14.79
Corner Post Compressions	63.57	46.23	64.62	79.10	75.58	79.58	84.82	80.35	82.07	82.29	82.15	82.64	81.26	74.64	78.79	79.95	62.88	46.71	65.02
Corner Cast Compressions	80.84	60.67	79.68	94.64	90.82	91.24	97.80	93.72	93.99	97.53	97.28	99.05	96.56	90.15	94.21	95.19	78.14	62.45	80.95
Shear Forces	6.98	5.30	5.60	5.82	5.69	5.74	5.94	5.56	5.88	5.92	6.20	6.31	5.93	5.82	5.77	5.72	5.61	5.67	6.56
Lashing Rod Tensions	13.47	14.28	17.64	19.75	19.02	18.44	20.49	20.16	18.81	20.53	20.88	21.72	21.17	19.16	19.97	19.78	17.37	14.81	13.80
Actual Limits																			
Corner Castings	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Transverse Racking Forces	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Longitudinal Racking Forces	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Pull Out Forces	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Corner Post Compressions	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40	86.40
Corner Cast Compressions	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80	110.80
Shear Forces	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Lashing Rod Tensions	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00

Figure 41: Example of force table in Loadstar
Source: Maersk A/S

The force table stated the calculated stress loads acting on each row/stack by presenting the actual load, actual limits and the actual load’s percentage of the limits. Following stress loads were included in the calculation: corner casting load, transverse and longitudinal racking force, pull out forces for baselocks and twistlocks, corner post and corner cast compression load, shear forces and lashing rod tension load. The loads calculated were thereby not limited to lashing gear only, but also the containers’ holding capacity.

If the limits were exceeded in the calculation, a warning would be prompted in the status bar. During DMAIB’s examination of the system, it was not possible to verify how the limits for stress loads were calculated in Loadstar, but DMAIB has been informed that Loadstar applied the safe working load of the lashing equipment.

Lashing operation prior to the accident

The crew perceived that the cargo operation in Xiamen went smoothly and that there was sufficient time for checking all lashings thoroughly prior to departure. During the port stay, there was a repair team on board which required the ship to stay in port longer than usual and afforded the crew more time to check the lashings. During the cargo operation, the deck officers observed that a few lashings had been applied wrongly, which were corrected prior to departure. The deck officers were familiar with the lashing system and were convinced that all lashings were applied correctly upon departure. However, during the unloading of the ship after the accident some lashing irregularities were found.

On passage, the crew usually checked the lashings weekly and after the ship had experienced weather conditions that might have caused the lashings to loosen. The lashings were checked on 8 January, and it was planned that the crew was to check and tighten the lashings again on 16 January, as it had been a week since the last check, and the ship had encountered rough weather conditions a few days earlier. The weather and sea conditions were also deemed to be favourable for the task.

The CSM required the lashings to be checked daily. However, this was not practised on board MAERSK ESSEN. It is not known why the crew's usual practice differed from the CSM requirement, but as a check of the entire cargo deck would be a very time-consuming task and frequently constrained by weather and sea conditions, it is questionable whether the CSM requirement for daily checks was achievable.

Findings: Cargo securing

The lashing system on board MAERSK ESSEN introduced variation affecting the lashings' holding capacity. These were mainly:

- Variation in tension applied to the lashings due to manual tensioning.
- Variation in application of lashing equipment due to complicated lashing system.
- Variation in equipment strength due to wear and tear.

Loss of cargo

This section provides an overview of the location of the lost containers, a description of the damaged containers and details of the affected bays. The damages and the loss of containers are analysed to determine why some bays were more affected than others.

Overview affected bays

After all the containers on board had been accounted for, Maersk A/S informed DMAIB that 689 containers were lost and 258 were damaged. Eight bays aft of the accommodation were affected: Bays 38, 42, 46, 50, 54, 58, 66 and 74. In Figures 42 and 43, the location and number of missing and damaged containers on the affected bays are highlighted:

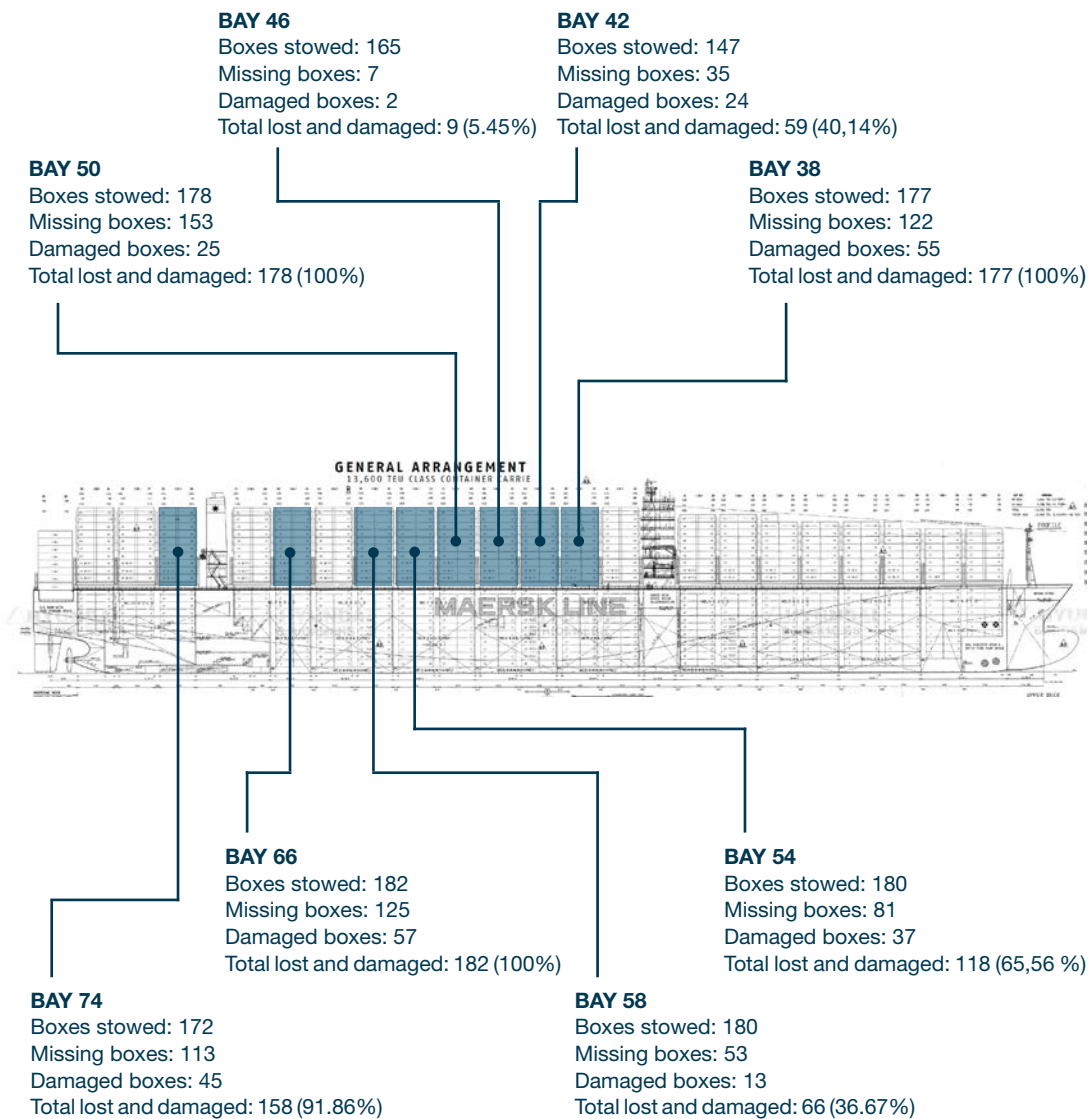


Figure 42: Overview damaged and lost containers based on Maersk info (DMAIB)
Source: MAERSK A/S / DMAIB

- Intact containers sitting in position
- Damaged containers
- Missing containers

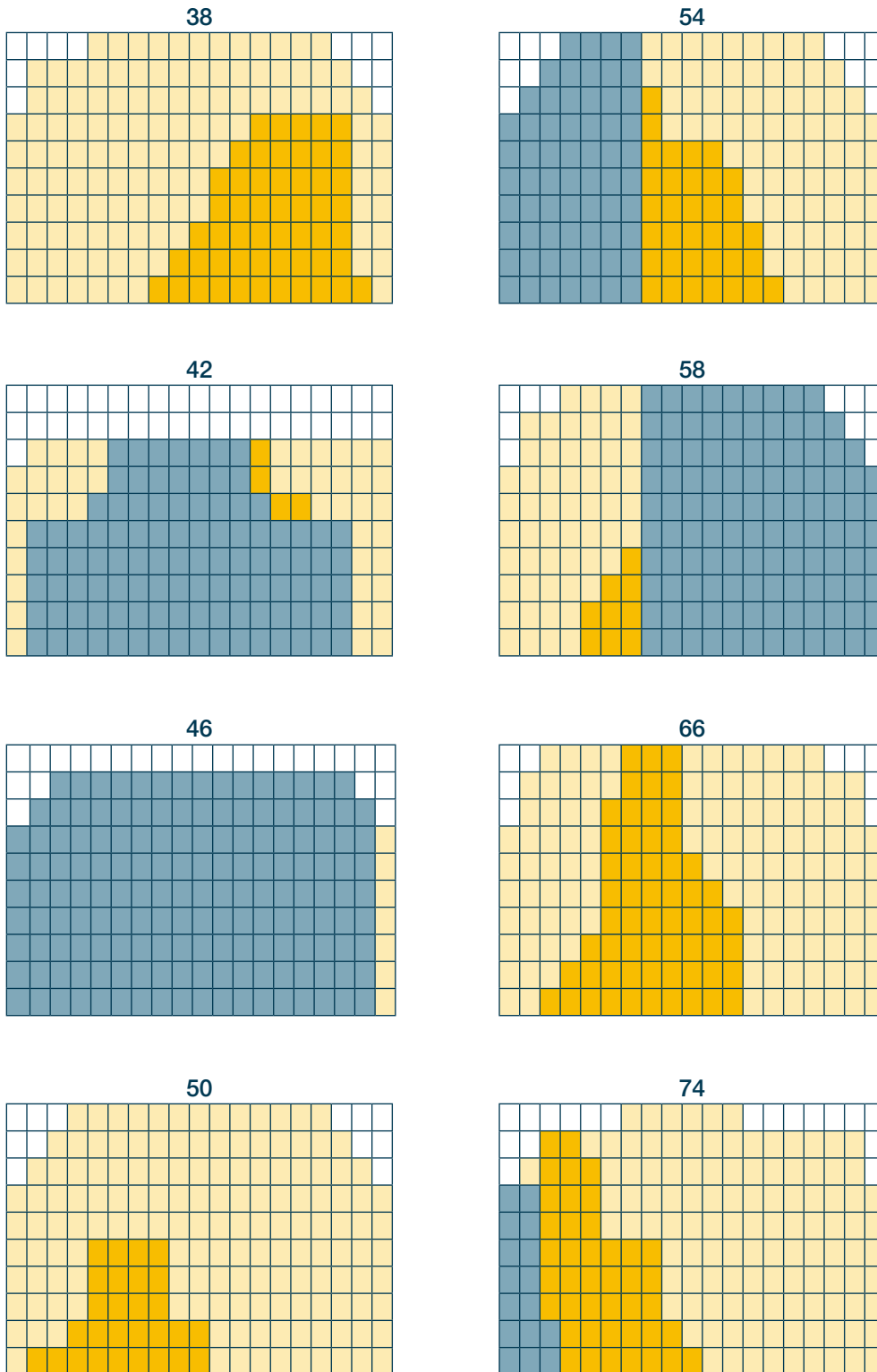


Figure 43: Overview damaged and lost containers based on Maersk info (DMAIB)
 Source: MAERSK AIS / DMAIB

Damage detail on the affected bays

The description of the damages on the affected bays is based on photographs taken by the crew and company at sea, and when the ship came alongside.

Bays 38, 50 and 66 suffered total collapse, with all containers lost or damaged. The containers remaining on board were fractured with indents to the side plating along with damaged corner posts and corner casts due to excessive loads or pressure compressing from other containers. Containers were hanging over both the port and starboard sides. On bay 50 and 66, the remaining containers were separated from the stacks and had toppled over in a chaotic pattern. On bay 38, containers were toppled over towards the port side and were still partly connected in stacks by twistlocks (Figure 44). This indicates that the bay collapse was mainly affected by a port side roll.



Figure 44: Bay 38 after the accident
Source: Maersk A/S

On Bay 58 port side, seven rows of containers were missing or damaged. The containers were toppled over to port, while still being partly connected in stacks by twistlocks. On the port side of the bay, containers were compressed underneath rows that had falling from the middle of the bay. Lashings on the remaining starboard rows were intact. This indicated that the collapse of stacks had occurred during a port side roll.

On bay 54 port side, the containers on the seven outermost rows were still in position, while the remaining twelve rows of containers were missing or damaged. The damaged containers were closest to the intact container rows on the port side, while the outermost containers on starboard side had fallen overboard. Figure 45 shows five rows had toppled over towards the starboard side, while still being partly connected by twistlocks, with the top of the stacks missing. This indicates that the entire row had collapsed when the ship rolled to starboard.

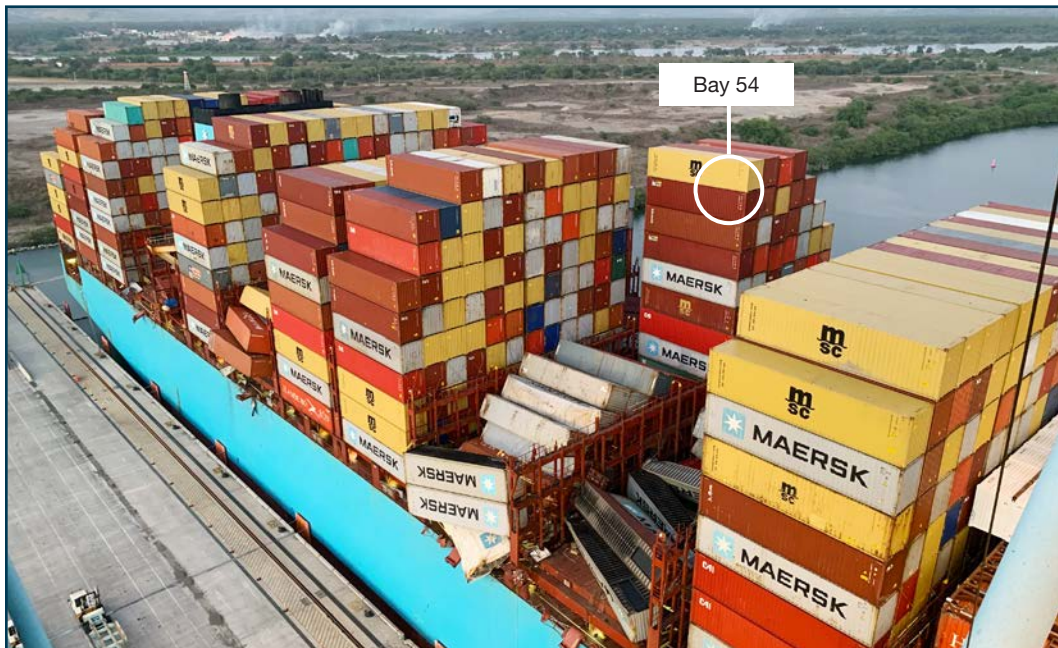


Figure 45: Bay 54 after the accident

Source: Maersk A/S

Bay 70 also showed indications of being affected by a starboard roll. The lost containers were primarily stowed on starboard side and centreline, while the outer rows on port side were largely undamaged and the port side inner rows were damaged, but still sitting on board. The toppled containers were leaning to starboard with many still connected by twistlocks.

Bay 46 had lost one row on its starboard side, which could have resulted from either acceleration force overload during a starboard roll or from the row being struck by containers tumbling from bay 42 (Figure 46). The remaining rows were sitting in position with their lashings intact.



Figure 46: Bay 42 after the accident. Bay 46 behind the white containers.

Source: Maersk A/S

The damages to bay 42 differed from the other affected bays, as the containers of the top tiers had tumbled to both sides, while the part of the stack secured to the lashing bridges remained in place with the lashings intact. The outboard rows on both sides were missing, which again might be due to acceleration forces acting directly on the stack during a roll or to being struck by containers tumbling from the upper tier.

On all affected bays, turnbuckles and lashing bars were hanging loose from lashing bridges and containers, showing signs of having been torn apart (Figure 48). In other places, turnbuckles and lashing rods which were still connected had been bent out of shape, as the container stacks had collapsed (Figure 47).



Figure 47 and 48: Example of detached and bent lashings (bay 66 and 54)
Source: Maersk A/S

DMAIB was informed that loose locking pins and nuts were seen on the deck after the accident. However, it cannot be determined whether these had loosened during the voyage, during the heavy rolling episodes, or if they had not been fitted securely prior to departure.

From the photographs available, it could be determined that ISO sockets were damaged on bays: 38, 42, 46, 50, 54, 66 and 74. Some of the sockets were fractured as the twistlock seated in the container had been forced out of the socket (Figures 49 and 50). A number of the sockets also appeared to be corroded, but DMAIB has not been able to determine whether the corrosion was superficial, or if it had the potential to impair load bearing capacity.

Both damaged and undamaged base locks were found in the sockets on the affected bays. In some cases, the locking pins seemed to be in the open position, but damages to container corner castings and twistlocks indicate they had been locked, but that the locking pins had been forced open when the container stacks toppled (Figure 51 and 52).



Figures 49 and 50: Example of socket fractures – bay 66 and 38
Source: Maersk A/S



Figure 51: Example of twistlock in open position, though socket and twistlock are broken.
Source: Maersk A/S

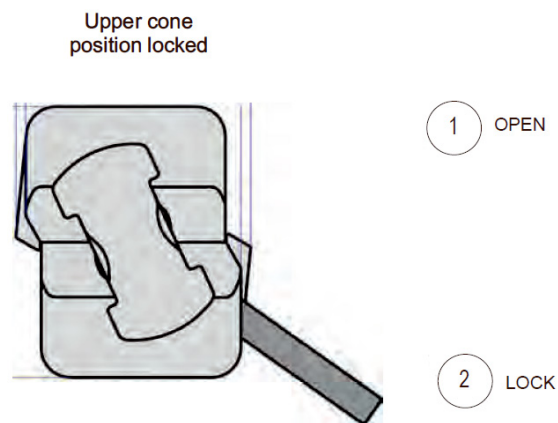
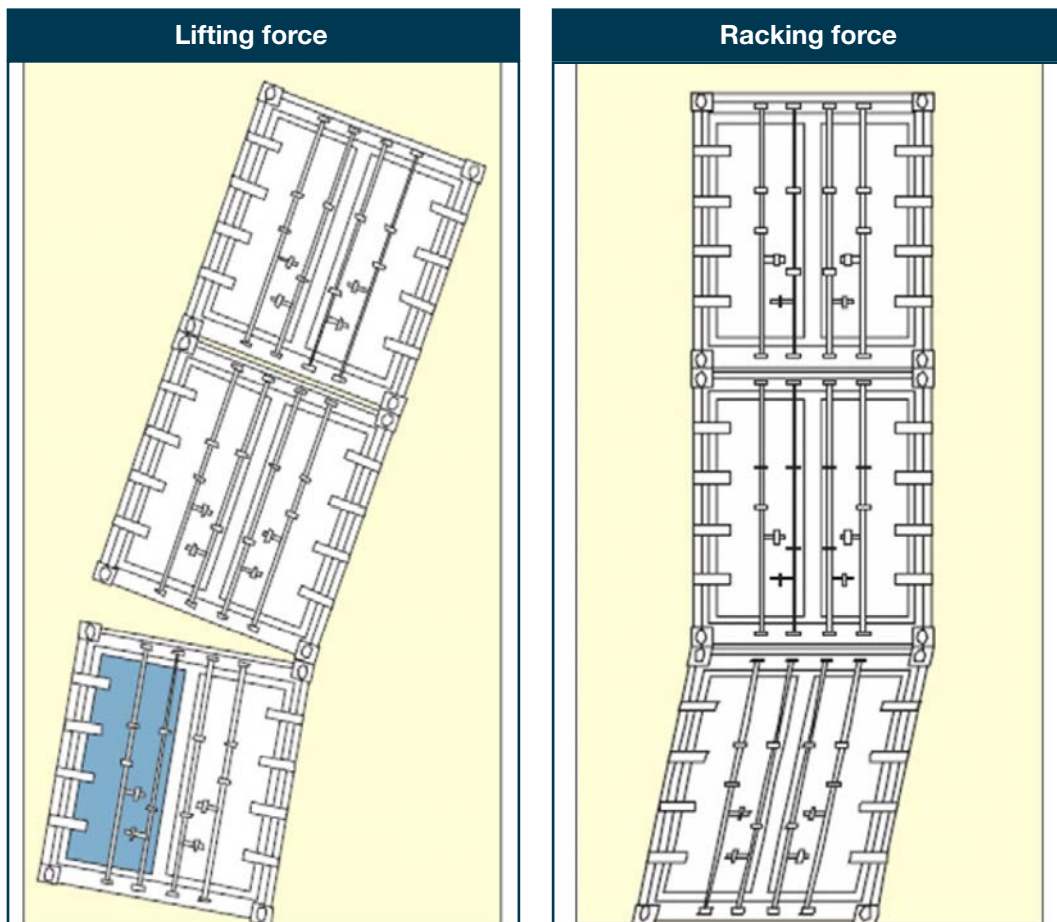


Figure 52: Base lock mechanism from CSM
Source: Maersk A/S

A mechanical root cause analysis of the container stack collapses and the loss of containers conducted by examining the damages to lashings and fall patterns is inherently uncertain, because some critical evidence was no longer on board. Additionally, the sequence in which the lashing equipment failed cannot be established with certainty because of the variabilities of the lashing system which influence the holding capacities of the lashing equipment securing each individual container. With the extensive damage seen on MAERSK ESSEN, searching for a root cause of the container collapses will be speculative. What can be concluded is that the lashing rods and turnbuckles were not able to withstand the stress load acting on them during the heavy rolling motions and were pulled apart or deformed. The twistlocks held the lower tiers of the stacks together, but they tended to fail at the top of the stacks where the acceleration forces were greater.

The ISO sockets, which had the lowest holding capacity, were damaged on most of the affected bays. Fractures on sockets, corner castings and base-locks often related to overload caused by lifting and separation forces induced by heavy rolling, which resulted in a tipping moment (Figure 53). However, the corner post load or lifting force might also have resulted from other dynamics within the individual stack, such as acceleration forces at the top leading to racking forces towards the middle of the stack, which then results in lifting/compression in the bottom of the stack (Figure 54). This type of dynamic will increase with stack height, especially for stacks with the tiers above the lashing bridge connected by twistlocks only. Furthermore, impact from collapsing adjacent stacks can also induce a tipping moment.



Figures 53 and 54: Racking and lifting force
Source: UK P&I Club, modified by DMAIB

Trend analysis of container stack collapse

DMAIB has compared the number and location of missing and damaged containers with Loadstar simulations of lashing stress loads at a roll angle of 25°, which is considered a conservative estimate of the roll angles experienced by MAERSK ESSEN. The simulation resulted in lashing errors on 17 bays, of which seven were bays from which containers were lost on 16 January 2021. No lashing errors occurred on bay 42, although this bay suffered container loss. To identify commonalities and differences between the bays losing cargo and the bays not losing cargo, DMAIB compared the following parameters:

- Stack weight: All stack weights were within the limits defined in Loadstar. No pattern in stack weight differences could be detected between the affected and unaffected bays.
- Stack height: Eight bays were stowed ten tiers high. Six of these had lost cargo and had suffered most damage out of the eight bays affected. Bay 38, 50, 66 and 70 had suffered a total bay collapse, while bay 54 and bay 58 had suffered half-sided bay collapses.
- Heavy over light: No pattern was detected with errors identified on both affected and unaffected bays, although with slightly more on the unaffected bays.
- Overload indicators in Loadstar: Except for bays 42 and 46, the affected bays had a high number of overload errors compared to the unaffected bays. The overload types were primarily corner post and cast compression, lashing rod tension and pull-out forces, which corresponds to damages observed.

Bay 42 had no lashing errors. Bay 46 had a few overload warnings for lashing rod tension, but the location of the warnings did not correspond to the row on the bay that lost containers.

The comparison of the Loadstar simulation against the actual loss of cargo and the container damages does not offer a substantive explanation of why cargo was lost or damaged on some bays but not others. Importantly, however, it confirms that the roll angle experienced induced a stress load that exceeded the intended limit that was applied to all of the stowage. That not all bays lost containers or suffered damage was due to the influences of a wide range of variations and uncertainties, such as lashing application, maintenance condition and stowage variation which are not accounted for in Loadstar. Such variabilities will influence the entire stack dynamic and holding capacity to an uncertain degree and impact the cargo securing equipment with an uncertain stress load.

The most significant trend observed in the comparison between the container losses and simulations, concerned the container stacks that were ten tiers high. Six out of the eight of these bays suffered total or partial collapse, and were also identified during the Loadstar simulation to have numerous lashing errors. This can be explained by high stacks being more sensitive to acceleration forces during rolling motions. In addition, the five top tiers are secured with twistlocks only, which allows for more movement in the stack.

Findings: Loss of cargo

- Loadstar simulations of the lashing stress loads at the time of the accident showed that the limit was exceeded in most bays. However, containers were not lost on all bays. DMAIB found no clear indication of what caused cargo to be lost from some bays and not others.
- Variability in stowage and cargo securing might have influenced the stress loads and holding capacity. However, the direct cause of the lashing failures was the excessive roll angles, which exposed the lashing gear to forces beyond their intended load limit.
- Analysis of damage patterns indicated that bays stowed with ten containers in height were more exposed to acceleration forces than bays with lower stacks.

Analysis

Analysis of causal factors

Loss of cargo

In the morning on 16 December 2020, MAERSK ESSEN experienced heavy rolling motions lasting six minutes with roll angles reaching between 25-30°. As a consequence, the cargo securing equipment failed to keep the containers in position.

In the ship's loading and stability software, Loadstar, the maximum roll angle was set to 19.18°. This meant that it was a requirement that the ship be stowed in a manner which – at 19.18° roll angle – did not result in forces that exceeded the defined stress load limits for lashings and containers. A roll angle of 19.18° was thereby the intended operational limit for the ship. The stress loads presented in Loadstar's lashing module were theoretical stress loads based on calculations of the acceleration forces acting on the individual container's position, size, weight and to some degree load dynamics within the stack. The force table in Loadstar showed that MAERSK ESSEN's loading condition at departure and on the day of the accident was within the required limits. For simulations for a 25° roll angle, the software identified lashing errors on the majority of the bays. That only eight bays were affected by the heavy rolling indicates a safety factor on the equipment and/or the possible application of safety margin to the stress load limits within Loadstar.

DMAIB has found that the cargo stowage and securing operations on MAERSK ESSEN were open to uncertainties and variabilities which could influence both the forces acting on the container stacks and the holding capacity of the cargo securing equipment. By themselves, these uncertainties and variabilities did not have the potential to cause the container stack collapses seen on MAERSK ESSEN.

By studying the damages on the affected bays and the simulations in Loadstar, DMAIB established that the affected bays did not share the same pattern of cargo loss and had thus been affected differently. However, the bays loaded with ten tiers of containers were more exposed to lashing overload during the Loadstar simulations, and these bays sustained more damage than the other affected bays. The stacks with ten tiers will be more exposed to acceleration forces, as the top five containers are secured by twistlocks only, which allows for more transverse movement. When experiencing increased roll angles, the top will be more susceptible to swaying, which can result in racking forces in the middle. In turn, this results in tipping forces acting on the base locks. While the analysis of the affected bays found that the ten tier stacks were more exposed to the acceleration forces once the heavy rolling was in effect, stack height in itself was not a cause of MAERSK ESSEN losing cargo.

The rolling angles experienced by MAERSK ESSEN exceeded the ship's operational limit. Therefore, the main casualty event on 16 December 2020 was MAERSK ESSEN being exposed to conditions resulting in excessive roll angles; the loss of containers was the inevitable consequence of that event.

Heavy rolling

The investigation of the heavy rolling on the day of the accident concluded that MAERSK ESSEN most likely experienced parametric resonance, possibly in combination with pure loss of stability on a wave crest. This resulted in large roll angles building up during a six-minute period.

Parametric rolling is not directly excited by impact from waves, but by a frequency-coupled interaction between sea state and ship motions. This interaction depends on wavelength, wave period, the ship's natural roll period, ship length and the ship's speed and course. DMAIB has found that on the day of the accident the relationship between these parameters created a risk of parametric resonance.

The crew's records of sea state observations along with hindcast analysis provided by weather service providers confirm that MAERK ESSEN was not experiencing extreme weather. At the time, the ship was north of Hawaii in an area of long residual swells of about 6 m, which was a normal sea state in this area. The ship had experienced similar or worse sea conditions earlier on the voyage without apparent difficulties. This is supported by calculation of the ship's roll angles prior to the episodes of parametric rolling. The ship was proceeding at slow speed of 10-11 knots, and the ship was loaded and ballasted to keep the GM low, which was normal for ocean voyages. This means that the parameters forming the triggering conditions for parametric risk resonance occurred within the normal operating conditions of MAERSK ESSEN.

The crew did not perceive the ship to be situated in a sea state likely to cause heavy rolling motions. Earlier in the voyage, the crew had prepared a heavy weather check list, but did not find this relevant on 15 or 16 January prior to the accident. Instead, the crew were scheduled to check the cargo lashings on deck.

All of the crew perceived parametric rolling to be a rare event. However, the triggering conditions were not rare for this type of ship in this sea area. The crew stated that they had experienced an occasional deep roll during the voyage and a few hours prior to the accident the ship took a sudden full roll cycle of approximately 15°. These might have been caused by parametric resonance which was soon interrupted by a change in parameters.

Weather routing

To avoid excessive roll angles, MAERSK ESSEN carried out weather routing on board based on information from SPOS and weather routing advice from WNI. The weather routing request to WNI from MAERSK ESSEN stated a maximum significant wave height of 5 m for the voyage. The correspondence between MAERSK ESSEN and WNI did not specifically mention parametric resonance or rolling. Thus, the navigational officers did not consider WNI's messages about potentially damaging conditions and vessel motions as a warning of risk of parametric rolling.

MAERSK ESSEN received a recommended route change on 14 January 2021 which predicted adverse sea state on 16 and 17 January, suggesting altering course to the south and speeding up. The master followed the advice to alter course but maintained the ship's speed at between 10 and 11 knots. His decision was influenced by his concern of arriving early in Los Angeles and having insufficient fresh water to remain at anchor and await a berth.

He was not concerned by the wave height predicted by WNI, as his experience was that the waves would not adversely affect the ship to any significant degree. That MAERSK ESSEN rolled only 2-3° prior to the heavy rolling episodes supports the master's assessment. Parametric rolling is induced by the ship's stability coupled with the encounter frequency of wave to the ship. This is a completely different phenomenon to the adverse weather referenced in WNI's route recommendations. Therefore, there is no connection between the master's decision to only partially follow WNI's routing advice and the episodes of parametric rolling on MAERSK ESSEN.

Assessing risk of parametric rolling was not a part of the weather routing on MAERSK ESSEN, but the navigational officers were aware of the phenomenon. There were no readily available tools on board to help carry out the calculations for this assessment, and the crew stated that they did not have any methods to predict and then avoid parametric rolling. The only option was to mitigate the effects of parametric rolling once it occurred, typically by changing course and speed.

DMAIB has examined the tools for predicting risk of parametric resonance made available to the company's fleet. Common to them was that they were dependent on forecast data. Forecasts are encumbered by uncertainty and will vary depending on the weather suppliers' data sources and calculation models. The parametric risk calculators were found to be prone to this type of uncertainty, which can result in misleading indications of risk.

Conclusion

Accident causation

In the morning of 16 December 2020, MAERSK ESSEN lost 689 containers overboard 450 nm north of Hawaii. The loss occurred during a 6-minute period of heavy rolling in which roll angles reached between 25° and 30°. The investigation determined that the heavy rolling was most likely a result of parametric resonance. The acceleration forces acting on the container stacks during the heavy rolling exposed the cargo securing equipment to stress loads which they were neither designed nor able to withstand. MAERSK ESSEN's loading condition required the ship to avoid roll angles exceeding 19.18° in order to stay within the stress load limits defined in the ship's loading and stability computer. This limit was exceeded at the time of the container loss.

To avoid heavy rolling, the ship used weather routing on board and received weather routing advice from an external weather service supplier. The weather routing focused on avoiding heavy weather and rough sea states. Parametric resonance was not mentioned in the correspondence between the crew on MAERSK ESSEN and the weather service supplier, and the crew had no onboard tools to analyse or monitor the risk of parametric resonance. They had to rely on reactive strategy, if the phenomena occurred. During the heavy rolling episodes, the bridge crew took action to stop the rolling motions by altering course and speed. By then, the container stacks had already collapsed.

The conditions triggering the parametric rolling of MAERSK ESSEN were within the spectrum of normal operational conditions for the ship and in normal sea conditions for the area. These circumstances add a critical dimension to the risk of parametric rolling, because the development of the conditions required to trigger this phenomenon occurred without being evident to the crew. Consequently, normal work continued, and on the day of the accident the crew was minutes away from entering the cargo deck to check lashings, as the rolling occurred. If the crew had been on deck, the collapsing container stacks could have resulted in fatalities.

The investigation of MAERSK ESSEN's heavy rolling accident concluded that parametric rolling was considered a rare phenomenon by the crew. However, the triggering conditions for parametric rolling were not rare for this type of ship in this sea area, and hence it is likely that the ship had experienced resonance effects earlier and on previous voyages, and that accidents are likely to occur again unless effective efforts to avoid the triggering conditions are implemented.

Safety learning

Detecting risk of parametric resonance rolling based on forecasted sea conditions can be problematic as forecasts are encumbered by uncertainty. No matter how automatised and detailed the onboard tools for monitoring parametric resonance are, they are prone to the uncertainty of the forecasts which make them unreliable as tools, unless a broad risk margin is applied.

DMAIB encourages companies and authorities to explore and test options for predicting resonance effects that are based on real-time conditions rather than forecasts.

Preventive measures

Actions taken after the accident

DMAIB received information that Maersk A/S and WNI have initiated following preventive actions as a response to the accident:

Actions taken by Maersk A/S

”Immediate preventive measures

- *Fleet wide knowledge sharing to vessel crew re-emphasizing importance of route advises*
- *Procedure reviewed pertaining*
 - *Navigation in adverse weather*
 - *Flowchart in vessel emergency response manual*
 - *Reiterating guidance and onboard calculator basis MSC1228*
 - *Revision of onboard heavy weather checklists*
- *Procedure revision in collaboration between WNI (Weather Route provider) and Maersk including a revision of severity thresholds for weather route advise*
- *Review of crew training material pertaining parametric roll*

Preventive measure established - 2021

- *The roll out of SPOS-Octopus onboard seakeeping module was accelerated and completed now covering all large ocean crossing vessels in the fleet. The tool is part of an onboard forecast tool - predicting vessel roll motion basis weather forecast and vessel profile*
- *Maersk and WNI have in collaboration improved information and detail level of Weather Route advise pertaining to risk of parametric roll on the specific voyages*
- *Shore based seakeeping through WNI’s weather platform is currently being trialed with select vessels . Aim is to evaluate if shoreside seakeeping is possible as an added level of safety by providing early warning of rolling phenomenon’s to vessels for appropriate action to taken.*
- *A joint detailed investigation between Maersk and “Technical University Hamburg” was concluded focusing on vessel technical design parameters*
- *Bilge keel sizes on larger vessels was reviewed and incorporated in a number of vessel design specifications*
- *Pilot project with onboard live sensors alert has been established with several vendors in the industry. Aim is to identify a reliable and operational usable onboard real time warning system for parametric roll*
- *We are part of a joint Industry Project “Top Tier” in cooperation with World Shipping Council. The project is besides addressing technical designs also addressing regulatory framework in the industry”*

Actions taken by WNI

"Over the past few years, WNI have recognized that the common approach of avoiding specific wind or wave thresholds is not enough to avoid the risk of damaging situations, because the majority of accidents occur below the commonly applied high wave thresholds, and are related to vessel motions. As such, we have been working to improve understanding and prediction of vessel motions to strengthen the safety value of voyage optimization, and specifically communicating risk associated with vessel motion to minimize marine accidents at sea.

The challenge of communicating weather-related risk to vessels at sea requires ongoing refinement: firstly, improving understanding of what risks exist through upgrading forecast technology, forecast evaluation, and simulation processes; secondly, effectively communicating those risks for recipients (ship masters at sea and shoreside operators) in order to take action.

In this respect, one learning point of this accident in terms of communicating risk is related to the specificity of warnings and understanding under what context those warnings may be assessed by the recipient. Are the warnings clear and understandable? Do they target the correct risks? Will the recipient understand what actions may be required to mitigate those risks?

As such, WNI has expanded the ability to simulate vessel motions based on forecast data and DR data in order to identify periods where vessel motion risks are present: synchronous and parametric rolling, shipping seas, successive wave attack, loss of intact stability, and a proprietary damage risk model for containerships developed based on historical accident and associated meteorological data.

Forecast uncertainty exists as a challenge for predicting risks, so the methodology includes buffers to account for possible forecast changes or inaccuracies in rolling period or GM calculations.

In terms of communication, types and periods of risks associated with vessel motions are now presented in .pdf format, complementing the text alerts sent to vessels to allow recipients to better visualize both the specific vessel motion risks, and time periods where risks are present. Simulations of vessel motion risk for multiple route options are also available, for understanding risks associated with various voyage optimizations for master and shoreside decision support.

WNI is committed to safety and will always work to improve products and services with safety in mind."

Appendix

SHIP PARTICULARS

Name of vessel:	MAERSK ESSEN
Type of vessel:	Container ship – New Panamax
Nationality/flag:	Denmark
Port of registry:	Copenhagen
Call sign:	OYID2
IMO no.:	9456783
DOC company:	Maersk A/S
IMO company no. (DOC):	5808451
Classification society:	Lloyd's Register
Year built:	2010
Shipyard/yard number:	Hyundai Heavy Industries Co Ltd – Ulsan Yard/No.:2153
Overall length:	366.45 m
Breadth overall:	48.26 m
Draught max.:	16.00 m
Gross tonnage:	141,716
Engine rating:	48,000 kW
Service speed:	24.70 kts
Hull material:	Steel
Hull design:	Single hull

VOYAGE DATA

Port of departure:	Xiamen, China
Port of call:	Los Angeles, United States of America
Type of voyage:	International
Cargo information:	General cargo in containers
Manning:	25
Pilot on board:	No
Number of passengers:	None

WEATHER DATA

Wind – force, direction:	Strong breeze - ENE
Wave/swell height:	6 m
Current- speed, direction:	South – 0.15 knots
Visibility:	Very good
Weather conditions:	Overcast
Light/dark:	Light

MARINE CASUALTY INFORMATION

Type of marine casualty:	Loss of cargo
IMO classification:	Serious
Date, time:	16 January 2021, 0804 LT (UTC-10)
Location:	Pacific Ocean
Position:	28°33.76 N - 154°0.72 W
Ship's operation:	In passage, midwater
Place on board:	Cargo deck
Human factor data:	Yes
Consequences:	689 containers were lost over board and 258 damaged. Ship suffered damages to structures on cargo deck.

SHORE AUTHORITY INVOLVEMENT AND EMERGENCY RESPONSE

Involved parties:	US Coastguard Honolulu was notified on containers over board
Resources used:	None
Actions taken:	None
Results achieved:	None

RELEVANT PERSONS

Master:	61 years old. Had served as master in the company since 2008, and on MAERSK ESSEN since 2020.
Chief Officer:	36 years old. Had served in the company since 2007 and since 2020 on MAERSK ESSEN.
3 rd officer:	23 years old. Had served in the company since 2018 and on MAERSK ESSEN since 2020.

