Danish Maritime Accident Investigation Board

MARINE ACCIDENT REPORT
December 2013

EMMA MÆRSK
Flooding of engine room on 1 February 2013

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This marine accident report is issued on 19 December 2013

Case number: 2013002165

Front page: Water ingress in engine room. Source: Maersk Line

The marine accident report is available from the webpage of the Danish Maritime Accident Investigation Board www.dmaib.com.

The Danish Maritime Accident Investigation Board

The Danish Maritime Accident Investigation Board is an independent unit under the Ministry of Business and Growth that carries out investigations with a view to preventing accidents and promoting initiatives that will enhance safety at sea.

The Danish Maritime Accident Investigation Board is an impartial unit which is, organizationally and legally, independent of other parties

Purpose

The purpose of the Danish Maritime Accident Investigation Board is to investigate maritime accidents and to make recommendations for improving safety, and it forms part of a collaboration with similar investigation bodies in other countries. The Danish Maritime Accident Investigation Board investigates maritime accidents and accidents to seafarers on Danish and Greenlandic merchant and fishing ships as well as accidents on foreign merchant ships in Danish and Greenlandic waters.

The investigations of the Danish Maritime Accident Investigation Board procure information about the actual circumstances of accidents and clarify the sequence of events and reasons leading to these accidents.

The investigations are carried out separate from the criminal investigation. The criminal and/or liability aspects of accidents are not considered.

Marine accident reports and summary reports

The Danish Maritime Accident Investigation Board investigates about 140 accidents annually. In case of very serious accidents, such as deaths and losses, or in case of other special circumstances, either a marine accident report or a summary report is published depending on the extent and complexity of the events.

Contents

1. SUMMARY

On the evening of 1 February 2013, a severe leakage occurred in the container ship EMMA MÆRSK while the ship, loaded with general cargo in about 14,000 containers, was about to pass southbound through the Suez Canal.

The leakage was caused by a mechanical break-down of a stern thruster situated at the aft part of the ship's shaft tunnel whereby the shaft tunnel was flooded. The bulkhead between the shaft tunnel and the main engine room could not withstand the hydrostatic water pressure and eventually the main engine room was also flooded.

The situation became complicated because the ship had just initiated a passage in a convoy through the Suez Canal. Loss of the ship's own propulsion, electric power, steerage and manoeuvrability could be foreseen and eventually occurred.

The main technical sequence of events were a break-down of the forward stern thruster causing a major leakage into the shaft tunnel, a collapse of the watertight integrity of the bulkhead between the shaft tunnel and the engine room, primarily caused by non-effective cable penetration sealings and some undesirable properties of the bilge system and the emergency bilge suction from the engine room. Throughout the course of events, all officers and crew members were constantly disturbed and highly stressed by the sound of countless alarms, which made it extremely difficult to concentrate on the many challenges that appeared.

Despite a series of technical breakdowns and system weaknesses, the shipboard organization remained resilient, and despite the breakdown of the structural barriers, the ship's officers and crew managed to contain the emergency situation and bring the ship alongside at the Suez Canal Container Terminal without any personal injury or pollution to the environment.

The report contains information about the preventive measures taken by the shipping company, the classification society and other parties involved. The report contains no safety recommendations from the Danish Maritime Accident Investigation Board.

2. FACTUAL INFORMATION

2.1 Photo of the ship

Figure 1: EMMA MÆRSK
Source: Maersk Line

2.2 Ship particulars

Name of vessel:	EMMA MÆRSK
Type of vessel:	Container ship
Nationality/flag:	Denmark (DIS)
Port of registry:	Taarbæk
IMO number:	9321483
Call sign:	OYGR2
DOC company:	A.P. Møller-Mærsk A/S
IMO company no. (DOC):	0309317
Year built:	2005
Shipyard/yard number:	Odense Staalskibsværft A/S/203
Classification society:	American Bureau of Shipping
Length overall:	397.71 m
Breadth overall:	56.40 m
Gross tonnage:	170,794
Deadweight:	156,907 t
Draught max.:	16.02 m
Engine rating:	80,080 kW at 102 RPM
Service speed:	24.50 knots
Hull material:	Steel
Hull design:	Double hull

2.3 Weather data

Wind – direction and speed:	Northwesterly – 12 m/sec.
Visibility:	Good
Light/dark:	Dark

2.4 Voyage particulars

Port of departure:	Tangier
Port of call:	Suez Canal
Type of voyage:	Merchant shipping, international
Cargo information:	General cargo in containers
Manning:	25
Pilot on board:	Yes
Number of passengers:	0

2.5 Marine casualty or incident information

Type of marine casualty/incident:	Flooding of shaft tunnel and engine room
IMO classification:	Serious
Date, time:	1 February 2013 at 2141 hours, local time
Location:	Port Said, entrance of the Suez Canal
Position:	31°27.8' N – 032°20.1' E
Ship's operation, voyage segment:	Manoeuvring
Place on board:	Shaft tunnel and engine room
Human factor data:	Yes
Consequences:	Shaft tunnel and engine room flooded with seawater. Extensive damage to all machinery in main engine room and shaft tunnel and minor damage to hull. Nobody injured and no pollution to marine environment. The ship was out of service for six months due to repairs.

2.6 Shore authority involvement and emergency response

Involved parties:	The Suez Canal Authorities
Resources used:	Four tug boats
Results achieved:	The ship was manoeuvred and towed into Port Said Container Terminal and kept alongside by tugs until firmly moored and discharged.

2.7 Key persons

Master:	48 years of age. Holding a certificate as a master mariner, served in this company for 22 years, 12 years of which as a master and six years of which as the master of EMMA MÆRSK.
Chief officer:	36 years of age. Holding a certificate as a master mariner, served as a chief officer for three years, two years of which as the chief officer of EMMA MÆRSK.
Chief engineer:	51 years of age. Holding a certificate as a chief engineer, served in this company for 24 years, 16 years of which as a chief engineer, six years of which as the chief engineer of EMMA MÆRSK.
2^{nd} engineer:	39 years of age. Holding a certificate as a chief engineer, served in this company for 13 years, five years of which as a 2^{nd} engineer, two years of which as the 2^{nd} engineer of EMMA MÆRSK.

2.8 Scene of the accident

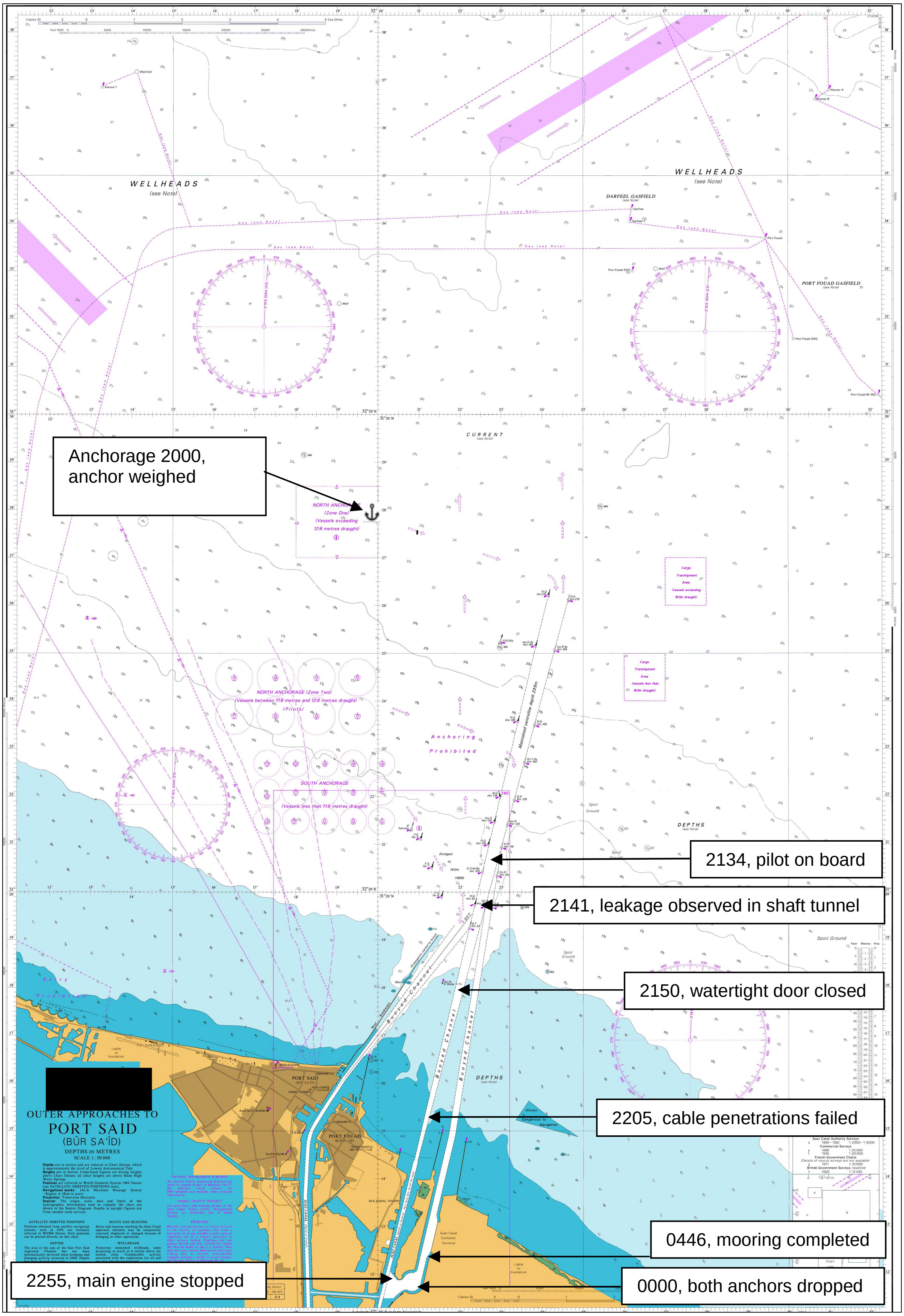

Figure 2: Sites of events

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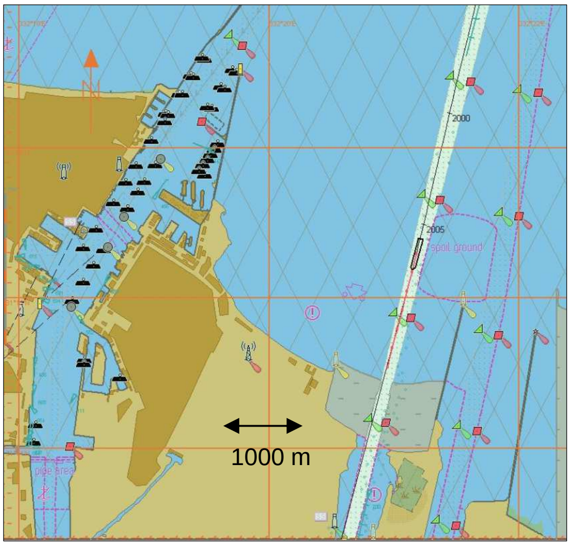


Figure 3: Excerpt from VMS recording at 2206 hours
Source: Maersk Line

Figure 4: Excerpt from VMS recording at 2236 hours
Source: Maersk Line

Figure 5: Excerpt from VMS recording at 2241 hours
Source: Maersk Line

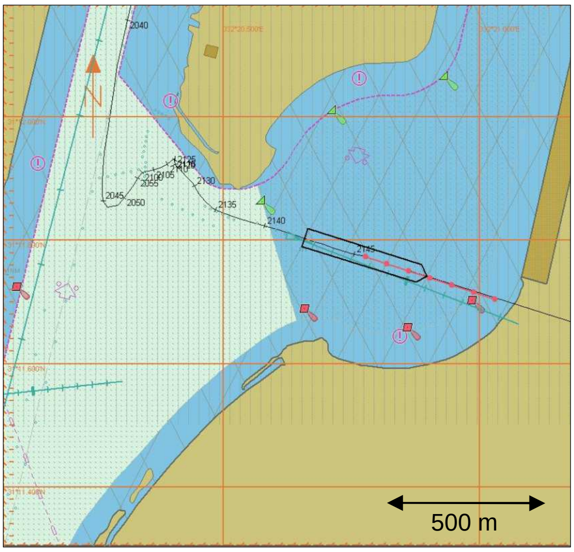


Figure 6: Excerpt from VMS recording at 2346 hours
Source: Maersk Line

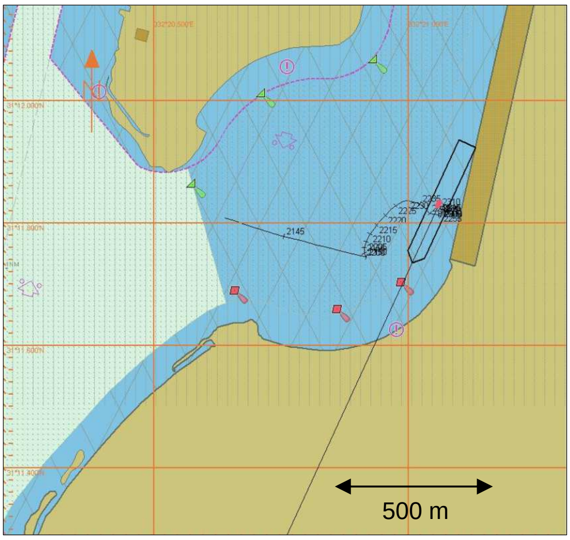


Figure 7: Excerpt from VMS recording at 0021 hours
Source: Maersk Line

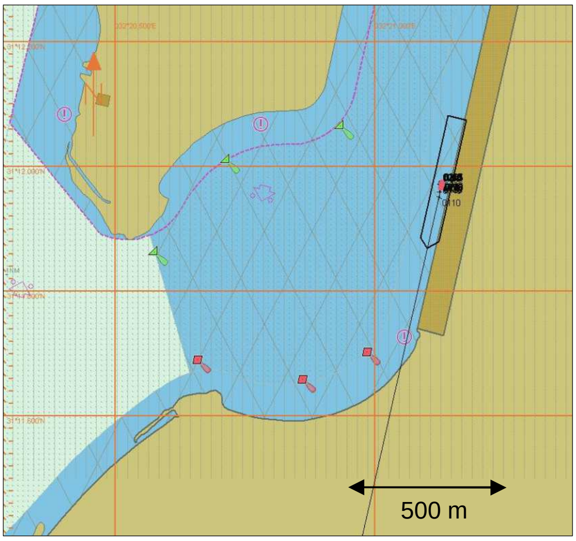


Figure 8: Excerpt from VMS recording at 0446 hours
Source: Maersk Line

3. Narrative

3.1 Introduction

The container ship EMMA MÆRSK was operating in scheduled service between Northern Europe and East Asia via the Suez Canal.

On 27 January 2013, EMMA MÆRSK departed from Tangier, Morocco, heading for the Far East via the Suez Canal. The ship was loaded with general cargo in about 14,000 containers and the draught was 15.0 m fore and 15.1 m aft.

In this report, all indications of time are given as the ship's local time. A chart with indication of sites of events is presented as figure 2 on page 7, and chronological excerpts from the ship's VMS (vessel management system) recordings of the ship's movements from the entrance of the canal until moored alongside quay are presented as figures 3, 4, 5, 6, 7 and 8 on page 8.

The narrative will be presented from two perspectives: One from the bridge and one from the engine room.

3.2 The sequence of events on the bridge

On 1 February 2013 at 1900 hours, the ship anchored at the deep water anchorage appr. 14 nautical miles north of Port Said waiting for a pilot and southbound passage through the Suez Canal (figure 2 on page 7). Before the anchor was weighed and the ship departed from the deep water anchorage, at 2000 hours, the steering gear, thrusters and emergency controls of the main engine were tested as per standard procedure and found in good order.

On the bridge were the master, the 3rd officer and an able seaman who was at the helm and steered by the master's orders. The chief engineer and a 3rd engineer were on duty in the engine control room.

As the ship was proceeding slowly towards the Suez Canal, both bow thrusters and both stern thrusters were running with no pitch. The bow thrusters were briefly used when the anchor was weighed. The stern thrusters were not used.

There was a north-westerly wind of 12 m/sec. pushing the ship towards the port side, making it necessary to give starboard helm to maintain a proper course to enter the Suez Canal fairway. EMMA MÆRSK was the third ship in the convoy to pass the Suez Canal. The second ship in the convoy, about 1½ nautical mile ahead of EMMA MÆRSK, was another container ship of appr. the same dimensions, tonnage and draught as EMMA MÆRSK.

When entering the fairway, it became apparent that the container ship ahead of EMMA MÆRSK did not correct for drift and was approaching the port side of the Suez Canal fairway. The master of EMMA MÆRSK who was familiar with the waters predicted that, if the vessel ahead went aground, the situation could result in a collision or grounding because EMMA MÆRSK was restricted by her draught and could therefore not manoeuvre out of a critical situation. He therefore called the chief officer to the bridge to assist in the navigation.

The master called the Suez Canal VTS (vessel traffic service) and urgently requested that the ship ahead of EMMA MÆRSK was told to increase the speed. Simultaneously, he decreased the speed of his own ship to obtain a slightly greater distance to the other ship even though this caused a deterioration of the steering capability. The latter, however, posed no immediate risk because EMMA MÆRSK was on a favourable course towards the canal.

The VTS called the ship ahead of EMMA MÆRSK and gave course and speed instructions. This, however, seemed to have no effect and the ship hit a buoy at the fairway.

EMMA MÆRSK and the ship ahead continued the passage without any further problems and after appr. 20 minutes, the chief officer left the bridge and went to his cabin as the possible problematic situation with the steering of the other ship seemed to be solved.

At 2134 hours, the pilot embarked EMMA MÆRSK (figure 2 on page 7).

At 2141 hours, shortly after the pilot's arrival on the bridge, a fire alarm sounded. It had been activated by a push button (manually operated call point) in the aft part of the shaft tunnel. Immediately after, three bilge alarms were activated in the shaft tunnel. The alarms were silenced by the 3rd officer and thereafter a large number of new alarms came up and were disruptive and distracting for the crew. In addition, for the next several hours, the situation on the bridge became even more difficult and complicated by constantly loud VHF communication between pilots, tugs and shore authorities in Arabic.

In the engine room, the chief engineer and the 3rd engineer hurried to the shaft tunnel to ascertain the reason for the alarms.

The chief officer heard the fire alarm when he was in his cabin, observed that it was activated by a push button and hurried to the ship control centre at the deck office. On his way he noticed that all fire doors had closed. At the deck office, the crew assembled according to the fire muster list and the chief officer saw that the fire alarm had been activated from the aft part of the shaft tunnel. The chief officer imagined that somebody was fighting a fire in the shaft tunnel and needed assistance. He therefore let another officer take census and hurried himself to the shaft tunnel to investigate the reason for the fire alarm.

In the shaft tunnel, the chief officer saw a severe ingress of seawater in the aft part. He noticed the 3rd engineer engaged at the ingress close to the forward stern thruster and other engineers were also present. He knew there was nothing for him to do at the site and he was aware that there were problems with the communication to the bridge. Therefore he placed himself at the bottom of the emergency exit shaft from where he knew the VHF connection to the bridge was better and acted as a liaison link between the engineers in the shaft tunnel and the master on the bridge and forwarded situation briefings to the master.

It was reported continuously from the engine room that a blackout could be expected. The engineers reported to the master that there was a large ingress of seawater into the shaft tunnel and they had to withdraw from the shaft tunnel because of the rising water level.

As a blackout was predicted, the master instructed the helmsman to keep a close eye on the magnetic compass and be prepared to use it. When the water level in the shaft tunnel reached the threshold at the watertight door in the bulkhead between the engine room and the shaft tunnel, the master ordered to close the watertight door, at 2150 hours (figure 2 on page 7).

After a brief evaluation of the situation between the master and the chief engineer, the master believed in a fair chance of reaching the Suez Canal Container Terminal at the port of Port Said by the ship's own propulsion. The chief engineer advised the master to not use high revolutions of the main engine.

The master realized it was of crucial importance that the ship did not ground on a slope or a bank from which it later would be impossible to unload the ship's containers.

The ship was steered an appropriate course, taking set and drift into consideration. Within a few minutes, it was reported from the engine room that seawater was now flowing into the main engine room in huge quantities, and the bilge pumps could not keep up and discharge as fast as the seawater flowed in.

The master realized that the situation was grave and he predicted that the ship would soon lose propulsion and manoeuvrability. He therefore speeded up the main engine to 60 RPM which corresponded approximately to “full ahead” when manoeuvring. The master attempted to reach the turning basin of the Suez Canal Container Terminal on the eastern side of the channel, prior to the anticipated blackout, and to bring the ship to a safe position. He saw this as the only opportunity to save the ship.

Astern of EMMA MÆRSK in the convoy was a very large LNG (liquid natural gas) carrier. This ship had come into the Suez Canal fairway when the technical problems occurred on board EMMA MÆRSK. But the master managed to warn the VTS in time and the rest of the convoy astern of the LNG tanker was stopped.

The 2nd officer was called to assist on the bridge. Once he was on the bridge, he was given a brief status report and the master instructed him to call the company and inform them about the situation. As the company was informed, the pilot informed that a chief pilot was about to embark the ship.

The 3rd officer was sent to pick up the chief pilot and escort him to the bridge, and the 4th officer and an AB were sent to prepare anchors and lines for tugs forward.

The chief officer returned to the deck office and instructed as many crew members as possible to go to the shaft tunnel, as he believed that the engine crew could use assistance. He then went to the bridge to assist the master and take over from the 2nd officer who was sent to the aft station to prepare lines for tugs.

Once the 3rd officer had returned to the bridge with the chief pilot, he was instructed to proceed to the forward station to join the 4th officer and the AB who had prepared the anchors for let go and lines for the tugs.

The master instructed the 3rd officer to prepare for emergency release of the windlass because a blackout might be expected to occur.

In addition to a variety of other circumstances that the master had to deal with, he was also occupied with the idea that four young and inexperienced cadets were on board as their first time at sea. Therefore, even though he knew very well that all life-saving equipment was in fact always ready and in a good condition, he instructed the chief officer to reassure that the lifeboats were ready for embarkation and launch.

It appeared that there was also ingress of seawater into cargo hold No 21. The master consulted the stability book regularly and realized that a list at that stage would be critical. It was of the utmost importance to get the ship as close as possible to the Suez Canal Container Terminal. Although the water depth was indicated in the chart as 16.5 metres, he knew it was actually 17.2 metres several places in the harbour area. He requested four tugs for assistance as he intended to get EMMA MÆRSK into the turning basin and thus make free passage for the LNG tanker in the canal.

Five tugs arrived. One tug was made fast forward close to the centre lead. A second tug was made fast on the starboard side aft. However, this line burst. Another line was then used and that burst as well.

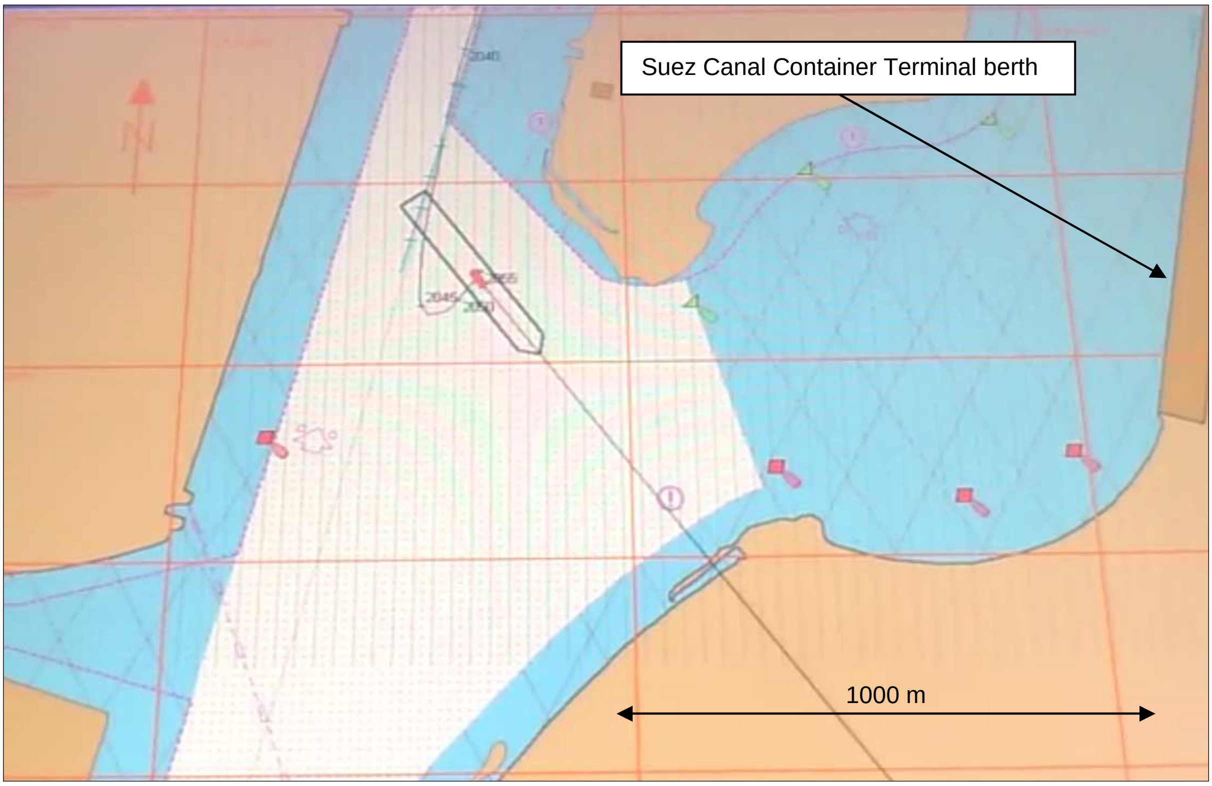


Figure 9: Excerpt from VMS recording at 2255 hours when the main engine stopped
Source: Maersk Line

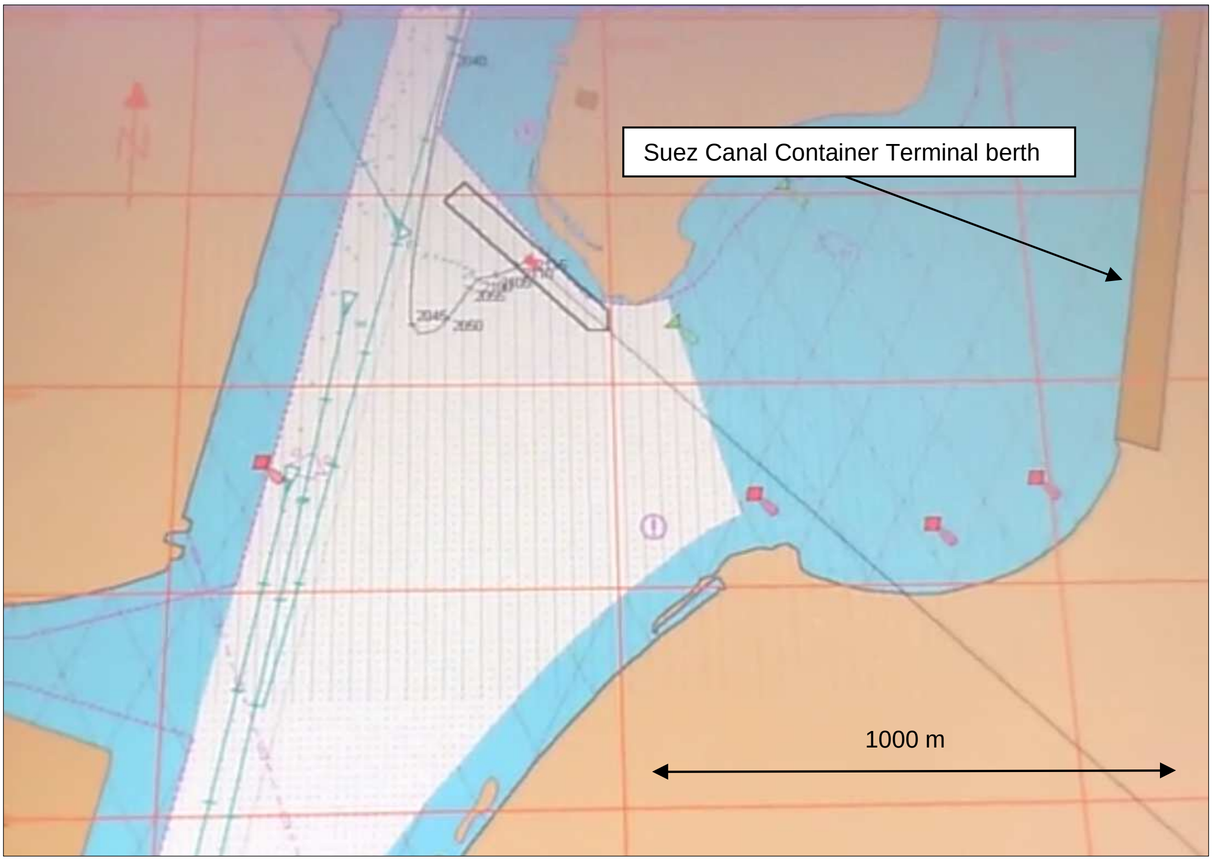


Figure 10: Excerpt from VMS recording at 2315 hours
Source: Maersk Line

Because of the difficulties in getting the aft tug fast, it was not possible to hold the stern of EMMA MÆRSK in position. So the ship was stopped prior to turning to port into the turning basin and then manoeuvred very slowly towards the turning basin and made a turn to port at the northern point of the entrance (figures 9 and 10 on page 12). The LNG tanker passed in the canal and when, at about 2255 hours, the master attempted to start the main engine, it could not be started due to a high level of water in the engine room although there was still electrical power supply in the ship.

Eventually, it was possible to make the tug fast aft.

The water depth at the entrance to the turning basin was appr. 20 metres. The continuous ingress of water and the increasing draught posed a risk of grounding at the port entrance. Therefore it was a priority to get the ship alongside at the Suez Canal Container Terminal as soon as possible. The forward tugs pulled the stern south-eastward into the turning basin where there was a depth of 16.5 metres (figure 10 on page 12). The ship's speed was appr. 1.9 knots.

The anchors were lowered to two metres above the water level using the windlass. When the ship's bow was about 15 metres from the easternmost buoy of the turning basin, the anchors were disengaged from the windlass, ready to let go.

The tugs connected to the aft were unable to stop the forward momentum so, at about 0000 hours, the port anchor was dropped with 2½ shackles in the water and soon after also the starboard anchor with 2½ shackles (figure 11 below). The ship's speed decreased and the anchors stopped the ship about 15 metres from the south-eastern bank of the turning basin. At that time, the master considered it of the utmost importance to get the stern to the quay and subsequently, if possible, to berth the ship at the quay.

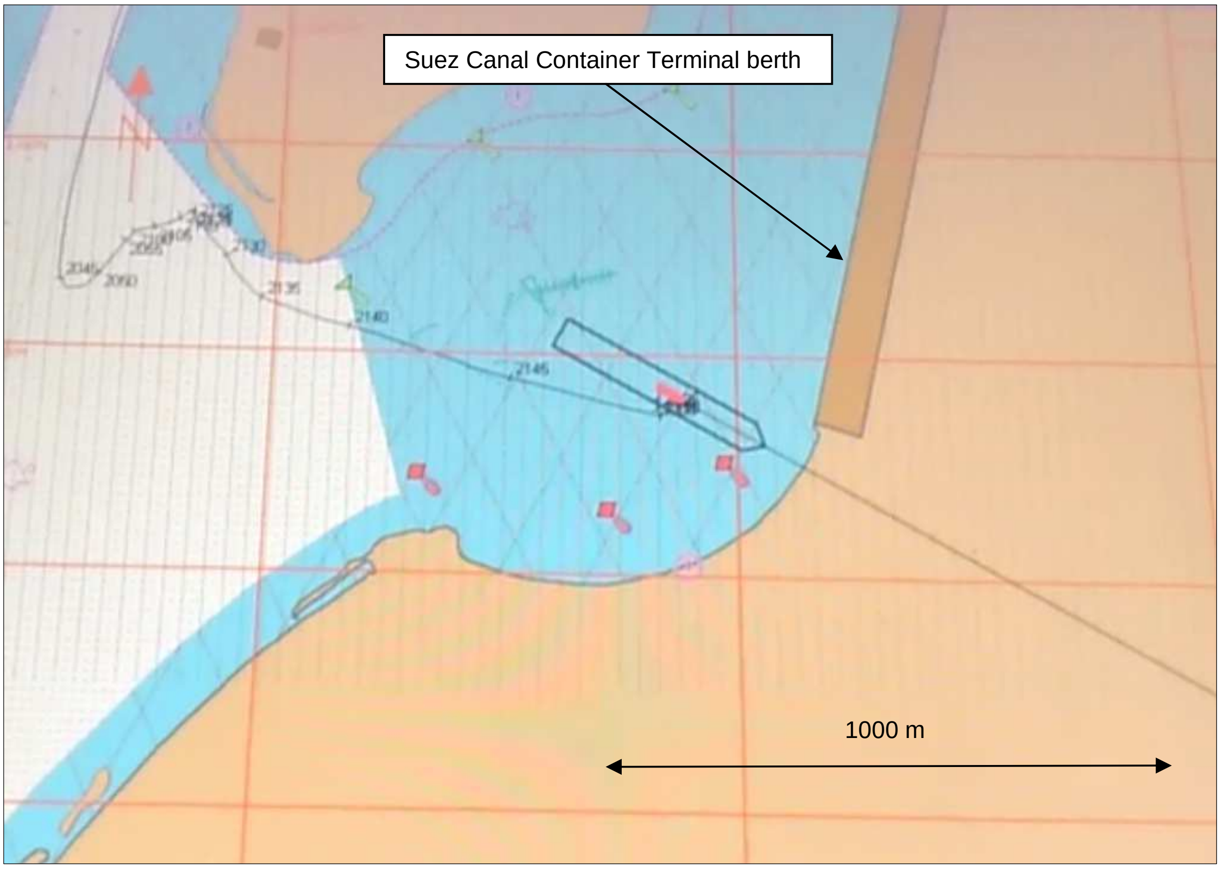


Figure 11: Excerpt from VMS recording at 0000 hours when the anchors were dropped
Source: Maersk Line

When the anchors were dropped, the master told the chief engineer to stop the auxiliary engines to prevent accidents caused by electrical short circuits as the water was approaching the level of the generators in the engine room. The auxiliary engines were then stopped and the engine compartments were abandoned.

Then, suddenly the wind of about 12 m/sec. shifted from northwest to southwest and pushed the stern into a north-easterly direction and the ship came to be almost parallel to the quay. It was not possible to properly establish towlines to the tugs. One line burst and the ship's port quarter slightly hit the quay and a bollard causing minor dents in the plating. The master considered it important to get the ship astern as soon as possible and as far as the gantry cranes could operate in the entire ship's length and at that stage the master had only the anchors to rely on.

As the electrical power supply was no longer available, the windlass and mooring winches could no longer be used. All hands available were needed on deck to manually operate the hydraulic pump for release of the windlass brake and to manually operate two mooring lines aft. These tasks demanded many persons' hard labour. The anchor chains were eased out to 13 shackles, two mooring lines burst and after midnight, at about 0200 hours on 2 February 2013, the ship was berthed with the port side towards the quay, and at 0446, it was moored. The ship's draught was then appr. 16 metres aft.

The ship was thoroughly inspected for damages other than the leakage and flooding of the shaft tunnel and the engine room. There were two minor indentations at the port quarter caused by contact with the quay and bollards and some ingress of seawater was observed in cargo hold No 21.

Nobody was injured.

Although berthed alongside quay, the ship was not firmly moored because the mooring winches could not be operated, and the heavy mooring lines could not be tightened sufficiently by hand. Therefore two tugs were kept standby to continuously hold the ship's position alongside the berth.

Soon when the ship was moored, inoperative because of a flooded engine room and shaft tunnel, and a comprehensive repair and recovery work was foreseeable for a long period ahead and with that exceedingly intense traffic in the ship's interior, a crew member suggested painting the stairs and exposed walking passages with non-slip paint to prevent any fall and slip accidents.

3.3 Sequence of events in the engine room

On the evening of 1 February 2013, the 3rd engineer and the chief engineer were on duty in the engine control room.

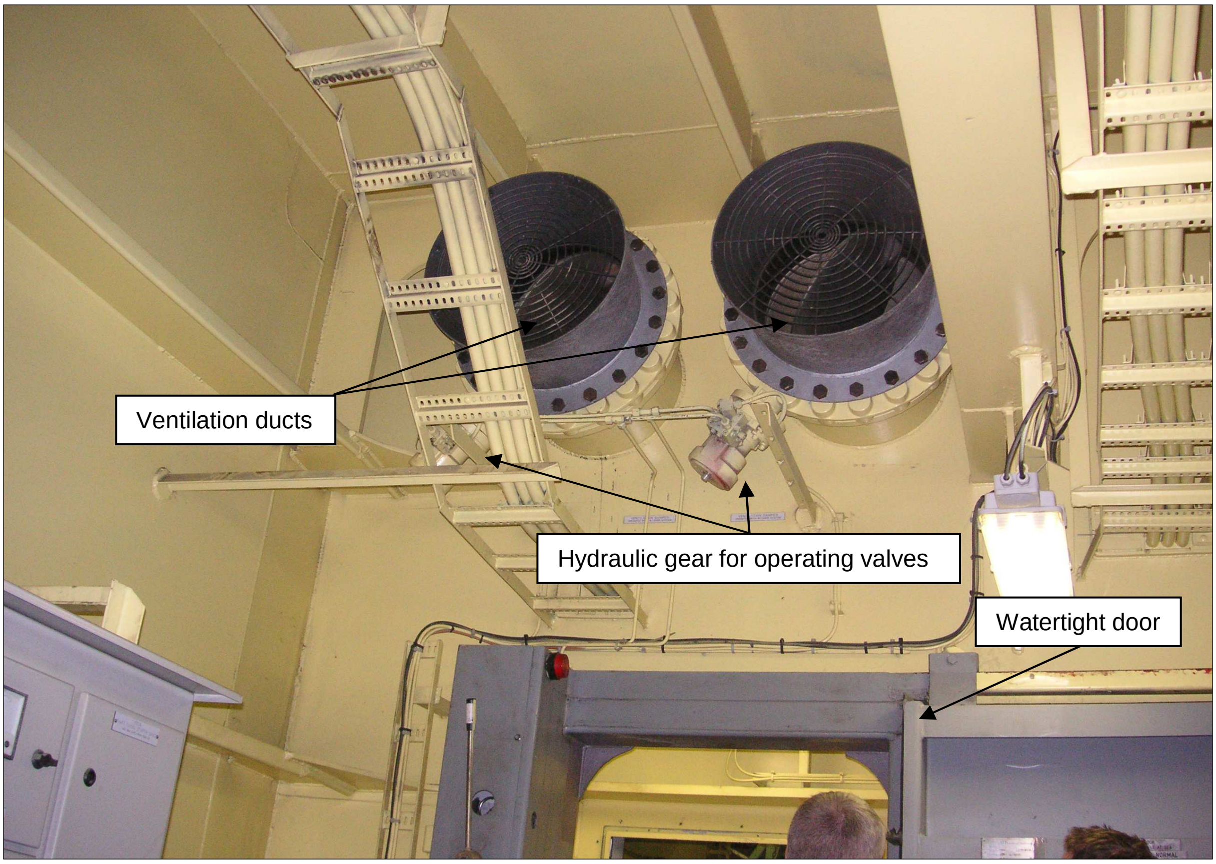
Suddenly, at 2141 hours, a fire alarm sounded indicating fire in the shaft tunnel. The 3rd engineer acknowledged the alarm and both engineers hurried towards the shaft tunnel to investigate the reason for the fire alarm, and before the 3rd engineer had left the engine control, an alarm also sounded for bilge water in the aft part of the shaft tunnel. While on their way to the shaft tunnel, more alarms occurred and the 3rd engineer returned to the engine control room to acknowledge the alarms that appeared to be bilge water alarms. Having acknowledged the alarms in the engine control room, the 3rd engineer went to the shaft tunnel. He met the chief engineer who told him there was a large ingress of seawater into the shaft tunnel.

The 2nd engineer who was in his cabin was alerted by the fire alarm. He dressed and hurried to the engine control room and found nobody there. He checked the alarm panel and found that the fire alarm came from a call point aft in the shaft tunnel. He called the bridge and informed that he was in the engine room as supposed to according to the fire muster list and that apparently there was a fire in the shaft tunnel which he was going to investigate. In the shaft tunnel, he immediately saw the large ingress of seawater at the forward stern thruster.

The 2nd engineer tried to get close to the leakage in an attempt to ascertain its origin and came as close as 1.5 – 2 metres from where he could see a dark area at the flange neck around the vertical shaft of the stern thruster. He realized that there was nothing to be done to stop the ingress and hurried back towards the engine control room and joined the chief engineer and the duty 3rd engineer at the system control computer on the 8th deck near the elevator.

They immediately opened the relevant valves in the bilge system and the chief engineer started both ballast ejectors to discharge the seawater from the shaft tunnel directly over board. To do so the 2nd engineer had to force his way past the water ingress to reach the aft bilge valves in the shaft tunnel. The discharging from the shaft tunnel functioned well but could not keep up with the water ingress and the water level steadily rose. The chief engineer reported to the master that it appeared to be a very serious situation and that the incoming water was discharged directly over board.

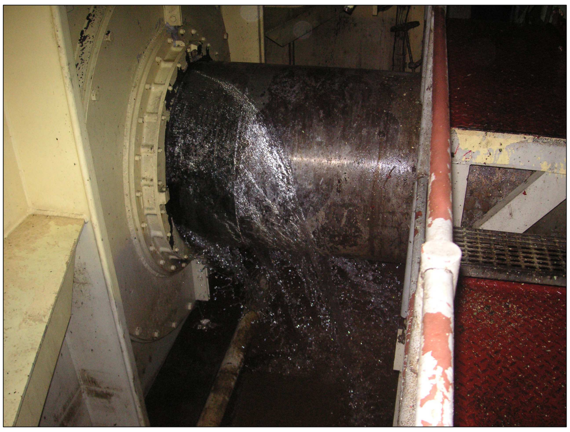
Realizing that it was impossible to stop the water ingress, the engineers withdrew from the shaft tunnel and prepared the closing of the watertight door in the bulkhead between the main engine room and the shaft tunnel. The door was closed manually half way on site so that it could soon be closed completely as soon as the water reached the threshold.



Figures 12: Hydraulically operated valves in ventilation ducts passing through the watertight bulkhead above the watertight door in a sister ship, viewed from the shaft tunnel
Source: DMAIB

The watertight door was closed appr. 10 minutes after the first alarm was heard and the chief engineer again called and informed the master about the situation. The watertight door was closed locally and functioned correctly. Then the 2nd engineer hurried to the ship control centre at the deck office and closed two hydraulically operated valves in ventilation ducts passing through the watertight bulkhead situated just above the watertight door. These valves were situated in the shaft tunnel, on the aft side of the bulkhead (figure 12 on page 15) and could not be operated locally like the watertight door. He waited in the ship control centre to see the control lamps indicate that the valves were actually closed.

To ascertain that these valves were effectively closed, the engineers drilled large holes in the bottom of the ducts. This revealed that no water came through and the valves were effectively closed. For a short while, the engineers believed that the water ingress was confined to the shaft tunnel, but after a few minutes, water flowed through the propeller shaft sealing in the watertight bulkhead (figures 13 and 14 below) and soon after some seeping water was also observed at four of the cable penetrations in the bulkhead, above and below the propeller shaft. This was observed by engineers standing close to the watertight bulkhead and it caused some concern.



Figures 13 and 14: Ingress of water from the shaft tunnel to the engine room at the propeller shaft sealing when, at the repair yard, water in the engine room is being discharged and the propeller shaft tunnel is still flooded.
Source: DMAIB

However, this ingress was still not greater than the bilge pumps in the engine room could keep up. The engineers gradually opened the bilge system valves on the aft part of the engine room.

The 2nd engineer checked that all safety critical machinery, e.g. generators and auxiliary systems, was in service. This was carried out manually on site because the automatic monitoring and alarm system was continuously indicating various alarms which meant that an audible alarm sounded constantly which impeded the overview of the machinery condition and the situation in the engine room in general. It was a priority for the engine crew to avoid a blackout and loss of propulsion.

The chief engineer started discharging by the use of all bilge pumps and ballast ejectors and instructed the engineers to be prepared at relevant sites in the engine room to open the suction valves in the bilge system. The only means for discharging not yet taken into service was the direct suction from the main engine room by the largest seawater pump, the so-called “emergency bilge suction”.

The master had increased the speed of the main engine in an attempt to reach as close as possible to the Suez Canal Container Terminal before loss of propulsion and manoeuvrability. He asked the chief engineer for the bow thrusters' operation. The chief engineer attempted to connect the thrusters to the electrical power distribution system, however in vain, because the seawater had caused disturbances in the electrical power distribution system.

At about 2205 hours, a 3rd engineer, who was standing at the aft part of the main engine watching the situation develop, became aware that water unexpectedly began flowing from a 440 volt AC outlet at the port side of the engine room some five or six metres from the watertight bulkhead (figure 15 below).

Figure 15: 440 volt AC outlet from which seawater began flowing out
Source: DMAIB

As the 3rd engineer investigated this unexpected scenario, he heard a sudden blast and saw one of four cable penetration sealings in the watertight bulkhead give way to the water pressure followed by a massive ingress of seawater. A few moments later, the other three cable penetration sealings also failed which resulted in an even larger ingress of water into the engine room.

With a draught of appr. 15.1 metres, the entire space of the shaft tunnel and the emergency exit, leading vertically from the aft part of the shaft tunnel to the cargo hold, had been filled by seawater. The water pressure at the propeller shaft sealing and cable penetrations of the watertight bulkhead was therefore equal to a water column of appr. 8.9 metres.

The chief engineer notified the master of the increasing water ingress and that it was unlikely that they could contain and recover from the situation. It became difficult to operate the main engine because the automatic safety devices were disturbed by the large ingress of water.

The chief engineer attempted to override the automatic functions to keep the main engine running in an emergency mode. However, this was not possible and at 2255 hours the main engine could no longer be started. The diesel generators that were placed at a higher level were still kept in service.

To avoid anyone being caught by the flooding in the engine room, the crew members whose presence was not necessarily needed in the engine room were told to leave and to go to the muster station in the ship control centre at the deck office on the A deck.

When the water level in the engine room rose above the level of the lubrication oil pumps, cooling water pumps, etc., the chief engineer switched off all electrical consumers for safety reasons. Excepted were those ballast pumps, bilge pumps and seawater pumps that were necessary for discharging water from the engine room.

3.4 The ingress of water

At 2141 hours, a fire alarm was activated by ingress of seawater into the aft part of the propeller shaft tunnel. And at 2205 hours, the cable penetrations in the bulkhead between the shaft tunnel and the engine room burst. Thus the shaft tunnel (figure 16 below) was flooded within 20-25 minutes.

Figure 16: Part of the main propeller shaft tunnel of a sister ship, viewed from fore towards aft
Source: DMAIB

Within the following few hours, the main engine room was flooded up to the level of the exhaust valves of the main engine equivalent to the ship's draught (figures 24 and 25 on page 23). The total ingress of seawater into the shaft tunnel and the main engine room is estimated at 14,000 m^3 (figures 17, 18, 19, 20, and 21 on pages 19, 20, 21 and 22).

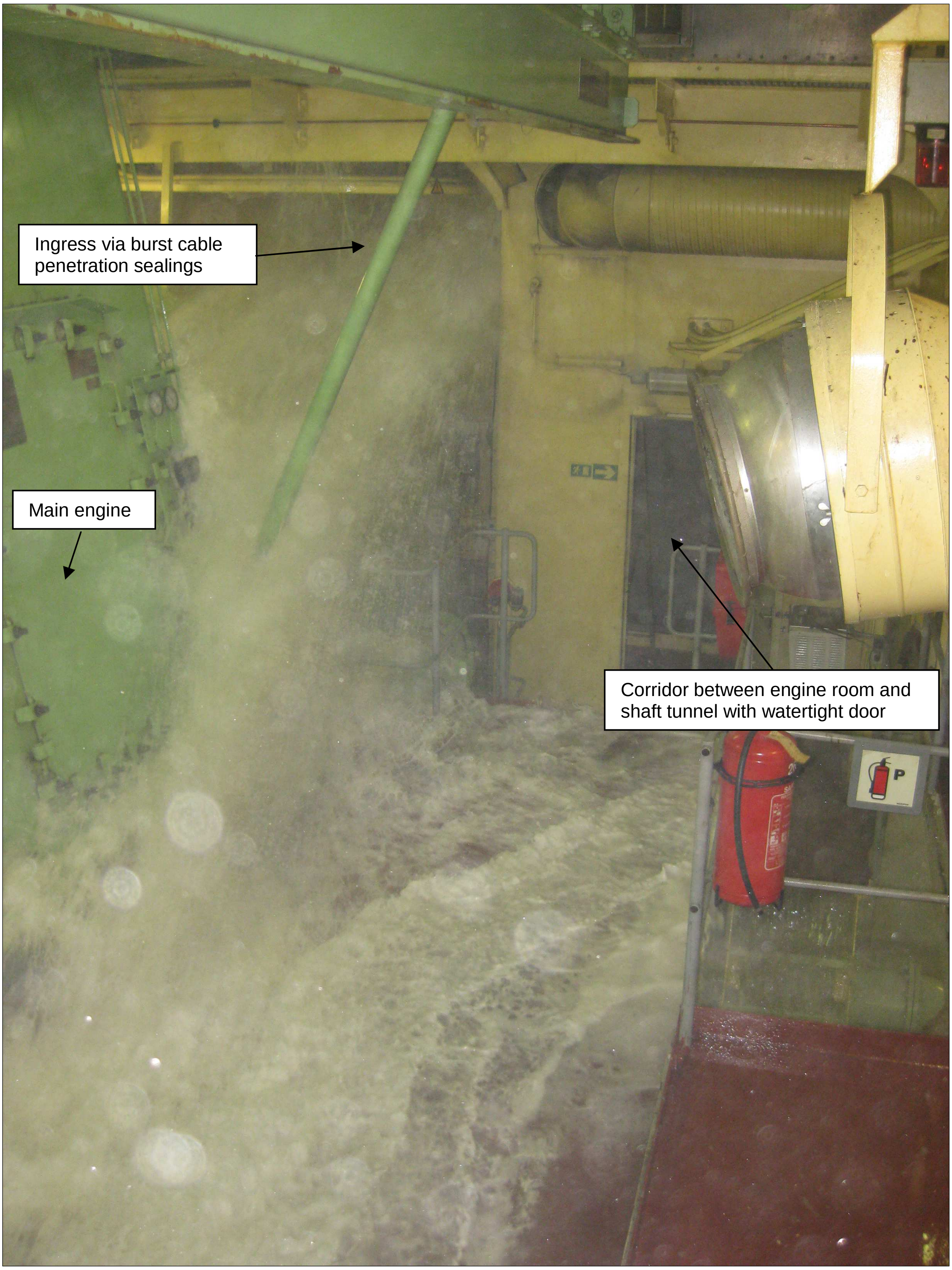


Figure 17: Seawater ingress from propeller shaft tunnel into the main engine room via burst cable penetration sealings in the watertight bulkhead, viewed from the port side of the engine room
Source: Maersk Line

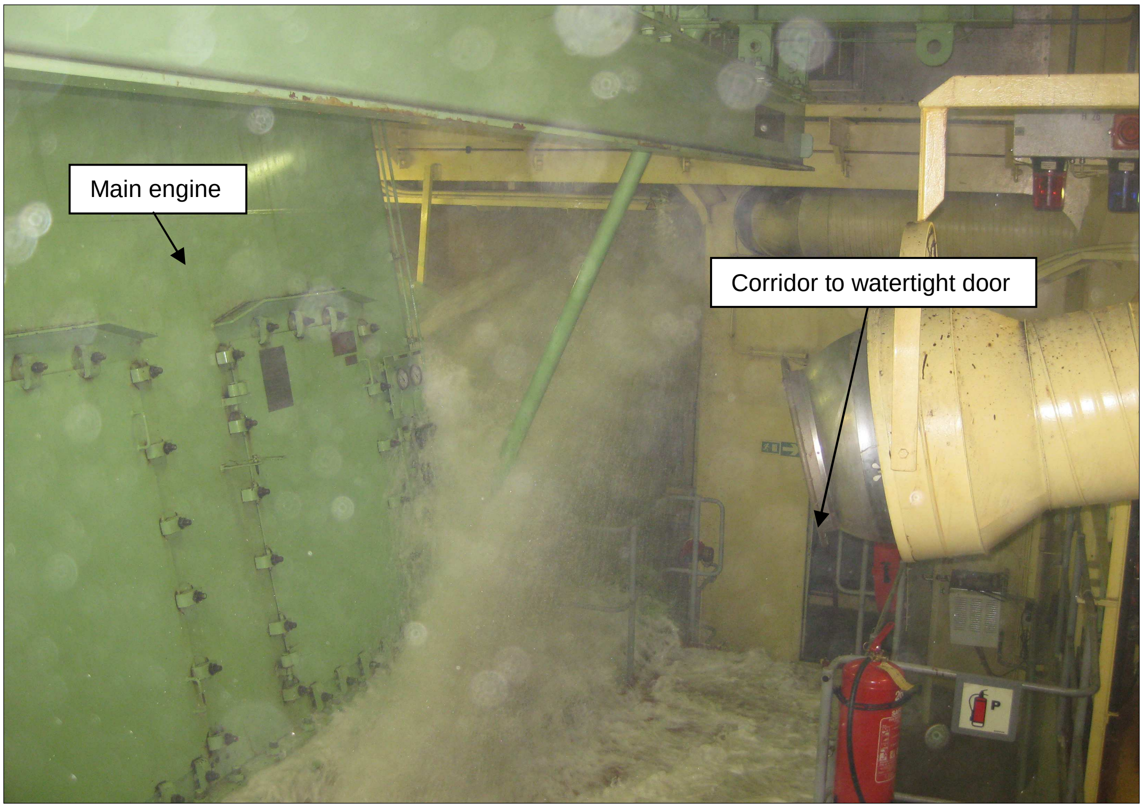


Figure 18: Seawater ingress from propeller shaft tunnel into the main engine room via burst cable penetration sealings in the watertight bulkhead, viewed from the port side of the engine room
Source: Maersk Line

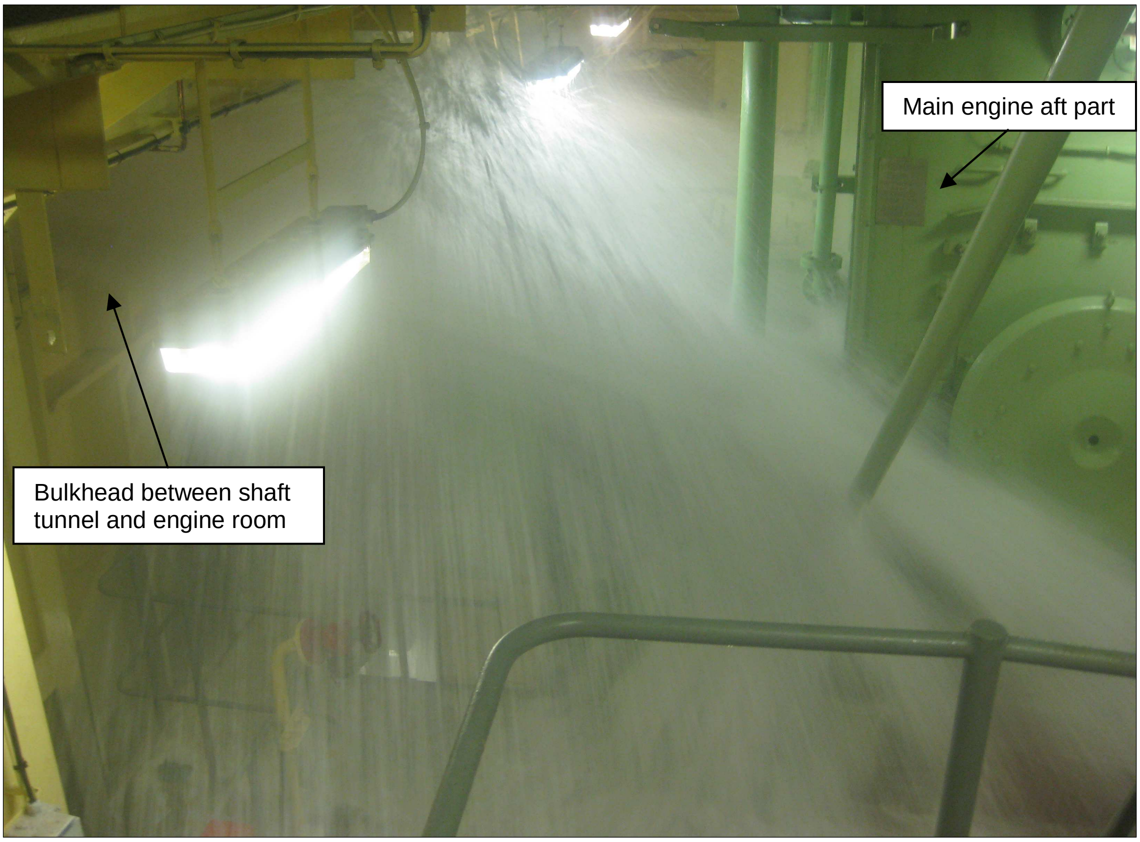


Figure 19: Seawater ingress from propeller shaft tunnel into the main engine room via burst cable penetration sealings in the watertight bulkhead, viewed from the starboard side of the engine room
Source: Maersk Line

Figure 20: Engine room getting flooded, viewed forward from the aft of the engine room port side
Source: Maersk Line

Figure 21: Engine room getting flooded
Source: Maersk Line

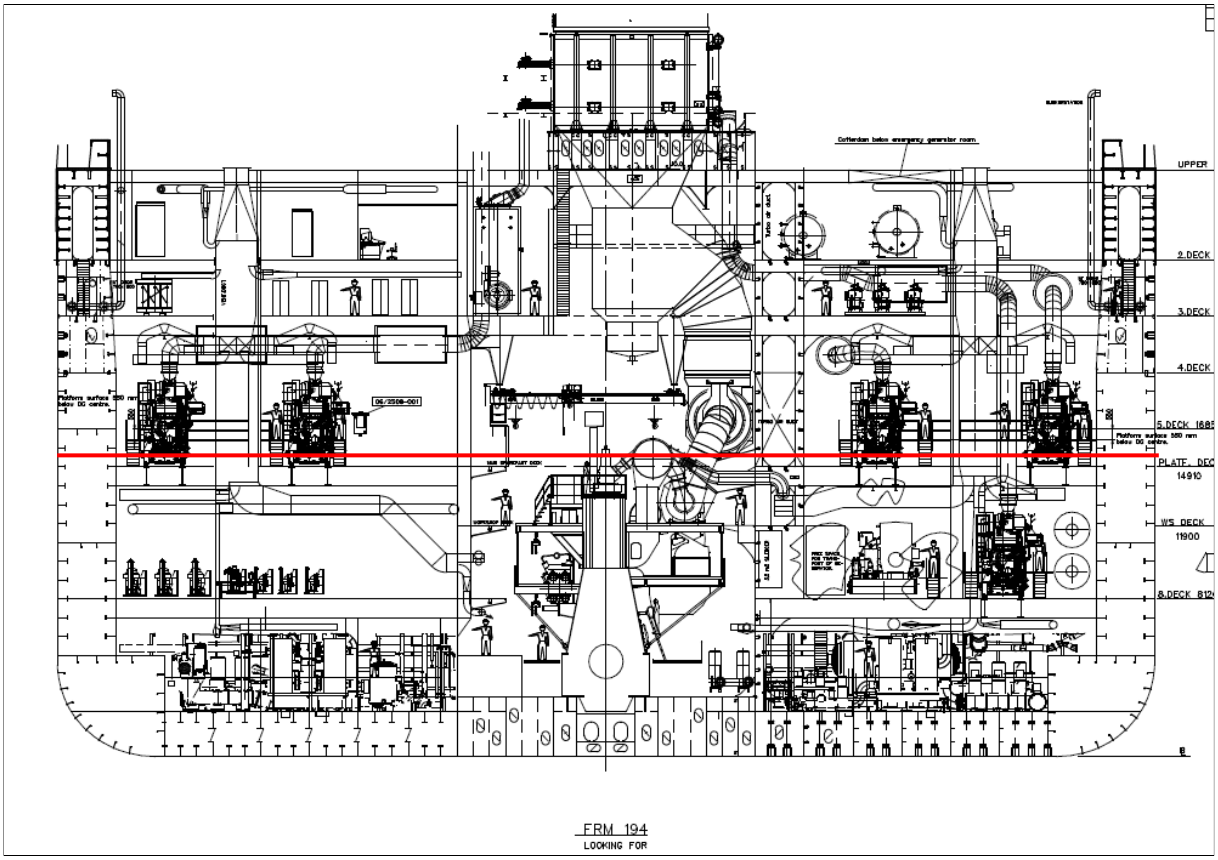


Figure 22: Transverse section of the engine room with a red line indicating the maximum water level
Source: Maersk Line

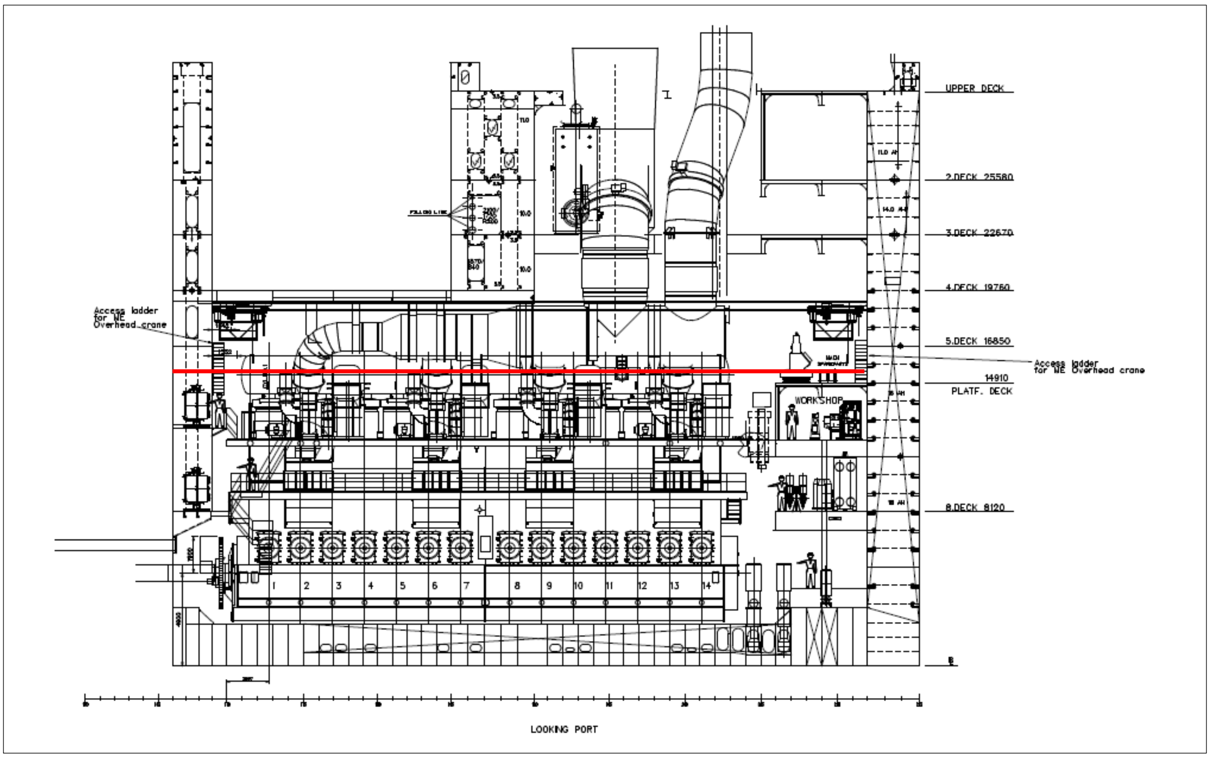


Figure 23: Longitudinal section of the engine room with a red line indicating the maximum water level
Source: Maersk Line

During the attempt to get the ship safely into the Suez Canal Container Terminal, appr. 0.35 metres of water was sounded in cargo hold No. 21. It was found that this ingress had occurred through a cable penetration in the transverse bulkhead at frame 53 between the cargo hold and the emergency exit from the aft part of the shaft tunnel (figure 24 below). The collapse of this cable penetration, which at a later investigation was found to have been improperly installed or re-installed and consequently presented a risk of flooding the cargo hold, was soon countered by the crew by putting a wooden bar jammed with wedges (figure 25 on page 25).

The cable penetration in question was situated in the emergency exit shaft at a height so that the damage waterline corresponded to a hydrostatic pressure of appr. 0.5 bar.

An on-site examination of this collapsed cable penetration installation was not possible due to the salvage efforts. A photo inspection of the cable penetration in question was carried out by the manufacturer of the cable penetration.

Figure 24: Cable penetration in bulkhead between emergency exit and cargo hold during collapse
Source: Maersk Line

Figure 25: Temporary repair of cable penetration in bulkhead between emergency exit and cargo hold
Source: Maersk Line

3.5 Bilge system for engine room and shaft tunnel

3.5.1 Pumps

In addition to the relatively small bilge pumps designated for 15 ppm and 100 ppm bilge water separators with a capacity of 5 m^3/h and 25 m^3/h, respectively, the ship was equipped with:

- one main bilge pump of 25 m^3/h capacity
- two ballast stripping ejectors each of 408 m^3/h
- one seawater pump (emergency bilge suction) rated to 3200 m^3/h at a pressure head of 2.4 bar designated for central cooler purpose

3.5.2 Piping

The engine room is equipped with a bilge main of 100 mm diameter with suction from bilge wells in the engine room and the shaft tunnel.

The ballast stripping ejectors are connected to a piping of 400 mm but, when in service for bilge purposes, the suction line is reduced to 100 mm diameter at the bilge main.

The valves in the bilge system for the engine room and the shaft tunnel were to be operated manually on site at each bilge well. When the shaft tunnel was completely flooded and the watertight door was closed, it was not possible to enter the shaft tunnel and close the bilge suction valves. Nor could the bilge suction line in the shaft tunnel be isolated, which caused the entire bilge line to be pressurized.

3.5.3 Emergency bilge suction

The emergency bilge suction pipe has a 600 mm internal diameter. It was situated just below the pump 50 mm above the tank top and had no strainer (figure 26 below). The area made up by this elevation (50 mm) multiplied by the pipe circumference is only one third of the internal area of the inlet pipe. Therefore the flow to the pump was reduced to an unknown proportion of what would be the case with an inlet area under the suction pipe equally large as the pipe itself.

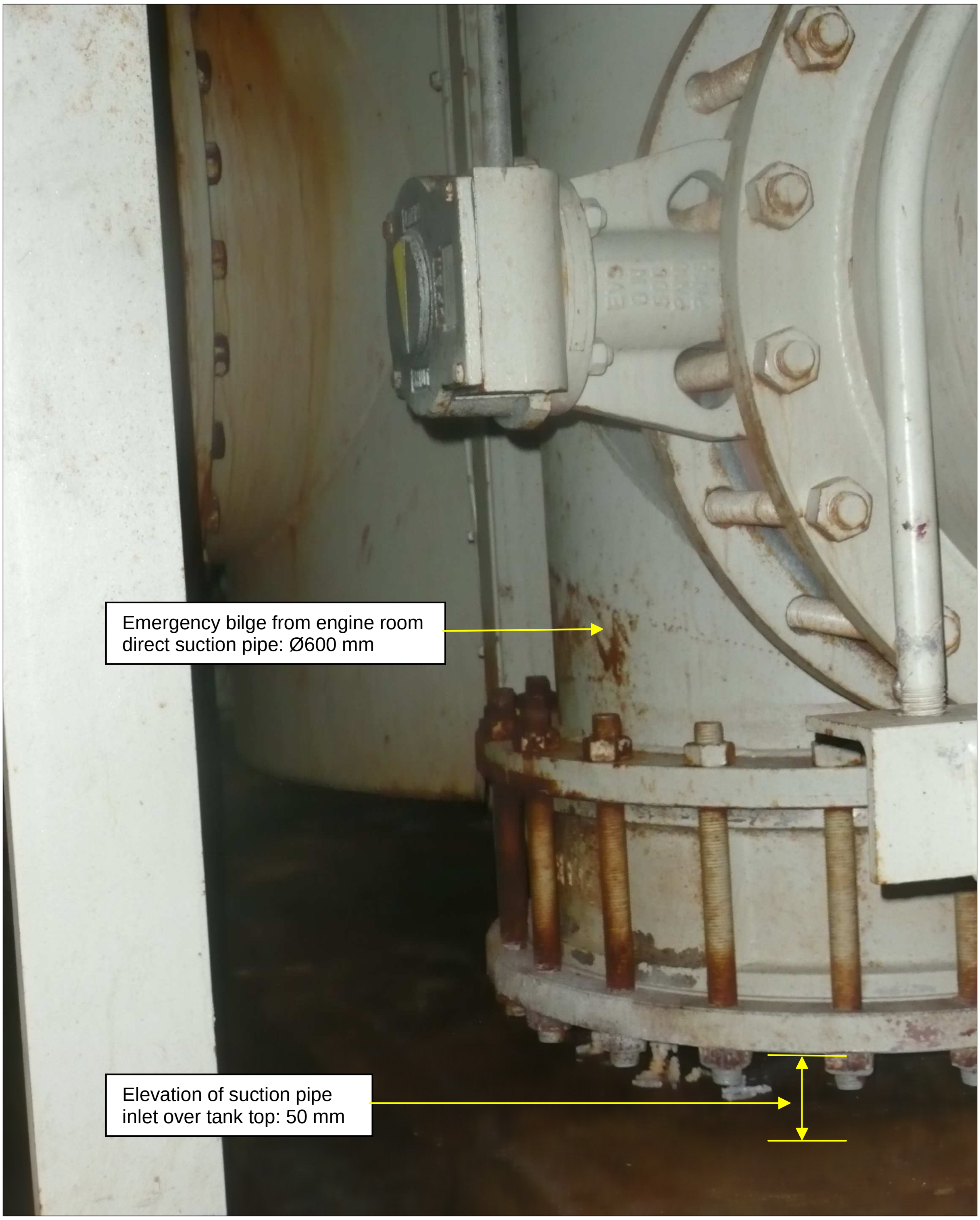


Figure 26: Emergency direct suction from engine room by largest seawater pump of a sister ship
Source: DMAIB

Furthermore, the pump was running in parallel operation with the other seawater pump that was serving as a cooling water pump and the discharge from both pumps had to pass via the central cooler giving a pressure head of 3.0 bar. The backpressure from the coolers contributed to a diminished capacity of the pump.

The emergency bilge suction valve provides direct suction from the engine room tank top. The opening of the suction valve was supposed to be carried out manually by a large handwheel just above the floor plate (figure 28 on page 28). The suction valve was situated just above the tank top and its spindle was connected to the handwheel by an extension rod (figure 29 on page 28) fitted to the valve spindle by a cardanic connection, the bushing of which was locked to the rod with steel pins (figure 27 below).

When operating the handwheel, a steel pin broke and the handwheel could not be used. The engineer then crawled under the floor plates and used a wrench to open the valve while standing on the tank top in water to the knees.

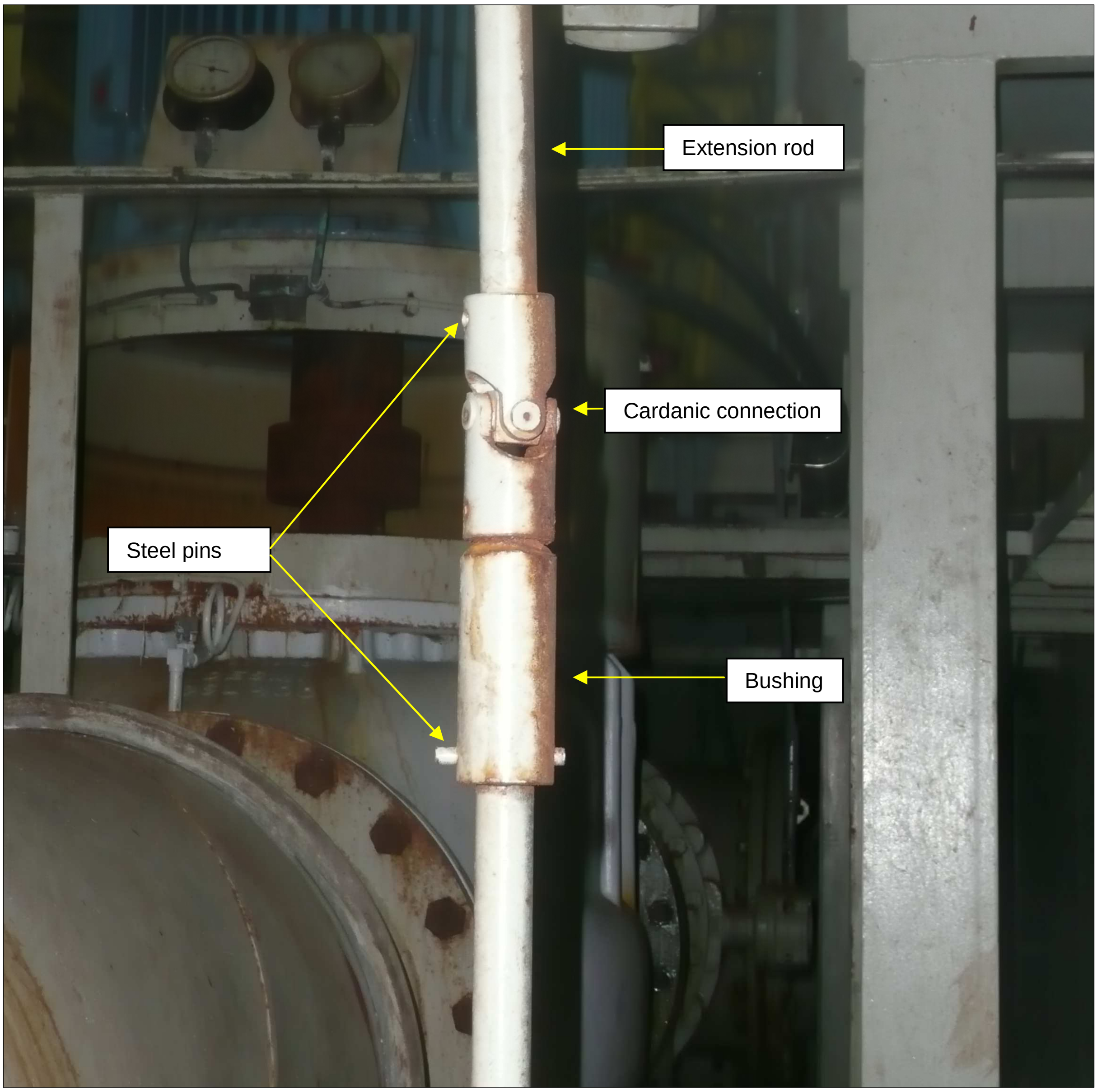


Figure 27: Extension rod with a cardanic connection fitted with a bushing and steel pins, in a sister ship and of the same type and principles as in EMMA MÆRSK
Source: DMAIB

Figure 28: Handwheel for emergency direct suction from the engine room by the largest seawater pump of a sister ship
Source: DMAIB

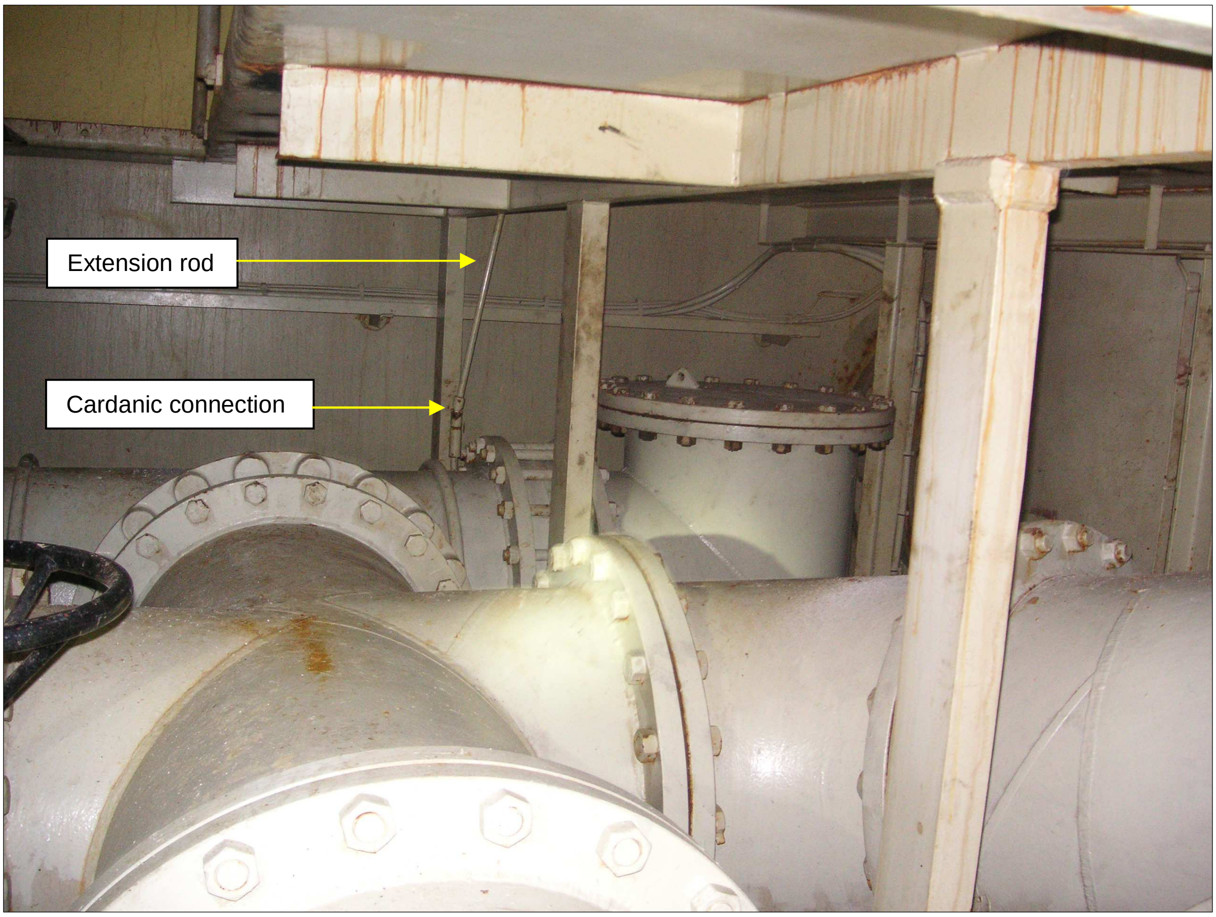


Figure 29: Piping arrangement for cooling water pumps on the tank top in the engine room of a sister ship with extension rod and a cardanic connection in the background
Source: DMAIB

3.6 Watertight bulkhead between engine room and shaft tunnel

The bulkhead between the engine room and the shaft tunnel, situated at frame no. 166, was designed, constructed, approved and relied on as a watertight bulkhead (figures 30 and 31 on page 30).

This bulkhead had not been constructed to meet the ship's damage stability conditions, but rather to limit the needed capacity of the CO_2 fire extinguishing plant. It was not compulsory according to SOLAS regulations.

Even though not prescribed and necessitated by the ship's damage stability conditions, the bulkhead's watertight integrity was a major factor for the ship's damage stability. And in case of a leakage into the compartments aft of the engine room, the intactness of this watertight bulkhead was of the utmost importance to the ship's ability to operate.

The ship's engine compartments were protected by a fixed fire-extinguishing plant for total flooding of CO_2 and in that respect it was essential to be able to separate the engine room from the propeller shaft tunnel in order not to have to flood both of these huge spaces with CO_2 in case of a fire in the engine room. The construction of this watertight bulkhead was motivated by limitation wishes.

In the port side of the watertight bulkhead between the engine room and the shaft tunnel, there was a watertight sliding door. The watertight door could be operated locally from both sides, in the engine control room and the ship control centre.

Above the watertight door, there were two air ducts each of 600 mm diameter that went through the bulkhead for ventilation of the shaft tunnel. For each air duct there was a hydraulically operated valve fitted at the aft side of the bulkhead. The valves were remotely operated from the engine control room and the ship control centre at the deck office. They could not be operated locally. The position of the air ducts in the watertight bulkhead is shown on figure 12 on page 15.

There were six cable penetrations in the watertight bulkhead: Four for electric high voltage power supply for the shaft motors, and two for other purposes, one of which above and one of which below the watertight door. These cable penetrations are dealt with separately in the next section.

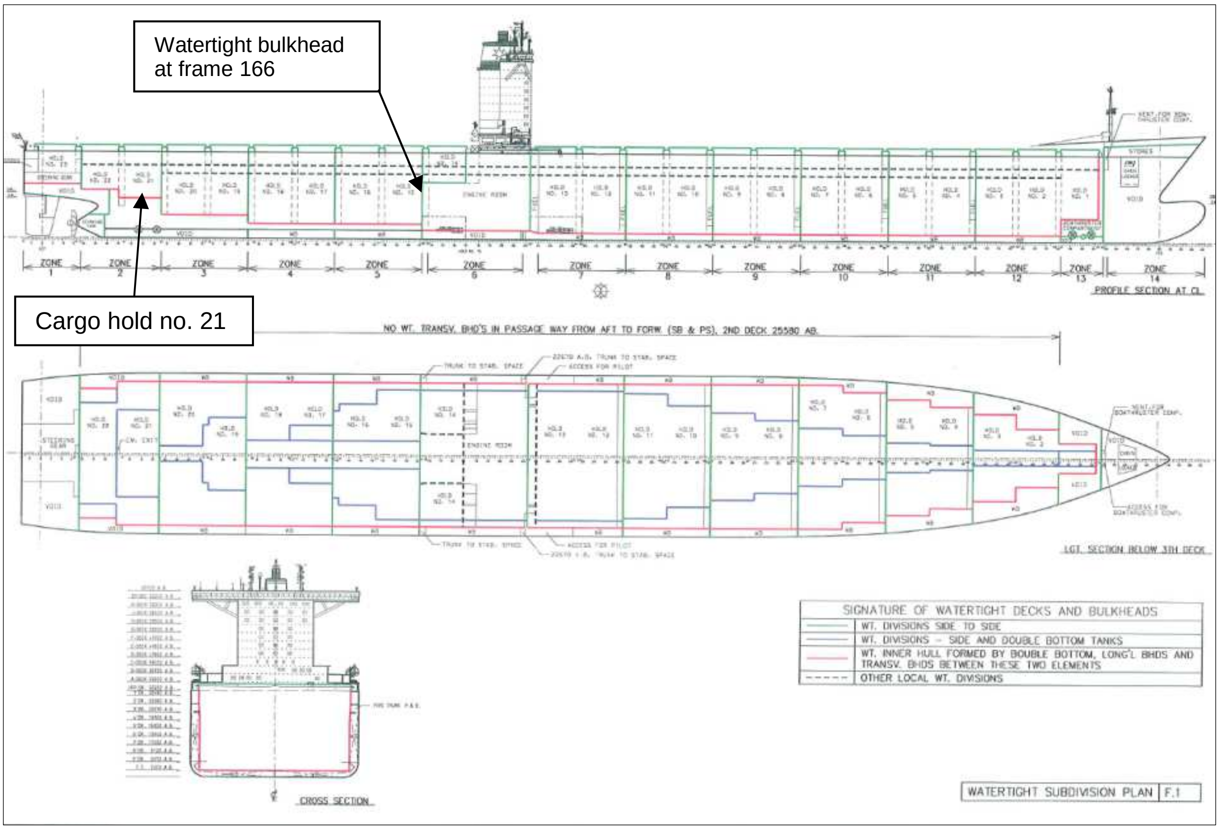


Figure 30: The ship's watertight subdivision and watertight bulkhead at frame No. 166
Source: The ship's damage stability booklet

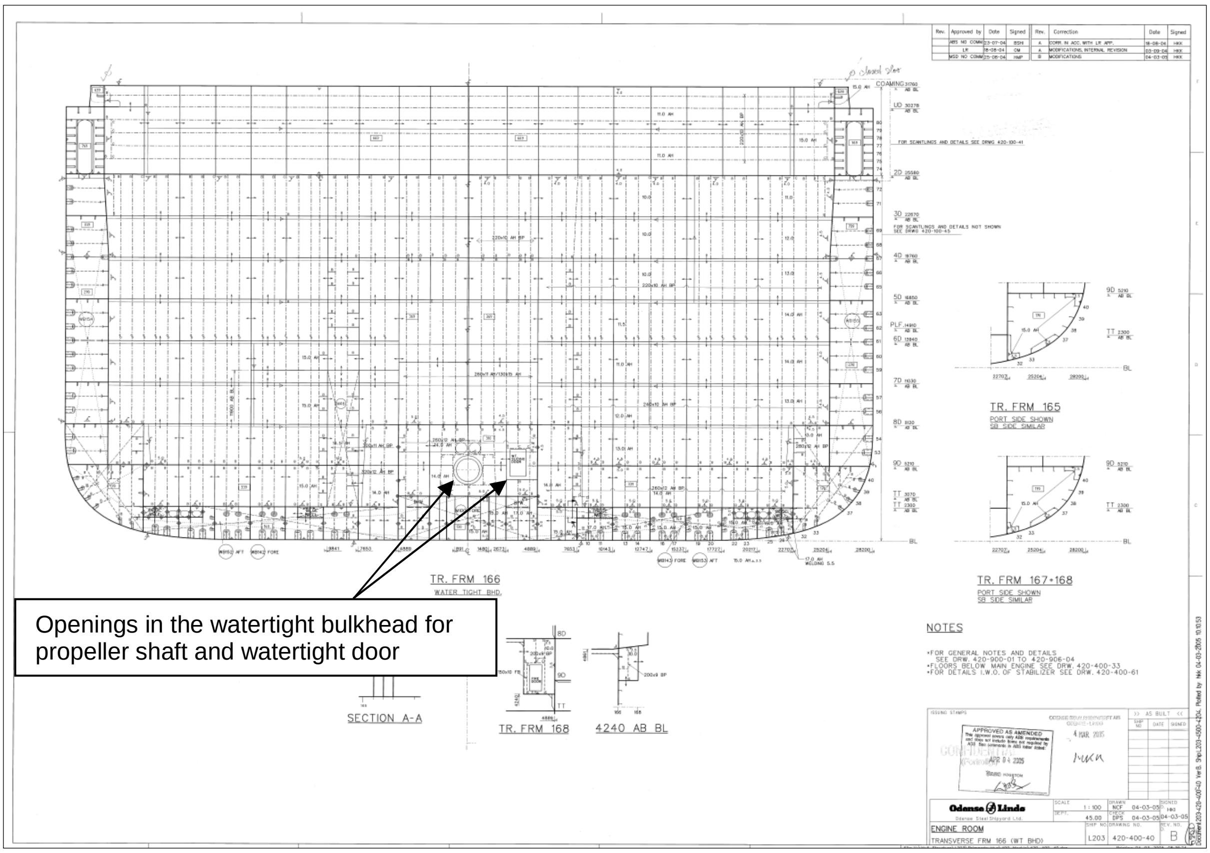


Figure 31: Watertight bulkhead at frame No. 166 viewed from fore
Source: ABS

3.7 Cable penetrations in the watertight bulkhead

Cable penetrations in the ship's bulkheads, be it watertight bulkheads or non-watertight bulkheads, were of a system named "GK Packing System", which is a modular cable and pipe penetration system (figure 32 below).

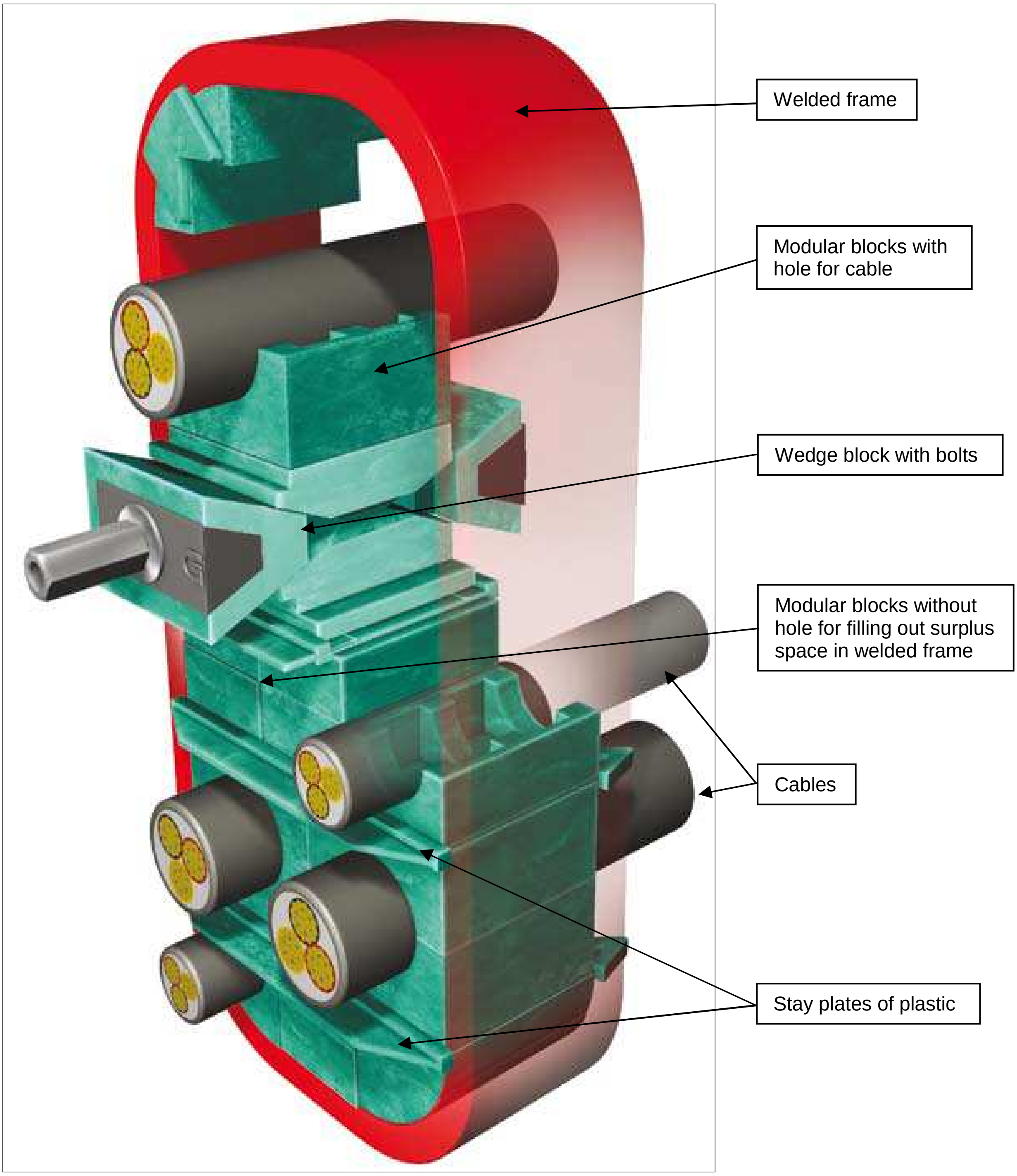


Figure 32: Sectional drawing with details and components from cable penetration system named "GK Packing System"
Source: http://www.gk-system.com/gk.htm

This cable penetration system consists of a welded frame filled out by modular blocks; some of which have a hole for the cables and some of which are of a solid type. There is a wedge sealing block to expand between the other modular blocks making the construction tight and firm. Stay plates are fitted between the layers of modular blocks to ensure that the modular blocks keep their right position in the welded frame (figure 32 on page 31 and figure 33 below).

Figure 33: Principle of cable penetration system named "GK Packing System"
Source: http://www.gk-system.com/gk.htm

The modular blocks consist of a thermoplastic elastomer which is flameproof, self-extinguishing, halogen-free and UV-resistant.

The stay plates are made of plastic material (elastomer), galvanized steel or stainless steel (figures 34 and 36 on page 33). It should be noted that the plastic stay plates mounted in EMMA MÆRSK were not marked with any maximum pressure.

The cable penetration system named "GK Packing System" with stay plates of plastic is designed to withstand fire and gas.

According to the manufacturer's product information, cable penetrations with stay plates of plastic material are suitable for a maximum pressure of 1.0 bar. However, the system was not approved to withstand a static water or gas pressure with plastic stay plates.

According to the manufacturer's product recommendations, cable penetrations with metal stay plates were tested to a water pressure of 5.5 bar and a gas pressure of 0.3 bar, while plastic stay plates were limited to 1 bar and 0.3 bar, respectively.

Stay plates of galvanized steel cannot be used in cable penetrations for high voltage AC installations because the high voltage current will induce overheating in the stay plates.

Compared to rigid metal stay plates, the stay plates of plastic material offer significant advantages regarding installation and weight.

The "GK Packing System" had been used by the construction yard as a standard system for cable penetrations since 1994. During this period, the electrical installations had been made by a subcontractor. Neither the shipyard nor the subcontractor company exists anymore.

The "GK Packing System" was type approved as a cable penetration sealing system for installation in Class "A"[1] bulkheads and decks by the ship's classification society. The approval is conditional upon, among other things:

[1] Class A bulkhead as per SOLAS, as amended, Chapter II-2, Regulation 3.2.

- The selection of packing system components for specific application is to be in accordance with the manufacturer's recommendations.

- The water-tightness and gas-tightness of the packing system with metal stay plates have been tested by the manufacturer in class witnessed tests to 5.5 bar and 0.3 bar, respectively.

Cable penetrations with metal stay plates had been approved by class in fire rated class "A" bulkheads and decks and in watertight bulkheads and decks in accordance with the test results 5.5 bar water pressure and 0.3 bar gas pressure.

Cable penetrations with plastic stay plates had been approved by class in fire rated class "A" bulkheads and decks in accordance with test results, but had not been approved in watertight bulkheads and decks.

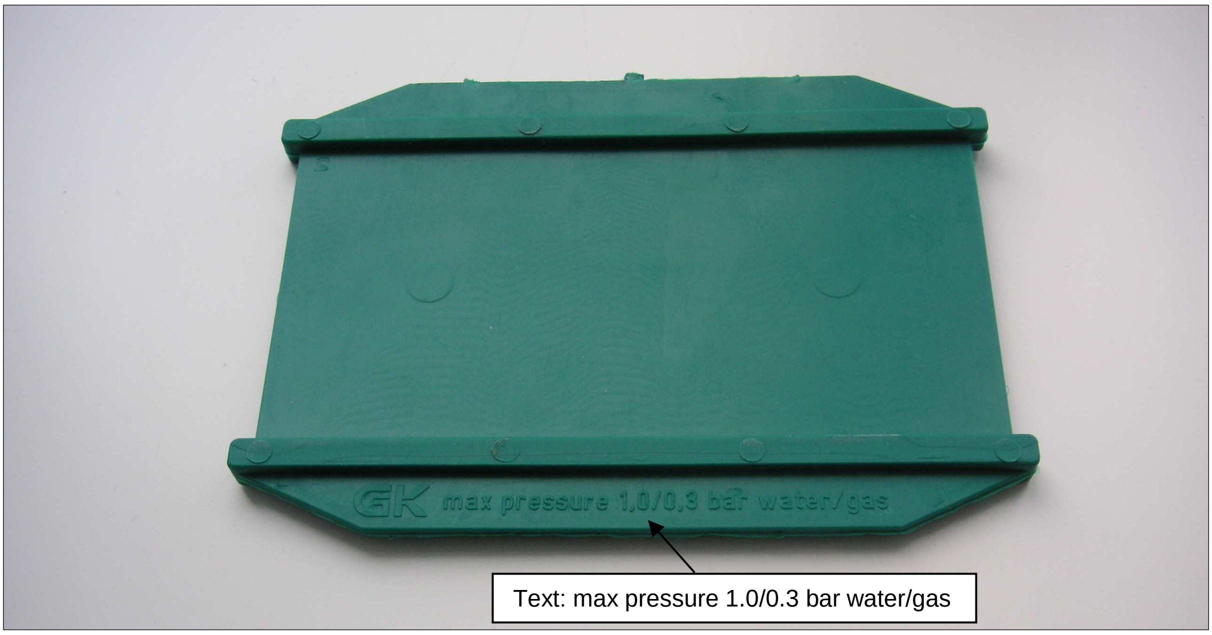


Figure 34: Stay plate of plastic (elastomer) for "GK Packing System"
Source: DMAIB

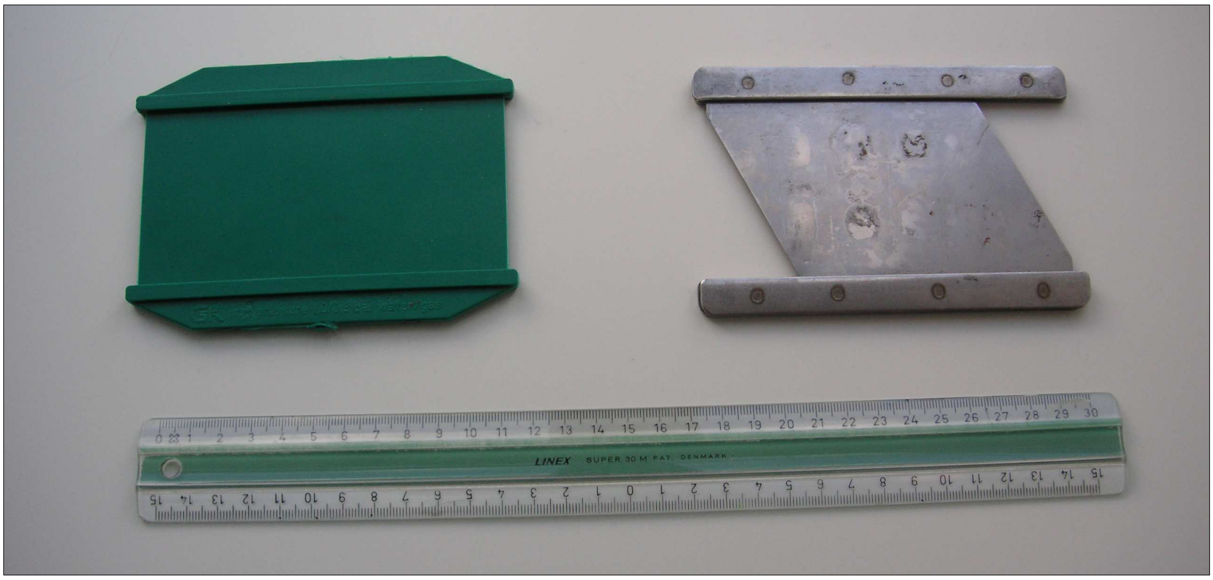


Figure 35: Stay plates of plastic (elastomer) and stainless steel for "GK Packing System"
Source: DMAIB

The class approval certificate of the “GK Packing System” contained no obvious specification or differentiation between metal and plastic stay plates and their intended use, but referred to the selection of packing system components to be in accordance with the manufacturer’s recommendations.

The subcontractor installing the cable penetrations in this and other ships at the construction yard never discussed with class, yard, or owner whether cable penetrations at specific positions should be able to withstand a specific hydrostatic pressure. There had never been any focus on this issue. However, the system’s fire resistance was a general issue and in that respect installations with plastic stay plates were approved and fulfilled the requirements as did installations with stainless steel plates.

Cable penetrations were primarily fitted with plastic stay plates instead of stainless steel plates because they were easier to install and were less costly. The four high-voltage cable penetrations located above the propeller shaft in the watertight bulkhead at frame 166 were all fitted with stay plates of plastic. Another cable penetration located in the same bulkhead and below the floor plates was fitted with a stay plate of stainless steel.

When the four high voltage cable penetration sealings collapsed, the ship’s draught was about 16 metres. The high voltage cable penetrations in the watertight bulkhead were situated about seven metres above the ship’s basis line. Thus, the cable penetrations collapsed at a hydrostatic water pressure corresponding to the maximum water column of appr. nine metres equal to appr. 0.9 bar.

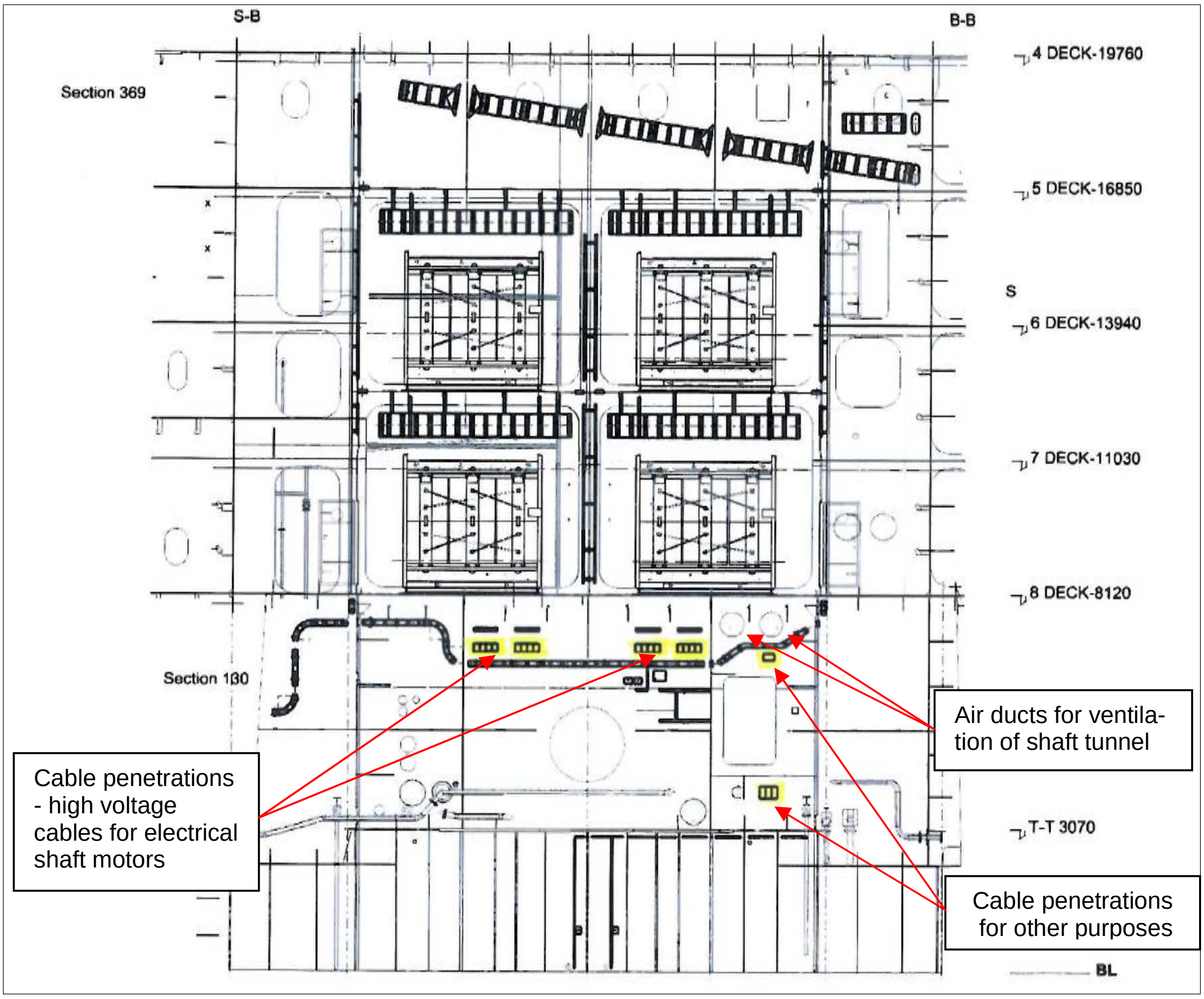


Figure 36: Detail of watertight bulkhead at frame No. 166 transverse section viewed from forward
Source: The ship’s damage stability booklet

3.8 Stern thrusters

EMMA MÆRSK has two bow thrusters and two stern thrusters – all of the same make and type: Rolls Royce Marine AS, tunnel thruster type TT2400 AUXD CP. The thrusters are operating at 257 RPM, each creating a thrust of about 250 kN. The thrust is regulated by a hydraulically controlled pitch propeller system. The blades are made of Ni Al Bronze (figure 37 below).

Figure 37: Stern thruster on a sister ship, viewed from the gearbox side
Source: Maersk Line

Figure 38: New supporting plate in upside down position
Source: Maersk Line

Each stern thruster is built into an 8 metre long transverse tunnel with a diameter of 2.4 metres and each tunnel has a stainless steel lining where the thruster propeller is rotating. In the tunnel the thruster is supported underneath by a supporting base plate (figure 38 on page 35). The upper part of each stern thruster tunnel is built in as a part of the ship's propeller shaft tunnel (figure 39 below and figure 40 on page 37).

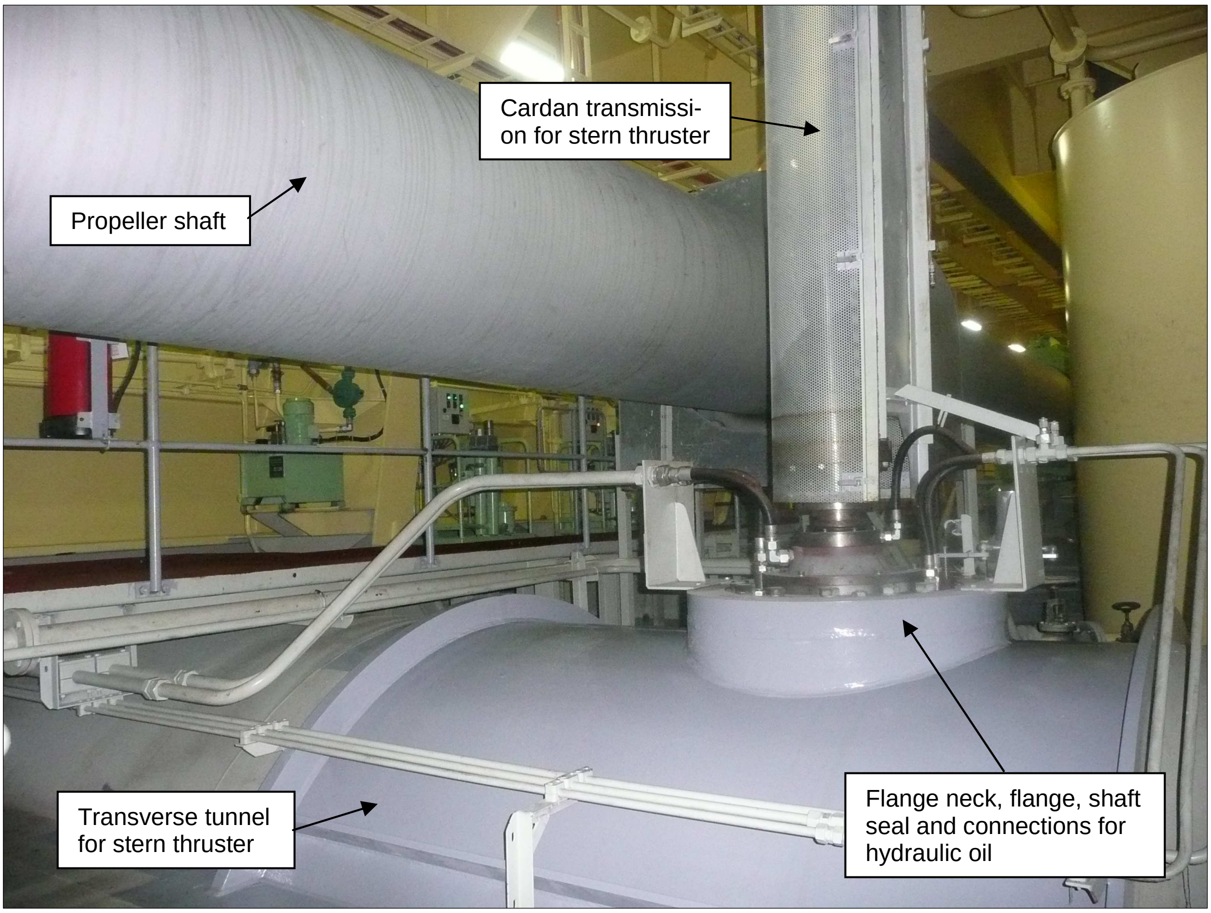


Figure 39: Upper part of stern thruster tunnel in propeller shaft tunnel of a sister ship
Source: DMAIB

Each stern thruster is separately powered by a 1750 kW high voltage electrical motor, situated in a compartment above the shaft tunnel, and mechanically driven by a vertical cardan transmission between the electric motor and the thruster gear housing in the transverse tunnel. On top of the thruster tunnel, there is a flange neck and a flange with a shaft seal and connections for hydraulic oil to the pitch propeller system (figure 39 above and figure 40 on page 37).

The thrusters' service hours since the last dry docking were 250-500 hours (estimated) and 3000-3500 hours (estimated) since the ship's delivery in 2006.

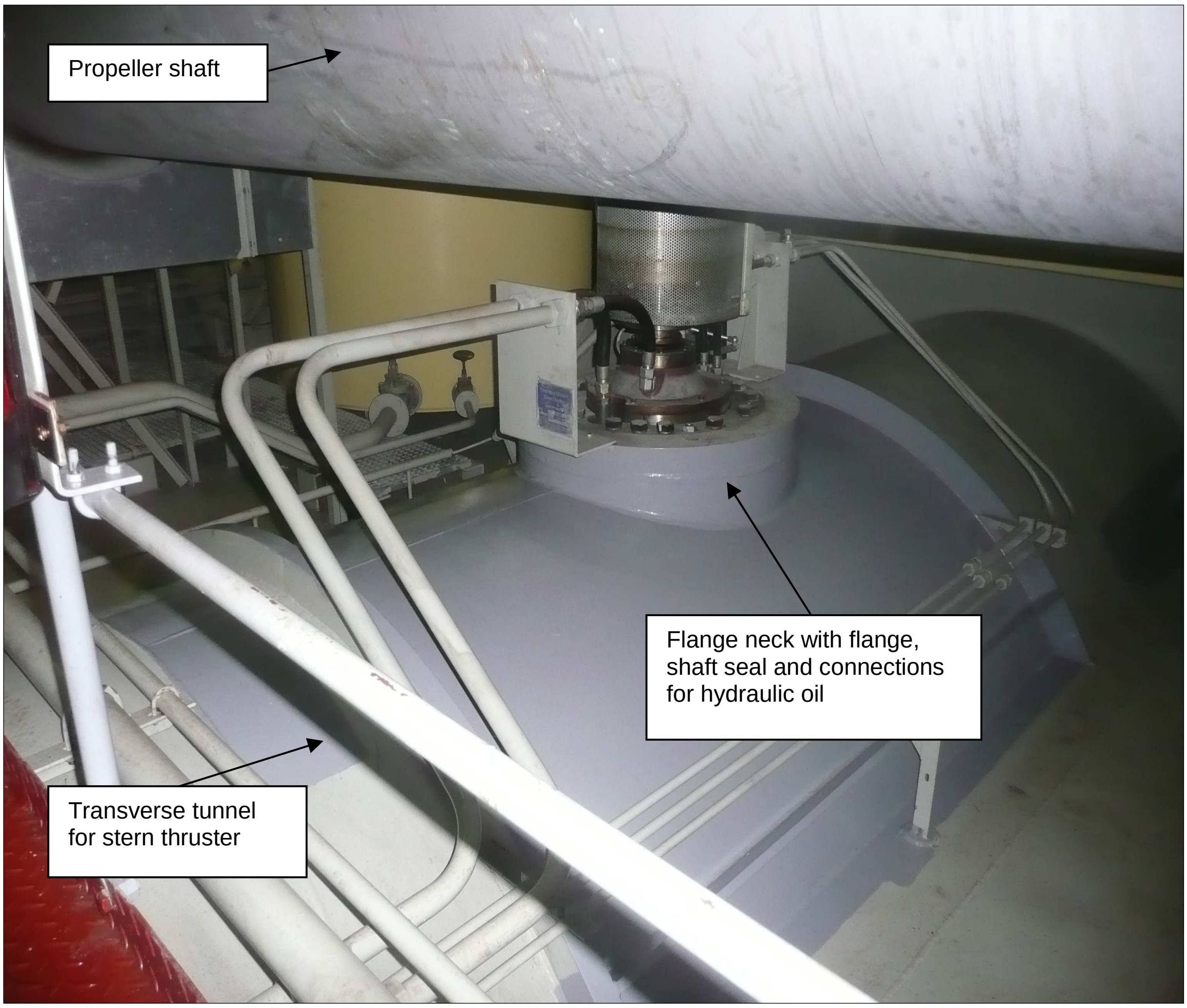


Figure 40: Stern thruster tunnel with flange neck, flange, shaft seal and hydraulic connections in the shaft tunnel of a sister ship
Source: DMAIB

3.8.1 Damage to both stern thrusters

During a bottom survey and propeller polishing carried out by divers in Rotterdam in August 2012, it was found that one blade of the aft stern thruster had broken off, while the remaining three blades were still intact. The cause for this incident was not investigated at that opportunity and hence not determined.

Apart from this discovery, nothing exceptional had been observed at the aft stern thruster when in operation.

The broken off blade was replaced by a new one from the same manufacturer in October 2012, and no operational problems had been experienced with this stern thruster since the replacement.

As described in section 3.2, the water ingress into the shaft tunnel occurred at the flange neck of the forward stern thruster shaft sealing.

The entire flange neck was basically torn off the transverse tunnel at the welded connection between the flange neck and tunnel and moved forward creating a gap (figure 41 on page 38).

The stern thrusters were in idling mode, i.e. running at normal speed of 257 RPM, and there was no pitch on the propeller when the incident occurred.

The thruster is provided with an electric overload function on the electric motor. However, in the event log there were no signs of automatic overload cut-out.

Figure 41: Breakage at the flange neck to the transverse stern thruster tunnel
Source: Maersk Line

3.8.2 Examination of the damaged forward stern thruster

Soon after the accident on 1 February 2013, it was mutually agreed by all stakeholders that a root-cause analysis of the stern thruster breakage should be carried out by the independent non-profit institution FORCE Technology, Denmark, as a third party investigator.

The forward stern thruster arrangement was examined on site whereafter the entire stern thruster, including all loose parts and damaged objects, were taken out and sent to FORCE Technology, Denmark, for full investigation.

On-site inspection

An on-site inspection of the damaged stern thruster arrangement after the incident revealed, among other things:

- *The damaged "hatch" of the thruster tunnel was sheared off completely throughout the whole circumference of the welding connection between the horizontal thruster tunnel and the vertical "hatch".*
- *The thruster including the loose "hatch" was relocated about 30 – 40 mm in forward direction and was resting on the edge of hole in the thruster tunnel.*

- *Three propeller blades were broken off at the base and missing.*
- *One bolt was broken.*
- *The supporting base plate was broken close to the attachment flange where narrowest.*
- *A section, broken off from the supporting base plate, was still bolted to the propeller head.*
- *One fracture of the supporting base plate was severely deformed and hammered and the other fracture was going through one of the bolt holes.*
- *Three bolts for the supporting base plate were broken off, three bolts missing and six bolts at the supporting base plate were loose but still in position, secured by welding.*
- *Two bolts for the bevel gear cover at the flange in top were broken off.*
- *The thruster was not hanging in the coupling since it was resting as describe above.*
- *No damage to the cardan transmission arrangement including bearings and electric motor.*
- *Feedback arrangement with linkage was in good order but the shaft coupling was slightly twisted due to the relocation of the thruster.*
- *Partly rupture of welding and rupture of the steel plating throughout the damaged area.*
- *Burs from scoring on remaining blade's tip edge.*
- *Propeller hub, crosshead, crank discs, and crank shoes were all in good visual condition.*
- *The thruster was completely jammed.*

Examination by FORCE Technology

An examination of the thruster parts carried out by the FORCE Technology revealed, among other things:

- *The breakage of the three propeller blades appeared to be new i.e. in connection with the incident 1 February 2013.*
- *The propeller blades appeared to have failed in this order: #3, #2, and #4.*
- *Fractures of blades were not initiated at the same time.*
- *The fracture surfaces indicated obviously fatigue.*
- *One blade bolt had a cracked head. The top of the head fell off when the securing wire was removed.*
- *The unbroken blade had cracks at the same side and the same area as in the other blades.*
- *The unbroken blade had light impact damage at the leading edge.*
- *There were indications that there was bending fatigue in the blades, to be further investigated by the manufacturers.*
- *There was no evidence to indicate that the breakage of propeller blades was caused by material defect or welding.*
- *The mechanical properties were on the low side, possibly lower than the minimum requirements for test pressure with respect to heat stress and tensile strength.*
- *Uniform and similar hardness and same chemical composition in all blades.*

The examination by FORCE Technology led to a report: *Stress analysis, fracture mechanics and fatigue assessment of Emma Maersk Thruster,* dated 30 June 2013.

Excerpts from the report:

> ***"The scope of work:***
> *FORCE Technology has carried out stress analysis, fracture mechanics failure assessment, fatigue life estimation and missing propeller blade unbalance force calculation of the T-joint connection.*
>
> *The finite element analysis includes calculation of the stress concentration at the critical saddle point of the tubular tunnel tube and flange neck joint exposed to axial top flange load and out-of-plane bending moment of the T-joint.*
>
> *A fracture mechanics failure assessment of the welded connection is carried out in order to estimate the failure load related to the weld imperfection quality.*
>
> *The applied failure load is estimated for the plastic yield failure and the brittle toughness failure modes.*
>
> *The fracture mechanics fatigue failure loads is calculated with TWI Crackwise Version 4.3 program in accordance with recommendations in BS 7910:2005 "Guide on methods for assessing the acceptability of flaws in metallic structures", British Standard Institution.*
>
> *The estimation of the expected mean fatigue lives for variable load ranges is based on the recognized BS 5400 S-N fatigue curves for welded connections.*
>
> ***The conclusions:***

- *The estimated failure loads of the welded tunnel tube and flange neck welded to normal weld quality according to ISO 5817 are approximate an axial load of 4700 – 5500 kN or an out-of-plane bending moment of 3200 – 3750 kNm.*
- *The expected mean fatigue life due to the unbalance force from 2 missing propeller blades is greater than 20 days of continuous propeller rotation.*
- *Failure assessment of the 2 missing propeller blades load condition has shown the failure introduced by the unbalance force from 2 missing propeller blades is only expected if there is a flaw of height 4.6 mm present in the welded connection."*

Figures 42 and 43: Fractured surfaces from the forward stern thruster's blade bases no. 2 and no. 3
Source: FORCE Technology

Figure 44: Fractured surface from the forward stern thruster blade base no. 4
Source: FORCE Technology

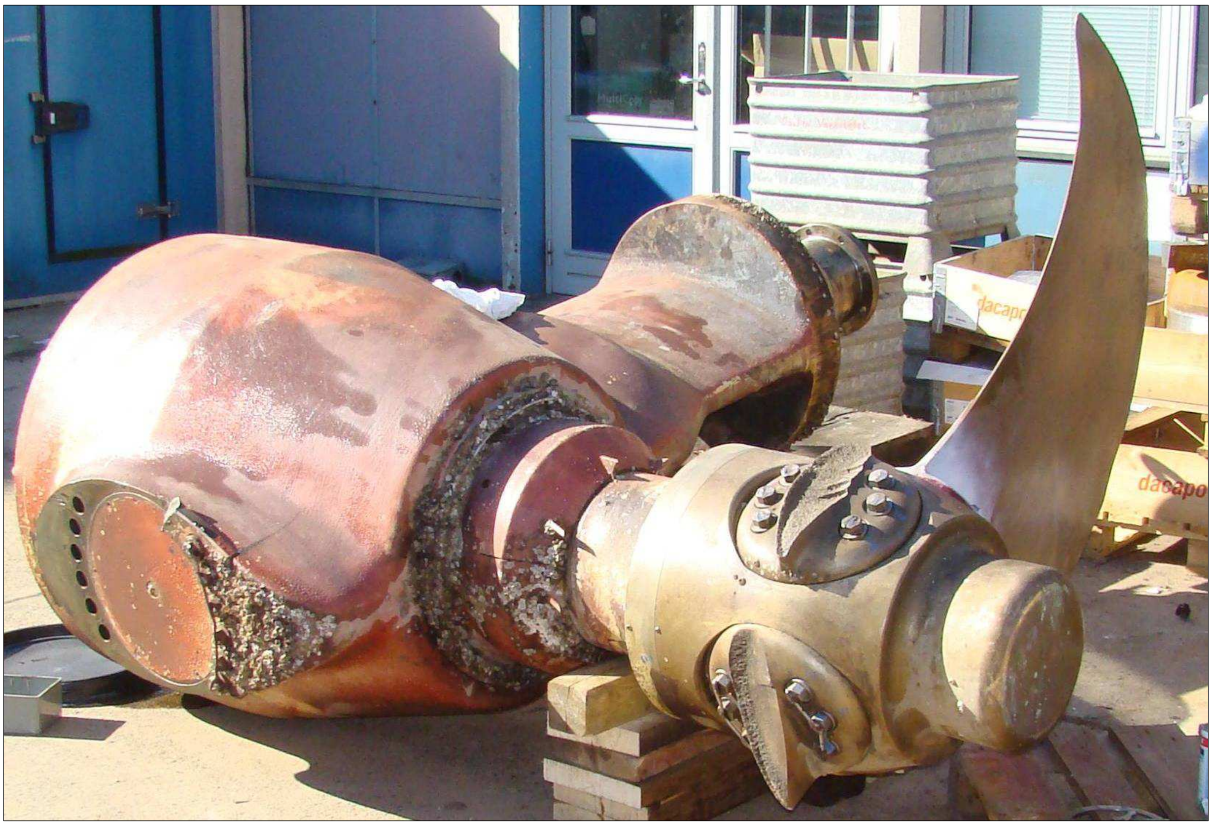


Figure 45: The damaged forward stern thruster before dismantling
Source: FORCE Technology

3.8.3 Examination of the aft stern thruster

The base of the propeller blade that had broken off the aft stern thruster in August 2012 was examined together with the damaged parts from the forward stern thruster by FORCE Technology.

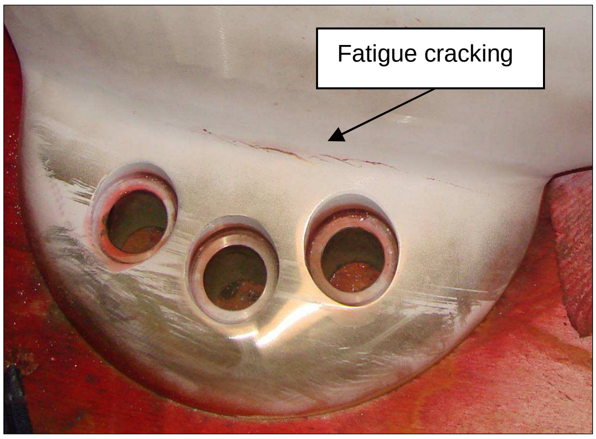
The fractured surface from the base of the broken propeller blade of the aft stern thruster (figure 46 on page 42) had the same pattern of fatigue and had basically the same hardness and chemical composition as those broken off the forward stern thruster. There was no repair welding, and no material defects in crack starts.

Figure 46: Fractured surface from the aft stern thruster blade base that was replaced by a new one in October 2012
Source: Force Technology

During EMMA MÆRSK's yard stay in Palermo, the entire aft stern thruster was removed and transported to the manufacturer's facilities in Norway for inspection of the blades and mechanical parts. It was then found that the supporting base plate for this stern thruster was broken almost in the same place and manner as it was on the forward stern thruster (figures 42 and 43 on page 40 and figure 44 on page 41).

A concerted investigative meeting was held at the manufacturer Rolls Royce Marine's facilities in Norway on 20 August 2013 with the participation of stakeholders.

It was found that the three remaining original blades had cracked in way of the transition between the propeller blade and base. All cracks had occurred on the same side, i.e. the side pointing away from the thruster drive. Thus, all eight original propeller blades from the stern thrusters of EMMA MÆRSK had experienced fatigue cracking. All fatigue cracking had the same pattern and appeared at the same area of the propeller blades (figures 47 and 48 below and figure 59 on page 43).



Figures 47: Crack indication on front side of blade 1 on the aft stern thruster
Source: Force Technology

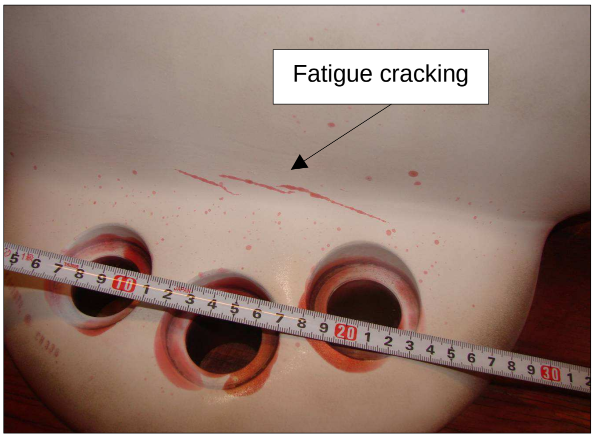


Figure 48: Crack indication on front side of blade 3 on the aft stern thruster
Source: Force Technology

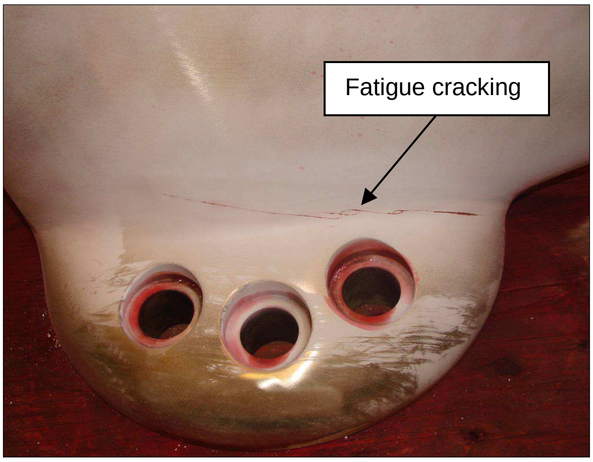


Figure 49: Crack indication on front side of blade 4 on the aft stern thruster
Source: Force Technology

Furthermore, it was revealed that the propeller blade that had been fitted as a replacement on the aft stern thruster in October 2012 was of a different design than that of the original propeller blades. An immediate visible difference was a significantly smaller radius of the transition between the propeller blade base and the blade itself.

Examination and findings by the manufacturer
Further examinations were carried out by the manufacturer Rolls Royce Marine and its consultants BANDAK Engineering in Norway. Parts and objects from the forward stern thruster were also brought to the manufacturer's plant in Norway for other examinations and investigations.

Because it was known that one blade of the aft stern thruster had broken off in August 2012, about half a year prior to the incident on 1 February 2013, it was decided to conduct a thorough examination of this stern thruster too.

The radius of the transitions between the propeller blade bases and the blades was measured, which revealed that the radius on the blades of the original design varied from 10 to 12.5 mm and on the blade of the new design 35 mm. According to the manufacturer's drawing, the root radius is to be 25 mm.

The calculations and investigations of both stern thrusters carried out by the manufacturer Rolls Royce Marine AS and its consultants BANDAK Engineering led to a report*: "EMMA MÆRSK, Structural Assessment of RR TT 2400 AUX CP THRUSTER", dated 20 September 2013.*

Excerpts from the report:

> *"**Background***
> *…….*
> *The main objective has been to investigate the capacity with respect to structural strength and fatigue of an intact TT 2400 RRM thruster as installed in the Emma Mærsk.*
>
> *In this work, special emphasis has been put on the fatigue capacity of the defective lower stay and the propeller blades, which is reported to have failed due to fatigue cracking. Additionally the scope of work included the analysis of the thruster system in the damaged stay condition in order to assess if such damage could lead to collapse of the actual support system.*

Conclusions

- *It may be concluded that the intact capacity is high and that operational load for an intact thruster could not have caused plastic collapse failure or fatigue failure in the top flange. Manual calculations indicate a very high top flange plastification load capacity as compared to operational loads.*

- *When the thruster is damaged by the loss of the stay connection, failure of the top flange may occur due to fatigue and/or plastification.*

- *Based on the analysis results it may be concluded that the defective stay on the two aft tunnel thrusters on Emma Mærsk may likely have failed due to fatigue.*

- *The main reason is possible high dynamic loadings and an unfavourable design related to a sharp notch that is associated with high local stress concentrations.*

- *At this stage we have not found any evidence indicating that a defective stay could lead to fatigue failure of the propeller blade. However, fatigue failure of the stays may occur after a short time operating at full load when the thruster is damaged by the loss of one or more propeller blades.*

- *FE analysis work has detected high stress levels at the blade root. This is primary explained by the very small root radius.*

- *Fatigue will likely occur for a small blade root radius when subjected to relatively high dynamic loadings.*

Recommendations

- *It is recommended to perform more detail assessments with respect to potential dynamic excitations and dynamic loadings. This should include more refined modelling, modelling of rotor (propeller) dynamics, modelling of the drive line, dynamic simulations and also estimation of the dynamic load levels, possible interaction effects and added mass using CFD methods. Such analysis work has not been part of the defined scope that this report is based on.*

- *The size of the ship and the length of the tunnel could indicate that the thrusters are operated under relatively calm and stationary conditions. However, large interaction effects with the main propulsion system cannot be ruled out, especially under harbour conditions when the main propulsion system is reversed. Other sources may neither be ruled out, e.g. cavitation effects, effect from fairings, operational effects. This should be further investigated.*

- *On location vibration measurements and measurement of dynamic stress levels could also be useful in order to detect and identify potential dynamic effects that have not yet been accounted for.*

- *Propeller blades should be designed / fabricated with a higher root radius.*

- *It is believed that the stay plate design with respect to fatigue can be rectified to a large extent by:*
    - *Removing the notch and/or by using a larger notch radius.*
    - *Reinforcing the stay plate with a wider rim segment.*

3.8.4 Change of thruster propeller blade design

The original propeller blades were designed in 1994 by the company KaMeWa AB that has now been acquired by Rolls-Royce.

The standard production method for propeller blades was milling of the blade by CNC machines (Computer Numerical Control). However, the blade foot area was ground and polished by hand (figure 52 on page 46).

In 2006/2007, the production methods were changed to increase the efficiency and accuracy in propeller blade manufacturing. With the new production methods, the blade foot area was also milled by means of CNC machines.

During the preparation for the new production technology, all previous propeller blade designs had to be transitioned from 2D drawings into 3D models by CAD (Computer Aided Design).

It was discovered that the radius of the transition between the blade base and the blade itself was too small. This applied to several blade designs and hence Rolls Royce Marine decided to change the design and immediately informed the relevant foundry to modify the relevant patterns.

The propeller blades of the new design differ from the original design by weighing 4.5 kg less and having a considerably larger radius of the transition between the blade base and the blade.

During the change of production method, it was also discovered that two of the Rolls Royce Marine manufacturing plants had been using different design philosophies with respect to indicating the radius of the transition between the blade base and the blade. This radius, if indicated on a drawing, is only an indication. The 3D shape of the blade is complex and radiuses will vary depending on which section of the root/blade is measured.

It is hard to make a standardized and exact measure of the radius of the transition between the blade base and the blade and there are no requirements for this in neither ISO484-2[2], nor in the relevant Class Society rules. Bearing this in mind, the manufacturer found that the relevant radius was below what was indicated on the drawing.

This is explained as a mistake made during the pattern production process, or as the method of grinding by hand in the blade foot area (prior to 2006/07) leading to excessive material removal; a deviation that was not captured by the manufacturer’s internal quality system.

The new propeller blade on the aft stern thruster that was fitted as a replacement in October 2012 was of the new design from after 2006/2007 and its radius of the transition was 35 mm.

The damaged forward stern thruster that caused the leakage had a propeller design of the older design with a smaller radius.

[2] ISO484-2 “Shipbuilding – Ship screw propellers – Manufacturing tolerances – Part 2: Propellers of diameters between 0.80 m and 250 m inclusive”.

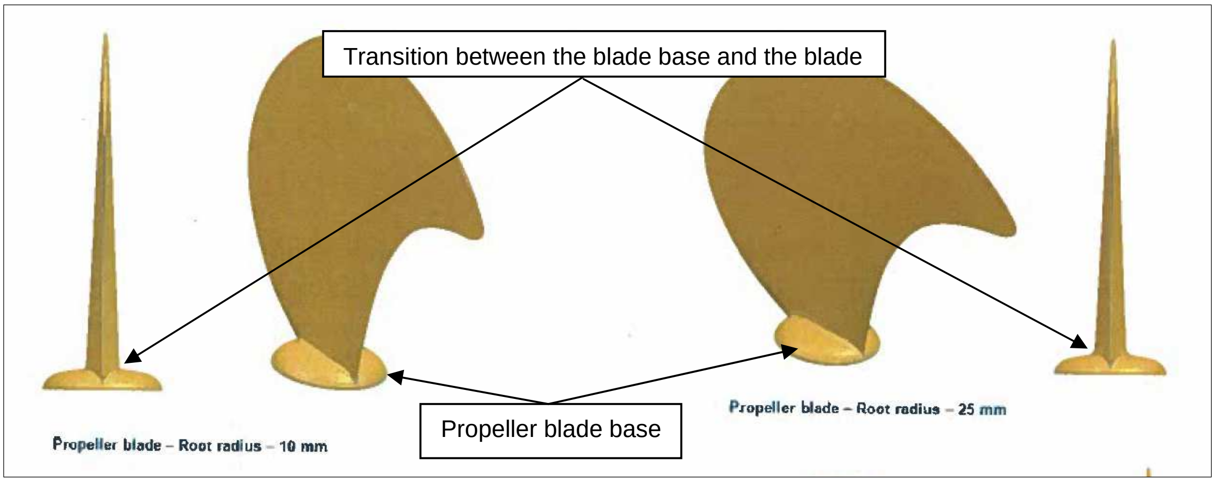


Figure 50: Excerpt from presentation RRM – TT2400 EM Structural assessment, 03.09.2013
Source: BANDAK Engineering

3.8.5 Blade dynamic balancing

The weight of the new propeller blade that was mounted on the aft stern thruster in 2012 is 4.5 kg less than the weight of each of the original blades. This resulted in an imbalance creating a centrifugal alternating load on the structure of 4.9 kN at the operating speed of 257 RPM (4.28 Hz) corresponding to 3% of the forces from loss of one blade.

The dynamic balancing of the original four blades is according to ISO Class II. After the replacement of one propeller blade by a blade of the new design, the dynamic balancing of the propeller exceeds ISO Class II. When replacing the broken propeller blade, it was advised by Rolls Royce Marine to also replace the opposite propeller blade by a new one, not only the damaged one.

3.8.6 Damage to the stern thrusters' supporting base plates

On both stern thrusters, the supporting base plate was found to have broken off at some of the welded connections to the thruster tunnels and at the narrowest segment adjacent to the bolted connections to the bottom side of the stern thruster (figure 53 on page 47).

The supporting plate of the forward stern thruster had actually broken in three places, one of which was through a bolt hole (figure 52 on page 47). Four out of five fractures of the supporting base plates were of the same pattern, going from one corner of the base plate where a notch in the transition between the machined part and the non-machined part of the plate meets the outside corner, very much like the result of a notch effect (figures 53 and 54 on page 48).

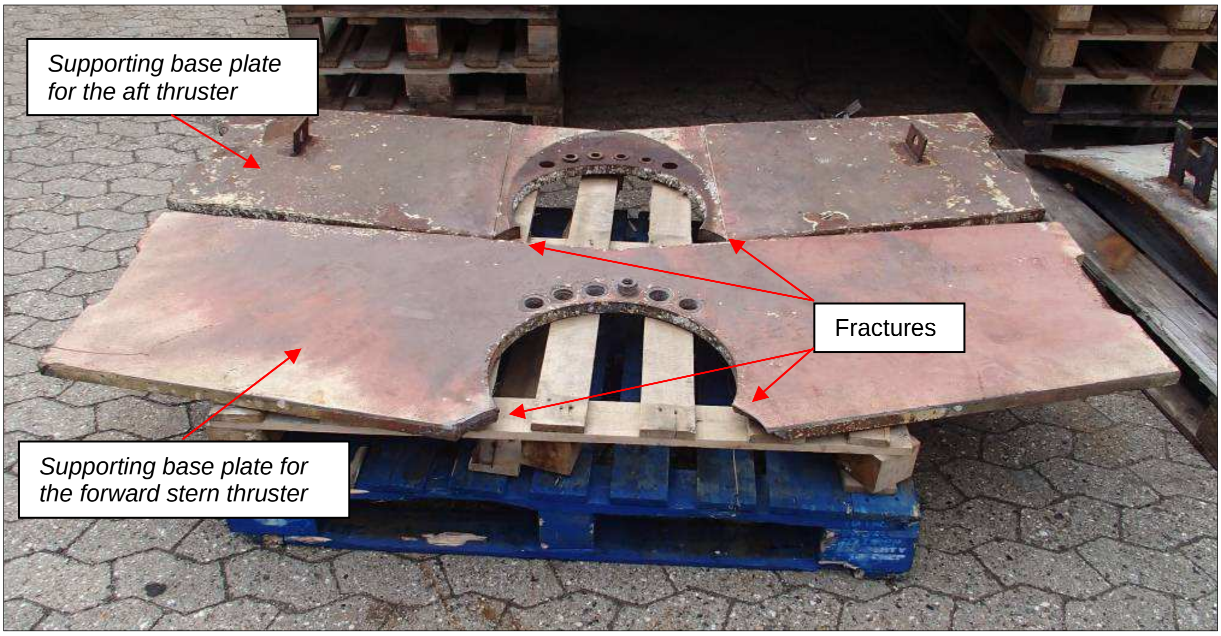


Figure 51: Broken supporting base plates for the forward and the aft stern thruster
Source: Force Technology

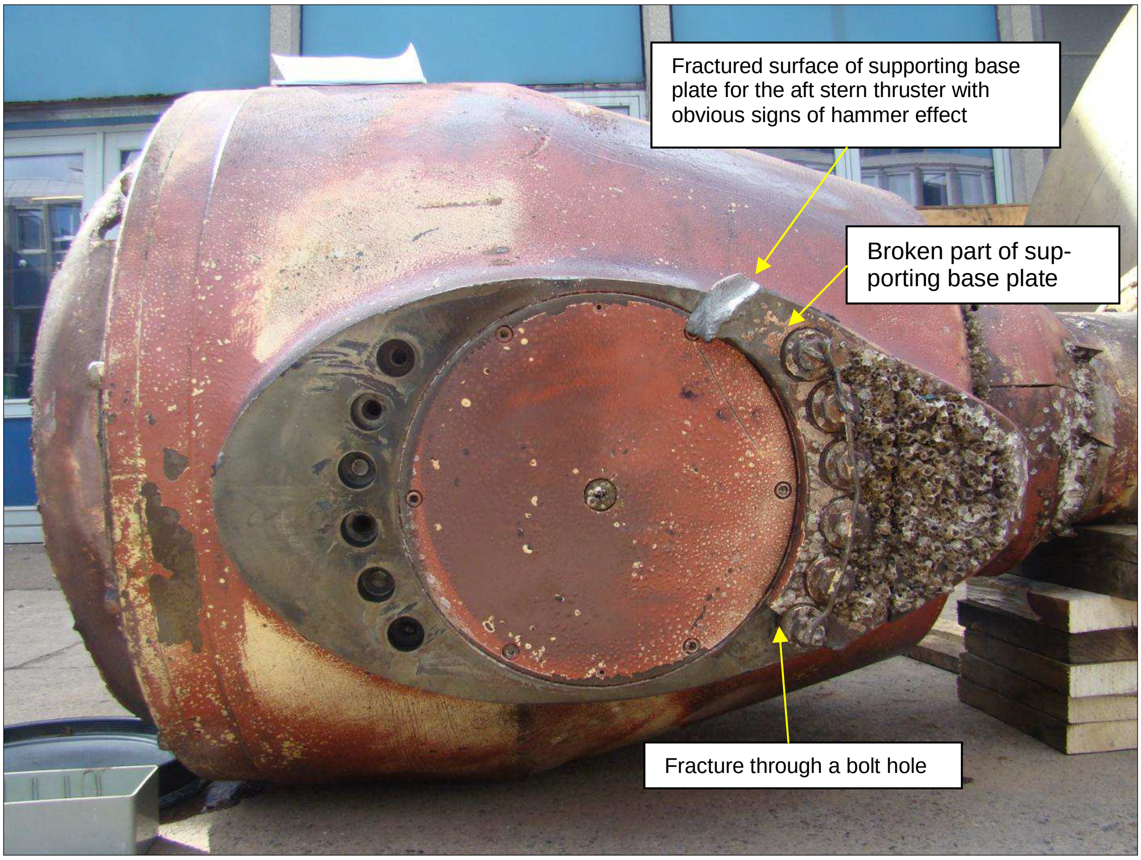


Figure 52: Bottom side of the damaged forward stern thruster with the broken part of the supporting base plate
Source: Maersk Line

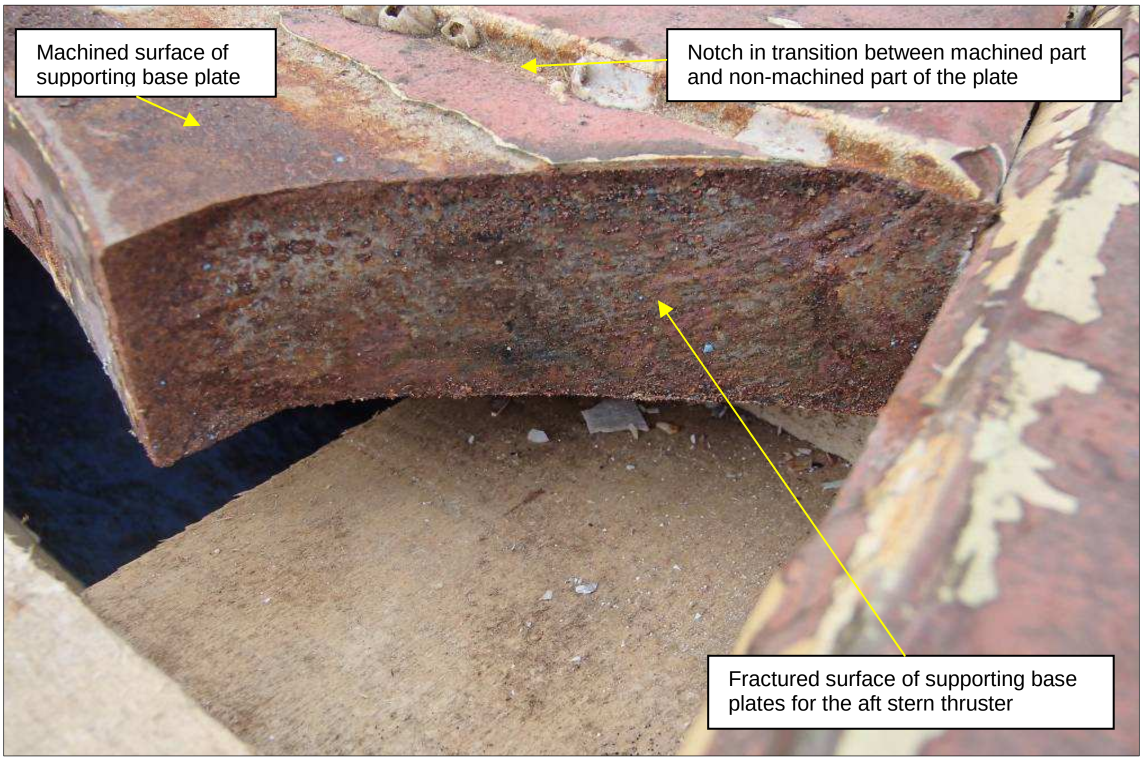


Figure 53: Fracture of supporting base plate for the aft stern thruster
Source: Force Technology

Figure 54: Fracture of supporting base plate for the aft stern thruster
Source: BANDAK Engineering/Rolls Royce Marine

Figure 55: Fracture of supporting base plate for the aft stern thruster
Source: BANDAK Engineering/Rolls Royce Marine

4. ANALYSIS

4.1 Stern thrusters

The damaged forward stern thruster caused a fracture in the flange neck on top of the transverse thruster tunnel that resulted in severe water ingress into the shaft tunnel.

Fatigue failure and/or plasticization and the resulting fracture at the flange neck may have occurred due to the loss of support by the supporting base plate that created excessive vibration in the thruster vertical shaft.

The forward stern thruster was, furthermore, damaged in such a way that three propeller blades broke off at their bases due to fatigue failure.

Operation with a thruster which is missing one or more propeller blades will result in an imbalance and create a centrifugal alternating load on the structure and hence fatigue failure of the supporting base plate. This, combined with the design of the supporting base plate which has the potential for a notch effect and high local stress concentrations, seems to be the reason for fatigue failure in the supporting base plate construction.

There is no evidence that a defective supporting base plate could lead to fatigue failure and breakage of the propeller blades.

The manufacturer of the stern thrusters changed the design of the propeller blades in 2006/2007, and the original propeller blades in the stern thrusters of EMMA MÆRSK were all of the design from prior to 2006/2007. On both stern thrusters, all the propeller blades of that design had either broken off or had crack indications.

The significant differences between the original and the new propeller blades were the method of shop finish, the weight and the radius of the transition between the blade base and the blade itself.

Of specific interest in this context, because the propeller blades broke off at their bases due to fatigue failure, is the radius of the transition between the blade base and the blade.

High stress levels and hence fatigue failure at the propeller blade base will likely occur on a propeller blade with a small root radius when subjected to high dynamic loadings. The fatigue failure on the propeller blades of the stern thrusters of EMMA MÆRSK can primarily be explained by the small root radius.

However, the recommendations by the manufacturer as presented in the report of 20 September 2013 indicate that also other factors should be taken into consideration such as interaction effects with the main propulsion system, especially under harbour conditions when reversing, and other effects such as cavitation effects, effects from fairings and operational effects.

4.2 Watertight bulkhead with watertight door, valves, shaft and cable penetrations

The watertight bulkhead was not necessary for meeting the damage stability requirements, but had nevertheless been designed and was perceived by the crew as a barrier for preventing flooding of the engine room. The master and the chief officer soon realized that the damage stability was not an immediate problem in case of a flooded shaft tunnel and engine room.

However, the bulkhead between the shaft tunnel and the engine room was vitally important in terms of watertight integrity, because it was considered imperative to keep the propulsion machinery running in order to get the ship out of the fairway and safely into the harbour area.

4.2.1 Cable penetrations

Four large cable penetration sealings mounted in the bulkhead at frame 166 burst whereupon the watertight barrier was no longer effective.

At the shipyard, the GK Packing System had for many years been used as a standard cable penetration system. The system appeared easy to assemble, and because it had been type approved by the classification society, there was confidence in its effectiveness.

When the "GK Packing System" was introduced as a standard cable penetration system at the shipyard in 1994, the system was introduced to the craftsmen via an installation training course. This training course was not followed up by additional courses, instructions or certifications to later employed craftsmen or installers of the subcontractor company. New employees only received an information pamphlet from the subcontractor with installation instructions in English and German with a translation into Danish made by an employee at the subcontractor.

Without systematic training, the necessary general and skill-based knowledge to carry out an effective installation of a cable penetration was obtained by "on the job training" with the risk that important elements with regard to correct mounting were not taken into account. It was therefore up to the individual craftsman to determine which components were to be used for each cable penetration.

The choice of stay plates of plastic/elastomer or stainless steel was essential for the installation to meet the criteria of the watertight bulkhead. The craftsmen were not aware that there was a difference between the criteria for watertight bulkheads and non-watertight bulkheads. There was only a dedicated focus on the issue of fire resistance. The choice of stay plates depended on what was easiest to install and/or what was readily available. It was also a question of price because plastic/elastomer stay plates were significantly cheaper than those of stainless steel and were therefore more readily available.

Before the cable penetrations burst, water was seeping from the cable penetrations indicating that, besides the use of plastic stay plates instead of steel stay plates, there were other problems with the assembly of the cable penetration components.

The type approval was system-based and not component-based. This means that the approval was not based on a specific configuration of the cable penetration system, but dependent on correct installation in any given circumstance. Without any test procedure after the installation, the quality of the cable penetration system was entirely dependent on the knowledge and skill of the individual craftsman. When installed, it was difficult to identify any discrepancies from the installation guidance whereupon the approval rested.

As per procedure, the on-site surveyor to the classification society based his approval of the cable penetrations of the watertight bulkhead on the type approval certificate and on a visual inspection. He did not have detailed knowledge of how the cable penetration system was supposed to be fitted and he could not react to the discrepancy as the installations did not appear to be any different from other cable penetrations. Nor did the surveyors of the yard or the owners reveal that the cable penetrations did not meet the type approval criteria.

An examination of watertight cable penetrations in the sister ships revealed a number of watertight cable penetrations that had not been correctly mounted and needed to be refitted.

In order to understand why the cable penetrations in the watertight bulkhead had been mounted incorrectly and why it went unnoticed, one must look beyond the failure of the individual craftsman and address several systemic issues:

- In the design process, focus was on the steel construction of the watertight bulkhead entailing quality control of the design and testing of the welding and thickness measurements of the steel. The cable penetrations were viewed from a component viewpoint without quality control and with separate approval procedures that did not involve testing.

- The cable penetration system was approved as a system and not as a single component on conditions that finally rested on the individual craftsman assembling the system. The craftsman did not have detailed knowledge about the status of the bulkhead as a whole.

- There was no readily available testing method for assuring the quality of the fitted cable penetration system.

- The classification survey process was not performed by a person with detailed knowledge of the cable penetration system. Therefore, the survey process rested on the type approval certificate.

There was a gap between the approval process and the construction process, where an inevitable individual failure became critical. Making the effectiveness of such a safety critical installation dependent on one craftsman reveals a weakness in the construction and approval process of the watertight bulkhead. Bearing in mind that the construction and approval of other parts of the watertight bulkhead is subject to several quality control measures, it becomes apparent that there is less focus on the cable penetration system.

4.2.2 Ventilation duct valves in the watertight bulkhead

The watertight door was closed locally by the 2^{nd} engineer, but the two hydraulically operated valves in the ventilation ducts situated just above the watertight door could not be operated locally and had to be operated from the ship control centre.

In terms of fire-fighting or fire precautions, it may make sense to operate the valves from the ship control centre from where all other fire-fighting systems are controlled. However, as an element in the bulkhead's watertight integrity, it is inexpedient that the valves in the ventilation ducts cannot be operated on site like the watertight door.

In this particular emergency, it did not pose any significant risk. However, there is a long distance from the watertight door to the deck office, which may complicate rapid and rational actions in the complex circumstances of an emergency.

4.2.3 Bilge system

The engine crew had opened the bilge suction valves in the shaft tunnel, and no valves had been fitted for isolating the shaft tunnel bilge system from the rest of the engine room. Therefore, after the flooding of the shaft tunnel and the closing of the watertight door, the engine crew were not able to empty the bilge wells in the engine room because the entire bilge system was pressurized by the flooded shaft tunnel. This left the engine crew with limited options to empty the bilge wells in the engine room that were being filled by the water ingress through the main engine shaft sealing and the seeping cable penetrations.

4.3 Emergency bilge system

In the event of water ingress of this magnitude, the bilge pump capacity and the functioning of the system as a whole are essential to either contain the situation or to gain the necessary time for limiting the consequences – abandoning the ship or getting the ship alongside.

The ship was equipped with means for discharging water in accordance with class rules. However, there was a mismatch between the expected discharge capacity and the actual discharge capacity. This mismatch was caused by the reduced inflow area of the inlet to the large seawater pump (emergency bilge suction) and by the discharge water being pumped through the central cooling system, which created a back pressure reducing the capacity.

The opening of the suction valve for the emergency bilge suction by the large seawater pump was delayed because of a broken steel pin in a cardanic connection between the handwheel and the suction valve. But because of rapid and rational actions, the engineers managed to open the emergency suction anyway by other means. In order to follow up on this experience, the shipping company investigated the test schedule for emergency suction, including the condition of the valves and valve actuation gear on board all sister ships. On all ships the linkages were found in good condition and fully operational. However, the fact that an emergency bilge system could be put out of function by a broken steel pin illustrates that a simple solution can create fragility in a complicated technical system.

Weaknesses in the emergency suction system could not have been detected during periodic testing because of the limited scope of the testing procedures. A full-scale test of the system would have entailed a flooding of the engine room, which was not considered feasible.

4.4 Disturbances by alarm systems

Throughout the entire course of events, the officers and crew were constantly disturbed and highly stressed by the sound of countless alarms, which made it extremely difficult to concentrate on the many challenges that appeared one after another.

Even though the alarms were acknowledged continuously on the bridge and in the engine control room, it was not possible to keep up paying attention to the incoming alarms. Thus, it became necessary to concentrate on basic observations and to act manually accordingly.

Because of the very high pace of incoming alarms and the distracting noise, there was a desire to be able to switch off the alarm sounders for the sake of effective communication and not being unduly stressed. But there was no such possibility. It takes manpower and concentration to operate and acknowledge alarms, and in this case the multiple alarms were a distraction more than an aid to officers and crew. It illustrates that the design feature of the monitoring and alarm systems that perform well in normal situations is not necessarily a help when handling a complex emergency situation – to some degree quite the contrary. Although it was not the case in these events, it may limit the crewmembers' cognitive capabilities and the prioritizing necessary for handling an emergency situation.

4.5 Handling of the emergency situation

Due to the adaptive behaviour of the crewmembers, the shipboard organization remained resilient despite the breakdown of the structural barriers, and even though no one had complete knowledge about the situation. The master had knowledge about the navigational situation, but limited knowledge about the events in the engine room. The chief engineer only had knowledge about the situation in the engine room. The crew therefore had varying priorities and concerns as they got more knowledge and evaluated the unfolding events.

When, at an early stage, the master together with the chief officer and the chief engineer realized that there was a very large and uncontrollable ingress of seawater into the ship, the master knew that the situation contained a huge potential for a disastrous outcome as regards safety of life, safety of his own ship and its cargo, safety of other ships, risk of pollution of the environment and risk of blocking the Suez Canal. The main priority, therefore, was to get the ship to berth at the Suez Canal Container Terminal even though it could mean a total breakdown of the ship's propulsion machinery.

It was essential for the prioritization and outcome of the situation that the master had detailed knowledge about the waters and harbour area.

5. CONCLUSIONS

The accident and its consequences were the result of a breakdown of structural barriers – i.e. the hull of the ship and the watertight bulkhead. Furthermore, the events of the accident revealed weaknesses in the functional barriers – i.e. the bilge system, the emergency bilge system and the alarm system. Despite the breakdowns and weaknesses, the shipboard organization managed to contain the emergency situation and bring the ship alongside. The events of the accident did not result in more severe consequences due to the behaviour of the crew who managed to adapt to the situation and prioritize the recovery effort to meet the unfolding events. Furthermore, the outcome was favoured by the ship's position close to the Suez Canal Container Terminal.

The watertight bulkhead did not function according to the designed intentions as a result of the gap in the continuity between the construction and approval process. There will inevitably be some difference between a design and its construction. Any weaknesses in these discrepancies can be revealed by a functional test, but these tests can prove difficult to carry out on structural barriers such as watertight bulkheads.

The survey process has its limitations, primarily because the surveyors do not necessarily have any detailed knowledge about the mounting of the cable penetration system and consequently rely on the type approval of the system. Therefore, the structural integrity of the watertight bulkhead rested solely on the craftsmen assembling the cable penetration system, and they may not have been aware of the safety critical status of that particular penetration as part of a watertight installation. Any mistake made during the mounting of the cable penetration would, in the given circumstances, remain unnoticed.

The alarm system, which was an integral part of the everyday operation of the ship, proved to provide little or no overview of the emergency situation. As the amount of alarms accumulated, the mental and practical workload of the crew increased, whereby the alarm system became a burden to the adaptive behaviour of the crew rather than an aid. This issue has come to the attention of the investigation board in connection with several other accident investigations.

Overall, it is evident from this accident that it is inherently difficult to design safety measures to meet the complexity of accidental events and that the creation of safety and recovery from accidental events rests with the ship' crew.

6. ACTIONS TAKEN AND PREVENTIVE MEASURES

Against the background of this accident, the companies involved have informed about actions taken and preventive measures as indicated below:

6.1 Cable penetration system

GK Marine Product Management has informed:

> *"In the 2.5 bar WT bulkhead, plastic stayplates intended for up to A-rated fire divisions and limited to ≤ 1 bar water pressures were mixed up with metallic stayplates intended for e g WT ratings corresponding to the particular bulkhead. In order to avoid this type of mix-ups, i e to simplify for the installer to select the correct article for the installation and to easier detect the article in the following quality check, the following preventive actions will be taken:*

A. *The plastic stayplate shall be discontinued as a ≤ 1 bar water pressure article and clearly be marked "Not for use in WT areas" or similar.*

B. *The mounting instructions will be modified accordingly.*

C. *The shape of the plastic stayplate will be changed to separate it more clearly from the shape of the metallic version. This change will simplify quality checks, even if the whole installation is subsequently painted over.*

> *The plastic stayplate was at the time of construction not type approved for WT applications. Despite this, the plastic stayplate was included in the mounting instructions as an article limited to ≤ 1 bar. Preventive actions to eliminate the risk of recurrence include improved internal routines:*

A. *Procedure to detail and include more clearly article identifications into type approvals.*

B. *Procedure to check that ingoing article identifications in mounting instruction are also included in type approvals.*

> *These procedures will provide increased means to detect and avoid possible use of not type approved articles.*

> *In order to address the use of plastic stayplates in historical ≤ 1 bar WT installations, type approval applications have been made based on witnessed pressure tests."*

6.2 Class

The classification society American Bureau of Shipping has informed:

> *"Steel Vessel Rules [see 4-8-1/ 5.3.1], maintain a longstanding requirement for a 'Booklet of Standard Wiring Practices' to be submitted for approval by builder before proceeding with the work. For cable penetrations through watertight, gastight and fire rated bulkheads and decks, evidence of penetration design approval is to be submitted. For watertight and gastight cable penetration approval, certificates issued by a competent independent testing laboratory would be acceptable.*

Alternatively, hydrostatic and pneumatic pressure testing of penetrations carried out at the manufacturers' facility and witnessed by an ABS Surveyor or other competent third party would be accepted.

Additional Preventative Measures:

2013 July 1st – ABS Steel Vessel Rules [see 1-1-7/3] were amended to require that 'Ship Equipment List' include not only item label, model & type but also 'manufacturer'. Additionally, the following was added "Where electrical cables, hydraulic lines, etc., penetrate watertight or fire rated bulkheads by the use of standardized penetration kits, a schedule is to be provided indicating the location, number, manufacturer, model number and type of Bulkhead Penetration Devices provided to maintain the bulkhead integrity."

Corresponding 'Initial New Construction Survey tasks' (questions) exist as Nos. 175, 363 & 491 on surveyors checklist with similar intent / text as above.

2013 July 1st – ABS Steel Vessel Rules [see 7-6-2/1.1.8] were amended to by adding "1.1.8(b) Cable Penetrations (1 July 2013). Watertight and fire-rated cable penetrations in decks and bulkheads to be generally examined for alterations and continued effectiveness."

An 'Annual Machinery Survey' checksheet task (no 15) has been created to insure that the intent of the rules is carried out.

2013 August 6th - ABS Chief Surveyor, Mr. L.A. Pendexter, issued a 'Surveyor Awareness' letter to surveyors worldwide listing changes to the Steel Vessel Rules with specifics.

Ongoing – as part of ABS continuous improvement program and engineer / surveyor training schemes, these subjects are reinforced during trainings carried out at ABS academies (e.g. ESVT / EEVT), within surveyor meetings at all levels and on project specific cases.

Summary:

ABS places significant emphasis on watertight & firetight boundaries in accordance with ABS Steel Vessel Rules and international conventions. Aforementioned changes have been effected to strengthen awareness and adopt additional measures as part of new construction and after construction survey process."

6.3 The owners

Maersk Line has informed:

"Stern Thruster Operation

After the incident on Emma Maersk all Stern Thrusters operation was immediately prohibited. Maersk Line will not allow to run the Stern Thrusters on the Emma class series before appropriate countermeasures/modifications has been implemented based on the learnings and findings from the root cause investigations.

Thruster inspections on sister vessels

Maersk Line immediately initiated complete diver inspection of all thruster units on sister vessels. Additionally a dye penetrant check was carried out on all welding seems of thruster foundations from inside shaft tunnel. No cracks or abnormalities found.

Root cause investigation of Stern Thruster Damage

Immediately after the incident on Emma Maersk a Root Cause investigation of the Stern Thruster damage was initiated by Maersk Line. It was mutually agreed between stakeholders that FORCE Technology as an independent institution specializing in, among other things, metallurgy should lead that investigation.

Immediately after the water was pumped out of the shaft tunnel, the forward stern thruster including shaft arrangement and hull structure was examined on site together with all involved parties. The complete stern thruster, including all loose parts and the damaged hull structure was taken out and sent to FORCE Technology, Denmark, for full investigation.

The AFT stern thruster was taken out as well and sent to Rolls Royce workshop in Ulsteinvik Norway for full investigation.

Based on the findings during the Investigations of the thruster units at FORCE and Rolls Royce a full underwater inspection with focus on cracks in blades, stay plates and profile of blade roots on all the thruster units of the E-class vessels was carried out.

Several follow up meetings have been carried out between all the involved parties.

Based on the remaining collection of data from the underwater surveys it will be decided in the near future if more investigations and tests are necessary in order to identify the countermeasures enabling operation of the Stern Thrusters.

Following countermeasures are presently considered:

- *Replacement of thruster propeller blades to latest design*
- *Reinforcement of thruster tunnel structure*
- *Replacement of thruster support plates to an improved design*

Cable Penetrations

Immediately after the incident on Emma Maersk a Root Cause investigation of cable penetration failures was initiated by Maersk Line in corporation with the Maker. Based on the findings sister Vessels have been checked and material replaced in critical bulkheads accordingly.

All Maersk Line operated vessels have inspected cable penetrations mounted in water tight bulkheads in accordance with Damage Control Booklet/Damage Control Plan.

Afterwards a test of cable penetrations in watertight bulkheads has been carried out in accordance with revised ABS requirements. Record of the result has been entered in a logbook with location (frame number/deck) for presenting to the attending surveyors.

For the ongoing new building projects work instructions for Site Supervision have been enhanced. Meetings with Class, Yard and Makers on site have been carried out in order to confirm and ensure correct material specification/certification as well as correct installation method.

Inspections of cable penetrations have been added to planned maintenance program carried out on all Maersk Line operated Vessels.

Emergency Bilge system

Based on reported feedback from Engineers onboard Emma Maersk during the flooding of engine room the following issues have been investigated on the Emma Class series.

Emergency Bilge Pump capacity in relation to operational profile, pipe design and as built pipe installation onboard. The investigation has revealed that the throughout put of the Emergency Bilge pump can have been unnecessary restricted by both pipe design and the way pumps can be operated during an emergency bilge situation.

Engine room Emergency Bilge system including valve drives has been checked on all sister vessels and found in good order. Planned maintenance activities are considered sufficient in order to keep all equipment in relation to the bilge system in good condition.

Load Computer

During the salvage operation in Port Said it was decided to keep the water in the engine room in order to preserve the machinery components flooded. In this special situation it was revealed that ship's load computer could not handle data when water level in engine room was higher than sea level. In order to handle this situation in the future all load computer programs have been modified onboard all Maersk Line Vessels accordingly."

6.4 The manufacturer of stern thrusters

Rolls-Royce Marine Services has informed:

"Rolls Royce Marine Services has carried out investigations of thrusters on all sister ships of the EMMA MÆRSK class, and Rolls-Royce Root Cause Investigation is not yet completed. At the time of issue of this report, it is still being investigated why and when thruster's propeller blades are exposed for the dynamic load.

A new comprehensive and advanced CFD-analysis (Computational Fluid Dynamics) of stern thruster application is due to be completed, several conditions have been analyzed as part of this CFD-calculation scheduled to early 2014.

Output from CFD-model is expected to provide new knowledge essential to the Rolls-Royce Root Cause Investigation."