Norwegian Safety
Investigation Authority

Issued November 2023

REPORT MARINE 2023/06

Marine casualty involving the cruise ship ‘Viking Polaris’ south-east of Cape Horn, 29 November 2022

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The Norwegian Safety Investigation Authority (NSIA) has compiled this report for the sole purpose of improving safety at sea.

The object of a safety investigation is to clarify the sequence of events and causal factors, elucidate matters of significance for the prevention of maritime accidents and improvement of safety at sea, and to publish a report with possible safety recommendations. The NSIA shall not apportion any blame or liability.

Use of this report for any other purpose than for improvements of the safety at sea shall be avoided.

Photo: NSIA

This report has been translated into English and published by the NSIA to facilitate access by international readers. As accurate as the translation might be, the original Norwegian text takes precedence as the report of reference.

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Notification

On Wednesday 30 November 2022, the Norwegian Safety Investigation Authority (NSIA) was notified by the Norwegian Maritime Authority that an accident which occurred on 29 November, involving the passenger ship 'Viking Polaris' had taken place just south of Cape Horn,. In the report it was stated that the ship had been struck by a large wave and that several stateroom windows had been knocked in. One passenger had died and four were injured (later changed to eight people). The ship was en route from Antarctica to Ushuaia in Argentina when the accident occurred.

The NSIA initiated a safety investigation and travelled to Ushuaia on 1 December 2022 to interview the crew, obtain information and inspect the ship. Information was later received about another accident, involving one of the ship's Zodiacs, that had occurred on 28 November. One person suffered serious fractures to both legs, and one fell into the water and suffered minor injuries.

Figure 1: The accident occurred on 29 November in the Drake Passage between the southern tip of South America and the Antarctic Peninsula.
Map: Norwegian Coastal Administration AIS

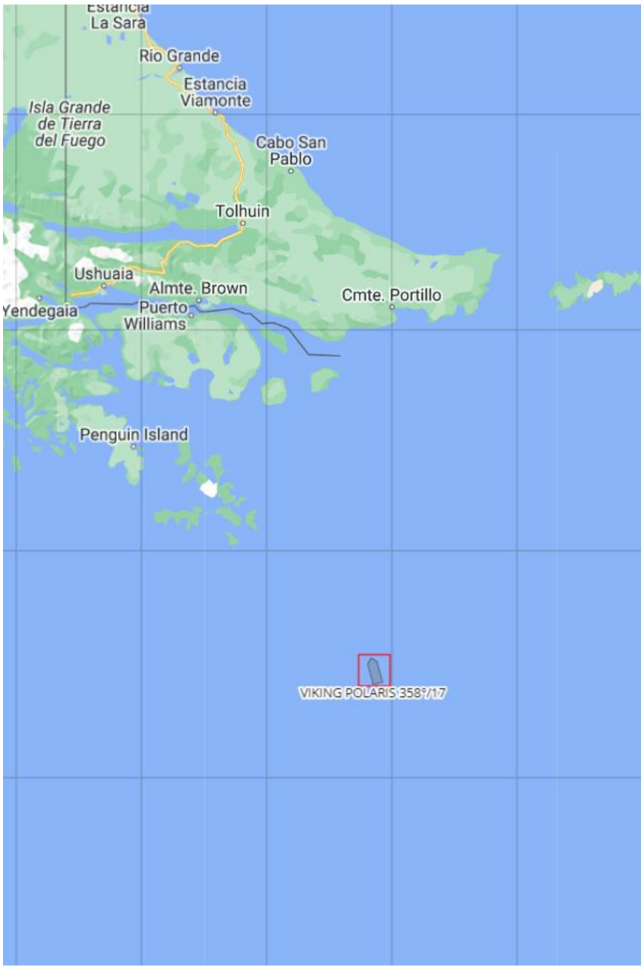

Figure 2: The map section shows the position where the accident occurred en route from Antarctica to Ushuaia in Argentina on 29 November.
Map: Norwegian Coastal Administration AIS

Summary

On 28 November 2022, there was an incident involving one of the ship's Zodiacs[1] in Antarctica. One passenger was injured and another ended up in the water. Following the incident, the ship had to interrupt the cruise to perform a medical evacuation. On 29 November 2022 the ship was therefore crossing the Drake Passage from Antarctica to Ushuaia, when she was hit by a breaking wave just south-east of Cape Horn. The accident caused seven stateroom windows to break and caused major damage inside the staterooms in question. One passenger died and eight were injured.

The investigation has shown that the ship was struck by a breaking wave that, in combination with the ship's course and speed, caused the windows to shatter. At the time of the accident, the crew did not have the sufficient premises for predicting the risk associated with a breaking wave would reach so high up on the shipside with such great force. Based on the knowledge that existed at the day of the accident, the NSIA is of the opinion that the assessments made in connection with the voyage planning and operation seemed reasonable.

The examination of the design basis for the ship's windows identified no faults or non-conformities that would have had a bearing on the outcome of the wave hitting the windows. Nor have faults been found in the windows' installation and manufacturing basis. Further, the investigation has shown that the pressure from the breaking wave exceeded what the windows were designed to withstand.

It is not identified rules for ships or ship windows in any of the IACS-members ship rules, including DNV's rules for ships which accounts for the effects of breaking waves towards the shipside. The NSIA is of the opinion that the windows were inadequately dimensioned and that the design pressure requirements in the current regulations for windows in this position yield too low values to be able to withstand pressure loads from breaking waves within the extent of the validity of the rules. The NSIA addresses one recommendation concerning regulatory requirements to DNV relating to this matter.

The weather conditions in the Drake Passage and other areas with similar weather conditions will have a probability of breaking waves that has to be taken into account when operating in these waters.It is therefore a possibility that 'Viking Polaris' and her sister ship 'Viking Octantis' will be exposed to breaking waves against the side of the ship if they are operating in beam sea with increasing wind. The NSIA considers that a robust design that takes account of breaking waves will be a necessary barrier to reduce the probability of damages to the shipside. The current dimensioning of the windows means that they will not be able to withstand the pressure from all breaking waves which may arise within the extent of validity of the rules. The NSIA addresses two recommendations concerning reinforcement of the windows, one recommendation concerning this matter to the Norwegian Maritime Authority and one to Viking Expedition Ship II LTD in collaboration with Wilhelmsen Ship Management (Norway) AS.

[1] *Zodiac MilPro MK 5 HD.*

About the investigation

Purpose and method

The NSIA has classified the incident as a very serious marine casualty. The purpose of this investigation has been to determine the cause of the Zodiac accident and why the windows in several staterooms broke. The NSIA has also considered what can be done to improve safety and prevent the recurrence of similar incidents in future.

The accident and the circumstances surrounding it have been investigated and analysed in line with the NSIA's framework and analysis process for systematic safety investigations (the NSIA method[2]).

Organisation of the investigation

The safety investigation into this incident is being conducted in accordance with the Norwegian Maritime Code, chapter 18 II implementing IMO Resolution MSC.255(84) Casualty Investigation Code (CIC) and Directive 2009/18/EC of the European Parliament and of the council of 23 April 2009.

The Norwegian Safety Investigation Authority (NSIA) has been the lead investigating authority. The United States of America (USA) and Argentina were considered Substantially Interested States (SIS) in accordance with the Norwegian Maritime Code section 474. The United States Coast Guard (USCG) and the Junta de Seguridad del Transporte (JST) has worked with the NSIA as representatives of SIS. Personnel from USCG Activities Europe participated and assisted the NSIA throughout this investigation.

Sources of information

The factual information is based on interviews with crew members and passengers on board in addition to documentation from the classification society, shipyard, ship management company and suppliers. In addition, the Zodiac's inflatable centre keel has undergone examination by the research institute SINTEF. The keel was examined for external damage and structural defects.

The consultancy company 7Waves has assisted the NSIA in reviewing the basis for design, construction and installation. The consultancy company has also provided assistance in the review of the regulatory framework and investigation of the wave's characteristics.

The investigation report

The first part of the report, 'Factual information', describes the sequence of events, related data and information gathered in connection with the accident, what the NSIA has investigated and related findings.

The second part, the 'Analysis' part, contains the NSIA's assessment of the sequence of events and contributing causes based on factual information and completed investigations/examinations. Circumstances and factors found to be of little relevance to explaining and understanding the accident will not be discussed in any detail.

The final part of the report contains the NSIA's conclusions and safety recommendations.

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[2] *See https://www.nsia.no/About-us/Methodology*

1. Factual information

1. Factual information

1.1 Sequence of events

1.1.1 EVENTS LEADING UP TO THE ACCIDENT

On Friday 25 November 2022 at 18:00[3], the cruise ship ‘Viking Polaris’ left Ushuaia in Argentina for an eleven-day Antarctica cruise, scheduled to return to Ushuaia on 6 December 2022; see Figure 3 for an overview of the area. The ship had a crew of 266 and 309 passengers on board. On 27 November, ‘Viking Polaris’ arrived at Brabant Island in Antarctica; see Figure 4.

Figure 3: Map of the waters between the mainland and the northern tip of the Antarctic Peninsula where ‘Viking Polaris’ was to conduct her voyage. Map: Norwegian Coastal Administration AIS / Text by the NSIA

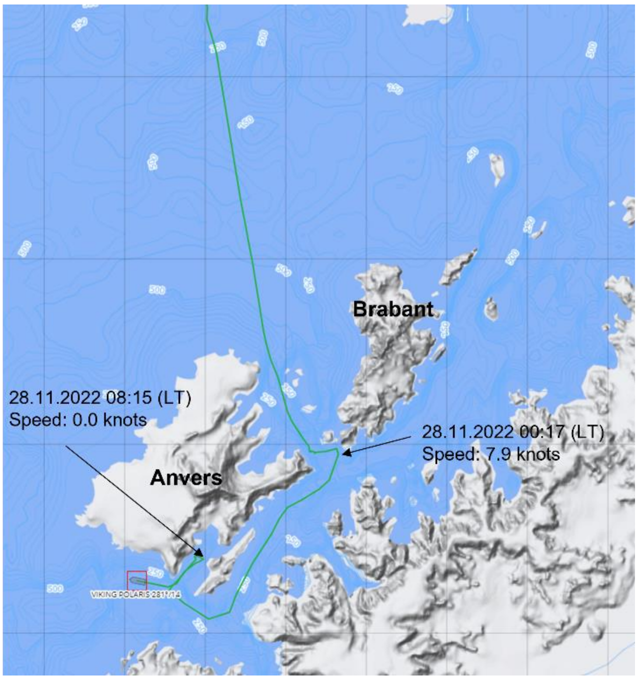

Figure 4: AIS track for ‘Viking Polaris’ when she reached Antarctica and the islands of Brabant and Anvers. Map: Norwegian Coastal Administration AIS / Text by the NSIA

On the morning of 28 November, ‘Viking Polaris’ was south of Anvers Island in Antarctica, and the plans for the day included various activities for the passengers involving the ship’s Zodiacs and one of the submarines. Several Zodiacs were launched before the excursions to be prepared and inspected to ensure that they were properly inflated etc. In that connection, it was decided that Zodiac number 22 would be brought back on board to be topped up with air.

The Zodiac’s inflatable keel and main tubes were inflated using compressor air, but the pressure was not checked with a pressure gauge/manometer. At about 07:32, Zodiac number 22 was relaunched.

Six passengers who were going on a submarine excursion boarded Zodiac number 22, which was to transport them to the submarine. They were all wearing inflatable lifejackets and the expedition clothing available to passengers. As the submarine was not quite ready for them to embark, the able seaman who was operating the Zodiac was told to take a short trip around to look at the local

[3] Local time

fauna first. The Zodiac was travelling at a speed of about 1 knot, and the wind and wave conditions were calm.

Suddenly some sort of explosion occurred on board the Zodiac. One of the passengers, who was seated forward on the starboard side of the boat, experienced to be thrown into the air and fell down into the Zodiac. The passenger sustained fractures in both legs. Another passenger, who was seated in the middle position on the starboard side and holding on to the rope running along the tube with one hand, was thrown overboard by the explosion. He did not let go when he fell overboard and was therefore pulled along by the Zodiac for a few seconds until the boat came to a stop. His lifejacket did not inflate. Two of his fellow passengers grabbed him and tried to pull him up with his back against the tube. As the expedition clothing was wet and slippery, it took two or three attempts before they finally succeeded in pulling him back on board with the help of the able seaman. See Figure 5 for an overview of where the passengers were seated on the Zodiac.

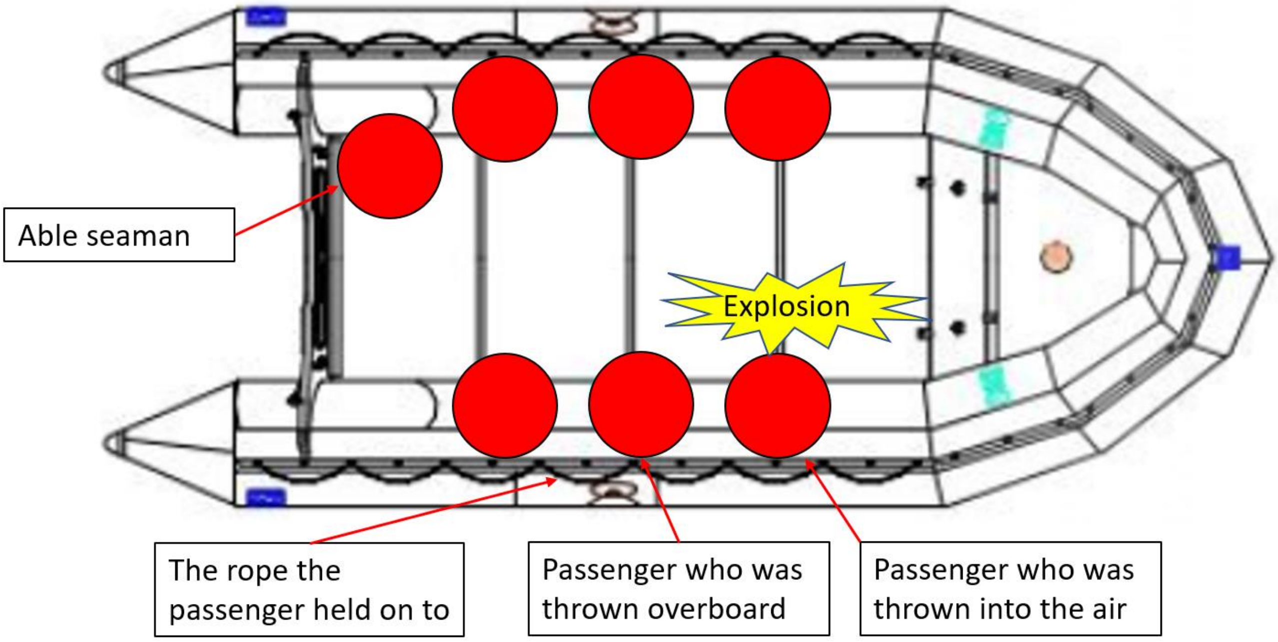

Figure 5: Overview of the positions of the passengers and the able seaman on board the Zodiac. Illustration: Supplier/NSIA

At 08:20, immediately after the incident, the Zodiac operator called 'Viking Polaris' on the radio to report the incident and request assistance. The ship's special operations boat (SOB) Sierra 4, which was about 500 metres away, immediately went to assist the Zodiac. At 08:24, they started to transfer the passengers from Zodiac 22 to Sierra 4. Another Zodiac without passengers also arrived to help.

At 08:35, a crew member from Sierra 4 entered Zodiac 22 to help with the injured passenger. Sierra 4 then reported back to 'Viking Polaris' that the passenger's injuries made it impossible to transfer her to Sierra 4, and it was decided that she had to be transferred directly from Zodiac 22 to 'Viking Polaris'.

At 08:47, the injured passenger was transferred from the Zodiac to the ship, and at 08:52, all the passengers were being taken care of in the ship's medical centre.

The ship's master, who had been informed of the incident immediately, and several of the ship's officers considered how to get the injured passenger ashore for further treatment. This was based on the medical assessment provided by the onboard medical personnel. Three different alternatives were considered for transporting the injured person to hospital. The alternatives were an evacuation by air (organised by Chile) from King George Island, approx. 200 nautical miles away, a transfer to their sister ship 'Viking Octantis', which had an earlier arrival date in Ushuaia, or interrupting the cruise and heading for Ushuaia. The master was also aware that the wind was picking up and decided that all expedition activities were to be discontinued.

The weather forecast for the area around King George Island predicted poor conditions, and the voyage there was estimated to take 16–20 hours. Considering that the aircraft only had a four-hour window on the following day, in combination with the fact that the patient would have to be put in a Zodiac again to be transported to shore (0.7–1 nm), evacuation by air was not deemed to be a good solution. It would also have been highly stressful for the patient. Nor was it considered a good solution to transfer the patient from 'Viking Polaris' to 'Viking Octantis', as this would have involved putting the patient in a Zodiac again, which was deemed too stressful for the injured passenger. The master informed the ship's owner of the situation, and they agreed that the safest option was to return to Ushuaia. It was therefore decided to interrupt the cruise and head for Ushuaia. The master informed all the passengers about the decision in the ship's aula, and the information was transferred live to all staterooms over the PA system.

1.1.2 THE ACCIDENT

On 28 November at about 15:00, the ship started her voyage towards Ushuaia from a position directly south of Anvers Island. The master checked the weather forecast in the afternoon of 28 November and noted that the weather would worsen the closer they came to Cape Horn as 29 November wore on. The forecast predicted westerly winds of up to 40 knots and a significant wave height of as much as 6 metres with wave periods of 11 seconds. The bridge team were also aware that they might experience higher wind speeds and waves than forecast, which they also took into consideration. In their experience, the ship's stability was excellent and she did not move much, not even in heavy weather, so they did not expect the weather forecast to present a problem for the ship. Based on the above, they set a straight a course as possible for Ushuaia based on a speed of 16–17 knots to beat the worst of the weather forecast south of Cape Horn. They checked weather forecasts from several different sources, and the master also used a weather app where you could enter the route and continuously monitor the weather on a mobile phone.

Before departure from Antarctica, the master and officers had discussed the route and weather conditions. This was in accordance with normal procedures on board. In connection with the route planning, the navigation officer had drawn up a passage plan with waypoints, route, speed, ETA[4] etc. that was evaluated in consultation with the master. A short meeting to review the passage plan was then held on the bridge with key officers including the navigation officer, staff captain, officer of the watch and master.

A heavy weather checklist was also completed, since the weather was expected to worsen as they approached Cape Horn. This checklist included assessments of the course, speed and weather forecast, which were carried out and checked off. At 18:08, the master issued a message to all departments on board the ship for the crew to secure their workplaces and staterooms and close deadlights because high swells and strong winds were expected during the crossing of the Drake Passage. Stronger westerly winds and swells of around 7 metres were forecast from the afternoon of 29 November.

The chief engineer was instructed that they needed full speed on all four engines. The ship kept a steady course of around 356 degrees (COG[5]) and an even speed of 16–17 knots.

At 08:30 on 29 November, the ballast was adjusted to prevent the ship from listing to starboard in the wind by transferring 47.2 m^3 from starboard ballast tank number 34 to port ballast tank number

[4] Estimated time of arrival.
[5] Course Over Ground.

33. Forward trim adjustments were made at 09:20 and 10:20 by emptying the aftmost ballast tanks, numbers 44 and 43, with 65.1 m^3 and 80.2 m^3, respectively.

Later that day, shortly before 20:00, the second officer came on duty. The bridge team on this watch (20:00–24:00) also comprised two third officers, one of them a junior officer, and an able seaman in the role as lookout. The bridge team checked the weather forecast as they normally did every hour. The forecast showed increasing winds, and gusts of up to 75 knots were measured. The ship was still on a steady northbound course (about 354 degrees COG) travelling at a speed of approx. 16 knots.

The ship was listing about 1 degree to starboard due to the strong westerly wind, and another ballast transfer was carried out at 20:44 by transferring 56.7 m^3 from starboard ballast tank number 18 to port ballast tank number 17.

There was not much movement in the ship even though the weather was worsening as they approached Cape Horn in the evening of 29 November. The bridge team observed that the waves were coming from the same direction to a greater extent than earlier during the voyage, but the ship was stable and did not roll much. The master and the staff captain paid a visit to the bridge at around 20:22 in the evening to check with the officers on watch that things were going as planned. They noticed that the waves lifted the ship slightly, but there was no crashing against the side of the ship or any concerns relating to the ship's movements. The master then left the bridge and went to the passenger areas to check that everything was all right there too. During the half hour leading up to the accident, sea spray reached the bridge several times. The master returned to the bridge at 22:30 to check the weather conditions.

At approximately 22:35, a powerful wave hit the port side of the ship. Figure 6 to Figure 11 show how the wave hit the side of the ship, viewed from cameras on deck 5 on the port side.

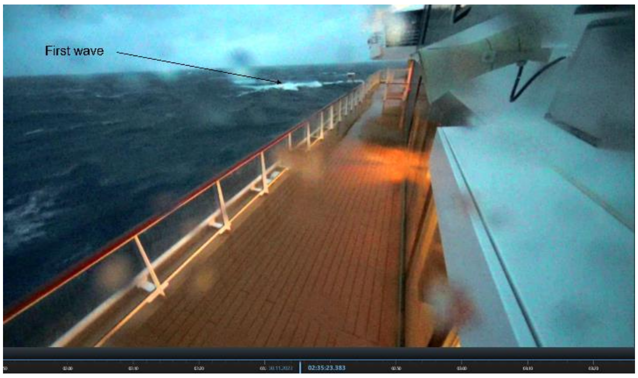

Figure 6: The first wave at 22:35:23. Source: CCTV

Figure 7: The first wave hitting the side of the ship. White foam is visible in the trough that follows at 22:35:28. Source: CCTV

Figure 8: The second wave near the side of the ship at 22:35:34. Source: CCTV

Figure 9: The second wave approaching the side of the ship at 22:35:36. Source: CCTV

Figure 10: The wave hits the side of the ship at 22:35:37. View from the forward camera on deck 5. Source: CCTV

Figure 11: The wave hitting the side of the ship at 22:35:37. View from a camera further aft on deck 5. Source: CCTV

Immediately before the accident, the ship was sailing on a course of 344 degrees (COG 353 degrees) at a speed of 16.7 knots. The bridge team heard a crash against the ship's side, and for a moment they could not see out of the bridge windows because of the wave washing up the ship. Items fell to the floor, and the ship vibrated briefly following the wave impact. Several of the passengers and crew members had to hold on to something so as not to fall over, and some people fell out of the chairs they were sitting in. Shortly thereafter, an alarm went off indicating that the smoke detectors on deck 2 were disconnected, and the staff captain arrived on the bridge. The staff captain was then ordered to go down to deck 2 to get an overview and arrived at approximately 22:38. Another crew member had already arrived. The staff captain called the bridge to inform them that there was water ingress and tell them to change course immediately to turn the stern to the wind. The bridge crew forwarded this message to the master. Via CCTV, the bridge team could see that there was water entering the corridor on deck 2, that there was a strong wind and that some of the passengers had started to come out of their staterooms.

Figure 12: Broken windows in staterooms on deck 2 on board 'Viking Polaris' after arrival in Ushuaia. Photo: NSIA

The passengers who exited the damaged area after the incident were promptly taken care of by the crew members who had arrived. The staff captain started a systematic search of all staterooms in the damaged area on deck 2. It was quickly ascertained that the damage was significant (see Figure 13 and Figure 14), and the master and the bridge team were informed.

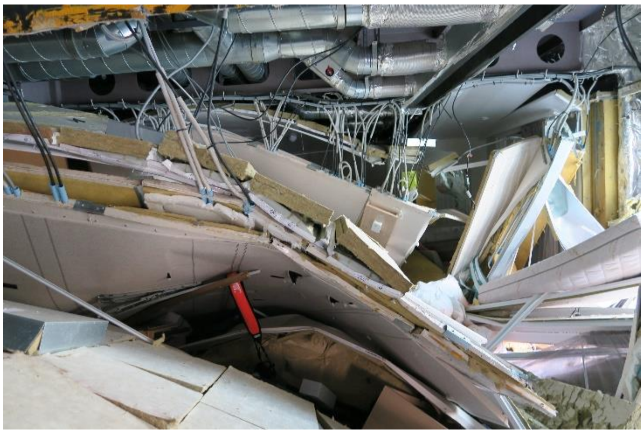

Figure 13: Photo from stateroom area showing damage to partition walls, floor and furnishings. Photo: NSIA

Figure 14: Broken windows in staterooms 2016 and 2014. Photo: NSIA

At 22:40, the master announced code Delta[6] (damage) on deck 2 in fire zone 2 on the port side. The crew therefore proceeded to their posts according to the emergency code. At the same time, the master ordered a course change to protect the damaged section on the port side from the weather, and the ship proceeded on a more north-easterly course (50–60 COG).

As more people emerged from the damaged area, they got a clearer picture of the extent of the damage, and medical personnel on board were called, as several of the passengers had sustained injuries. At 22:47, an announcement was made over the PA system informing everyone on board that the ship had sustained water ingress and that there were broken windows forward on decks 2 and 3 on the port side. The staff captain and the master agreed not to raise the general alarm and muster the passengers, as the damage was limited to a small area and they believed the situation was under control. It was later confirmed that there were no broken windows on deck 3. One minute later, another announcement was made instructing all passengers to remain in their respective staterooms except for the passengers in the damaged area, who were instructed to proceed to deck A midship.

At 22:53, the master ordered the speed to be reduced from about 15 knots to 10 knots. At 22:57, the master called the ship management company's emergency number to inform them about the incident. At 23:05, the staff captain reported that all the staterooms from 2000 to 2016 had been cleared. It was confirmed that a passenger had been found dead in stateroom 2020. The person was found on the floor under partition walls, pieces of ceiling and furniture that had been thrown about by the wave. At 23:14, another PA announcement informed the passengers that several windows had been broken on deck 2, but that the situation was now under control.

At about the same time, the onboard medical personnel confirmed that three passengers had suffered minor physical injuries and one had sustained a back injury and hypothermia, but was in a stable condition. The injured passengers were immediately attended to by medical personnel. At approximately 23:24, the deceased was removed from stateroom 2020, and an order was issued to account for all passengers on board. At 23:52, it was reported that all passengers had been accounted for.

At 24:00, another vessel about 25 nautical miles north of 'Viking Polaris' was contacted for information about the weather conditions in the area. The vessel reported back that there were north-westerly winds of 25 knots and swells of 4 metres. The course was then set to 40 degrees, and the master ordered the damaged area to be monitored until they arrived in sheltered waters.

[6] *Code used to notify the crew of water ingress or grounding.*

'Viking Polaris' arrived in Ushuaia at about 10:00 on 30 November. Figure 15 shows the AIS track for 'Viking Polaris' from the ship left Antarctica until arrival in Ushuaia.

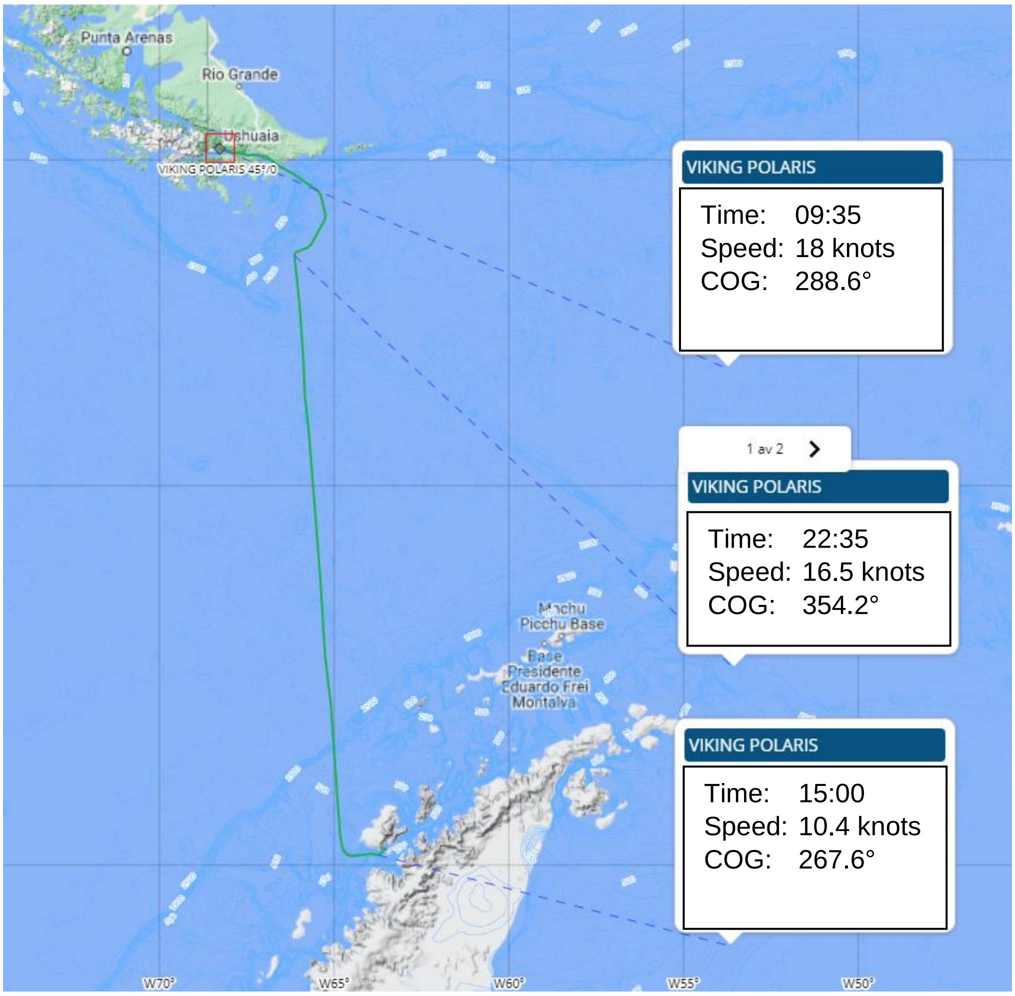

Figure 15: AIS track of 'Viking Polaris' from the ship left the south side of Anvers Island on 28 November until arrival in Ushuaia on 30 November 2022. Map: Norwegian Coastal Administration AIS

1.2 Personal injuries

One person sustained severe fractures to both legs and one fell into the water and sustained minor injuries as a result of the incident on board the Zodiac on 28 November 2022.

One person died as a result of injuries sustained in connection with the wave that crashed into the stateroom area on board 'Viking Polaris' on 29 November 2022. Based on the patient overview after the accident, eight people in the same stateroom area sustained injuries as a result of the wave that struck.

1.3 Damage to the ship and equipment

1.3.1 WINDOWS AND FIXINGS

Seven stateroom windows on the port side of deck 2 shattered when the wave struck the ship. The first broken window was the fifth window on the port side of deck 2; see Figure 16 and Figure 17. No damage was observed to the hull plate directly below the windows. NSIA has later been information about some water entering two staterooms on deck 3. These windows were replaced, along with a total of 9 windows on deck 2 in connection with the repair work.

Figure 16: Staterooms where the windows were damaged indicated in red. Photo: NSIA

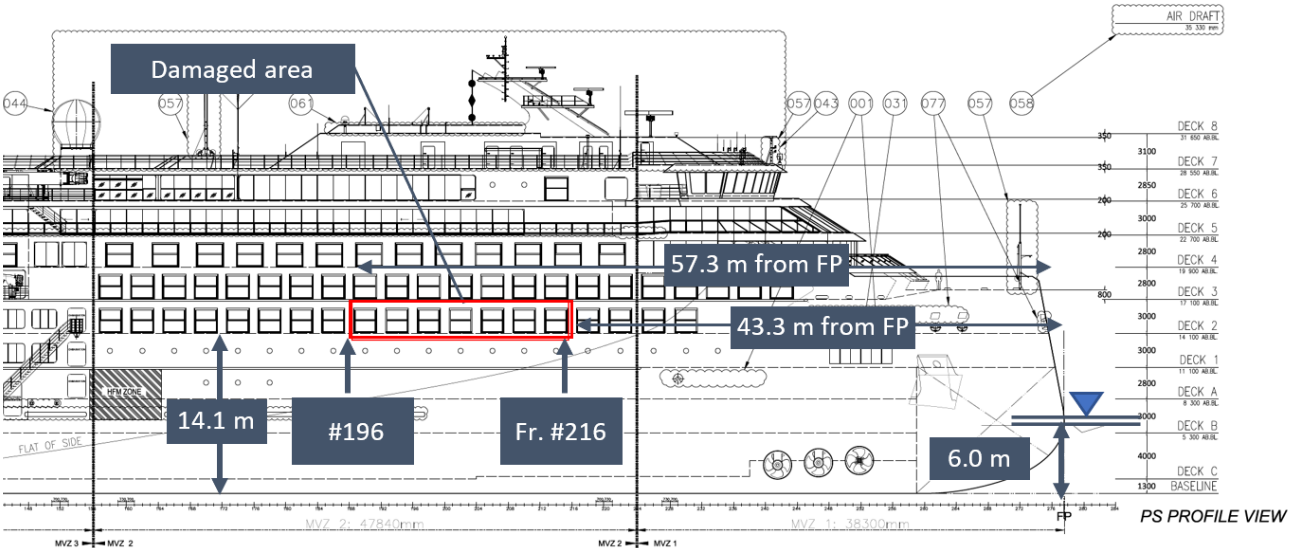

Figure 17: Illustration of the damaged area. The drawing is from starboard side, however the vessel has corresponding arrangement on port side where the damages occurred. Technical drawing: Shipyard, text boxes: consultant

Figure 18 shows a close-up of the broken windows. In several of the staterooms where the windows had broken, the frames were damaged and had been pushed into the stateroom, mainly in the bottom aft corner. In four of the seven staterooms, both the upper and lower windows were broken, while in three staterooms, the upper window was intact.

Figure 18: Damage to windows and frames in the damaged area on deck 2. Photo: NSIA

Figure 19 to Figure 31 show damage to the windows and frames in the seven staterooms in question.

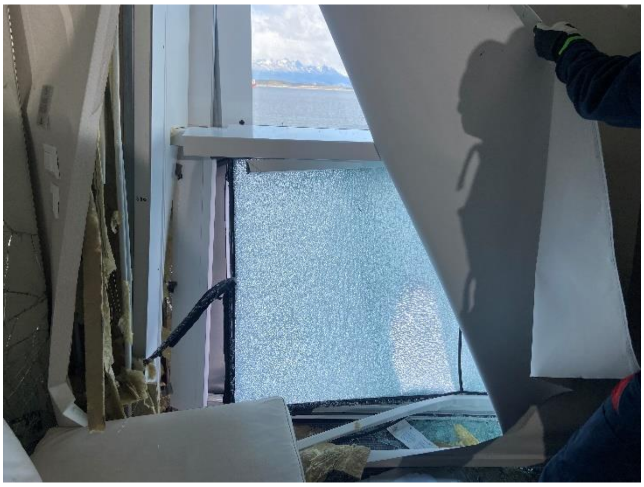
Figure 19: Damage to window and frame in stateroom 2008. Photo: NSIA


Figure 20: Damage to window and frame in stateroom 2008. Photo: NSIA


Figure 21: Damage to window and frame in stateroom 2010. Photo: NSIA


Figure 22: Damage to window and frame in stateroom 2010. Photo: NSIA

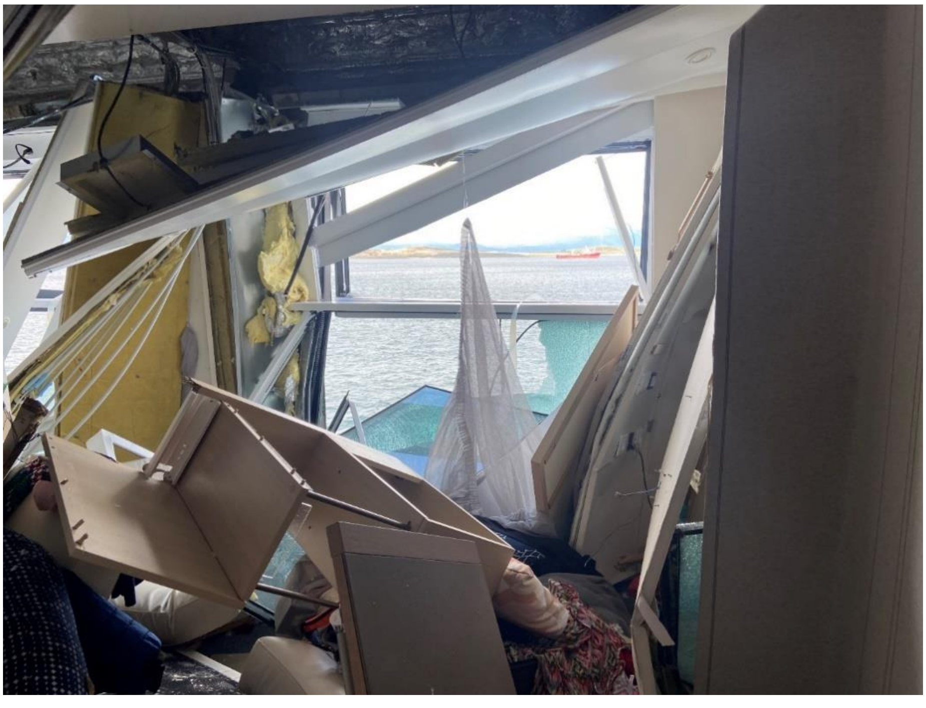
Figure 23: Damage to window, frame and stateroom 2012. Photo: NSIA

Figure 24: Damage to window in stateroom 2014. Photo: NSIA

Figure 25: Damaged window frame in stateroom 2014. Photo: NSIA

Figure 26: Broken window in stateroom 2016. Photo: NSIA

Figure 27: Broken window in stateroom 2016. Photo: NSIA

Figure 28: Damage to window in stateroom 2018. Photo: NSIA

Figure 29: Window frame in stateroom 2018. Photo: NSIA

Figure 30: Damage to window and frame in stateroom 2020. Photo: NSIA

Figure 31: Damage to upper window frame in stateroom 2020. Photo: NSIA

Issues had been reported with gaskets on some of the windows on deck 2 that did not provide a proper seal, resulting in noises in strong wind. This did not apply to the damaged windows, and has therefore not been looked into in more detail.

1.3.2 STATEROOMS AND CORRIDOR

There was extensive damage in the stateroom area. The damage from the seawater entering through the broken windows resulted in extensive damage from stateroom 2008 back to stateroom 2022, a total of 8 staterooms. The ceiling, furniture and partition walls were dislodged, and the walls were open between several of the staterooms. Figure 32 and Figure 33 show damage to staterooms 2010 and 2012.

Figure 32: Damage in stateroom 2010. Photo: NSIA

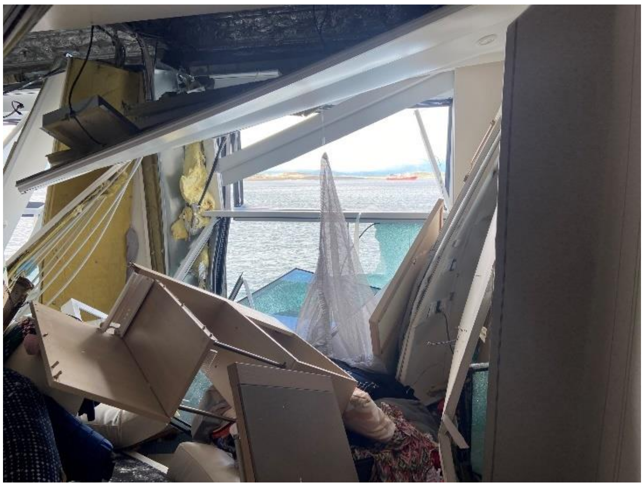

Figure 33: Damage in stateroom 2012. Photo: NSIA

Figure 34 and Figure 35 show the part of the stateroom area that sustained the most damage. The ceiling had fallen down and walls between staterooms had been torn up and pushed backwards.

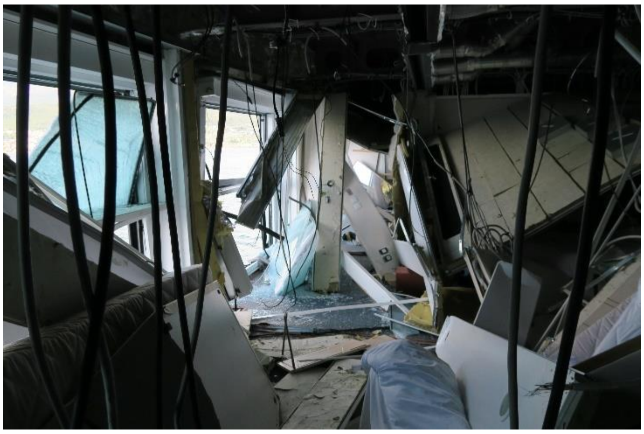

Figure 34: Photo taken from stateroom 2018 also showing damage to staterooms 2016, 2014 and 2012. Photo: NSIA

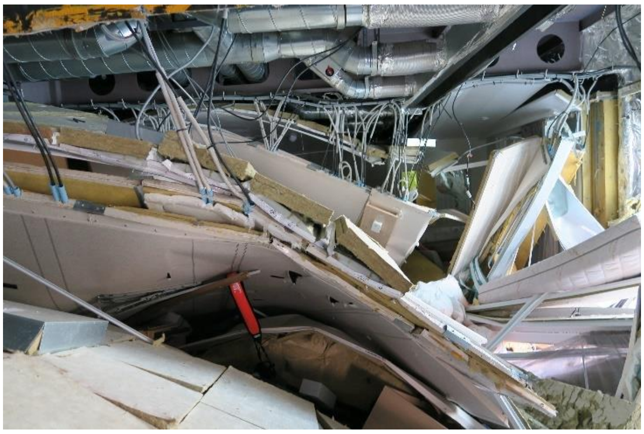

Figure 35: Photo from the damaged stateroom area showing how the ceiling and walls have been dislodged and pushed together. Photo: NSIA

Figure 36 and Figure 37 show damage to the corridor on deck 2 on the port side.

Figure 36: Damage to corridor viewed from staterooms 2010 and 2012 on deck 2, view towards the stern. Photo: NSIA

Figure 37: Damage to corridor and ceiling. Forward view. Photo: NSIA

The air pressure created by the wave had travelled up via the ceiling and pushed the wall of the corridor on the oposite side of the staterooms outwards.

1.3.3 DAMAGE TO THE HULL

Following the incident, a dent has been observed in the bow on the ship's port side. It was there also immediately after the incident, but rust has since formed around the edges of the dent; see Figure 38 and Figure 39. It cannot be confirmed whether this dent arose in connection with the wave that caused the accident. Shortly after the accident, there was a dent with no rust, and some months later, rust had formed.

Figure 38: Dent on the port side of the bow marked by a red square, photographed on 5 December 2022. Photo: NSIA

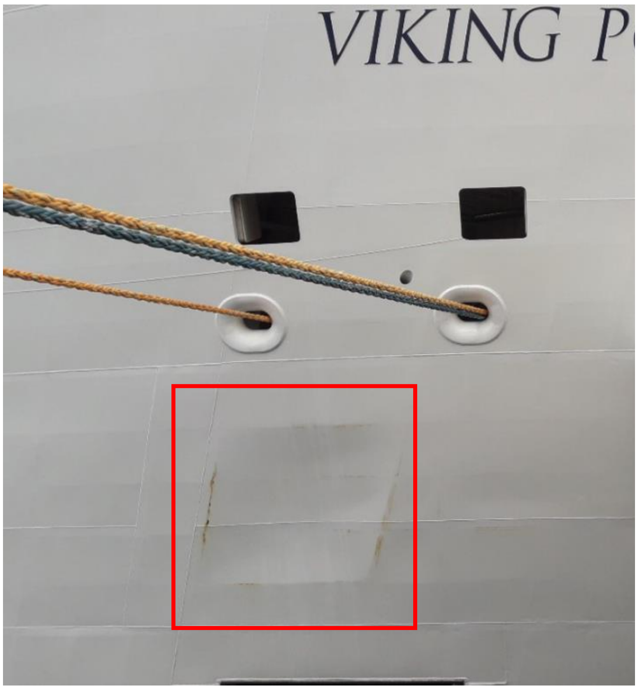

Figure 39: Dent on the port side of the bow marked by a red square, photographed on 25 February 2023. Photo: The ship management company

The NSIA has attempted to gather documentation to confirm the period in which the dent arose. Based on the formation of rust since the accident, it seems highly likely that the dent arose on the day of the accident, but it has not been possible to confirm this. This will therefore not be discussed further in the analysis.

1.3.4 DAMAGE TO ZODIAC

The incident on board the Zodiac occurred as a consequence of some sort of explosion below the floorboards. Obvious dents were found in the aluminium floorboards. The floorboards were removed to inspect the damage. The centre keel below the floorboards had ruptured; see Figure 40. The keel was measured to 450 cm, and the tear was measured to 187 cm. No major foreign bodies were found at the bottom of the keel, but some sand was observed.

Figure 40 shows the Zodiac disassembled with the centre keel lying next to it, placed in a longitudinal position that reflects its position when attached to the boat. The velcro seen on top the keel was fastened to the keel.

Figure 40: The centre keel lying upside down next to the Zodiac. Photo: NSIA

The floorboards were reassembled and placed bottom up. There were clearly visible dents in the floorboard at the forward end of the boat on the starboard side, in addition to some minor denting where the keel had been; see the red circle in Figure 41.

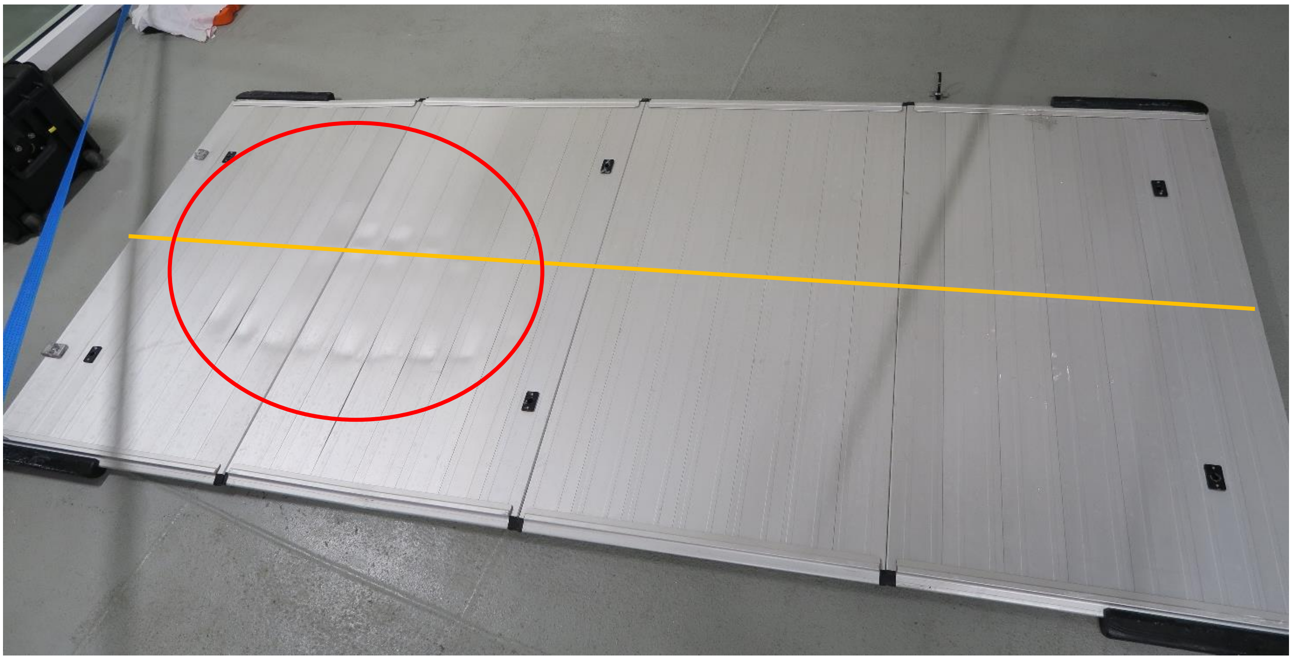

Figure 41: Floorboards lying bottom up. There are dents (red circle) that arose in connection with the incident. The orange line indicates where the central keel was located. Photo: NSIA

The centre keel was placed on top of the floorboards in its proper position, and when the torn part of the central keel was spread out, it followed the outline of the dents; see Figure 42.

Figure 42: The centre keel stretched out on the floorboards in the position it was in during the incident. Photo: NSIA

The floorboards in the damaged area were bent upwards by the explosion-like incident; see Figure 43 for a cross-section of a damaged floorboard.

Figure 43: The floorboards in the damaged area were bent. Photo: NSIA

During the investigations, glue separation damage was found in both futura tubes located under the Zodiac on either side; see Figure 44.

Figure 44: Glue separation damage on the futura tube. Photo: NSIA

1.4 Weather and sea conditions

1.4.1 GENERAL INFORMATION

The ship used weather services from the website Windy.com, NAVTOR and WeatherTrack for weather forecasts and weather monitoring during the voyage.

1.4.2 WEATHER AND SEA CONDITIONS ON THE DAY OF THE ACCIDENT

1.4.2.1 Weather forecast

Different weather forecast services were used on board to obtain information about what weather conditions to expect. It was not clearly stated which wave period parameters were given in the weather forecasts from the different services, i.e. whether it was Tp[7] or Tz[8]. According to the Norwegian research institute NORCE, a provider of wave forecasts, the norm is to use Tp, but Tz can also be used.

NAVTOR

The weather forecast service NAVTOR forecast increasing waves as the evening approached on 29 November along the route from Damoy in Antarctica to Ushuaia. With an estimated time of departure (ETD) of 18:00 (UTC), the weather forecast for the time when the accident occurred, 22:30 on 29 November, was as follows:

- Wind speed (10 m) of 40 knots (from west, northwest).
- Gusts of ~52 knots.
- Significant wave height (H_s) [9] of ~6 m with periods of 11 seconds.
- Maximum wave height ~10 m.
- Swells of ~5 m with wave periods of 11 seconds.

[7] Peak wave period. The wave period associated with the most energetic wave in the total wave spectrum at a specific point.
[8] Zero up-crossing period.
[9] The average of the highest one-third of wave heights. The maximum wave height can be significantly higher.

The NAVTOR weather forecast for the route from Damoy to Ushuaia on 28 November with an ETD[10] of 18:00 (UTC) and ETA[11] of 30 November at approximately 14:00 is shown in Figure 45 and Figure 46.

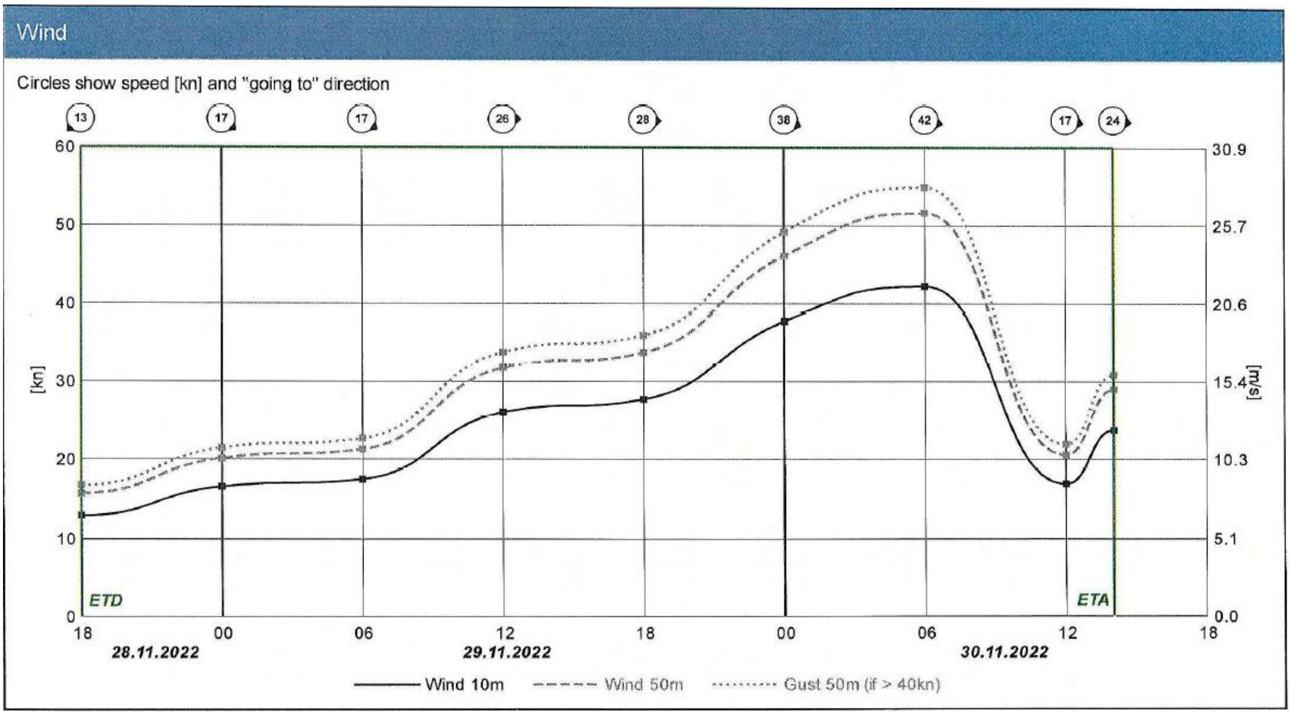

Figure 45: Weather forecast from NAVTOR – wind speed and direction. Source: Ship management company

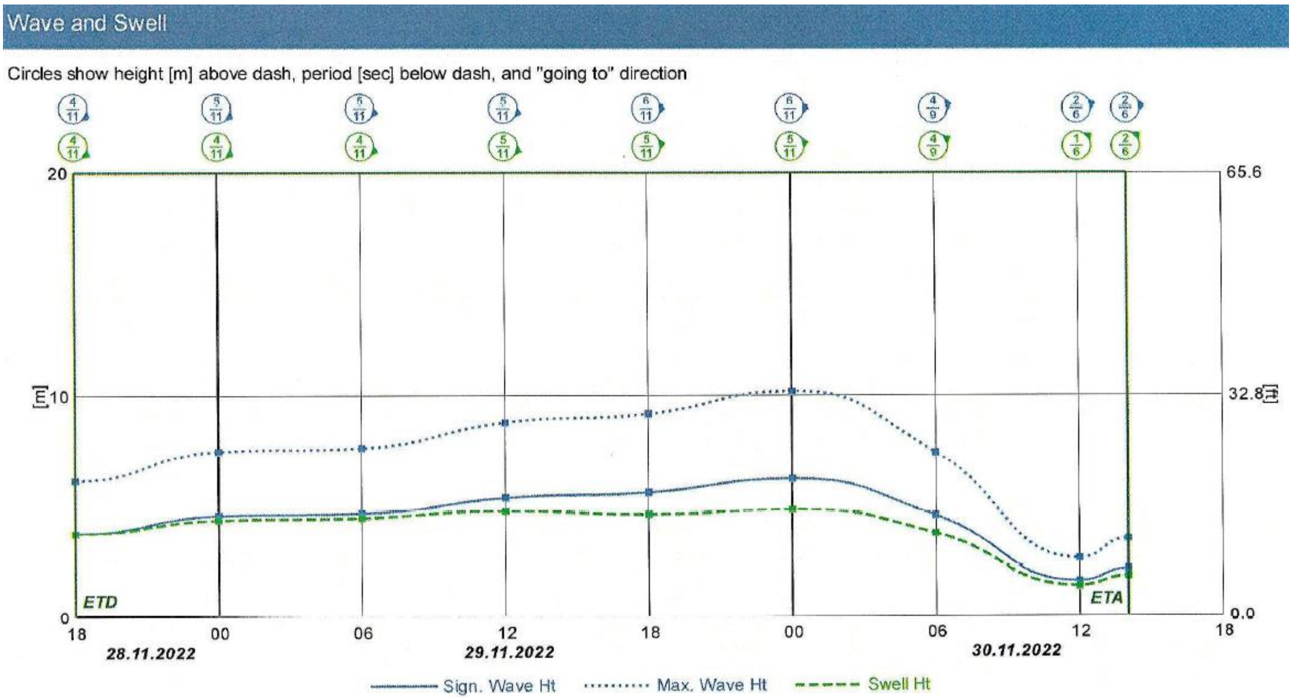

Figure 46: Weather forecast from NAVTOR – waves and swells. Source: Ship management company

Windy.com

The weather report retrieved from the Windy website at 05:49 (local time) in the morning of 29 November in the middle of the Drake Passage showed roughly the same as the weather

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[10] *ETD – Estimated time of departure*
[11] *ETA – Estimated time of arrival*

forecast from NAVTOR – wind from a northwesterly direction, and wind speed and gusts of 35 and 50 knots, respectively. The temperature was 2 °C, with light rain (~1 mm) in the air.

WeatherTrack

The weather forecast app also forecast wave heights of up to 6 m and wave periods of ~11 seconds, which tallies with both the NAVTOR and Windy forecasts; see Figure 47 and Figure 48.

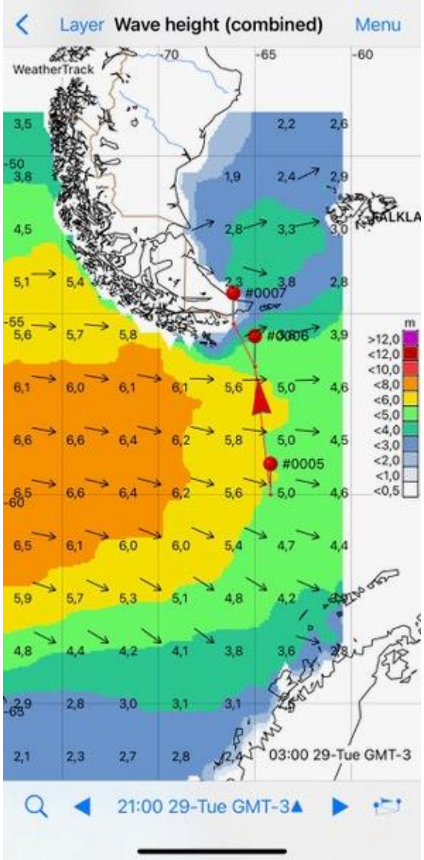


Figure 47: Wave height from weather app at 21:00 on 29 November 2022 LT. Source: Ship management company

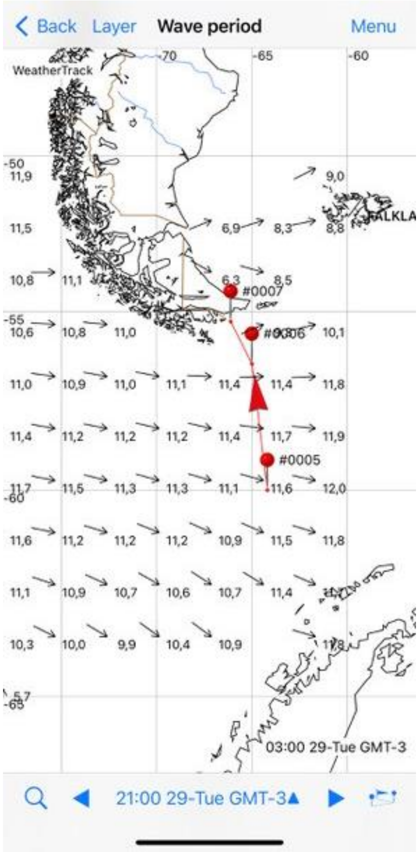


Figure 48: Wave period from weather app at 21:00 on 29 November 2022 LT. Source: Ship management company

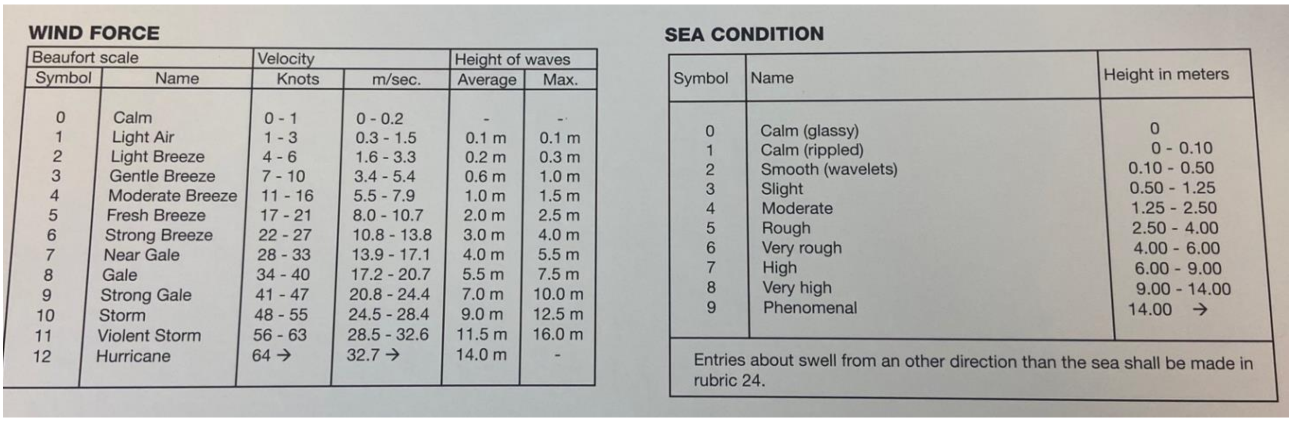
1.4.2.2 Weather observed on board

Table 1 shows observations from the deck log book in the hours leading up to the accident and at the time of the accident.

Table 1: Wind direction, wind speed and sea state from the deck log book for the hours leading up to the accident. Source: Viking Polaris

Ship time	Wind direction (from)	Wind speed	Sea state
18:00	West	Beaufort 9, strong gale	6, Very rough
19:00	West	Beaufort 10, storm	7, High
20:00	West	Beaufort 10, storm	7, High
21:00	West	Beaufort 10, storm	7, High
22:00	West	Beaufort 11, violent storm	7, High
23:00	West	Beaufort 11, violent storm	7, High

During the final five minutes before the accident, wind speeds of 27–39 m/s (53–76 knots) were measured on board the ship. Figure 49 shows codes from the deck log with pertaining values for wind force and sea condition. The bridge team had experienced that the wind could be even worse than what was forecasted, and that the weather could change quickly.



WIND FORCE

Beaufort scale		Velocity		Height of waves	
Symbol	Name	Knots	m/sec.	Average	Max.
0	Calm	0 - 1	0 - 0.2	-	-
1	Light Air	1 - 3	0.3 - 1.5	0.1 m	0.1 m
2	Light Breeze	4 - 6	1.6 - 3.3	0.2 m	0.3 m
3	Gentle Breeze	7 - 10	3.4 - 5.4	0.6 m	1.0 m
4	Moderate Breeze	11 - 16	5.5 - 7.9	1.0 m	1.5 m
5	Fresh Breeze	17 - 21	8.0 - 10.7	2.0 m	2.5 m
6	Strong Breeze	22 - 27	10.8 - 13.8	3.0 m	4.0 m
7	Near Gale	28 - 33	13.9 - 17.1	4.0 m	5.5 m
8	Gale	34 - 40	17.2 - 20.7	5.5 m	7.5 m
9	Strong Gale	41 - 47	20.8 - 24.4	7.0 m	10.0 m
10	Storm	48 - 55	24.5 - 28.4	9.0 m	12.5 m
11	Violent Storm	56 - 63	28.5 - 32.6	11.5 m	16.0 m
12	Hurricane	64 →	32.7 →	14.0 m	-

SEA CONDITION

Symbol	Name	Height in meters
0	Calm (glassy)	0
1	Calm (rippled)	0 - 0.10
2	Smooth (wavelets)	0.10 - 0.50
3	Slight	0.50 - 1.25
4	Moderate	1.25 - 2.50
5	Rough	2.50 - 4.00
6	Very rough	4.00 - 6.00
7	High	6.00 - 9.00
8	Very high	9.00 - 14.00
9	Phenomenal	14.00 →

Entries about swell from an other direction than the sea shall be made in rubric 24.

Figure 49: Codes from the deck log with pertaining values for wind force and sea condition. Source: Deck log

The bridge team have subsequently estimated the wave height of the wave that caused the accident to be about 12–14 metres.

1.5 Description of waters

1.5.1 GENERAL INFORMATION

The Drake Passage is the body of water that separates the Antarctic Peninsula from Tierra del Fuego and Cape Horn, the southern tip of Southern America, and links the southern Pacific Ocean with the southern Atlantic Ocean.

1.5.2 WIND AND SEA CONDITIONS

1.5.2.1 Sea conditions

According to the Admiralty Sailing Directions, Antarctic Pilot,[12] the waves in this area are created by wind and sea conditions throughout the year, and bear similarities with the sea conditions in the North Atlantic in winter. The worst conditions are found between 45 and 60 degrees south. The

[12] *Admiralty Sailing Directions, Antarctic Pilot, comprising the Coasts of Antarctica and all islands south of the usual route for vessel, ninth edition 2019.*

Southern Ocean is a stormy area, and there is a probability of encountering abnormally large waves. When waves move towards shallower waters, as they do in the Drake Passage, they will slow down and become steeper.

The wave data available for this area are very limited. The wave direction for the majority of sea states between Antarctica and Cape Horn are between SW and NW; see Figure 50 for the expected wave distribution for January. The direction of waves are towards the centre of the circle and the number indicates the percentage of calm sea, which in this area ranges between 0 and 2%. If we look at the wave heights west of Cape Horn, we see that they are mostly between 2.3 and 6.2 metres.

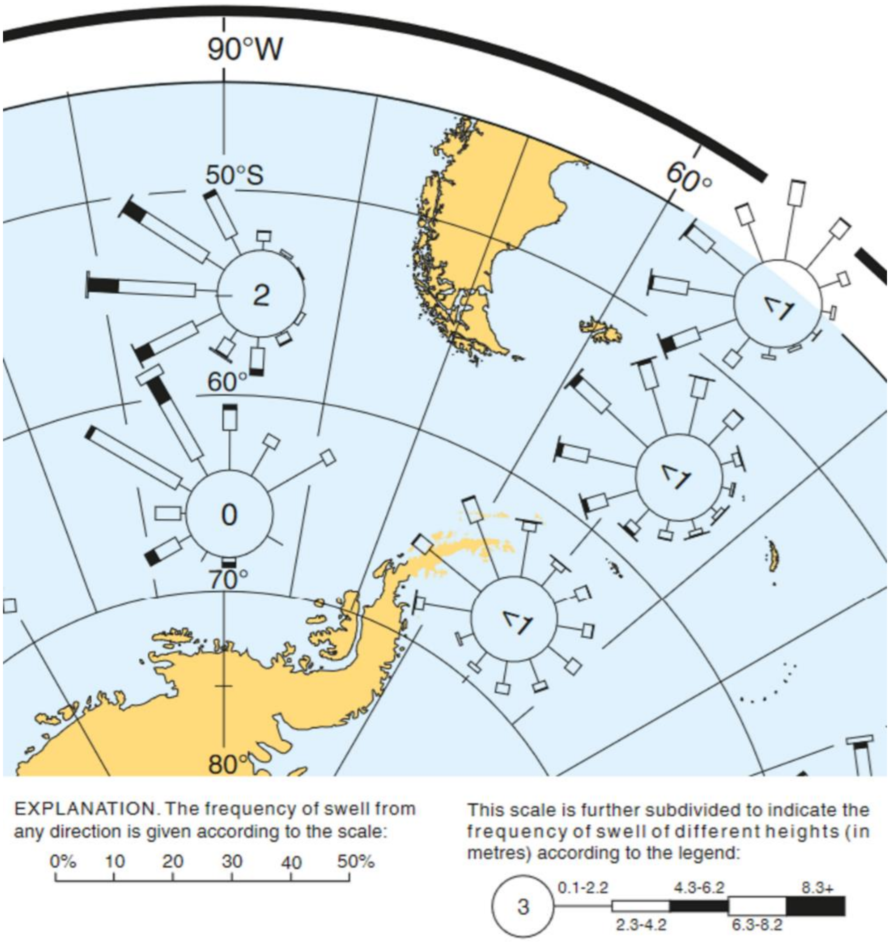


Figure 50: Wave distribution map describing the frequency of directions and heights of swells between Antarctica and Cape Horn. Illustration: The Admiralty

1.5.2.2 Wind conditions

The wind direction between Antarctica and Cape Horn in summer is mostly from somewhere between SW and NW; see Figure 51 for a breakdown of expected wind forces for November. The wind direction is towards the centre of the circle and the number indicates the percentage of calm, which is 1–2%. If we look at the wind force just south of Cape Horn, we see that it is mostly between 5 and 12 on the Beaufort scale.

Figure 52 illustrates how much of the time the wind force is Beaufort 7[13] or more in November. In the area where the accident occurred, it is expected to be 25–30% of the time. It is also stated that

[13] *Near gale, wind speed 28–33 knots, sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.*

the information should be treated with caution, as there are limited data available and the weather conditions are probably worse than the illustration shows.

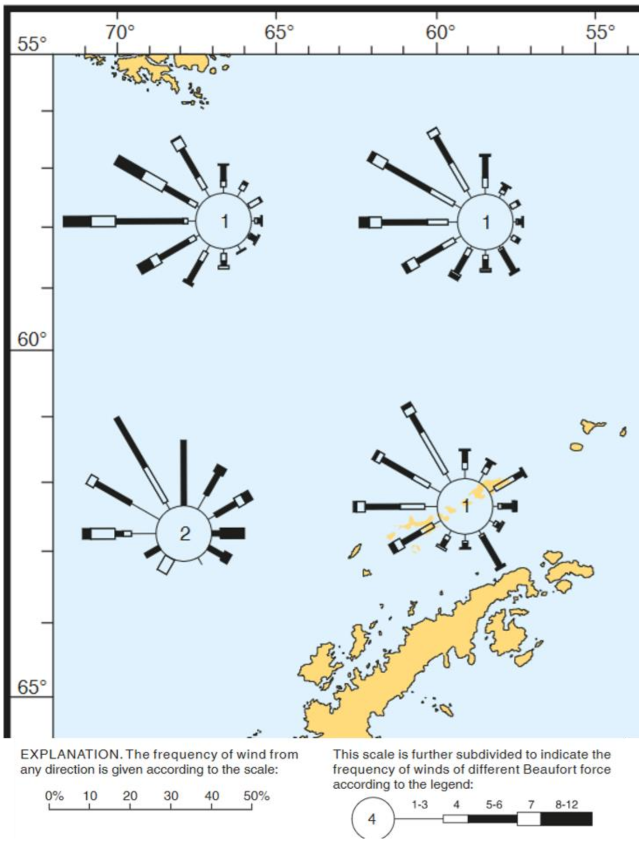


Figure 51: Wind speed distribution map describing the frequency of wind directions and force between Antarctica and Cape Horn in November. Illustration: The Admiralty

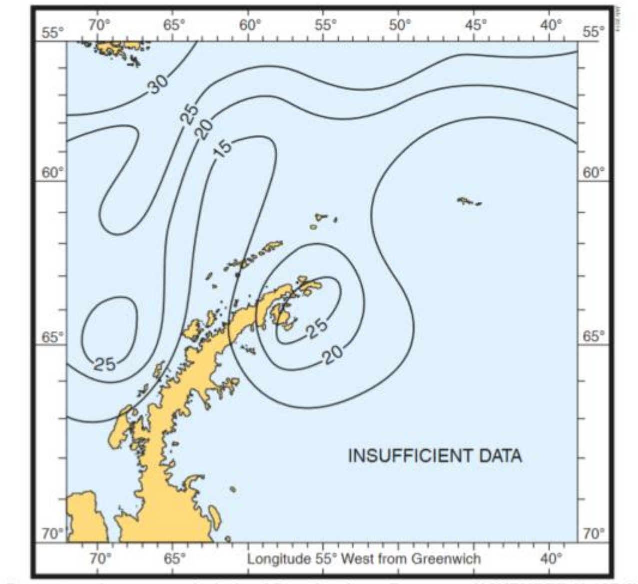


Figure 52: Percentage frequency of wind force 7 or higher on the Beaufort scale between Antarctica and Cape Horn in November. Illustration: The Admiralty

According to the Admiralty, storms, particularly from a westerly direction, are frequent in the Drake Passage, and visibility can be poor.

1.5.2.3 The effect of wind on the sea

Winds will have an effect on the characteristics of the sea and the development of wave patterns. Table 2 shows the effect of wind on the sea in open waters when the wind has been blowing for long enough for the characteristic wave pattern to have developed, i.e. fully developed sea state.

Table 2: The effect of wind on the sea from Beaufort force 6 and higher. Source: Store norske leksikon/Norwegian Meteorological Institute

Beaufort	Designation	Knots	The effect of wind on the sea
6	Strong breeze	22–27	Large waves begin to form; the white foam crests are more extensive everywhere. Probably some spray.
7	Near gale	28–33	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
8	Gale	34–40	Moderate high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.
9	Strong gale	41–47	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.
10	Storm	48–55	Very high waves with long over-hanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes on a white appearance. The ‘tumbling’ of the sea becomes heavy and shock-like. Visibility affected.
11	Violent storm	56–63	Exceptionally high waves (small and medium-sized ships might be for a time lost behind the waves). The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth.
12	Hurricane	>63	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.

As the wind grows stronger, the waves will absorb energy from the wind, and their size and speed will increase. The shape of the waves will also change in that waves become steeper, which increases the probability of the wave breaking. When a wave breaks, it will become less energetic, and the wave height will decrease.

Breaking waves:

Waves can break because they become too high in relation to their length. Breaking limits the growth of waves. Spilling breakers are characterised by white foam crests forming. The foam crest spills down the front of the wave, not unlike an avalanche; see Figure 53. This is the most common type of breaking wave formed in deep water, but it also occurs on beaches.

A breaking wave of the "plunging breaker" type is characterized by the fact that it is steeper than a "spilling breaker" and the wave crest falls forward as a well-defined curl with considerable energy, see Figure 54.

CCTV of the breaking wave, showhed that the wave can be characterized as a weak plunging breaker, including some of the characteristics of a "spilling breaker"

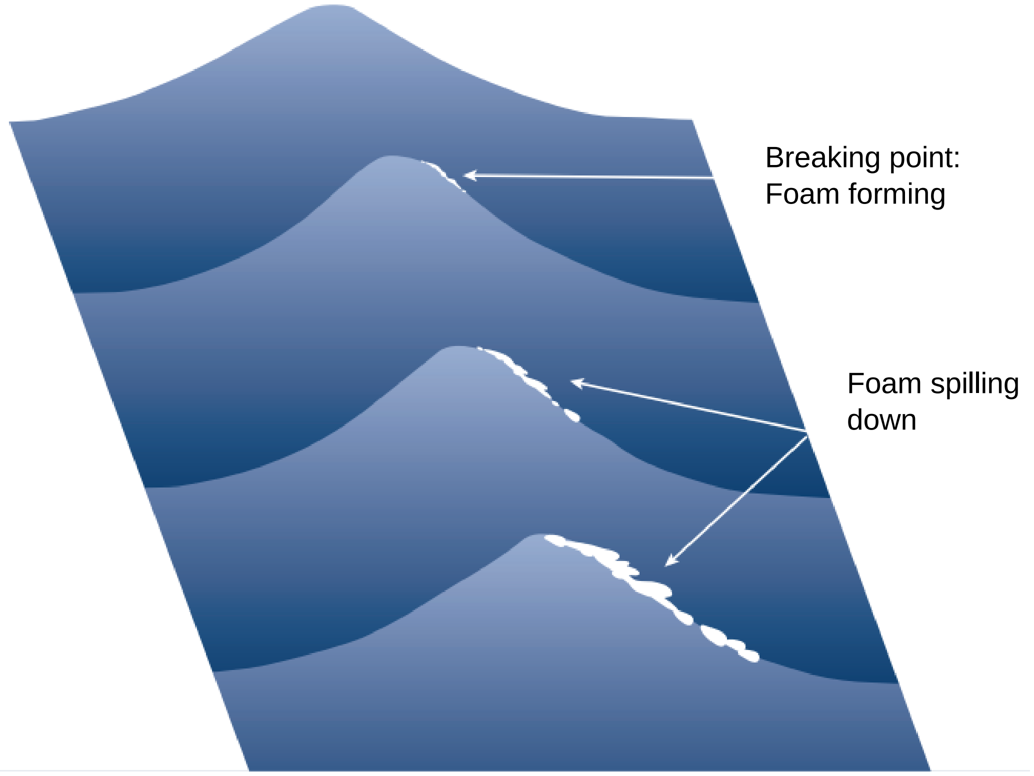


Figure 53: Illustration of how a breaking wave of a “spilling breaker" type arise. Illustration: Havromsteknologier – Havrommet og havmiljøet, NTNU, 21 October 2011

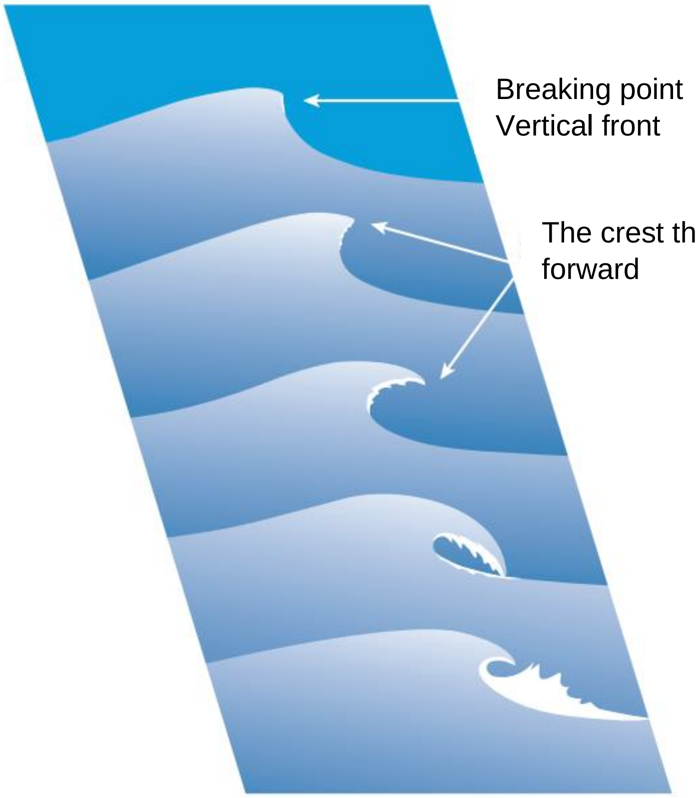


Figure 54: Illustration of how a breaking wave of a “plunging breaker" type arise. Illustration: Havromsteknologier – Havrommet og havmiljøet, NTNU, 21 October 2011

1.5.2.4 Wave Scatter Diagram

A wave scatter diagram (scatter plot) is a long-term statistical representation of observed sea states for a given area.

Following the incident, DNV has established a scatter diagram for the Drake Passage based on Hindcast[14] data, see Figure 55. The diagram shows the number of sea states defined with a significant wave height Hs and a wave period Tz, and forms a contour.

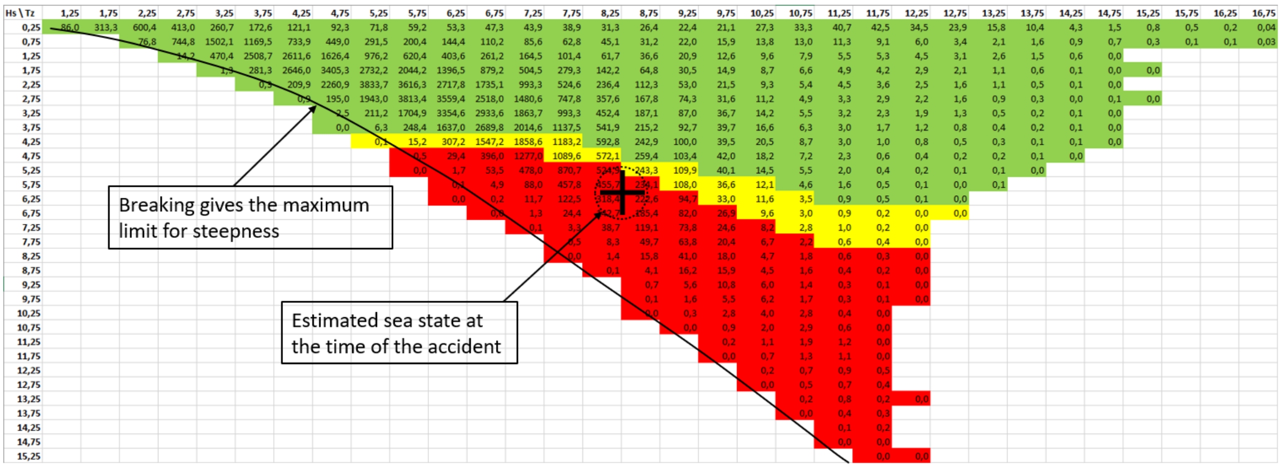


Figure 55: The scatter diagram for the Drake Passage. The line defines the maximum limit for steepness and the cross shows the forecasted sea state at the time of the accident. Source: Classification Society

The line in the scatter diagram defines the maximum limit for the steepness of the sea state. The waves will have an increasing steepness and probability of breaking when the sea state has a characteristic that approaches this limit. The colors in the diagram describe temporary operational weather restrictions that were introduced for Viking Polaris after the accident, and this is described in more detail in chapter 1.16.1.1.

The sea state at the time of the accident was forecasted to be Hs 6 m and Tp 11 s (roughly equivalent to Tz 8.5 s), marked with a cross in Figure 55.

1.6 Vessel

1.6.1 GENERAL INFORMATION

The passenger ship ‘Viking Polaris’ is registered in the Norwegian International Ship Register (NIS). The ship was designed and built to operate worldwide, including in Arctic and Antarctic areas in summer. ‘Viking Polaris’ is an expedition ship equipped for sightseeing and excursions off the ship. The ship was completed by the shipyard in Søviknes outside Ålesund and handed over on 27 September 2022. Then it sailed for Ushuaia in the south of Argentina. According to the shipyard, the ship is ice-strengthened to Polar Class 6 and is equipped with, among other things, state-of-the-art fin stabilisers to offer the most comfortable voyage possible in remote regions. The hull was built at the Vard Tulcea shipyard in Romania, which also partly fitted out the ship.

‘Viking Polaris’ is owned by Viking Expedition Ship II LTD, and makes up Viking’s expedition fleet together with ‘Viking Octantis’. Details of the ship are shown in Table 3.

[14] *A statistical calculation determining probable past conditions.*

Table 3: Vessel data

Name of ship	Viking Polaris
Length overall (LOA)	205 m
Breadth	23.5 m
Design draught	6.0 m
Number people on board (max.)	631 (378 passengers and 253 crew)
Class notation	1A Passenger ship BIS BWM(T) Clean COMF(V-1) DYNPOS(AUTS) E0 LCS(DC) NAUT(NAV) PC(6) Recyclable Silent(E)
Polar code certificate	B
Build year	2022

The propulsion system consists of two propulsion units and four generators.

The ship was optimised to sail at a speed of 16.5 knots, which is achieved by using three generators at 85% of maximum capacity. The maximum speed was 18 knots when using all four generators at maximum speed.

1.6.2 STABILISATION SYSTEMS

The ship was equipped with stabilisation systems to reduce heeling and roll motions for optimum passenger comfort. The systems consisted of fin stabilisers and active mass stabilisation systems in the form of anti-heeling and anti-roll tanks.

1.6.2.1 Fin stabilisers

The ship was equipped with fin stabilisers, one on the starboard side and one on the port side. They were designed to reduce rolling when the ship was under way and could be retracted into the hull when not in use. At a speed of 18 knots, they were designed to reduce roll motions by up to 85%. The fins were most effective at high speeds, and an increase in speed would give greater reduction of the roll motion. The fin area was approximately 13 m^2 in size and located amidships on deck C, immediately forward of the engine room; see Figure 56.

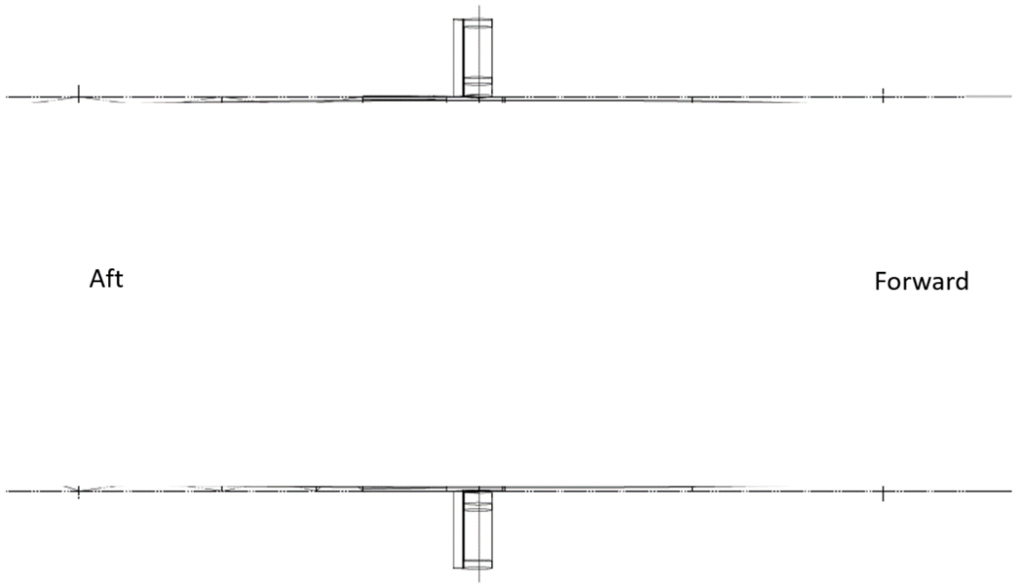


Figure 56: Fin stabilisers located amidships. Drawing: Shipyard / modified by the NSIA

1.6.2.2 Anti-heeling tanks

The anti-heeling tank system consisted of a pair of tanks and a pump used to pump ballast water from one side to the other. The pump had a capacity of 200 m^3 per hour. This system could be automatically or manually adjusted to control the ship's heel. The system was installed with a set of tanks, one tank on the port and one on the starboard side, with a pipe running between them. This was a closed system, with no water entering or leaving the system. On even keel, the tanks were filled to 50% and had a capacity of 65.4 m^3. The tanks were placed amidships on deck B, immediately forward of the engine room.

1.6.2.3 Anti-roll tanks / U-tube tanks

Anti-roll tanks were installed on board the ship to reduce rolling. An anti-roll tank works by the liquid inside the tank moving in such a way that it generates a moment that counteracts the ship's roll motion; see Figure 57. The system was equipped with a U-tube tank system consisting of two wing tanks connected by a duct for water at the bottom and an air duct at the top, and is placed in the aft end of the ship. There was also a possibility for automatic control of air valves whereby the speed with which the water flowed from side to side could be controlled.

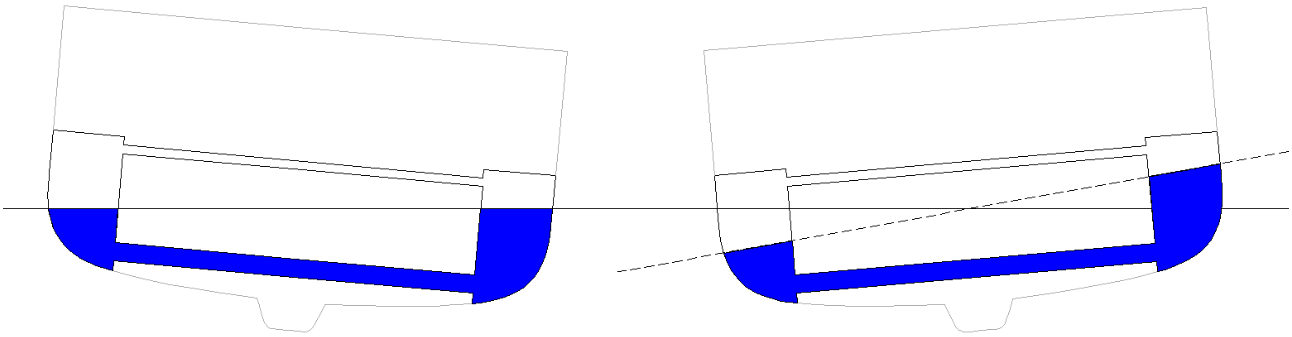


Figure 57: Cross-section of anti-roll tank where the liquid moves from side to side, generating a moment that counteracts the roll motion. There will be inertia in the liquid on the right-hand illustration. A roll motion in the opposite direction will therefore be counteracted by the weight of the water on the right-hand side until the water moves across to the left-hand side. Illustration: NSIA

1.6.2.4 Ballast system

The ship's water ballast system was designed with ballast tanks and pump systems that pumped water in from the sea with a possibility for cross-filling between the ballast tanks. The primary function of this system was to change the trim and list, and most of it was placed in the double bottom.

In the event of an emergency, the ballast system could be operated by two combined bilge/ballast pumps, bypassing the ballast water treatment process.

1.6.3 WINDOW DESIGN

1.6.3.1 Window arrangement

Sash windows were installed on decks 2, 3, 4 and 6 on board 'Viking Polaris'. The windows were designed in accordance with DNV's classification rules of January 2018; see also section 1.12. Different types of window configurations were installed on board in accordance with the dimensions of cutouts and design pressure provided by the shipyard. The main design was the same for all the windows, but the thickness of the glass varied depending on where on the ship the windows were located and the dimensions of the windowpanes.

The design pressure for the sash windows varied depending on where on the ship the windows were located. The design pressure was calculated to 2.5 kPa for deck 6, 12.5 kPa for deck 4 and 18.1 kPa for deck 3. For deck 2, the design pressure varied depending on position. The aft part of deck 2 had a design pressure of 24.4 kPa. This pressure applied to all windows except the foremost three on each side, which had design pressures of 26.5 kPa, 31.2 kPa and 35 kPa, respectively; see Figure 58. All the broken windows were located on deck 2 and had a design pressure of 24.4 kPa.

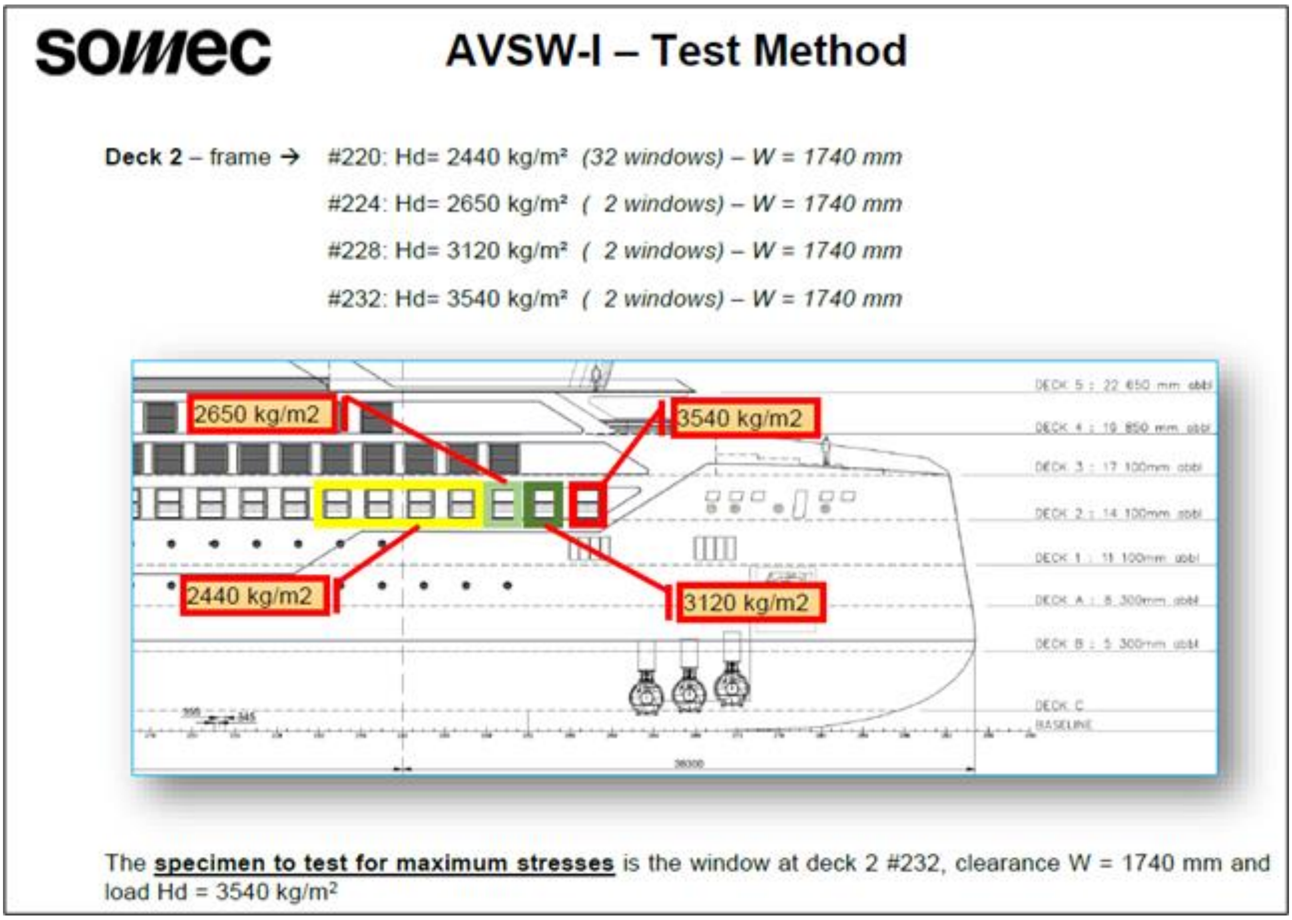


Figure 58: Design loads on deck 2. The highest design pressures apply to the windows closest to the bow. The drawing is from starboard side, however the vessel has corresponding arrangement and design pressure at port side where the damages occurred. Source: Window supplier

The windows consisted of two sections, where the upper part could slide up and down to open to the surroundings; see Figure 59. The operable part of the window opened and closed with the use of a switch beside the stateroom window, or could be closed automatically from the bridge. The window could also be operated manually in the event that the power supply to the system was disrupted.

Figure 59: Window of the same type as on deck 2. This photo was taken on deck 4. Photo: NSIA

The windows were made from laminated glass consisting of two thick layers with a thinner layer of rigid plastic foil called Sentryglas (SG) with thickness 1.5 mm in between The thicknesses used were indicated on the windows with a triangle representing the thickness of the glass; see Figure 60. Figure 60 also shows the windows' design pressures and other design parameters.

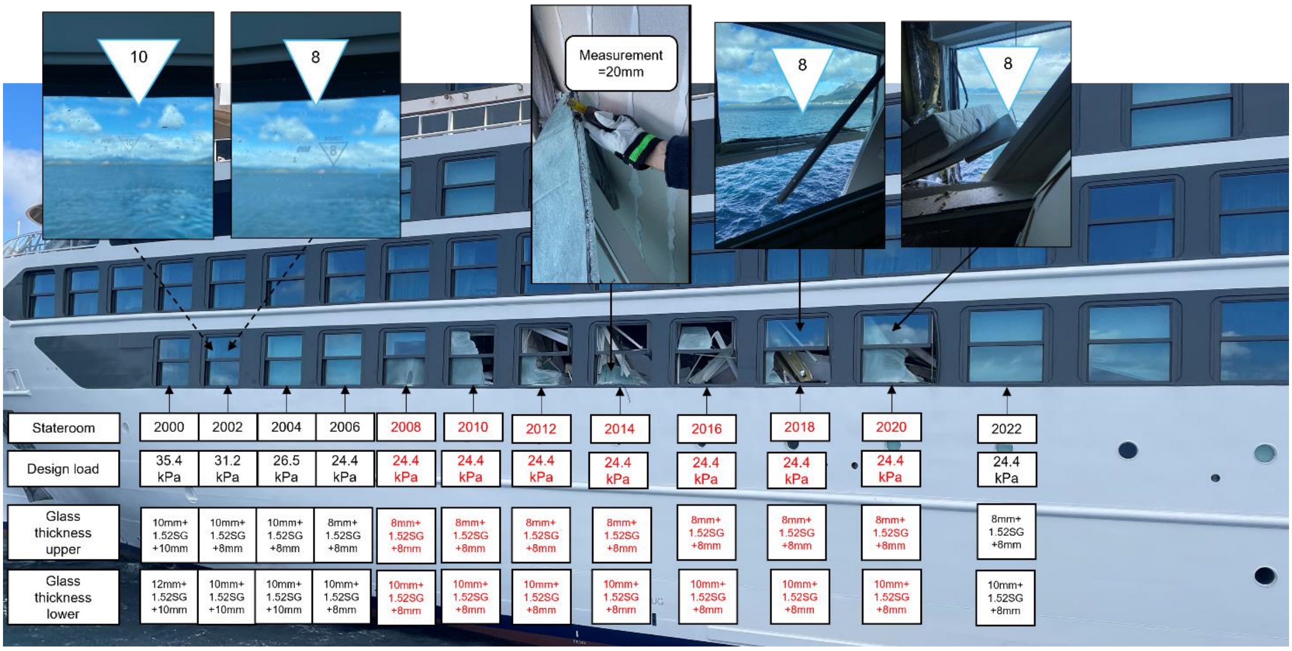


Figure 60: Design loads and glass thickness for the upper and lower windows on deck 2. Red text indicates which windows were broken. Photo/illustration: NSIA

The dimensions of the windows on deck 2 were 1,740 x 804 mm on the upper part, and 1,740 x 948 mm on the lower part. The cutouts in the ship's side were 2,230 x 2,065 mm (B x H).

According to the window supplier, similar windows have been installed on a number of other cruise ships. With the exception of the sister ship 'Viking Octantis', all of these windows were installed on higher decks and have a design pressure of 2.5 kPa.

The design was based on a previous version that used many of the same components, but the window frame had been reinforced and a stronger motor was used to lift the heavier window. The weight of the window increased because of the thicker glass intended to withstand greater loads.

Further details about the windows and window frames are described in section 1.10.2.

1.6.3.2 Window installation

The windows were installed on board the ship by the window supplier, and were delivered as complete windows in the frame. The frame was then fitted to the hull. The window frame was identical for all the sash windows.

A stiffener was fitted in the window frame between the upper and lower part of the window, fastened to the side of the cutout. The window frame was made from aluminium and fastened to the hull with bolts on the top and bottom, but not on the sides; see Figure 61 and Figure 62.

Figure 61: Photo: The window frame was fastened with bolts on the top and bottom. The stiffener was fastened to the plates on either side; as indicated by the red circles. Photo: Shipyard / modified by NSIA

Figure 62: Window ready to be installed. Note the bolt holes on top of the frame and the horizontal stiffener in the middle of the window. Photo: Shipyard

1.6.4 ZODIAC

1.6.4.1 General information

The ship was equipped with 17 Zodiacs of the type Zodiac MilPro MK 5 HD to take passengers on excursions; see Figure 63. Each of these inflatable boats could take 13 passengers and were 5.85 m in length.

Figure 63: One of the ship's Zodiacs. Photo: NSIA

The boats were built in the USA and modified by the shipyard in Norway before delivery. The modifications involved installing an aluminium box at the bow containing a diesel tank, spare foot pump, batteries etc. All the boats were delivered with a manometer to measure air pressure, and two foot pumps. The boats were collapsible in that they could be deflated and the four aluminium floorboard elements removed.

The main tubes of the boat consisted of five air chambers in total. Each chamber had a combined inflation and overpressure relief valve; see Figure 64. The valves on the main tubes showed the prescribed air pressure. The chambers could be opened to allow for free passage of air between them, and only one inflation valve needed to be used to inflate the boat. This allowed for the pressurised air to be checked by means of a manometer fitted to another inflation valve; see Figure 65. Once the correct pressure had been achieved, the bypass valves were to be set to navigation mode. That would isolate each chamber from the others as a precaution against leaks.

Figure 64: Inflation valve with overpressure relief. Photo: NSIA

Figure 65: Manometer fitted to inflation valve. Photo: NSIA

The boats were delivered with a futura tube below each main tube, as well as an inflatable centre keel; see Figure 66. Neither of these were equipped with overpressure protection. The futura tubes were cylindrical and intended to improve buoyancy and manoeuvring characteristics at speed. The inflatable keel was cylindrical and located at the centre, below the floorboards, and extended from the stern the all the way to the bow. The centre keel was intended to tighten the fabric at the bottom of the boat and create a V-shaped design to improve its seagoing properties. The keel also pushed the floorboards up and made them stable to walk on, in addition to stiffening the boat. The futura tubes were inflated at the stern, where an extension hose was installed from both sides, and the inflatable keel was filled from the valve placed in the aluminium box at the bow.

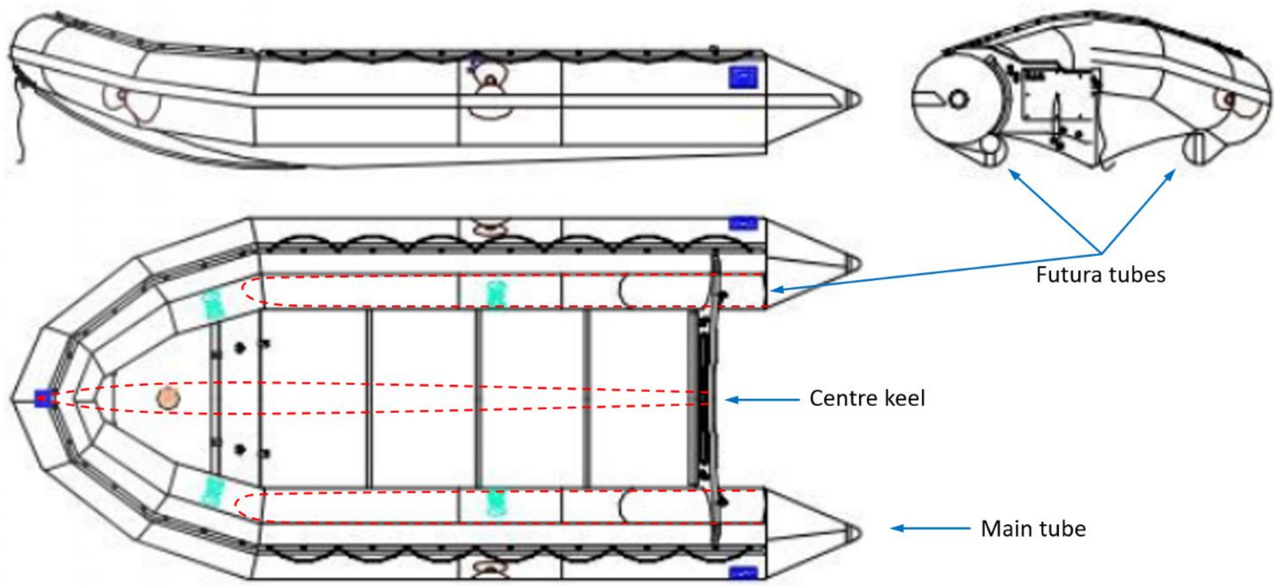


Figure 66: Overview illustration of Zodiac. Illustration: Manufacturer / text and dotted lines by the NSIA

1.6.4.2 Inflation

The manual for the boats stated that the air pressure in the buoyancy tubes, keel and futura tubes should be about 3.4 psi.

The manometer delivered with the boats was designed to be fitted to an inflation valve and the pressure read from the side. To read the pressure in the inflatable keel, one would either have to photograph the manometer while fitted to the inflation valve inside the box, or empty the aluminium box out and visually read the pressure upside down leaning forward with one's head in the box. Figure 67 shows the aluminium box at the bow and the valve for the inflatable keel.

Figure 67: The aluminium box at the bow of one of the Zodiacs. The valve for the inflatable keel is indicated by a red circle. Photo: NSIA

The manual also stated that compressors or air cylinders should not be used for inflation, and that inflation was to be done using the foot pump provided.

According to the supplier, the reason why compressed air from a compressor was not to be used was the risk of overpressure. This was particularly relevant to the inflatable keel and the futura tubes. Their volume was limited, and it would be difficult to control the amount of air if using inflation methods other than the foot pump. Unlike the main tubes, the inflatable keel and futura tubes had no overpressure protection or physical marking indicating what the pressure should be. The NSIA has been informed that the reason why the inflatable keel and futura tubes were not fitted with any such devices was that they contained a small amount of air. They would therefore have been vulnerable if an overpressure relief valve released air in response to an increase in pressure in connection with heavy seas or landings. With a single inflation valve it was also not possible to check the pressure while inflating them with compressed air, as was possible with the main tubes by putting the valves between the chambers in bypass mode.

The compressor system used air from the engine room at a pressure of approximately 7 bar (approx. 100 psi).

1.6.4.3 Pressure measured in the inflatable keel of other Zodiacs after the accident

Following the accident, the crew checked the pressure in the inflatable keel of other Zodiacs. They found significant overpressure in the keels of several boats compared with the recommended operating pressure of 3.4 psi; see Table 4.

Table 4: Pressure measured in the centre keel of different Zodiacs after the accident

Zodiac number	PSI (Pounds per Square Inch)
2	2.1
4	≥ 9
6	≥ 9
8	2.2
10	5
12	≥ 9
24	≥ 9
26	≥ 9

The maximum pressure the manometer could measure was 9 psi, which means that it is uncertain how high the pressure actually was in the keels measured to 9 psi.

1.6.4.4 Operation and maintenance

Before the accident, there were no procedures in the ship management company's management system describing how inflation was to take place. A practice had established on board whereby the able seamen topped up the boats with air before each expedition. The need for additional air was assessed by a visual check or by the crew feeling the tubes with their hands. The centre keel was usually topped up before each use.

1.6.4.5 Training and courses

In connection with the Zodiacs' delivery to the sister ship 'Viking Octantis', a user course was held for the launch team[15] at Vard Søviknes on 25 and 26 October 2021 by agreement with Viking. The Norwegian supplier offered the same course to 'Viking Polaris' as to 'Viking Octantis'. No such course was held for this delivery, as the owner did not request it.

According to the supplier, the course for 'Viking Octantis' took two days and covered general use, test runs and maintenance. The structure of the boat was covered, including a review of all its valves. This included the inflation valves for the keel, futura tubes and main tubes, as well as how to assemble and disassemble them. Information about the correct inflation pressure was also provided. No specific instructions were given regarding inflation using compressed air, but the delivery included only manual foot pumps.

The ship management company has stated that some of the crew members from 'Viking Octantis' took an instructor course provided by a representative of the Royal Yachting Association (RYA). The RYA-approved instructors then instructed the crew of 'Viking Octantis' in the use of Zodiacs.

[15] The crew involved in readying the vessel.

RYA-approved instructors from the training for ‘Viking Octantis’ then trained the crew of ‘Viking Polaris’. The course material does not show that inflation procedures were reviewed as part of this course.

1.6.4.6 Challenges associated with the futura tubes

About a month after the ship had left the shipyard and been put into operation, the Zodiac supplier received a complaint from the ship management company concerning challenges associated with several of the futura tubes. The complaint was that the glue had separated where the tubes’ protective covering was glued to the main tube. It was agreed that this would be looked into and repaired by the US manufacturer.

The crew documented the following glue separation challenges associated with futura tubes:

- Voyage 2: glue separation detected on Zodiacs 4 and 12. They were taken out of operation.
- Voyage 3: partial glue separation detected at the futura tubes of Zodiacs 20 and 24 and on one side of Zodiac 28.
- Voyage 4: glue separation detected on Zodiac 22 in connection with the accident.

Figure 68: Glue separation at futura tube of Zodiac 12. Photo: Ship management company

Figure 69: Glue separation at futura tube of Zodiac 12. Photo: Ship management company

The air pressure of the centre keel of all these Zodiacs was measured to PSI ≥9 after the accident; see section 1.6.4.3.

1.7 Operating conditions

1.7.1 GENERAL INFORMATION

‘Viking Polaris’ and her sister ship ‘Viking Octantis’ were designed to operate in different parts of the world, including in Antarctic and the Arctic during the summer season.

The ship was equipped for passenger excursions off the ship. The equipment included submarines, Zodiacs, kayaks and special operations boats (SOB).

The following section describes relevant operating conditions such as route planning in connection with voyages, ballast operations for passenger comfort and Zodiac excursions off the ships.

1.7.2 ROUTE PLANNING AND WEATHER CONDITIONS

Obtaining weather information for the planned route was part of the normal procedures on board, and was also done before departure from Antarctica. The weather forecast services Windy, NAVTOR and a weather forecast app were used to retrieve weather forecasts and monitor weather conditions during the voyage. The weather forecasts were updated hourly on the bridge, printed out from the Windy website and posted on the bridge.

It was standard procedure on board for the master and officers to discuss the route and weather conditions before every voyage. In connection with the route planning, the navigation officer had drawn up a passage plan with waypoints, route, speed, ETA etc. that was evaluated in consultation with the master. A short passage plan meeting attended by key officers including the navigation officer, staff captain, officer of the watch and master was then held on the bridge at which the plan was reviewed and factors such as waypoints, hazards, weather, ice conditions, environmental considerations etc. were discussed.

In the safety management system the definition of heavy weather was provided, see chapter 1.11.3.1. If the master expected heavy weather or the conditions to change during the voyage, a heavy weather checklist was to be completed. The checklist was completed prior to departure Antarctica on 28 November 2022. Among others the following was checked off:

- Course and speed for safest navigation in heavy weather.
- Forecast established.
- Considered alternative route/delaying departure/seeking shelter.
- Conduct internal communication with ship staff and passengers.
- Optimize stability, trim, hull stress and draughts.
- Complete heavy weather ballasting operation.

In addition it was checked off that areas and equipment on deck and in the accommodation area was secured.

As part of this checklist and the heavy weather procedure (see section 1.11.3.1), a DPA (Designated Person Ashore) was to be contacted to discuss the preparations for the voyage and the weather conditions. The DPA was not contacted before this voyage, as the bridge team had already assessed the forecast weather conditions and planned the course and speed based on this information. However, the owner of the ship was contacted before departure from Antarctica to discuss the options for evacuating the patient, and agreement was reached that returning to Ushuaia was the best solution. It has emerged that it was not standard procedure to call the DPA to discuss weather forecasts, and this had not happened since the ship was put into operation.

1.7.3 PROCEDURES FOR BALLAST TRANSFERS AND ADJUSTMENT OF HEEL/LIST

The ship was equipped with both fin stabilisers and U-tube tanks to reduce rolling. She was also equipped with an anti-heeling system to control heel/list; see section 1.6.2. Experience had shown that the anti-heeling tanks were not large enough to prevent the ship from listing, particularly in strong winds, which meant that the ballast tanks were used to adjust the ship's heel/list.

The ballast tanks were also used to adjust heeling the night before the accident. Since ballast transfers with the ballast tanks was a time-consuming procedure, it was not considered a good way of reducing the heel/list, particularly not in bad weather, as it would take a long time to implement changes, for example in the event of changes to the weather or other circumstances on board the ship.

Ballast operations were initiated on the orders of the master or the staff captain.

1.7.4 ZODIAC EXPEDITIONS

In Antarctica, the Zodiacs were used to transport passengers to shore for excursions in inaccessible locations that cannot be reached directly from the cruise ship. They were also used for sightseeing trips along the shore to take in nature and wildlife in places where larger vessels cannot go. 'Viking Polaris' had two submarines. Passengers boarded the submarines at sea and were taken to the submarine by Zodiacs.

It was the master's responsibility to determine whether sea conditions were calm enough to use the Zodiacs and whether planned excursions could take place or had to be cancelled. This could be a challenging assessment for the master to make, as weather conditions often changed rapidly.

1.8 Crew

1.8.1 GENERAL INFORMATION

At the time of the incident, the bridge team consisted of the master, the second officer, two third officers, of which one junior, and an able seaman in the role as lookout.

The staff captain, who has head of the deck department, was in the office by the bridge when the accident happened. The staff captain is the master's deputy and assumes command of the ship if the master is unable to or is absent.

1.8.2 EXPERIENCE AND HANDOVER

1.8.2.1 Ship master

The master had a nautical education and had been in service on different vessel since 1995. The master had experience of polar waters, among other things from icebreakers, and had worked as the master of different cruise ships for more than six years.

The master came on board 'Viking Polaris' on 22 October 2022 and completed a handover cruise (11 days). The master had also taken several courses under the auspices of Wilhelmsen Ship Management (WSM) in autumn 2022, including a BRM[16] course and a five-day cruise of the Great Lakes on board 'Viking Octantis' in September 2022 to become familiar with the ship. The master took command of 'Viking Polaris' on 3 November 2022.

1.8.2.2 Staff captain

The staff captain had sailed since 1998 after taking up the first job as a master in 2007 and had experience from cruise ship, supply ship and ferry operations. The staff captain had also served as staff captain on other Viking ships. The staff captain had worked for WSM for 1.5 years, and boarded 'Viking Polaris' on 24 November 2022 with no particular handover.

1.8.2.3 Second officer

The second officer had served as a second officer for different cruise lines for more than 15 years, with this being the third expedition vessel and third season in Antarctica. The second officer had taken part in one previous cruise with 'Viking Polaris' from Ushuaia to the Antarctic. No particular handover was completed on arrival on board 'Viking Polaris'.

[16] *Bridge Resource Management.*

1.8.2.4 Navigation officer (first officer)

The navigation officer on board had experience from cruise ships along the coast of Norway, started working for WSM in 2022 and had worked on the sister ship 'Viking Octantis' as a navigation officer since February 2022. The navigation officer boarded 'Viking Polaris' on 13 November 2022, but had no handover.

1.8.2.5 Third officer

The third officer had been a navigation officer in international service (bulk ships and expedition ships) since 2011. The third officer had experience of sailing the North Sea in difficult sea conditions and had worked on board 'Viking Polaris' since she was put into operation in September 2022, and was part of the launch crew.[17] This was the officer's first contract on board a Viking ship.

The officer was part of the launch crew and therefore had no handover. Senior officers and other experienced officers from 'Viking Octantis' were tasked with organising familiarisation and training.

1.8.2.6 Junior officer

The junior officer had previously completed a cruise as an able seaman on board 'Viking Polaris', but this was the first voyage as a third officer.

1.8.2.7 Overall experience and handover

The master and the staff captain both had relatively limited experience of the ship and her sister ship 'Viking Octantis', although they both had long experience from other cruise ships. It was the staff captain's first season in Antarctic.

The staff captain and the second officer had virtually no handover and consequently very little transfer of experience. The navigation officer also had no handover, but came from the same position on board 'Viking Octantis'.

Overall, the senior officers had limited experience of this particular ship as well as of sailing in Antarctica. Several had little or no handover when they joined the crew. The investigation has not identified that lack of or limited handover has affected the outcome of this accident.

1.9 Medical and health information

The deceased was found under pieces of furniture, walls and ceiling, and the post mortem report stated that the injuries were consistent with the sequence of events. The cause of death was recorded as due to head injuries.

The NSIA is not aware of any other medical or health factors of relevance to this investigation.

1.10 Technical investigations

1.10.1 OTHER VESSELS IN THE AREA

There were several other vessels in the area at the time 'Viking Polaris' was struck by the wave that broke the windows of seven staterooms; see Figure 70.

[17] *The crew involved in readying the vessel.*

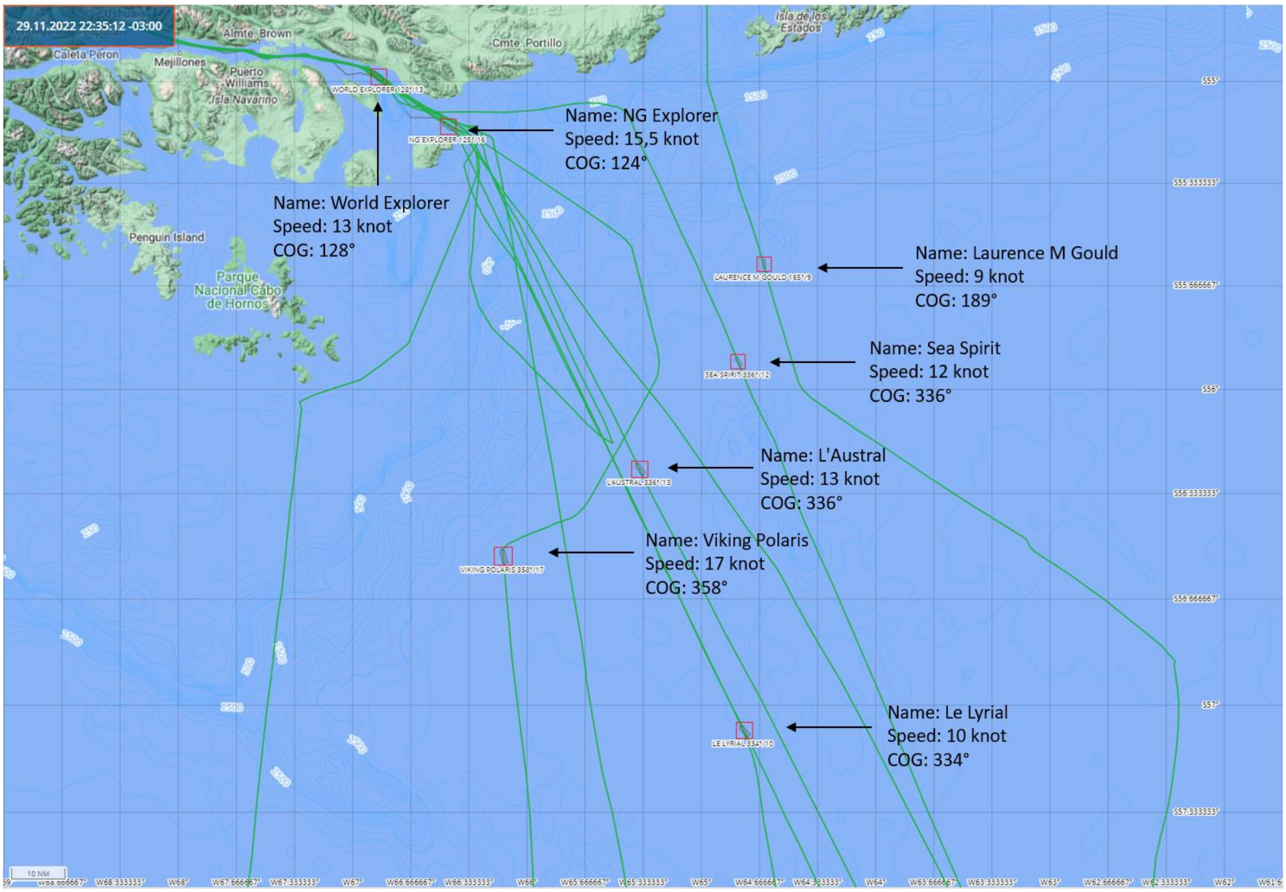


Figure 70: AIS track, position and speed of other vessels in the area in relation to 'Viking Polaris' at about 22:35. Map: Norwegian Coastal Administration AIS / Text by the NSIA

The following information has been obtained about other vessels in the area:

- The AIS track shows that the cruise ship 'World Explorer' sailed south from Ushuaia, but turned around to sail back north at 05:46 on 30 November. Based on information received, the ship turned around due to rough weather and because one of the windows on her starboard side aft of midship was knocked in. No personal injury was reported in connection with the damaged window.
- 'L'Austral' had noted Beaufort force 8, westerly winds and Rough (5) for sea state in her deck log at 22:00 and 23:00 on 29 November.
- 'Le'Lyrial' had noted Beaufort force 8, westerly winds and Very Rough (6) for sea state in her deck log at 22:00 and 23:00 on 29 November.
- 'Laurence M. Gould' was in the area on 29 and 30 November 2022. At 16:10 on 30 November, the ship was struck by a big wave, resulting in one of the crew members in the galley sustaining an injury. No damage to the ship was reported. The injured crew member was transported back to Ushuaia for medical care. The weather conditions noted in the deck log immediately before the incident were westerly winds at speeds of 35–45 knots and waves of 20–25 (ft).

1.10.2 EXAMINATION OF WINDOWS

1.10.2.1 Assignment

The NSIA commissioned a consultancy company to assist in the investigation of the design basis with a focus on wave loads and window design for staterooms on deck 2. The investigations mainly consisted of a review of rules and regulations, verification of regulation pressure calculations, and analysis of the broken windows. The consultant was also tasked with attempting to estimate the characteristics of the wave and the magnitude of the external pressure caused by the wave on the windows, including the window frame. The most important findings from this work are summarised below. The complete assignment is documented in Appendix B.

1.10.2.2 Rules and regulations

Relevant ship regulations are set out for the design of single-hull steel ships. For structure/strength calculations, the rules are structured in such a way that it is first specified how the design should be arranged with regard to definitions and general requirements for the arrangement of volume, tanks etc. This is used to determine the ship's main dimensions and general arrangement. The next part of the rules deals with the definition and calculation of loads the design is intended to withstand. When designing ships not subject to sailing restrictions, a predefined set of wave data is used that is supposed to cover all highest expected loads a ship may encounter during its service life (25 years).

For ships, this is what is known as the North Atlantic scatter diagram with a 25-year return period (exceedance probability of 10^{-8}). More detailed information about the wave scatter diagram is available in 'DNV-RP-C205 Environmental conditions and environmental loads', Appendix C, Table C-2 (see also Appendix C). The wave data in DNV RP-C205 is based on the IACS Rec.34 Standard Wave Data for Direct Wave Load Analysis. The scatter diagram[18] is defined with a wave period Tz and a significant wave height Hs and form a contour. The highest significant wave height (Hs) in a 25-year contour equals 16.1 m. Sea states with the highest wave heights are typically dimensioning for global forces, while steep sea states along the contour with considerably lower wave heights and shorter wave periods is dimensioning for local forces as bow slamming or green sea on deck.

The requirements set out in the ship rules for the dimensioning of e.g. windows against external pressure are governed by where on the ship the window is located. The design pressure increases forward towards the bow and down towards the waterline. The magnitude of the hydrodynamic sea pressure is calculated based on what is known as equivalent design waves (EDW[19]).

If, for example, the window is placed far enough aft and above the waterline, the rules will result in such low hydrodynamic sea pressures that they will not be dimensioning in this position. In such cases, the rule uses a minimum pressure instead that is based only on the wave and block coefficients.

1.10.2.3 Other methods of calculating pressure from wave impact

There are other methods, based more on wave kinematics, for calculating the pressure from a wave breaking against a vertical surface (such as the windows of 'Viking Polaris'). These methods are based on the main parameters of the incoming wave, such as height, length and steepness. These methods are described in DNV's Recommended Practice[20] and in other literature for the engineering of ships and offshore structures.[21] What these methods have in common is that, when using wave parameters from the time of the accident, they will give a significantly higher pressure than the regulation pressure used to design the windows in the affected area on 'Viking Polaris'.

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[18] *Also referred to as «the extent of validity of the rules» in this report.*
[19] *EDW are a set of regular waves intended to represent the design loads a ship can be exposed to in operation.*
[20] *DNV, 'DNV-RP-C205 Environmental conditions and environmental loads', September 2021.*
[21] *O. Faltinsen, Sea Loads on Ships and Offshore Structures, Cambridge University Press, 1990.*

1.10.2.4 Review of regulatory framework and design basis

Design pressure

There are two formulas for calculating the design pressures of the windows along the hull, of which the highest design pressure shall be dimensioning:

1. P_W
2. P_{SI}

P_W was developed with regard to a 25-year return period where all sea states and directions have been considered. It also includes an operational factor (also known as the seaman's factor) that takes the heading into account. This is typically dimensioning for the bow of the ship. Pw is dimensioning for the parts of the ship that through conventional wave loads of ship, will be exposed to pressure forces from the waves. This includes the hull beneath the water line, as well as the structure above the waterline where the waves are expected to reach. In the bow loads from bow impact/slamming are dimensioning. These loads are especially developed to consider high loads (including loads from breaking waves) that can be expected in rough seas directly from ahead.

P_{SI} is the minimum design pressure for the external sides of superstructures and is based on experience and shipbuilding practices. It does not include any kind of wave analysis or an explicit operational factor. Neither P_W nor P_{SI} takes breaking waves into account.

In accordance with the rules, the windows on deck 2, which sustained damage, were located so far aft and so far above the waterline that the hydrodynamic sea pressure was no longer dimensioning, i.e. $P_{SI} > P_W$. As a result of the windows' location, the minimum pressure rule shown in Figure 71 was applied. This formula for minimum pressure is not based on an EDW such as P_W, but is based on experience and shipbuilding practices.

3.3 Sides of superstructures

3.3.1 The design pressure for the external sides of superstructures, in kN/m^2, shall not be taken less than:

$$P_{SI} = 3C_W(C_B + 0.7) - 2(z - T_{sc})$$

but shall not be less than:

- 0 kN/m^2 for direct strength analysis according to Ch.7
- 2.5 kN/m^2 for other cases.

Figure 71: Regulation pressure from DNVGL-RU-SHIP Pt. 3 Ch. 4 Sec. 5. Source: DNV

Forward of frame #223, the design pressure is calculated based on design waves for the oncoming sea, which results in increased design pressure requirements; see Figure 72. In order to verify the design pressure calculation, the consultant ran a separate analysis in the ship design tool Nauticus Hull (in which the formulas from the regulations are implemented) to determine the value of external pressure on the hull between decks 2 and 3. The results show good correlation between the pressures. Nauticus Hull was also used by the shipyard to calculate the design pressure on 'Viking Polaris' during the design phase.

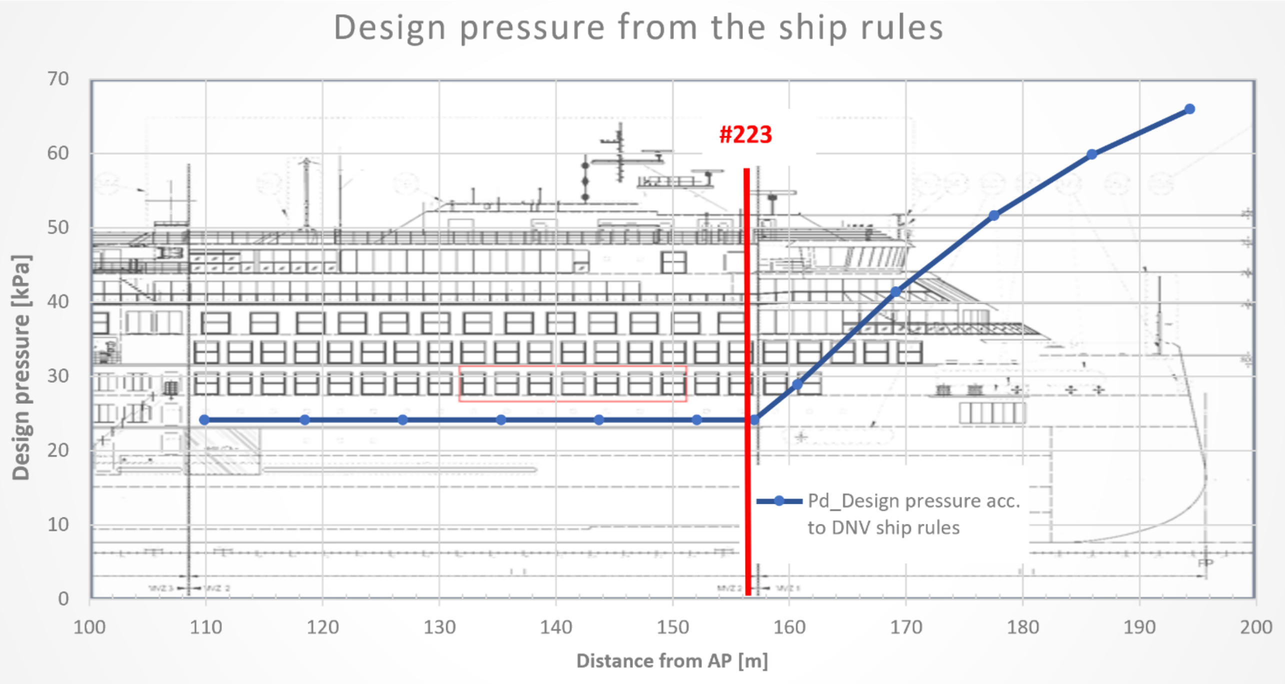

Figure 72: Regulation pressure for the side of the ship. Drawing is of starboard side, however the vessel has corresponding arrangement and design pressures on the port side were the damages occurred. Illustration: Consultant

The study therefore concluded that the design pressure used for the construction and testing of the windows and fixings were calculated correctly in accordance with the ship rules.

Glass thickness

The requirements to minimum glass thickness for ship windows originates from ISO standard number 21005 "Thermally toughened safety glass panes for windows and side scuttles". Most IACS class societies, including DNV, use this standard in their rules. The glass itself is designed with a safety factor of 4 compared with the surrounding steel. That means that the formula for required glass thickness includes a safety factor of 4. This safety factor is intended to take into account the different material properties of glass and steel. Among other things, glass is brittle and will break whereas steel will be deformed and absorb the energy from a breaking wave.

The rules for design pressure on the ship's side are based on static pressure and does not take into account impulse loads from breaking waves. A breaking wave that hits the ship's side will produce an impulse load whose pressure may exceed the static design pressure without the material breaking. Whether the material will break depends on the properties of the material combined with the characteristics of the impulse load such as maximum pressure and duration.

Laminated double-layer safety glass is used in the windows in question, and the window supplier has designed the glass thickness according to the required thickness (t_r), but not in accordance with equivalent thickness (t_e).[22] The ship regulations allow for the possibility of deviating from the formula for t_e if tests are performed in accordance with DNVGL-RU-SHIP, Pt 3, Ch.12, Sec. 6.

[22] Required thickness t_r applies to single-layer glass. An equivalent thickness t_e has therefore been introduced for glass with more than one layer to take account of weakening resulting from the glass being divided into several layers, unless it can be documented that the multi-layer glass is at least as strong as the single-layer glass, in which case t_r can be used.

Some minor non-conformities with the rules have been identified (see Appendix B section 9.1.3), but this would not have changed the outcome of the accident, because the actual pressure applied by the wave far exceeded the design pressure.

Fixings

The spacing between the screws fastening the window frame to the ship structure must not exceed 150 mm. The windows in question were attached with different types of screws that were also spaced at different intervals. The spacing between the load-bearing screws varied between 222 mm and 230 mm. The capacity of the window fixings, including frame, bolts and stiffeners, are evaluated by class society to be in accordance with the applicable rules through the equivalence principle stated in Pt.1 Ch.1 Sec.1 [2.5.9], by performing a strength test of the complete installation. The load-bearing screws are highlighted in Figure 73. The remaining screws hold a thin aluminium profile with low load-bearing capacity and are therefore not considered load-bearing.

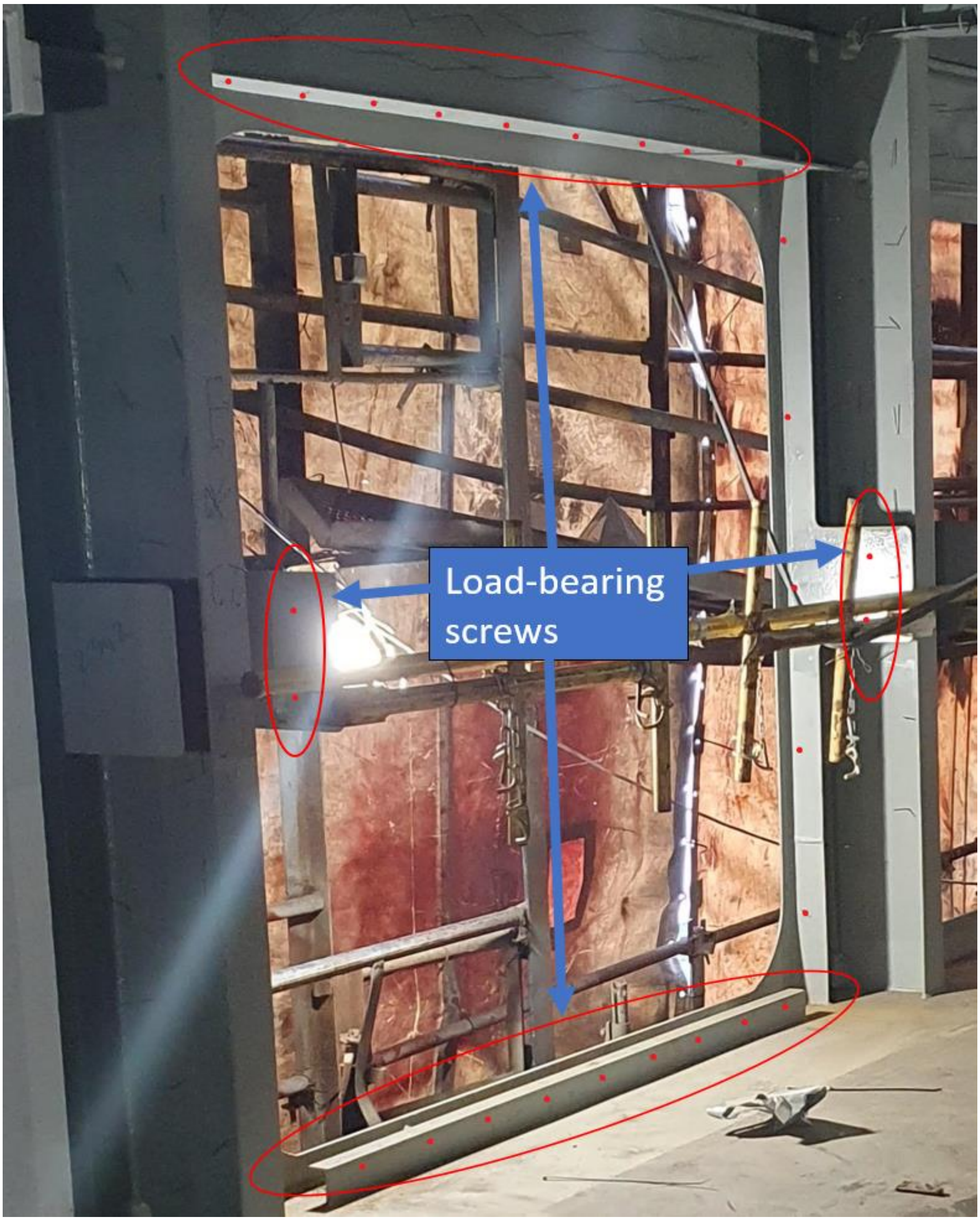

Figure 73: Screws fastening. The red dots show the location of the screws. The load-bearing screws are highlighted. Photo: Window supplier / modified by the consultant

No damaged or broken load-bearing screws were found for the windows studied in this report. It can therefore be concluded that the load-bearing screws were of sufficient strength for the windows in question.

1.10.2.5 The stateroom windows' failure modes

Lower windows, staterooms 2012, 2014, 2016, 2018 and 2020

In five of seven staterooms (2012, 2014, 2016, 2018 and 2020), the aft frame post has been knocked in; see Figure 74 and Figure 75. For these windows, the frame post was knocked in while pulling the shortest (aft) side of the window pane with it, thereby shattering the glass. That means that the window frame yielded before the pane, and that the pane shattered as a result of high pressure and inadequate support from the frame post.

Figure 74: The overview photo shows the damaged staterooms on deck 2. The staterooms where the aft frame post was knocked in on five of the seven damaged windows are circled in red. Photo: NSIA/consultant

Figure 75: Frame post pushed into stateroom 2014. Photo: NSIA/consultant

The full-scale pressure test (see section 1.10.2.6) showed that the frame was able to withstand a test pressure of 40 kPa. The windows and frames for these staterooms had a design pressure of 24.4 kPa.

Lower windows in staterooms 2008 and 2010

On the lower windows in staterooms 2008 and 2010, the frame remained intact, while the pane has shattered. In that respect, they differ from the lower windows in the other staterooms, where the aft frame post was pushed in.

Figure 76: The windows where the window pane is broken but the frame is intact are circled in red. Photo: NSIA/consultant

Upper windows, staterooms 2010, 2012, 2014 and 2016

Figure 77 shows the four upper damaged windows, where the frame is still intact. The pane was the weakest point of these windows, and not the frame as was the case for some of the lower windows.

Based on the findings described in chapter 1.10.2.5, we can conclude that the pressure has been higher than the glass was able to withstand.

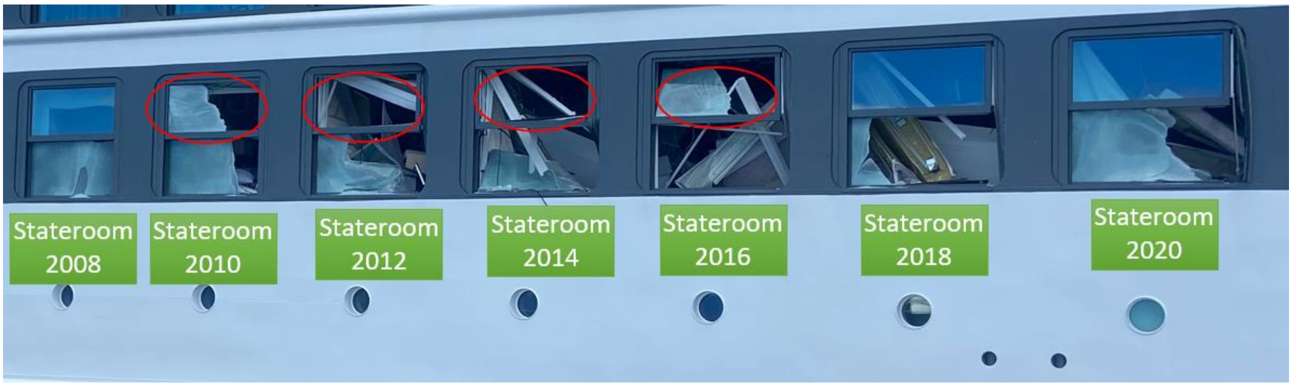

Figure 77: The windows where the window pane is broken, but the frame intact are circled in red. Photo: NSIA/consultant

1.10.2.6 Tests performed during the design phase

There are no uniform requirements in recognized international rules for ships for testing of windows, but it is generally required that recognized standards are used. The rules for Viking Polaris, in this case DNVGL-RU-SHIP, Pt.3 Ch.12 Sec.6 [1.1.5], require full scale testing. These windows were tested because the window area exceeded 1 m^2 in addition to the window fixings was of a new design and not standard.

The requirements for certification and testing in the rules for the windows concerned can be summarised as follows:

- Special full-scale test because the windows are larger than 1 m^2.
- The glass must be tested in accordance with EN 1288-3:2000 because it is not in accordance with the thickness requirements in the ship rules.
- The glass must be in accordance with ISO 21005:2018 and tested in accordance with ISO 614:2012.
- Hose test to verify that windows are weathertight.
- Impact test of balcony railings (applies to passenger ships).

The investigation of the window design testing shows that all required tests had been performed and approved.

The full-scale test was performed in accordance with the Rules for Ships Pt. 3 Ch. 12 Sec 6 [6.2] items 1–3. The test was performed on a hydrostatic test bench by statically applying the design pressure (35.4 kPa) over a period of five minutes; see Figure 78. This corresponded to the design pressure of the forward window in stateroom 2000, which was also the strongest on deck 2.

The purpose of the test is to verify that the window, including the frame and fixings, is able to withstand the design pressure. This means that the test is performed with an arrangement identical to how it was installed on the ship. The test was performed by the window supplier and observed by class society.

The window supplier has, on its own initiative, increased the pressure applied during the test to 40 kPa in order to test the windows' residual capacity. The test was positive, as no visible damage or deformations were registered.

Figure 78: The hydrostatic test bench used in the full-scale test. Photo: Window supplier

1.10.2.7 Weather and wave conditions

The weather forecast at the time of the accident predicted waves from 270 degrees (from the west). According to the Voyage Data Recorder (VDR), the ship's heading was 344 degrees immediately before the accident. This gives a wave direction relative to the sea state of 74 degrees to port relative to the ships length; see Figure 79. This wave direction is supported by observations from the CCTV cameras. The relative wave direction is therefore estimated to about 60–80 degrees to port.

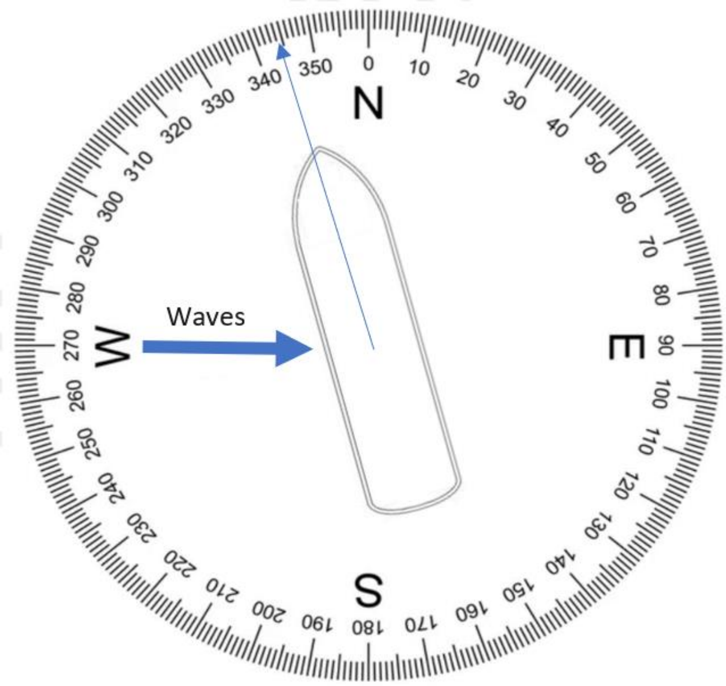

Figure 79: Relative wave direction. Illustration: Consultant

From the CCTV footage, it appears that the wave broke just before or as it struck the ship. Waves can break when they become too high in relation to their length. Strong winds or an opposing current can make the crest of a wave unstable and can also contribute to the wave breaking. Breaking waves are more common in a 'developing' sea state (when the wave height and wind speed are still increasing) and when the sea is choppy (shorter waves).

The wave was probably between 10.6 and 15.7 metres in height with a wave period of 8–9 seconds (see Appendix B), although the estimate carries a high degree of uncertainty because of the relative movement between the ship and the waves. The effect of the wake and 'wave climbing' probably contributed to further enlarging the wave.

The wave height and wave period was within the ship's trade area, i.e. the scatter diagram with a 25-year return period defined in the rules. The reason the wave broke has not been determined with certainty, but it was likely due to a combination of interference and strong winds, which made the wave crest unstable and caused it to break.

1.10.2.8 The ship's roll motion

An assessment has been made of the ship's roll motion after she was struck by the accident wave. The assessment was made on the basis of data from the ship's machinery log. How the ship rolled before and after the accident is visualised in the graph shown in Figure 80.

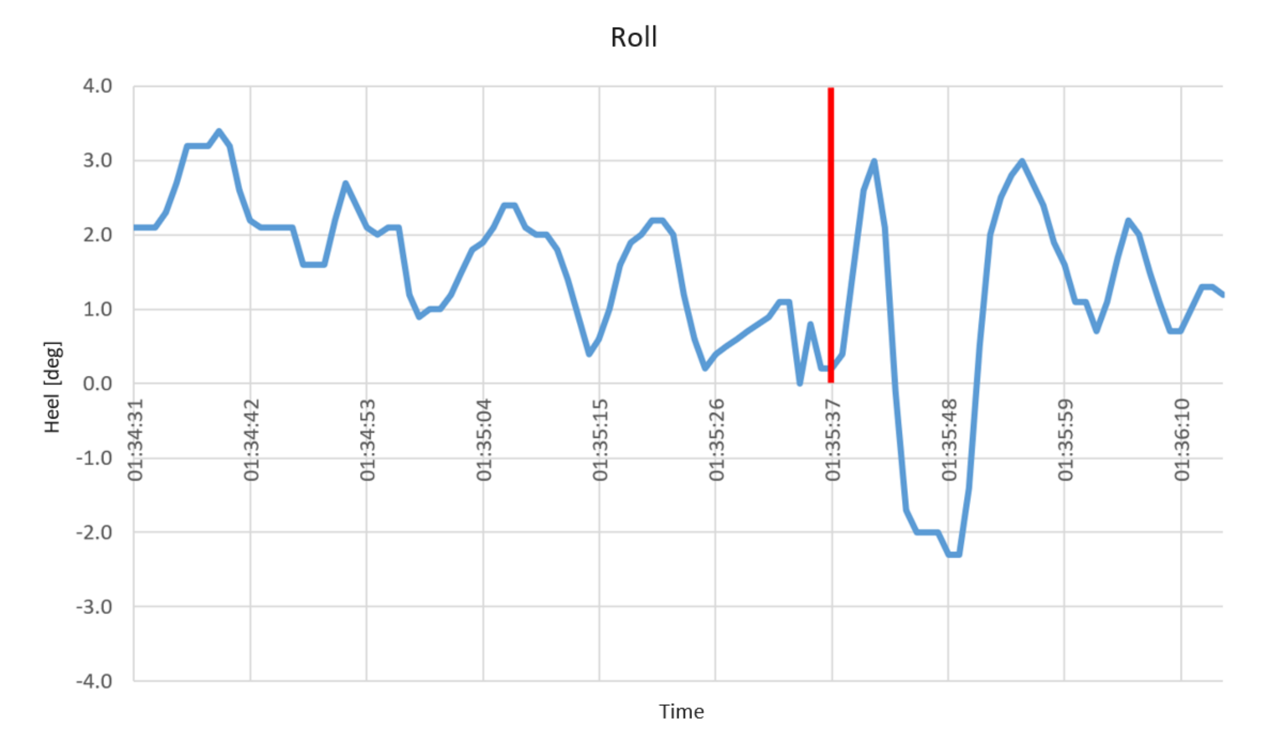

Figure 80: Roll motion after the accident. The wave strikes at 01:35:37. The positive angle is a starboard list. Source: The ship's machinery log.

The accident wave struck the ship on the port side at 01:35:37 (UTC). The wave can be characterised as an impulse load that sets the ship in motion and leads to a maximum angle of heel of 3.0 degrees to starboard 4 seconds after the impact, i.e. at 01:35:41. Then, the ship rolled to port with a maximum impact of -2.3 degrees after 11 seconds (at 01:35:48), before it rolled back to starboard with an angle of heel of 3.0 degrees after 18 seconds (at 01:35:55).

It took 'Viking Polaris' a few seconds to get full roll motion towards starboard after the impact of the accident wave (impulse load). We also see that the ship rolls with her own natural period until the movements have been dampened out.

There was a constant angle of heel of 1–2 degrees to starboard when the accident occurred. This is based on an average of the roll measurements. 'Viking Polaris' is equipped with fin stabilisers that dampen the roll motions, and we see that these fins dampen most of the roll motions after 30 seconds.

1.10.2.9 The rules' assessment of seamanship

The ship rules rely on the assumption of 'good' seamanship. That means that they assume that seamanship will comply with applicable practice, which means to avoid storms, change course or voluntarily reduce speed based on the prevailing weather conditions.[23]

The assumption of good seamanship is also reflected in the design phase when direct calculations of the rule loads are carried out in accordance with DNV-CG-0130, Wave loads. If directly calculated loads are applied, the loads must be adjusted by factors that, among other things, take account of the fact that seafarers change their course based on the weather forecast, and these factors are reflected in several of the formulas set out in the ship rules. Examples of such factors are f_R (operational factor) and f_β (heading correction).

[23] *DNV, 'DNV-CG-0130, Wave loads' October 2021.*

The design pressure calculation (P_{SI}) used for the windows that broke on board 'Viking Polaris' does not include an explicit seaman's factor or wave analysis because of the location of the windows on the ship.

1.10.2.10 The consultant's assessment of damage to the windows

Photos of the damage show that only the windows and frames were damaged, and not the steel in the ship's hull, despite the fact that both are designed to the same local pressure requirements. The reason only the windows and frames gave way is that the steel is dimensioned according to a minimum thickness requirement (DNVGL-RU-SHIP Pt.3 Ch.6 Sec.3 [1]), which result in greater strength than the local pressure requirement and allows the steel plate to withstand greater pressure than the windows. A rough estimate was performed to calculate the maximum statical pressure the surrounding steel could withstand. The calculations showed that the maximum statical pressure the surrounding steel could withstand was 107 kPa.

The rules also contain requirements for the minimum thickness of windows, but they provide less strength against lateral pressure than the minimum steel thickness requirements. The design criteria for the minimum thickness of windows include a safety factor of 4 that is intended to take account of the different material properties of glass and steel.

For the lower windows in staterooms 2012, 2014, 2016, 2018 and 2020 where the frame posts were knocked in, the pressure has been greater than 40 kPa. The glass panes were the weakest point for the lower parts in staterooms 2010, 2012, 2014 and 2016.

The review of the rules and regulations, and the investigations carried out show that the windows are dimensioned according to local pressure requirements. This meant that the windows were weaker than the surrounding steel, which caused them to shatter. The assessment found that the highest pressure from the breaking wave was in the range between 40 kPa (hydro static pressure test performed on the frame) and 107 kPa (calculated strength of surrounding steel). It cannot be ruled out that the maximum wave pressure has been greater than 107 kPa over a very short period.

1.10.2.11 The consultant's conclusion

The direct cause of the accident is deemed to be that the ship was struck by a large long-crested breaking wave at an angle of about 60–80 degrees on the port side. This created a pressure wave against the ship's side and windows in the affected area, that shattered several windows and damaged the interior of the ship.

The conclusions set out in the report are as follows:

- The window and adjacent ship structure were designed in accordance with the applicable rules. Some minor non-conformities were found, none of which were of any significance to the accident.
- The sea state at the time of the accident was within the sea states defined in the scatter diagram which the ship is designed to withstand. The pressure from the breaking wave exceeded what the windows were dimensioned for.
- The design pressure requirements for windows in this position, result in too low values to be able to withstand pressure loads from breaking waves within the extent of validity of the rules.
- Additional design requirements for windows in this position should be introduced to ensure that the shipside is dimensioned for breaking waves.

1.10.3 EXAMINATION OF THE ZODIAC CENTRE KEEL

1.10.3.1 Assignment and execution

On assignment for the NSIA, SINTEF has examined the damage to the inflatable keel to determine the cause of the damage. The keel was examined for external damage and structural defects. The damaged keel was also compared with a new undamaged keel.

The damaged keel was subjected to a visual inspection. It was observed that the keel had ruptured lengthwise, and the damage appeared to have originated around the middle of the keel and propagated in each direction until the energy at the tip of the rupture was insufficient to tear the material further.

Mechanical testing of the material in the damaged and new keels showed corresponding results. The material was cooled down to about 0°C before testing to replicate the environment in which the damage arose as closely as possible. The rupture produced during the tensile strength testing corresponded to what could be observed in the rupture on the damaged keel.

The results from the tensile strength test showed that the material from the new and the damaged keel, respectively, differed slightly in that the new stretched a little further before breaking, but the materials were relatively similar in terms of tensile strength. The observed difference in tensile strength and capacity to stretch could be due to the orientation of the weave, as the orientation of the fabric can vary slightly as a result of manual production.

1.10.3.2 The consultant's conclusion

No external damage or structural defects have been identified. The torn fibres along the edge of the rupture indicates overloading. External damage would have caused a cleaner rupture along the entire edge, with torn fibres more like the ends of the existing damage, rather than the torn fibres observed at the centre. The results of the analysis show that the operating pressure specified in the manual had a considerable margin compared with the material's capacity. Based on the findings described, it is probable that the keel was subjected to overpressure through inflation.

It has not been possible to determine on the basis of this examination whether the immediate cause of the incident was the inflation pressure alone or whether external loads such as wave impact or great changes in temperature could have triggered it. Based on the information that room temperature air had been used to inflate the keel and that the incident took place at low speed and calm sea, it is considered unlikely that these factors contributed to the damage observed.

1.10.4 INVESTIGATION OF LIFEJACKET WORN IN THE ZODIAC INCIDENT

1.10.4.1 Test performed by the NSIA

The NSIA tested an identical lifejacket of the type Viking 180N on 28 February 2023 in the NSIA's premises.

The test was performed by attaching a tape measure on the left-hand side of the lifejacket with the reference point at the centre of the hydrostatic release unit inlet (a little above the centre of the hydrostatic trigger). On the right-hand side, a reference point was indicated on the lower edge of the lifejacket.

The lifejacket was then immersed in a bucket containing about 40 litres of water at a temperature of about 10 °C. The lifejacket was lowered into the bucket at a speed of approx. 0.5–1.0 cm per second. After the hydrostatic release unit had been submerged, the one on the right-hand side was released approximately 3–4 cm into the water; see Figure 81 and Figure 82.

Figure 81: Position of hydrostatic release unit just before the right gas cylinder is released. Photo: NSIA

Figure 82: The right-hand side of the lifejacket inflates after being submerged to a depth of about 3–4 cm. Photo: NSIA

1.10.4.2 Test performed by the crew on board

Following the incident on board the Zodiac, the crew tested the lifejacket worn by the person who fell overboard on 28 November.

A bucket was filled with water and the lifejacket lowered into the bucket. The hydrostatic release unit was reportedly released after a few seconds.

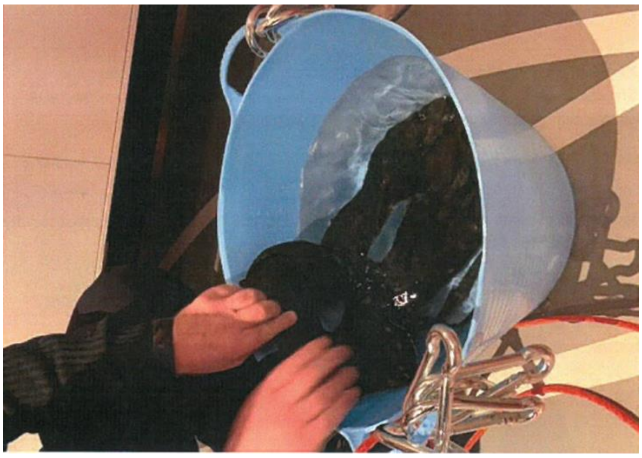

Figure 83: Lifejacket being lowered into a bucket. Photo: Crew

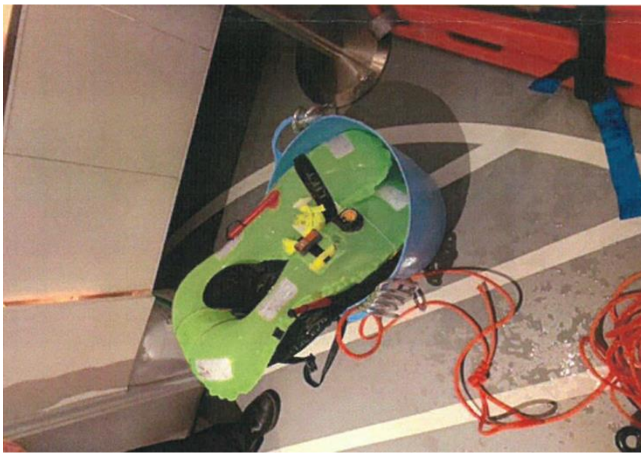

Figure 84: Lifejacket inflating. Photo: Crew

1.11 Vessel owners and safety management

1.11.1 GENERAL INFORMATION ABOUT THE OWNERS

Wilhelmsen Ship Management has technical and personnel responsibility for Viking Ocean Cruises and the expedition fleet.

1.11.2 ORGANISATION

The on-board organisation is shown in Figure 85 and consisted of the master and three departments.

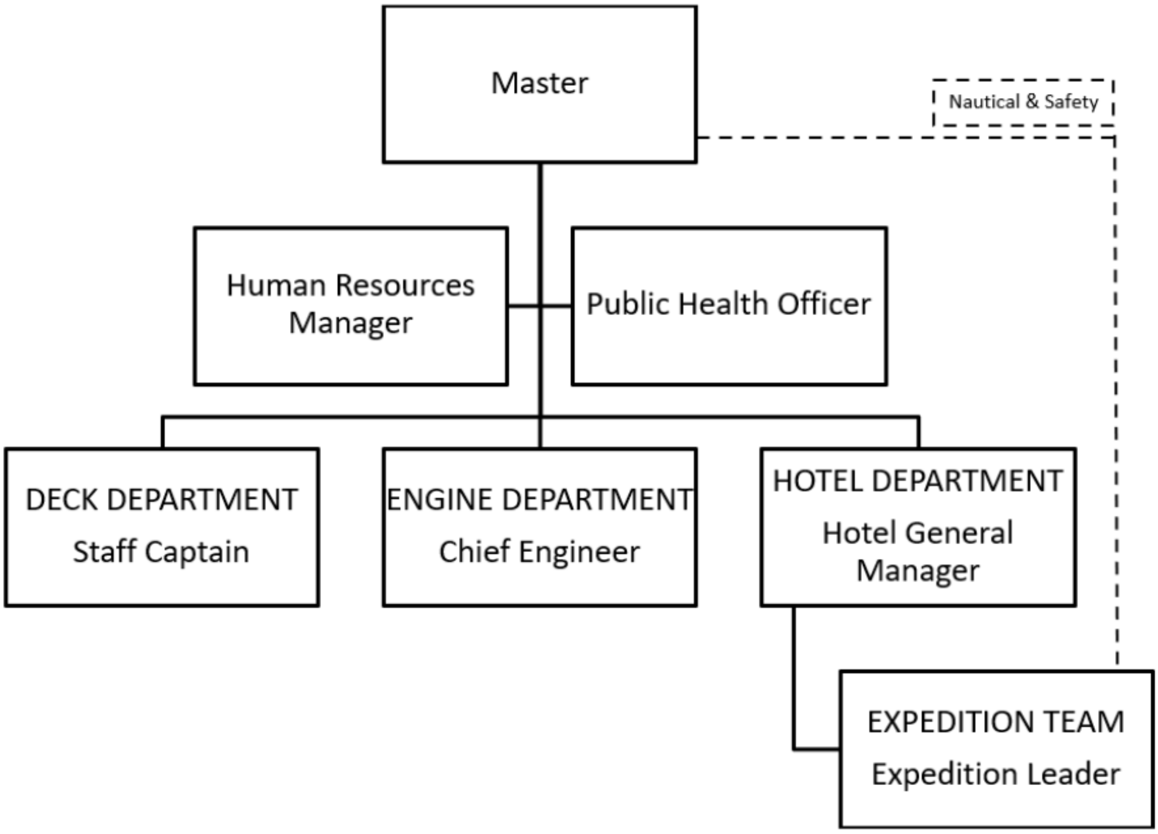

Figure 85: On-board organisation. Source: WSM

The hotel department also included an officer in charge of expeditions and maintenance. The position's areas of responsibility included:

- Training the crew in how to operate Zodiacs and special operations boats, and hangar procedures.
- Maintenance of Zodiacs and special operations boats.
- Drawing up guidelines for key procedures that involve department-related systems or equipment that could represent a risk to safety and/or the environment.

1.11.3 SAFETY MANAGEMENT

The management system included the manuals Operational Manual Cruise Vessel (OMCV) and Standard Operating Procedures (SOP), as well as the Bridge Procedure Manual (BPM). Many of the procedures were generic and applied to both Viking Ocean fleet and the Expedition fleet. There were also some procedures that were only applicable to the expedition fleet.

OMCV was structured in accordance with the ISM[24] Code and included procedures for organisational structure, job descriptions and important operations on board.

1.11.3.1 Procedures for voyage planning and heavy weather

Procedure 4.3 Responsibility and Planning Procedure was part of BPM and included guidelines for voyage planning. It stated that weather conditions and changes in the weather during the voyage are factors to be considered in connection with route planning.

[24] *International Safety Management*

Procedure 7.3 – Heavy Weather Precautions was part of Chapter 7 of OMCV entitled Key Operations and Procedures. According to the introduction, the purpose of the procedure was, among other things, to provide guidance when heavy weather is forecast in order to reduce the risk of personal injury, loss of and damage to the ship. The procedure included the following definitions of weather conditions and heavy weather:

> *'Reasonable weather' – Wind strengths of force six or less in the Beaufort scale, associated with sea states sufficiently moderate to ensure that green water is taken on board the unit's weather deck at infrequent intervals only, or not at all.*
>
> *'Heavy Weather' – Weather conditions above 'reasonable weather' and/or any weather conditions which elevates the risk of personal injury, pollution of the marine environment, damage to the ship's structure and equipment, loss of watertight integrity, machinery damage / overload, loss of maneuverability or cargo damage, or weather conditions above 'reasonable' weather where green water is frequently taken on board weather deck.*

The following is also quoted from the procedure:

> *'Where heavy weather is expected the Master is to complete a heavy weather checklist (B10) and call the DPA to initiate a discussion around the preparations and forecast weather conditions.'*

The checklist B10-Navigation in Heavy Weather comprised 48 check points. The checklist was completed and signed on 28 November 2022.

Procedure 7.3 went on to say that the master and heads of departments were to conduct a risk assessment specific to the ship and the voyage. The risk assessment was to be based on the generic risk assessment template and, as a minimum, take into consideration the capabilites of the hull, structures, manoeuvrability, machinery and equipment, as well as the crew and passengers on board. It also stated that close attention should be paid to the main engines' RPM, the vessel speed, list, roll etc.

The risk assessment template identified a number of pre-defined risks, including water ingress to the ship; see Figure 31. The NSIA has been informed that the risk assessment was conducted before departure from Ushuaia, but no documentation exists to confirm this. No new risk assessment was conducted in this format (Excel) before departure from Antarctica.

Top Event No	Description of potential Top Event	Causes	Possible Loss/Consequence	Likelihood	Severity	Initial Risk Level	Control Required? Y/N
6	Water ingress to the ship	Failure to warn or secure Inadequate planning Misjudgement Lack of knowledge / experience	Human- Fatality Environment - Short term impact to local area. Property - More than a million $ Reputation - Company exposed to society	2 Low	5 Extreme	10	Yes

Figure 86: Excerpt from the risk assessment in the ship management company's management system showing top event – water ingress to the ship. Source: WSM

The procedures also stated that everyone on board were to be notified as early as possible of any heavy weather expected. The master issued such a notification to all departments on board at 18:00 on 28 November 2022 on departure for Ushuaia.

1.11.3.2 Training and familiarisation

Procedure 6.1 Training and Familiarisation sets out guidelines for training and familiarisation.

The procedure includes a matrix describing requirements concerning certificates, experience and handover periods.

Table 5: Excerpt from the matrix in procedure 6.1 Training and Familiarisation. Source: Ship management company

Position	Minimum qualifications and experience		Minimum handover		
	Experience, new hire	**Combined experience**	**New hire**	**Internal transfer**	**Promotion, fleet transfer or new to the position**
Master	5 years in the same position on a similar vessel	A total of 1 year in the fleet	14 days	2 days	10 days
Staff Captain	3 years in the same position on a similar vessel		14 days	2 days	10 days
2nd Officer Navigation	1 year in same position on a similar vessel	A total of 1.5 years in the fleet and no more than one new hire	7 days	6 hours	3 days
2nd Officer Safety	1 year as an officer on a similar vessel		7 days	6 hours	6 hours
2nd Officer	1 year as an officer on a similar vessel		7 days	6 hours	6 hours
3rd Officer	1 year in the same position	A total of 6 months in the fleet	5 days	6 hours	6 hours

1.11.3.3 Zodiac & SOB cruising

SOP procedure 5.21 Zodiac & SOB cruising describes different aspects of operations involving Zodiacs and SOBs (Special Operations Boat). According to the procedure, its purpose is to ensure that Zodiac and SOB operations take place in a safe manner and maintain high quality.

Among other things, the procedure sets out requirements for Zodiac operators. All operators were to be certified in accordance with RYA Level 2 powerboat[25] and have completed STCW[26] Basic Safety Training, Marine First Aid or similar. In addition, all operators were to be checked and certified annually by a deck officer who was a certified RYA instructor, and attend annual orientation session on Zodiac equipment held by the deck officer.

It also stated that at least two Zodiacs should operate together to assist each other and ensure each other's safety if necessary.

The recommended number of passengers per Zodiac was 8 plus one operator, but they could hold up to 10 passengers if necessary.

The procedure also required a man over board (MOB) briefing to be held after the passengers had boarded the Zodiac. The briefing was to include information about safety equipment on board. In the event of a MOB incident, the procedure stated that passengers should remain calm and that the operators/crew member was responsible for getting the person on board the boat.

1.11.3.4 Medical evacuation from Antarctica

SOP Procedure 5.36 Medical Evacuation from Shore describes how a medical evacuation is to be carried out. It also states that Viking had a private medical evacuation agreement for Antarctica with AeroRescate/DAP Airline in Punta Arenas, Chile for all expedition vessels operating in Antarctica. The master thus had the following options to consider:

1. Evacuation by air – via Teniente Rodolfo Marsh Martin Airport (TNM) located on the Chilean base Frei Station on King George Island, South Shetland Islands.
2. Use of own vessel – return to the closest point where the patient could be put ashore.

[25] https://www.rya.org.uk/training/courses/level-2-powerboat-handling-pl2c
[26] *The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers*

The procedure also states that the master is to contact the Viking office.

1.12 Rules and regulations

1.12.1 DNV

The vessel was designed and constructed in accordance with DNV Rules of January 2018. This chapter will not go into all the requirements that apply to windows and window frames, but will discuss requirements of relevance to this investigation.

1.12.1.1 DNVGL-RU-SHIP Pt.3 Ch.4 Loads

DNVGL-RU-SHIP Pt.3 Hull Ch.4 Loads (January 2018 version) describes design loads for assessment of hull strength requirements. By assessment of strength is meant the assessment of the strength criteria excluding fatigue. Each design load scenario for strength assessment is composed of either a static (S) or a static + dynamic (S+D) load case, where the static and dynamic loads are dependent on the loading condition being considered. All dynamic load components for each dynamic load case shall be applied as simultaneous values. The strength assessment is to be undertaken for all design load scenarios, and the final assessment is to be based on the most onerous strength requirement.

The dynamic loads associated with each dynamic load case are based on the equivalent design wave (EDW) concept. Wave-induced dynamic loads for strength assessment has a probability of exceedance of 10^{-8}.

In "Section 5 External Loads" both the minimum design pressure (P_{SI}) for the outside of the superstructure and P_w which includes hydrodynamic seapressure are described. According to 3.5.1, the design pressure for side scuttles and windows shall be as follows:

Table 34 Design pressure for windows

Structure	*Design pressure [kN/m²]*
Superstructure side	Max(P_W; P_{SI})
Deckhouse side walls	P_A
Aft wall	
Front wall	

Figure 87: Design pressure for Windows. Source: DNVGL-RU-SHIP Pt.3 Ch.4 Loads, Section 5 External Loads

1.12.1.2 DNVGL-RU-SHIP Pt.3 Ch.12 Opening and closing appliances

DNVGL-RU-SHIP Pt.3 Ch.12 Openings and closing appliances includes requirements for windows to be installed in the hull. Requirements exist for the arrangement and strength of the window pane and frames, and methods for fastening the pane to the frame.

Section 6 chapter 1 Application and general requirements includes general requirements for testing and type of glass.

Section 6 chapter 4 Glass thickness sets out requirements for glass thickness and calculation of glass thickness.

Section 6 chapter 5 Mounting frame sets out requirements for how frames are to be mounted to the ship.

Section 6 chapter 6 Testing requirements sets out requirements for the testing of windows and frames.

1.12.1.3 Class Guideline – DNV-CG-0130 Wave loads

These guidelines describe the hydrodynamic analysis method and procedures as guidance on how to meet the requirements set out in DNV-RU-SHIP Pt. 3, 5 and 6. This includes procedures and methods for directly calculated hydrodynamic wave loads and ship motions. It also provides detailed information about sea states and wave statistics as a basis for calculations.

The wave scatter diagrams used as a basis for classification rules assume adequate seamanship according to good practice, e.g. avoiding storms, changing course and speed. A scatter diagram defines the probability of occurrence/frequency of the different sea states. Each sea state is defined by a wave height, Hs, and a period, Tz or Tp.

Extreme loading for strength assessment uses a return period of 25 years, which corresponds to the ship's design life, with a probability of exceedance of 10^{-8}. It is based on waves for the North Atlantic.

The loading used can be divided into still water loads (static) and wave-induced loads (dynamic/impulsive). Linear hydrodynamic calculations imply that the wave pressure is acting only up to the still water surface. In non-linear calculations, the pressure is acting up to the water surface, which may be above or below the still water surface. This is important to the assessment of splash zone effect for sea pressure and slamming.

1.13 Other stakeholders

1.13.1 THE NORWEGIAN MARITIME AUTHORITY

The Norwegian Maritime Authority (NMA) has delegated authority for the ship to DNV. The NMA has the administrative authority to ensure safety and must exercise this authority, regardless of the classification rules used.

1.13.2 DNV – CLASSIFICATION SOCIETY

DNV followed up the newbuild and has been the ship's classification society since it was delivered. The ship is registered in the Norwegian International Ship Register (NIS), and DNV has been delegated authority from the NMA. During the construction phase, DNV approved drawings, performed inspections and witnessed tests to ensure that the ship meets the requirements of the flag state, DNV's classification rules and mandatory international requirements.

1.13.3 SOMEC – WINDOW SUPPLIER

Somec is a glass supplier that designs and manufactures windows for cruise ships. The company supplied the windows for 'Viking Polaris' and manufactured, tested, delivered and installed the windows on deck 2.

1.13.4 VARD – SHIPYARD

'Viking Polaris' was built by Vard shipyard. The shipyard was responsible for the design, strength calculations etc., but based its work on classification rules in connection with calculations of design pressure for windows and window frames, among other things. The design loads were calculated by the shipyard using the Nauticus Hull software and class society confirmed that the loads specified from the designer by a design load plan fulfilled the minimum pressures set out in the regulations. Then these were forwarded to Somec for use in the windows' design and production.

Marine Interiors (a sister company of Fincantieri) was responsible for the hotel part of the ship and for the contact with Somec.

1.14 Previous incidents/accidents

1.14.1 INTRODUCTION

In this chapter, some accidents that have been investigated after vessels have been hit by strong waves are summarized. It is noted that these are not necessarily directly comparable to the accident with Viking Polaris, but have been included to highlight the problems in connection with exposure to strong and breaking waves.

1.14.2 ORIANA

On 28 September 2000, the cruise ship 'Oriana' was en route from New York to Southampton at a speed of about 19.5 knots when she was struck by a large wave amidships on her port side.[27] Three cabin windows on deck 5 and three on deck 6 were broken, causing personal injury and damage to cabins. The ship was experiencing storm force conditions and high seas.

Some of the contributory causes identified were:

- *The wave causing the damage was probably larger than 10 m and possibly impacted with a force greater than the designed strength of the windows.*
- *The cumulative effect of various defects made many of the windows significantly weaker than designed, and a number possibly weaker than required by BSMA.*
- *Had the windows been manufactured and installed as designed, they would have been more likely to have been able to withstand the pressure exerted by the wave.*

Other findings included:

- *The window design met the requirements of the regulations.*
- *The absence of forecast for the area Hectate is not considered to be significant.*
- *Although the height of the bridge, along with the overall size of the ship, and the use of stabilisers, could potentially have contributed to an under-estimation of the sea conditions, the captain's observations from various levels would have reduced this possibility.*
- *A speed of 19.6 knots was appropriate with the sea and swell on the port quarter, although a more 'down-sea' course might have reduced ship movement and been more comfortable for passengers.*

One of the recommendations were addressed to the Maritime and Coastguard Agency:

- *Investigate the revision of the existing standard for windows, taking into account their increasing size, and new technology.*

[27] *Report on the investigation of wave damage to the passenger cruise ship 'Oriana' in the North Atlantic Ocean 28 September 2000, Marine Accident Investigation Branch, Report No 36/2002, November 2002.*

1.14.3 MARCO POLO

At 13:05 GMT on 14 February 2014, the passenger ship 'Marco Polo' was hit on her starboard side by a large wave at a position approximately eight nautical miles from the entry point to the north-east bound traffic lane off Ushant.[28]

The wind speed was reported as 70 knots. The wave strike resulted in damage to four windows. The windows were located in the side shell at deck 6 in one of the ship's restaurants. Sixteen passengers and crew members were injured, two of whom suffered serious injuries, and one was declared deceased as a result of the injury.

The report states that searches have been carried out in IMOs' Global Integrated Shipping Information System database (GISIS) and other online sources. It emerges that there have been 16 reported incidences of window breakages on passenger ships since the year 2000. It was also reported that one of these incidents, involving M/V 'Louis Majesty', resulted in two fatalities and eighteen injured passengers.

1.14.4 COSL INNOVATOR

The mobile drilling unit 'COSL Innovator' was struck by a wave in the North Sea at 16:38 on 30 December 2015.[29] The impact occurred forward on the port side, and the unit suffered extensive damage. One person died and four were injured when the windows in several cabins were shattered.

The report from the investigation following the incident described the following findings:

- The superstructure with windows was not dimensioned to withstand horizontal wave loads, only hydrostatic pressure.
- Given the data available, the Petroleum Safety Authority Norway (PSA) has concluded that the wave was steep, but that the weather conditions on 30 December were probably within the limits the unit was designed for.
- In the PSA's view, the greatest uncertainty related to the description of the incident lies in the relative positions of the wave and the unit at the moment of impact.

1.14.5 VLCC ARAFURA

On 11 September 2021, the Belgian-flagged ship 'ARAFURA' was struck by a wave while rounding Cape Horn.[30] Two crew members on deck were struck by the wave and later died from their injuries.

It was concluded that the cause of the accident was that the ship was struck by a wave significantly higher than the other observed waves.

One of the contributing factors mentioned in the report was described as follows:

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[28] Report of the marine safety investigation into a passenger fatality following a large wave strike off Ouessant (Ushant) on February 14th 2014, the Bahamas Maritime Authority, 27th of October 2014.
[29] Investigation of a fatal incident on 'COSLInnovator' on 30 December 2015, 6 July 2016.
[30] Report on the investigation into fatal accident on board vlcc 'Arafura' near Cape Horn with decease of two crew members on September 11th 2021, Federal Bureau for the Investigation of Maritime Accidents, Report 2121/004987.

The occurrence of a freak wave was not taken into account in the assessment to proceed to the foc'sle:

- The area near Cape Horn was not known for freak waves. The occurrence of freak waves in the Cape Horn region was not mentioned in any nautical publication and no observations of freak waves were recorded by the local authorities.

- The development of general warning systems to detect the possibility that freak waves might occur was still in an academic stage:

- *There was no equipment on board to detect the occurrence of freak waves.*
- *There was no existing tool that could be used by weather forecasting organisations ashore to forecast the occurrence of freak waves in that region.*

1.15 Additional information

1.15.1 SEARCH AND RESCUE IN ANTARCTICA

In 1998, Argentina and Chile established a collaboration through the Joint Antarctic Naval Patrol (PANC) to coordinate SAR[31] activities in the area between them. The Joint Antarctic Naval Patrol is active between 15 November and 31 March every year in five-week rotations with activities and exercises relating to search and rescue, salvage, pollution monitoring and recovery. The objective is to ensure safe navigation, protect human life and help keep the ocean free of pollution. There are SAR coordination centres in Ushuaia and Punta Arenas that have support vessels at their disposal in the event of SAR incidents. There is also a SAR coordination centre in Puerto Williams that provides support in ongoing operations.

In principle, IAATO (International Association of Antarctica Tour Operators) operators should be as self-sufficient as possible, with the exception of major accidents such as groundings and collisions with icebergs, where it will be natural to call the RCC.[32] Operators in these areas are expected to have their own contingency plans in place for most incidents, for example medical evacuations, but ships in the area are also expected to support each other. All the operators take part in a tracking system that allows them to know the precise location of other operators, and they all have each others' contact details.

1.16 Implemented measures

1.16.1 SHIP MANAGEMENT COMPANY

1.16.1.1 Operational weather restrictions and wave radar

Following the accident, temporary operational weather restrictions were developed to provide guidance to the masters of both 'Viking Polaris' and her sister ship 'Viking Octantis' concerning, among other things, the probability of breaking waves. The guide comprised a traffic light system intended to provide information about which combinations of significant wave heights (Hs) and average wave periods (Tz) constituted conditions under which the ship could not sail. According to DNV, the numbers in the matrix are typical wind force when the sea state is non-stationary and

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[31] *Search and Rescue.*
[32] *Rescue coordination centre.*

increasing. The figures in the matrix were intended to correspond to the wind for the relevant sea state.

Hs \ Tz	1,25	1,75	2,25	2,75	3,25	3,75	4,25	4,75	5,25	5,75	6,25	6,75	7,25	7,75	8,25
0,25	5,9	3,3	2,1	1,5	1,1	0,9	0,7	0,6	0,5	0,4	0,4	0,3	0,3	0,2	0,2
0,75			11,6	8,0	5,9	4,6	3,6	3,0	2,5	2,1	1,8	1,6	1,4	1,2	1,1
1,25				17,5	12,9	9,9	7,8	6,4	5,3	4,5	3,8	3,3	2,9	2,6	2,3
1,75					21,4	16,4	12,9	10,5	8,7	7,3	6,3	5,4	4,7	4,2	3,7
2,25						23,9	18,8	15,2	12,6	10,6	9,0	7,8	6,8	6,0	5,3
2,75							25,4	20,5	16,9	14,2	12,1	10,5	9,1	8,0	7,1
3,25								26,3	21,7	18,2	15,5	13,4	11,7	10,3	9,1
3,75								32,6	26,8	22,5	19,1	16,5	14,4	12,6	11,2
4,25									32,3	27,1	23,0	19,8	17,2	15,1	13,4
4,75										31,9	27,1	23,3	20,3	17,8	15,8
5,25										36,9	31,4	27,0	23,5	20,6	18,2
5,75											35,9	30,8	26,8	23,5	20,8
6,25											40,5	34,8	30,3	26,5	23,5
6,75												39,0	33,8	29,7	26,2
7,25													37,6	32,9	29,1
7,75														36,3	32,0
8,25														39,7	35,1
8,75															38,2
9,25															
9,75															
10,25															
10,75															
11,25															
11,75															
12,25															
12,75															
13,25															
13,75															
14,25															
14,75															
15,25															

Hs \ Tz	8,75	9,25	9,75	10,25	10,75	11,25	11,75	12,25	12,75	13,25	13,75	14,25	14,75	15,25	15,75	16,25	16,75
0,25	0,2	0,2	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
0,75	1,0	0,9	0,8	0,7	0,7	0,6	0,6	0,5	0,5	0,5	0,4	0,4	0,4	0,4	0,3	0,3	0,3
1,25	2,0	1,8	1,7	1,5	1,4	1,3	1,2	1,1	1,0	0,9	0,9	0,8	0,8				
1,75	3,3	3,0	2,7	2,5	2,3	2,1	1,9	1,8	1,6	1,5	1,4	1,3	1,2	1,2			
2,25	4,8	4,3	3,9	3,5	3,2	3,0	2,7	2,5	2,3	2,2	2,0	1,9	1,8				
2,75	6,4	5,7	5,2	4,7	4,3	3,9	3,6	3,4	3,1	2,9	2,7	2,5	2,4	2,2			
3,25	8,1	7,3	6,6	6,0	5,5	5,0	4,6	4,3	3,9	3,7	3,4	3,2	3,0				
3,75	10,0	9,0	8,1	7,4	6,7	6,1	5,7	5,2	4,8	4,5	4,2	3,9	3,6				
4,25	12,0	10,7	9,7	8,8	8,0	7,3	6,8	6,2	5,8	5,4	5,0	4,6	4,3				
4,75	14,1	12,6	11,4	10,3	9,4	8,6	7,9	7,3	6,8	6,3	5,8	5,4					
5,25	16,2	14,6	13,1	11,9	10,9	9,9	9,1	8,4	7,8	7,2	6,7						
5,75	18,5	16,6	15,0	13,6	12,4	11,3	10,4	9,6	8,9	8,2							
6,25	20,9	18,7	16,9	15,3	13,9	12,7	11,7	10,8	10,0								
6,75	23,4	20,9	18,9	17,1	15,6	14,2	13,1	12,0	11,1								
7,25	25,9	23,2	20,9	18,9	17,2	15,8	14,5	13,3									
7,75	28,5	25,5	23,0	20,8	19,0	17,3	15,9	14,6									
8,25	31,2	27,9	25,2	22,8	20,7	18,9	17,4	16,0									
8,75	34,0	30,4	27,4	24,8	22,6	20,6	18,9	17,4									
9,25	36,8	33,0	29,7	26,9	24,4	22,3	20,5	18,8									
9,75	39,7	35,6	32,0	29,0	26,3	24,0	22,1	20,3									
10,25	42,7	38,2	34,4	31,1	28,3	25,8	23,7										
10,75		40,9	36,8	33,3	30,3	27,6	25,3										
11,25			39,3	35,6	32,3	29,5	27,0										
11,75			41,8	37,8	34,4	31,4	28,8										
12,25				40,2	36,5	33,3	30,5										
12,75				42,5	38,7	35,3	32,3										
13,25					40,8	37,3	34,1	31,4									
13,75					43,1	39,3	36,0										
14,25						41,3	37,9										
14,75						43,4	39,8										
15,25							41,7	38,3									

Figure 88: Traffic light model prepared following the accident. Source: Ship management company

The traffic light colours were explained as follows:

> *'Green condition' – normal and acceptable conditions where vessel can proceed nominally as per planned voyage*
>
> *'Yellow condition' – conditions where vessel should keep seas abeam with full speed to minimize exposure time. Follow Heavy Weather procedure if assessed to meet criteria in OMCV Ch. 7.3*
>
> *Note: Be alert and take mitigating measures if observing any 'slamming' in this condition.*
>
> *'Red condition' – high risk conditions vessel should avoid planned voyage. If developing into red condition (non-forecasted) during voyage, vessel should head into seas with reduced speed until conditions improve*
>
> *Note: Be alert and take mitigating measures if observing 'slamming'.*

The ship management company has informed the NSIA that they are in the process of installing a wave radar on board, which could aid the crew in estimating wave heights and periods. This measure is applicable for all vessels in the Viking Expedition Fleet consisting of Viking Polaris and Viking Octantis, and shall be used when the vessels are operating in the Drake Passage.

The system will use the radar to measure wave height and period, and indicate whether the sea state, combined with the vessel's heading, is "green" or "red". "Green" heading would indicate a low likelihood of breaking waves hitting the shipside windows. "Red" heading will indicate an increased risk of breaking waves hitting the shipside windows.

If the wave radar system stops working for one reason or another, the manual traffic light system that has already been implemented must be used to determine if conditions are acceptable.

1.16.1.2 Courses and updated procedures

The ship management company has stated that they have implemented the following measures:

- The ship management company has been certified by DNV under DNV-ST-0008 to organise training/courses in how to use Zodiacs.

- An operations manual and course manual for Zodiac operations have been prepared.
- A pilot course has been held on board 'Viking Polaris' in the presence of DNV representatives.
- The Hangar Operations procedure has been updated to include the correct inflation pressure and procedures for checking the inflation pressure, among other things.

1.16.2 DNV

Following the incident, DNV has initiated extensive work, including a review of the rules and regulations for dimensioning of ships with a focus on dynamic pressure from waves breaking directly against the side of the ship. DNV notice that the established analysis methods used to calculate dimensioning loads from waves onto ships do not account for breaking waves. DNV's analysis and findings following the accident include the following:

- *Rules are based on both calculations and experiences from operation. The experiences will naturally include all types of loads, including breaking waves. Changes in ship design, operation or wave conditions could lead to conditions outside of established experience and incidents with higher loads than what ordinary rules account for. In this context, the term 'rules' must be understood to include the rules of individual classification societies, IACS and international conventions regulated by IMO, load line conventions, SOLAS etc.*

- *DNV's mapping of wave conditions in the Drake Passage, where the accident occurred, was done by obtaining hindcast data from external sources.*

- *DNV has recently taken into use a non-linear wave model, Higher Order Spectral Method (HOSM), when characteristics and loads from steep sea states are evaluated. This can be used to simulate the sea state during the incident. It can with high degree of accuracy predict wave statistics and kinematics right up until the point of breaking when CFD must take over.*

- *Breaking waves are a phenomenon that has not been studied much, but numerical methods (Computational Fluid Dynamics, CFD) could give us a new understanding of the phenomenon that was previously impossible. In the past two or three years alone, a combination of increased computing power and improved methods has made it possible to simulate hundreds of breaking wave events.*

- *DNV has taken simulated waves from HOSM as its point of departure and used them as a basis for CFD calculations when waves approach breaking. CFD shows that the frequency of breaking increases and that waves reach higher than predicted by HOSM.*

- *A set of rare, but critical sea states in terms of breaking has been simulated in CFD. They show that there is a certain, but low, probability of waves reaching the level of the windows on 'Viking Polaris' in the sea state that prevailed when the accident occurred. Also, this probability increases if the sea becomes choppier, i.e. if mean wave periods decrease for an unchanged significant wave height. In less choppy seas than was the case at the time of the accident, the probability will decrease dramatically and be more or less eliminated. If the ship changes direction by turning her bow into the waves, the loads high up on the side of the ship will decrease and fade away.*

- *Similar analyses were conducted for another ship. The results showed that the shape of the hull and the ship's main dimensions influence the size of the loads and how high up the ship's side they reach. Further analyses are required to validate these findings and see how the information can be applied in the rules.*

DNV also went through other rules and regulations like ICLL[33], IACS UR S3[34] and IACS common structural rules, typical standards applied in shipbuilding industry, and other classification societies. No other rules or regulations were identified that dealt with ships and ship windows that accounted for breaking waves.

[33] *ICLL 66/88 International Convention of Load Lines.*
[34] *IACS UR S3: Strength of end Bulkheads of Superstructures and Deckhouses.*

2. Analysis

2. Analysis

2.1 Introduction

The accident on board the cruise ship ‘Viking Polaris’ occurred when the ship was in passage from Antarctica to Ushuaia in Argentina. One passenger died and several were injured when a breaking wave shattered seven stateroom windows.

The investigation has in particular focused on determining whether the windows in the ship’s side were designed in accordance with the applicable rules and regulations, and what the regulatory basis was for calculating design pressure on windows in the ship's side. There is some uncertainty about the precise characteristics of the wave and the pressure it applied on the ship.

The analysis starts with an assessment of the sequence of events, both for the incident involving the Zodiac and the broken windows. Subsequently the ship management company’s guidance and procedures for sailing in heavy weather, the design basis and rules and regulations applicable to the design of windows in the ship’s side are assessed. Finally, an assessment of the rescue efforts and evacuation from Antarctica is performed.

2.2 Sequence of events

2.2.1 EVENTS LEADING UP TO THE ACCIDENT – THE ZODIAC INCIDENT

Information from CCTV on board the ship showed that the centre keel was inflated using compressor air in the hours leading up to the accident. This was standard practice on board in preparation for Zodiac expeditions. When the Zodiac had been relaunched and the passengers were on their way to the submarine, the centre keel exploded. Following the accident, the crew checked the centre keel of several of the Zodiacs using a manometer, and six other Zodiacs were found to have significant overpressure compared with the recommended operating pressure. Based on observations, analysis and mechanical testing of the keel, it is probable that the damage was a consequence of overloading rather than external damage or structural defects. This suggests that the centre keel exploded because it was overinflated.

One of the passengers sustained injuries in the accident because the floorboards were pushed up with great force, and another passenger was thrown overboard by the force of the floorboards’ movement. The passenger who fell overboard managed to hold on to the rope along the buoyancy tube until the operator was able to stop the boat. This person’s lifejacket did not inflate. The NSIA has tested a lifejacket of the same type and found that the hydrostatic release device had to be submerged to a depth of 3–4 cm before being released. The lifejacket worn by the passenger was tested by the crew after the accident by immersing it in a bucket, at which point it did inflate. Based on the above, it is unclear to the NSIA why the lifejacket did not inflate when the person entered the water. It is a possibility that the person managed to remain sufficiently high in the water by holding on to the rope that the inflation mechanism was not sufficiently submerged to be released.

It was somewhat challenging to get the person back on the boat, and the operator needed the assistance of two passengers. This was not strictly speaking in accordance with the ship management company’s emergency procedure, whereby passengers were to remain still in the boat and the able seaman was to help the person back on board, but together, they got him back on board relatively quickly. The ship management company’s procedures stated that Zodiacs should operate in pairs during all expeditions, among other things for reasons of safety. As this was originally a transport leg to take passengers to a submarine excursion and an extra trip was taken because the submarine was not ready for them, it was not explicitly mentioned in the ship management company’s procedures. However, the NSIA cannot see that the fact that the Zodiacs did not operate in pairs had any significant bearing on the sequence of events in connection with this incident, as the passenger was quickly brought back on board and other vessels quickly arrived to provide assistance. It must nevertheless be pointed out that there is a high risk of hypothermia in such waters if a person is not brought out of the water quickly. It is vital to have sufficient resources to be able to quickly get people out of the water in the event of a man overboard (MOB) incident. The NSIA emphasises the importance of ensuring safety in connection with all Zodiac operations.

The ship management company’s inflation procedures are discussed in more detail in section 2.3.

2.2.2 THE ACCIDENT

Following the incident on board the Zodiac, several alternatives were considered for bringing the passenger with fractures to hospital. The decision was made to discontinue the cruise and return to Ushuaia. This was discussed and cleared with the shipowner, which was in line with the ship management company’s procedures.

The bridge team checked the weather report and started planning the voyage. As bad weather was forecast, particularly in the area south of Cape Horn, a Heavy Weather Checklist was completed as described in the ship management company’s procedures. No written risk assessment was conducted in accordance with the ship management company’s safety management system before departure for Ushuaia, but the bridge team carried out an assessment of the route, considering the weather forecast and the ship’s planned speed. It was concluded that the best option was to set as straight a course as possible. Based on the weather report, the weather was expected to deteriorate as evening approached on 29 November, and full speed was ordered to beat the worst weather. In addition, considerations related to stress on the hull, stability and ballasting was addressed, see also chapter 1.7.2. The crew’s previous experience of the ship in wind speeds approaching 60 knots was that the ship was stable with little movement. As mentioned, there are many considerations to be made in planning of a voyage. Based on all the considerations made prior to the voyage, in addition to previous experience, it was considered safe to follow the voyage plan and maintain the planned speed. It was also during the voyage continuously assessed and followed up on the change in weather conditions.

The DPA was not contacted prior to this voyage as the bridge team had already assessed the forecasted weather conditions and planned the course and speed based on this information. It has emerged that it was not standard procedure to call the DPA to discuss weather forecasts, and this had not happened since the ship was put into operation. Nor had it been requested by the ship management company. The NSIA is of the opinion that calling the DPA in this specific situation would not have changed the outcome of the accident, because the ship management company onshore did not have knowledge about the vulnerabilities in the windows on deck 2 during certain sea conditions. This is further discussed in chapter 2.5 about regulations and window design.

There were also other vessels in the area on the evening of the accident; see section 1.10.1. This means that several vessels had decided to pass through the same area in the weather conditions forecasted. The other vessels’ routes went further east, probably because they departed from locations further east in Antarctica. The bridge team on board ‘Viking Polaris’ were thus not the only ones to have decided to cross the Drake Passage on the evening in question.

On the day of the accident there existed no knowledge which gave a basis for predicting the risk of a breaking wave hitting that high onto the ship side with such great force. Based on the knowledge that existed on the day of the accident the NSIA is of the opinion that the assessments made in connection with the voyage planning and execution seemed reasonable, considering the ship management company's management system, the communication with the owner and the crew's previous experience of the ship's performance in heavy weather.

The fin stabilisers and anti-roll system meant that the ship's movement was very limited, even in heavy weather. The navigators' experience was therefore that the ship had excellent seagoing properties under heavy weather conditions. The officers and the master regularly monitored the weather conditions and the ship's speed, list, rolling etc. during the voyage. An analysis of the ship's roll motion before the accident showed that there was little movement and that she listed about one degree to starboard. There were no indications on board the ship that she could not withstand the weather conditions they were sailing in until the accident suddenly happened. The weather conditions deteriorated somewhat compared to the forecast, however not significantly worse than those considered by the crew before departure. There were no indications of abnormal movements on board the ship nor that the ship had challenges handling the prevailing conditions, but it was occasionally some sea spray on the bridge windows, which was considered normal in bad weather. The bridge team therefore did not see any particular reason to change the ship's course or speed during the voyage. The NSIA has not examined how much the course would have had to be changed or the speed reduced for the windows to withstand the load of the breaking wave.

The NSIA cannot see that the generic risk assessment or the ship management company's procedures contained information about vulnerabilities in the ship's side or particular weather restrictions to be followed.

The crew had long combined experience at sea, but because 'Viking Polaris' had only been in operation for a relatively short time, they had limited experience of the ship's design under all conditions.

Nor had the crew received any information that the stateroom windows on deck 2 were a potentially weak point under special wave conditions. The above, in combination with the fact that the ship had excellent seagoing properties in bad weather, made it challenging for the bridge team to identify the forces acting on the ship and assess which sea states that could result in exceedance of the design loads for the windows on deck 2.

CCTV footage reviewed after the incident has shown that the ship was struck by a breaking wave. Based on information about the position of the damaged area, CCTV footage, the crew's observations and wave height estimates, it has subsequently been estimated that the wave height was most likely 11–16 metres. According to knowledge about how the wind acts on the sea under the wind conditions that prevailed at the time of the accident, the probability of breaking waves was not insignificant. How the rules and regulations take account of breaking waves is discussed in more detail in section 2.5.2.

If the windows had not broken, sailing at this course and speed under the prevailing conditions would probably not have had any consequences for the passengers, and the speed would indeed have had a positive effect on passenger comfort due to the effectiveness of the fin stabilisers at high speed.

At the time of the accident, the crew's emergency response was swift, and the passengers affected by the accident in the stateroom area on deck 2 received immediate assistance. No circumstances have been identified that caused further negative consequences of the accident as a result of the crew's emergency response efforts.

2.3 The ship management company's procedures for Zodiac inflation and operation

The investigation has shown that the ship management company lacked procedures and training in relation to inflation of the Zodiacs. The supplier offered a course that covered inflation procedures and information about the correct inflation pressure, but only the crew of the sister ship 'Viking Octantis' took the course. The NSIA has been informed that an internal course was held for the crew of 'Viking Polaris' by instructors from her sister ship. The course material received does not show that inflation procedures were reviewed as part of this course.

There were also no procedures established in the ship management company's safety management system describing the inflation process, the correct inflation pressure or how to check the pressure, although this was all described in the user manual provided by the Zodiac supplier. The ship management company has confirmed that this has been updated in the management system; see section 1.16.1.2. Therefore, no safety recommendation is submitted on this matter.

Although the management system did not describe inflation procedures, it is worth noting that the inflation pressure was stated on the buoyancy tubes' inflation valves. This means that the information was available to the crew. On the other hand, the inflation pressure was not indicated on the inflation valves of the futura tubes and the centre keel, and it was more difficult to access the valve on the centre keel as it was located inside the box. The NSIA does not believe that the challenging design was the main reason why the pressure was not checked using a manometer, since it was also not checked for the main buoyancy tubes. The fact that the crew had not received any particular training in inflation procedures is probably one of the reasons why the centre keel was overinflated. This is supported by the significant overinflation detected in several other boats after the accident.

The investigation has shown that several of the Zodiacs that have had problems with glue separation also had overinflated centre keels. The NSIA has not looked further into the potential connection between glue separation and overinflation.

2.4 The ship management company's guidelines and procedures for sailing in heavy weather

The ship management company's safety management system contained procedures for route planning and precautions to be taken in heavy weather. Among other things, it stated that hull performance was to be assessed as part of the company-generic risk assessment. It also stated that passenger comfort was to be a factor in the assessment.

The risk assessment and procedures did not describe how certain sea states could give rise to breaking waves that could impose great loads on the stateroom windows and thereby challenge their tolerance limits. Nor was there any mention that the navigators needed to pay attention not to underestimate the wave loads on the hull because of the ship's limited movement, among other things due to the highly effective fin stabilisers. The NSIA cannot see that this risk had been clearly communicated to the crew on board the ship. The generic risk assessment contained no information about risks associated with underestimating the forces acting on the ship even though movement was minimal due to the ship's anti-roll systems, and it was thus left up to the crew to identify this risk.

Following the accident, the ship management company in cooperation with the class society developed weather restrictions for the purpose of providing more guidance for navigators regarding which sea states could give rise to breaking waves that reached the level of the windows and, consequently, when the ship should discontinue a planned voyage or turn into the waves and reduce speed. No information has emerged that the ship management company's management system included such operational restrictions before the accident, which indicate that the vulnerability represented by the windows on deck 2 under certain sea states was not known by either the ship management company or the class society. The background and basis for the window design are discussed in more detail in section 2.5.

2.5 Window design

2.5.1 DESIGN BASIS AND WAVE FORCES

The examination of the design basis for the ship's windows identified no faults or non-conformities that would have had a bearing on the outcome of the wave hitting the windows. Nor have faults been found in the windows' installation and manufacturing basis. The full-scale pressure test conducted on the strongest window on deck 2 showed that the window frame and pane were able to withstand a test pressure of 40 kPa. The windows, including the frames, that were broken by the breaking wave were dimensioned according to a design pressure of 24.2 kPa. The fact that the frame was identical for all the windows and withstood a pressure higher than its design pressure, but yielded first in some of the stateroom windows, suggests that the pressure has been higher than 40 kPa and thus significantly higher than what the windows were designed for.

It is possible that the frame would have been able to withstand the pressure from the wave if it had been attached to the hull with load-bearing screws. As the pressure from the wave far exceeded the design pressure, however, the window would in any case have been shattered. The wave forces acting on the windows were thus significantly higher than they were designed for.

As a consequence of the minimum thickness requirement, the surrounding steel was after the accident estimated to withstand a pressure of 107 kPa, which was significantly higher than the design pressure of 24.4 kPa that applied to both the ship's side and the windows in the damaged area. No damage was identified to the hull around and near the windows, which indicates that the pressure exerted by the breaking wave on some of the damaged areas was most likely in the area between 40 and 107 kPa.

As the window pane itself was designed with a safety factor of 4 in relation to the surrounding steel, the panes will in practice be able to withstand loads significantly higher than the design pressure. The safety factor is intended to take into account the different material properties of glass and steel. Among other things, glass is brittle and will break whereas steel will be deformed and absorb the energy from a breaking wave. The actual tolerance limit of the panes is uncertain, but it may have been about four times the design pressure, which would make it approximately 98 kPa.

The breaking wave produces an impulse load, and the pressure may therefore significantly exceed the design pressure without the material breaking. Whether the material will break depends on the properties of the material combined with the characteristics of the impulse load such as maximum pressure and duration. The scale of this impulse load is therefore uncertain, and no further investigations were carried out to estimate it. Consequently, it cannot be ruled out that the maximum wave pressure may in a short period have exceeded 107 kPa.

The breaking wave has not been found to have been abnormally large or outside what the ship was designed to withstand. The wave height was most likely in the range 11–16 metres with a period of around 8–9 seconds, which is within the extent of validity of the rules which was defined by the scatter diagram. The sea state the ship departed into (Hs 6 or 7 m and Tp 11 s) was defined as a part of the sea states defined in the rules, see Appendix C. There is nothing in the regulatory framework or the formula used to calculate the design pressure for the windows that assumed that the ship could not be exposed to waves from the side in these sea states.

The regulatory framework for calculating the design pressure on the ship's side and the windows that broke, as well as the extent to which breaking waves are taken into account in the formulas, are discussed in more detail in section 2.5.2.

2.5.2 RULES AND REGULATIONS

There are two formulas in the DNV classification rules, which are according to common requirements from IACS, for calculation of minimum strength of the shipside, where the highest is to be dimensioning. This pressure will constitute the dimensioning pressure for the windows. The two pressures considered are P_w and P_{si}. P_w takes account of all sea states and wave directions, and also includes an operational factor intended to factor in the ship's course in relation to the waves.

P_{si} is based on experience and includes no form of wave analysis or operational factor. For the position of the windows that broke, P_{si} was the dimensioning pressure (giving the highest design load). Although P_w is based on wave analysis, neither of the two calculation methods took breaking waves into account.

Several incidents have been reported in which windows have broken or cabin windows have been knocked in by breaking waves and rough seas; see sections 1.10.1 and 1.14. The investigations into some of these accidents pointed out that the windows had not been dimensioned to withstand the wave that hit them, but that the design complied with the applicable rules and regulations.

The Southern Ocean between Cape Horn and Antarctica is dominated by waves from the west, which will hit the vessels sailing this route from the side. In November, winds with a force of 7 (28–33 knots) or more on the Beaufort scale are expected for 30% of the time in the Drake Passage and the area where the accident occurred. The risk of breaking waves will be significant where the wind velocity is increasing. It is therefore not abnormal to encounter a lot of wind and also breaking waves on voyages crossing the Drake Passage. This was also the experience of the crews of both 'Viking Polaris' and 'Viking Octantis'.

Among other things, 'Viking Polaris' had fin stabilisers that were very effective in reducing movements, so a voyage under the prevailing conditions did not present any particular problems in terms of ship movement or passenger comfort. No operational restrictions had been developed prior to the accident, except what was stated in the regulations. At the time of the accident neither the crew, the ship management company nor the ship classification society had any knowledge which could predict the risk of a breaking wave hitting that high on the shipside with such great force. As a result, the weak points that windows constituted in this case had not been particularly considered or assessed as a risk during the voyage. Also, the crew were not aware of and had not been given any particular knowledge about the differences in tolerance limits (design pressure) between the windows and the steel of the surrounding hull.

The investigation has shown that the sea conditions at the time of the accident were within the sea states defined in the scatter diagram which the ship was designed for, and that no faults of significance to the outcome of the incident have been found in the design basis. The risk of breaking waves increases for steeper sea states, i.e. the risk increases for shorter wave periods for Hs greater than 4.25 m, see also Figure 86. The sea state at the time of the accident was within the critical area of the scatter diagram, which is defined a risk for braking waves to occur and reach the windows on deck 2.

It is not identified rules for ships or ship windows in any of the IACS-members ship rules, including DNV's rules for ships, which account for the effect of breaking waves on the shipside. The NSIA is of the opinion that the windows were inadequately dimensioned and that the design pressure requirements for windows in this position, as set out in the ship rules, yield too low values to be able to withstand pressure loads from breaking waves within the extent of validity of the rules. The NSIA addresses one safety recommendation to DNV on this matter. It must be noted that DVN has initiated extensive work to further map the local weather conditions in the area and analyse the effect of waves on different types of ships to generate new insight into breaking waves and loads in beam seas.

Since the accident, temporary operational restrictions have been put in place for both ‘Viking Polaris’ and her sister ship ‘Viking Octantis’ until it was uncovered what had happened. The operational restrictions was intended to take into account wave heights and periods that could cause waves to break and damage the ship. It is planned to introduce a permanent decision support system which will assist the crew identifying the risk for the ship being exposed to breaking waves which may cause damages to the vessel. This supports the view that the windows were inadequately dimensioned and that the rules did not take account of breaking waves.

The operational restrictions give an average period Tz, but the weather report normally used by the crew normally states a peak wave period Tp, which means that the crew have to convert this parameter from Tz into Tp. Moreover, weather reports and navigators rarely apply this level of precision (two decimals in the matrix) when it comes to wave heights and wave periods. It will therefore be challenging for the crew to use the traffic light model in its current form.

DNV’s work has shown that ships operating in the Drake Passage more often sail in sea states with Hs 4–6 metres than ships that operate in other areas[35]. In addition, they are more often exposed to beam seas in this area.

The operational restrictions introduced following the accident also indicate that it may be challenging for the ship to sail in sea states with Hs as low as 4.25 metres when combined with low wave periods. This appears to potentially challenge the whole concept of operations, as these are low sea states and not uncommon for the area in question. This will make further demands on the bridge team in terms of their knowledge and assessment of sea conditions, also in sea states that were perhaps initially not deemed problematic for the ships to operate in. Moreover, the weather changes quickly in this area, which means that clear guidelines should be in place as regards what to do if weather conditions change, as the present design is less robust in the event of waves breaking against the ship’s side. One measure described in the ship’s weather restrictions is to change course in case of unfavourable sea states, so as to have the ship sail at a reduced speed with the bow heading into the seas. The NSIA is of the view that this would be a problematic measure at the time of the accident, as it would have taken the ship straight into the worst of the weather at a course that would be completely off in relation to their planned destination. This would have significantly increased the duration of the ship’s exposure to the rough weather conditions. There are also other factors for the crew to take into consideration, including passenger comfort and logistics, and it would thus be a difficult measure to implement. The NSIA considers that a more robust window design that takes account of breaking waves will constitute a stronger barrier than operational measures alone.

Weather conditions in the Drake Passage and other areas with similar wind conditions will have a risk for breaking waves that has to be accounted for and assessed. ‘Viking Polaris’ and her sister ship ‘Viking Octantis’ may be exposed to breaking waves hitting the side of the ship if they are operated in beam sea in increasing wind conditions. The current dimensioning of the windows means that they will not be able to withstand the pressure from all breaking waves. The NSIA therefore submits two safety recommendations to the Norwegian Maritime Authority and the owner and the ship management company on this matter.

[35] By other areas it is referred to an average of all areas ships operate in, weighted by the number of observations.

2.6 Rescue and evacuation from Antarctica

Operators operating in Antarctica should be as self-sufficient and independent as possible. Operators in these areas are expected to have contingency plans in place for most incidents, for example medical evacuations, but ships in the area are also expected to support each other. This means that a ship may have to interrupt a cruise and return to the mainland for a medical evacuation, as was the case for 'Viking Polaris'. This can result in ships having to sail in worse weather than they would normally have planned for. It is therefore decisive that the rules account for the sea states, including breaking waves, which may arise within the extent of validity of the rules.

3. Conclusion

3. Conclusion

3.1 Main conclusion

The investigation has shown that the ship was struck by a breaking wave that, in combination with the ship's course and speed, shattered seven stateroom windows and caused extensive damage inside the staterooms. One passenger died and several others were injured in the accident. The accident happened when the ship was en route from Antarctica to Ushuaia because a medical evacuation was required following a Zodiac incident that occurred in Antarctica, injuring one passenger and causing another one to fall overboard.

The weather conditions deteriorated somewhat compared to the forecast, however they were not significantly worse than those considered by the crew before departure. The ship's fin stabilisers and anti-roll system meant that movement was very limited, even in heavy weather. There were no indications of abnormal movements on board the ship nor that the ship had challenges handling the prevailing conditions, but occasionally some sea spray on the bridge windows, which was considered normal in bad weather.

At the time of the accident, the crew did not have sufficient premises for predicting the risk associated with a breaking wave reaching so high up on the shipside with such great force. Based on the knowledge that existed at the day of the accident, the NSIA is of the opinion that the assessments made in connection with the voyage planning and operation seemed reasonable, considering the ship management company's management system, the communication with the owner prior to departure and the crew's previous experience of the ship's performance in heavy weather.

The investigation has shown that the sea conditions at the time of the accident were within the sea states defined in the scatter diagram which the ship is designed for, and no faults of significance to the outcome of the incident have been found in the design basis. The investigation has also shown that the wave forces acting on the windows were significantly higher than they were designed for.

It is not identified rules for ships or ship windows in any of the IACS-members ship rules, including DNV's rules for ships, which account for the effect of breaking waves towards the shipside. The NSIA is of the opinion that the windows were inadequately dimensioned and that the design pressure requirements for windows in this position, as set out in the ship rules, yield too low values to be able to withstand pressure loads from breaking waves within the extent of validity of the rules.

3.2 Investigation results

3.2.1 THE ZODIAC ACCIDENT

- Information from CCTV on board the ship showed that the centre keel was inflated using compressor air in the hours leading up to the accident, but the pressure was not checked using a manometer.
- Significant overinflation of the centre keel on several other Zodiacs was detected after the accident.
- Based on observations, analysis and mechanical testing of the keel, it is probable that the damage was a consequence of overloading rather than external damage or structural defects. This suggests that the centre keel exploded because it was overinflated.
- The investigation has shown that the ship management company lacked procedures and training in relation to inflation of the Zodiacs.

- There were also no procedures established in the ship management company's safety management system describing the inflation process, the correct inflation pressure or how to check the pressure, although this was all described in the user manual provided by the Zodiac supplier. The ship management company has confirmed that this has been updated in the management system.
- A lifejacket of the same type has been tested, and it was found that the hydrostatic release device had to be submerged to a depth of 3–4 cm before being released. The lifejacket worn by the passenger was tested by the crew after the accident by immersing it in a bucket of water, in which case the lifejacket inflated. Based on the above, it is unclear to the NSIA why the lifejacket did not inflate when the person entered the water. It is a possibility that the person managed to remain sufficiently high in the water by holding on to the rope that the inflation mechanism was not sufficiently submerged to be released.

3.2.2 THE ACCIDENT RESULTING IN BROKEN STATEROOM WINDOWS

- The investigation of the design basis for the ship's windows has not identified any faults or non-conformities that would have had a bearing on the outcome of the wave hitting the windows.
- The full-scale pressure test conducted on the strongest window on deck 2 showed that the window frame and pane were able to withstand a test pressure of 40 kPa. The windows, including the frames, that were broken by the breaking wave were dimensioned according to a design pressure of 24.2 kPa. The fact that the frame was identical for all the windows and withstood a pressure higher than its design pressure, but yielded first in some of the stateroom windows, suggests that the pressure has been higher than 40 kPa and thus significantly higher than what the window was designed for.
- The requirement to minimum thickness of the surrounding steel was roughly estimated to a capacity of 107 kPa. This was significantly higher than the design pressure that applied to the windows, which was 24.4 kPa. No damage was identified to the hull around and near the windows, which indicates that the pressure exerted by the breaking wave on some of the damaged areas was most likely in the area between 40 and 107 kPa, but it cannot be ruled out that the maximum wave pressure in a short period may have exceeded 107 kPa.
- There is some uncertainty associated with the estimated height of the breaking wave. The breaking wave has nevertheless not been found to have been abnormally large or outside what the ship was designed to withstand. The sea state the ship departed into (Hs 6 or 7 m and Tp 11 s) was defined as one of the sea states defined in the rules.
- There is nothing in the regulatory framework or the formula used to calculate the design pressure for the windows and the ship's side that assumed that the ship could not be exposed to waves from the side in these sea states.
- The regulatory calculation methods for design pressures in the damaged area did not take breaking waves into account. Nor have any other rules and regulations for ships and ship windows been identified that take account of breaking waves.
- Several incidents have been reported in which windows have broken or stateroom windows been knocked in by breaking waves and rough seas. The investigations into some of these accidents pointed out that the windows had not been dimensioned to withstand the wave that hit them, but that the design complied with the applicable rules.
- Among other things, the ship had fin stabilisers that were very effective in reducing movements, so a voyage under the prevailing conditions did not present any particular problems in terms of ship movement or passenger comfort. No operational restrictions had been developed prior to the accident, except what was stated in the regulations. At the time of the accident neither the crew nor the ship management company had the sufficient premises to

predict the risk associated with a breaking wave hitting that high on the shipside with such great force. As a result, the weak points that windows constituted in this case had not been particularly assessed as a risk during the voyage.

- The crew were not aware of and had not been given any particular knowledge about the differences in tolerance limits (design pressure) between the windows and the steel of the surrounding hull.
- Operators operating in Antarctica should be as self-sufficient and independent as possible. This means that a ship may have to interrupt a cruise and return to the mainland for a medical evacuation, as was the case for ‘Viking Polaris’. This can result in ships having to sail in worse weather than they would normally have planned for. It is therefore decisive that the rules account for the sea states, including breaking waves, which may arise within the extent of validity of the rules.

4. Safety recommendations

4. Safety recommendations

The Norwegian Safety Investigation Authority submits the following recommendations[36] for the purpose of improving safety at sea:

Safety recommendation Marine No 2023/07T

On 29 November 2022, the cruise ship 'Viking Polaris' was en route from Antarctica to Ushuaia in Argentina when a breaking wave struck the ship's side south-east of Cape Horn. The wave shattered the windows of seven cabins, resulting in one fatality and injuring another eight passengers.

The investigation has shown that the sea conditions at the time of the accident were within the sea states defined in the wave scatter diagram the ship was designed for. No faults of significance to the outcome of the incident have been identified in the design basis. However, it is revealed that the minimum requirements in the IACS class rules, including DNV, doesn't provide a dimensioning minimum pressure sufficient to withstand a breaking wave. The NSIA is of the opinion that the windows were insufficiently dimensioned to withstand the pressure loads from this breaking wave, and that the applicable IACS rules, international requirements and standards give too low values to withstand the pressure loads from breaking waves within the validity of the rules and regulations.

The Norwegian Safety Investigation Authority recommends that DNV promote the problem in question in the International Association of Classification Societies (IACS) to ensure that all class rules, independent of class society, are developed to include requirements that account for breaking waves against the shipside. This also has to be reflected in DNV's own rules.

[36] The investigation report is submitted to the Ministry of Trade, Industry and Fisheries, which will take the necessary steps to ensure that due consideration is given to the safety recommendations.

Safety recommendation Marine No 2023/08T

On 29 November 2022, the cruise ship 'Viking Polaris' was en route from Antarctica to Ushuaia in Argentina when a breaking wave struck the ship's side south-east of Cape Horn. The wave shattered the windows of seven cabins, resulting in one fatality and injuring another eight passengers.

Wind speeds that could cause waves to break are common for much of the year in the Drake Passage and the area where the accident happened. Under such conditions, it is therefore a possibility that 'Viking Polaris' and her sister ship 'Viking Octantis' will be exposed to breaking waves hitting the side of the ship. The NSIA considers that a robust design that takes account of breaking waves will constitute a stronger barrier than operational measures alone. The current dimensioning of the windows means that they will not be able to withstand the pressure from all breaking waves which may arise within the extent of validity of the rules and regulations.

The Norwegian Safety Investigation Authority recommends that the Norwegian Maritime Authority, which has the overall responsibility for safety at sea for vessels flying the Norwegian flag, ensure that Viking Expedition Ship II LTD conducts reinforcements to ensure that breaking waves do not cause damage to windows on the two existing expedition vessels.

Safety recommendation Marine No 2023/09T

On 29 November 2022, the cruise ship 'Viking Polaris' was en route from Antarctica to Ushuaia in Argentina when a breaking wave struck the ship's side south-east of Cape Horn. The wave shattered the windows of seven cabins, resulting in one fatality and injuring another eight passengers.

Wind speeds that could cause waves to break are common for much of the year in the Drake Passage and the area where the accident happened. Under such conditions, it is therefore a possibility that 'Viking Polaris' and her sister ship 'Viking Octantis' will be exposed to breaking waves hitting the side of the ship. The NSIA considers that a robust design that takes account of breaking waves will constitute a stronger barrier than operational measures alone. The current dimensioning of the windows means that they will not be able to withstand the pressure from all breaking waves which may arise within the extent of validity of the rules and regulations.

The Norwegian Safety Investigation Authority recommends that Viking Expedition Ship II LTD, in cooperation with Wilhelmsen Ship Management (Norway) AS, implement reinforcements to ensure that breaking waves do not damage the windows on the two existing expedition vessels.

Norwegian Safety Investigation Authority
Lillestrøm, 28 November 2023

Appendices

Appendix A Details of the vessel and the accident

Vessel	
Name	Viking Polaris
Flag state	Norway / NIS
Classification society	DNV
IMO number / call sign	9863209
Type	Cruise ship
Build year	2022
Owner	Viking Expedition Ship II LTD
Operator / Responsible for ISM	Wilhelmsen Ship Management (Norway) AS
Construction material	Steel
Length	205 metres
Gross tonnage	30,114
Voyage	
Port of departure	Anvers in Antarctica
Port of arrival	Ushuaia, Argentina
Type of voyage	International
Cargo	Passengers
Persons on board	A crew of 266 and 309 passengers
Information about the accident	
Date and time	29 November 2022, at approximately 22:35 (local time)
Type of accident	Heavy weather damage
Location/position where the accident occurred	South-east of Cape Horn / pos S56°31.896 and W66°08.197
Place on board where the accident occurred	Port side, deck 2
Injuries/fatalities	1 fatality and 8 injured passengers + 2 injured in connection with the Zodiac incident
Damage to ship/the environment	7 stateroom windows broken with consequent damage to the staterooms
At what point in the voyage was the vessel	Underway
Environmental conditions	Westerly wind, Beaufort force 11 (violent storm) 56–63 knots, sea state 7 (high sea)

Appendix B Consultancy company's report

Appendix B is available at the NSIA website https://www.nsia.no/Marine/Published-reports/2023-06

Appendix C Scatter diagram

Table C-2 Scatter diagram for the North Atlantic

T_z (s)	*3.5*	*4.5*	*5.5*	*6.5*	*7.5*	*8.5*	*9.5*	*10.5*	*11.5*	*12.5*	*13.5*	*14.5*	*15.5*	*16.5*	*17.5*	*18.5*	*Sum*
H_s (m)																	
0.5	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
Sum	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

The H_s and T_z values are class midpoints.

Figure 89: Scatter diagram for the North Atlantic Source: DNV-RP-C205

INVESTIGATION REPORT
VIKING POLARIS
NSIA PROJECT NO 22/661

This report is translated by the Norwegian Safety Investigation Authority (NSIA)

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Contents

1. SUMMARY

7Waves has been commissioned by the Norwegian Safety Investigation Authority (NSIA) to assist with the investigation of NSIA project no 22/661, relating to the accident on board 'Viking Polaris' on 29 November 2022. 7Waves has assisted by examining the design basis, focusing on wave load and window design for staterooms on deck 2.

The study consisted of a review of rules and regulations, verification of design pressure calculations and design basis, comparison of wave pressure with calculation methods from wave theory and offshore rules.

1.1 Conclusion

The conclusions of the study are as follows:

1. The window and adjacent ship structure were designed in accordance with the applicable rules and regulations. Some minor discrepancies were found, none of which were of any significance to the accident.
2. The sea state at the time of the accident was within the sea states defined in the wave scatter diagram which the ship is designed according to. The pressure from the breaking wave exceeded what the windows were dimensioned for.
3. The design pressure requirements for windows in this position, result in too low values to be able to withstand pressure loads from breaking waves within the extent of validity of the rules.
4. Additional design requirements should be introduced to ensure that the shipside is dimensioned for breaking waves.

1.2 Cause

The direct cause is deemed to be that the ship was struck by a large long-crested breaking wave at an angle of about 60–80 degrees on the port side. This created a pressure wave against the ship's side and windows in the affected area that shattered several windows and damaged the interior of the ship.

The failure modes for the different stateroom windows can be summarised as follows and are discussed in more detail in section 9.2:

- The pressure was highest (> 40 kPa) on the lower windows where the vertical posts of the frame of staterooms 2012, 2014, 2016, 2018 and 2020 were knocked in.
- The glass panes were the weakest point in lower staterooms 2008 and 2010 and upper staterooms 2010, 2012, 2014 and 2016.

Even though they are designed in accordance with the ship rules, the strength of both the window frames and panes was insufficient to withstand the wave pressure. This shows that the pressure from the breaking wave exceeded the design pressures.

It is worth noting that the aft parts of the windows have been subjected to the highest load, probably because the ship's speed caused the pressure wave to be directed aft. The windows were designed so that the lower part formed a recess from the ship's side, and the wave therefore caught the aft window frame. The speed also contributed to increase the pressure. Whether the speed- or wave-induced pressure contributed the most is uncertain.

Photos of the damage show that only the windows were damaged, and not the steel in the ship's hull, despite the fact that both are designed according to the same local pressure requirements. The reason only the windows broke is that the steel is dimensioned according to a minimum thickness requirement (DNVGL-RU-SHIP Pt.3 Ch.6 Sec.3 [1]), which result in greater strength than the local pressure requirement and allows the steel plate to withstand greater pressure than the windows. The rules also contain requirements for the minimum thickness of windows, but they provide less strength against lateral pressure than the minimum steel thickness requirements. The design criteria for the minimum thickness of windows include a safety factor of 4 that is intended to take account of the different material properties of glass and steel.

The review of the rules and the investigations carried out show that the windows are dimensioned according to a local pressure requirement. This meant that the windows were weaker than the surrounding steel, which caused them to shatter. The assessment found that the pressure from the breaking wave was in the range between 40 kPa (hydro static pressure test performed on the frame) and 107 kPa (roughly estimated capacity of surrounding steel). It cannot be ruled out that the maximum slamming pressure has been greater than 107kPa over a very short period.

Other contributing causes include:

- The windows were placed far down in the hull side.
- The windows were designed so that the lower part formed a recess from the ship's side, and the wave therefore caught the aft part of the window frame.
- The ship was travelling at high speed in heavy seas where the waves struck at an angle of 60–80 degrees from port, but the ship was dimensioned to travel at this speed in such weather conditions.
- The ship used active roll damping with stabiliser fins and the ship would thereby have been stable in the water with little roll-motion. Without active stabiliser fins, the ship master would probably have chosen a different course because the ship would have experienced excessive rolling movements.

The wave height and wave period were within the ship's trade area, i.e. the scatter diagram with a 25-year return period defined in the rules. The reason the wave "broke" has not been determined with certainty, but it was likely due to a combination of interference and strong winds, which made the wave crest unstable and caused it to "break".

1.3 Recommendations for further work

1. Carry out further investigations to determine the characteristics of the wave that caused the accident both through studies of existing data and observations, and by running a time-domain simulation of the wave conditions around the ship, among other things to estimate the pressure from the wave.
2. Perform a structural analysis of the window to test the hypothesis concerning the window's fracture mechanism.
3. Run a pressure impulse simulation to learn more about the wave force that caused the accident.

1.4 Incidents of a similar nature

The 'Viking Polaris' incident bear similarities with other incidents such as the accidents involving 'COSL Innovator' [1] and 'VLCC Arafura' [2]. The first-mentioned is similar because both concern windows above the freeboard water line that were shattered by breaking waves, and the last-mentioned because it happened in the same area under similar weather conditions and concerns a wave breaking over the deck.

2. INTRODUCTION

With reference to the NSIA's allocation letter dated 27 January 2023 NSIA Doc. no 23/67-9, 7Waves AS was commissioned to assist the NSIA in its investigation of an accident on board 'Viking Polaris' on 29 November 2022.

This sub-report describes scope, assumptions, methods and results from the examinations performed.

3. DEFINITIONS

Definitions and abbreviations are provided in Table 3-1.

Abbreviation	Explanation
AP	Aft perpendicular
Cb	Block coefficient
Cw	Wave coefficient
FP	Forward perpendicular
Hs	Significant wave height
LOA	Length overall
Tp	Peak period
VDR	Voyage data recorder

Table 3-1: Definitions and abbreviations

4. THE ASSIGNMENT

This study will address the following aspects of the accident:

1) Preliminary investigation to clarify the design basis used when dimensioning the ship's side and windows in the area that was damaged
2) Comparison of slamming pressure calculations for waves according to the ship rules [3] and offshore rules [4]
3) Investigate and describe the background for the calculation of external wave pressure in the ship rules
4) Based on information about the wave conditions at the time of the accident, perform a parameter study to determine whether it is possible to recreate an external pressure that can cause similar damage
5) Examine the design basis for the windows provided in [5] and [6], including:
    a. Testing methods and their documentation
    b. Verify whether the window glass used (type and thickness) and the fixings were in accordance with calculated loads
    c. Check whether as-built drawings were in accordance with the structural calculations performed during the design phase
    d. Assist in assessing whether the windows and fixings were in accordance with as-built drawings

5. THE SHIP

'Viking Polaris' is a cruise ship built for Arctic expeditions. At the time of the accident, the ship had completed several voyages in Arctic waters.

'Viking Polaris' was built and commissioned in autumn 2022. The ship is designed in accordance with DNV's Rules for Ships of January 2018, [5].

Figure 5-1 shows the ship's profile and general arrangement. The technical data and main dimensions are summarised in Table 5-1.

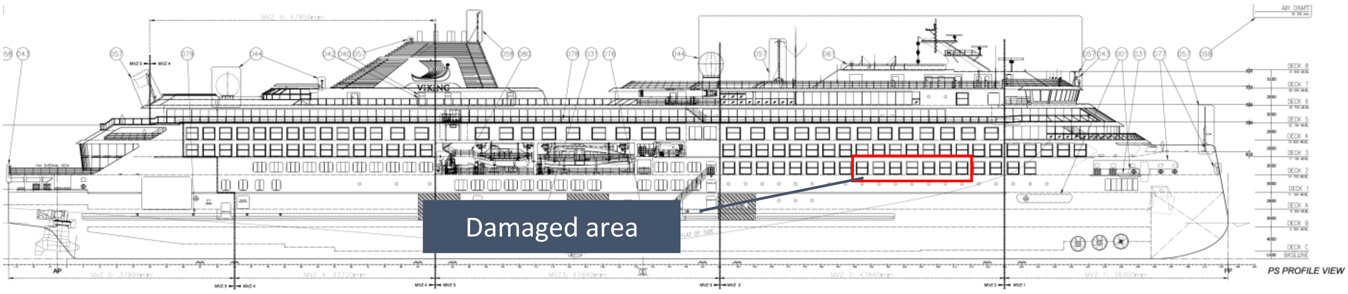


Figure 5-1: General arrangement and profile of starboard side where the damaged area is shown. Note that, although this figure shows the starboard side, the damage occurred on the port side, which has the same profile as the starboard side.

Technical data	
Design:	Vard 626
Classification society:	DNV
Built:	September 2022
Rules for classification:	DNV Rules for Ships, January 2018
Flag:	Norwegian, NIS
Shipyard:	Vard Søviknes
Name:	Viking Polaris
Class notation:	+1A Passenger ship BIS BWM(T) Clean COMF(V1)
	DYNPOS(AUTS) E0 LCS(DC) NAUT(NAV)
	PC(6) Recyclable Silent(E)
LOA	205.0 m
Breadth (MLD.)	23.5 m
Breadth max.	23.7 m
Design draught	6.0 m
Summer draught	6.2 m
Pax. (189 cabins)	378
Crew (157 cabins)	262
Total persons on board	640
Wave coefficient, Cw	9.79

Table 5-1: Technical data for the ship

6. DESCRIPTION OF DAMAGE AND DAMAGED AREA

The damage consisted of windows that were partially shattered and pushed in, and subsequent damage to fixtures and fittings in the staterooms. The area that was damaged was on deck 2, 14.1 metres above the keel and between 43 and 57 metres from the foreship (FP). The minimum still-water freeboard at the time of the accident is estimated to about 8 metres.

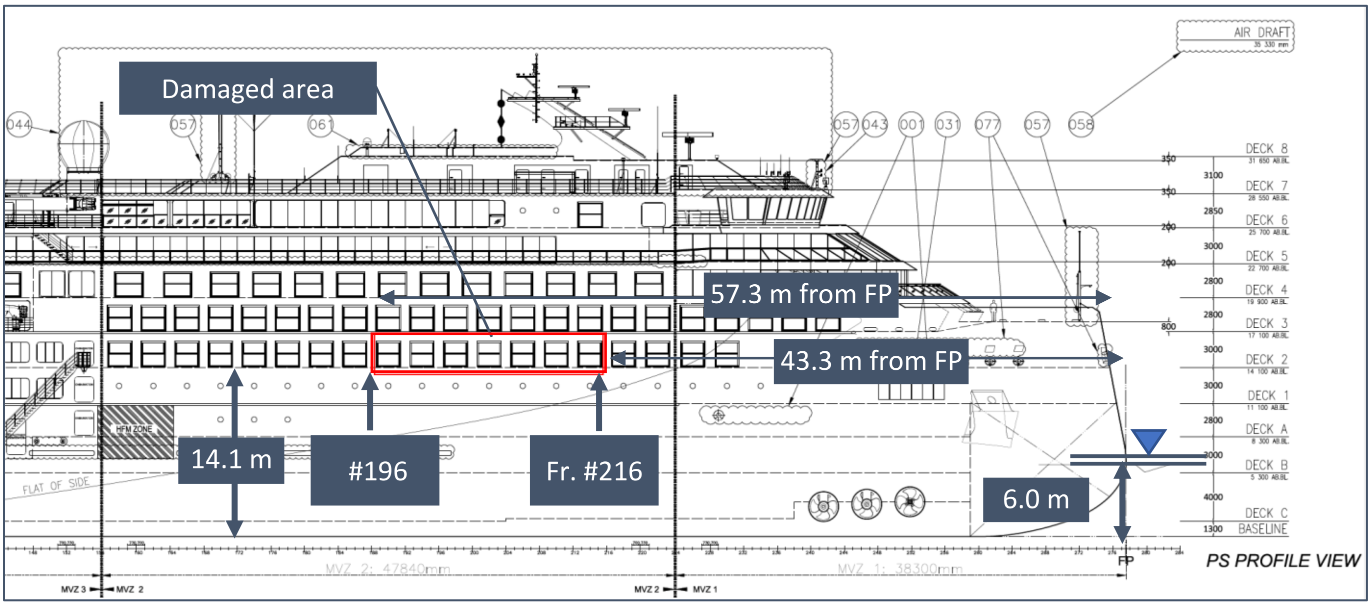


Figure 6-1 Illustration of damaged area – illustrated from starboard side on the drawing


Figure 6-2 Photo of damage to the port side of 'Viking Polaris', deck 2, November 2022

7. RULES APPLICABLE TO THE SHIP

7.1 General ship rules

Ship rules are prescriptive, partly based on experience from design and operation of ships accumulated through 150 years of ship classification [7]. Lessons learned from accidents have been an important source of regulatory development.

The rules are based on the assumption that the ship's main dimensions and proportions are within a certain range of validity, such as the length/breadth and draught/breadth ratios etc. The ship rules are retrospective by nature, which means that new types of design are not necessarily covered by the rules.

In this respect, they differ from the risk-based offshore standards developed for the design of oil and gas installations in the North Sea. This means that the structural design is dimensioned based on direct calculations of project-specific loads on the specific vessel. Unlike the ship rules, which assume the ship's shape etc., the offshore standards can in principle be applied to all types of floating structures of any geometrical shape under all weather conditions and operations. The aim is in any case for the design to meet the same level of safety.

Provisions relating to rules for the design of windows, and the calculation of pressure from waves on external surfaces, are particularly relevant to this study. Both the ship rules and the offshore rules contain calculation methods and formulas for use in such calculations.

The study shows that the formulas for calculating external pressure described in the ship rules were used in the dimensioning of windows and the ship's side in the damaged area on 'Viking Polaris'.

7.2 Structure of ship rules

The ship rules are made for the design of single-hull steel ships. For structure/strength calculations, the rules are structured in such a way that it is first specified how the design should be arranged with regard to definitions and general requirements for the arrangement of volume, tanks etc. This is used to determine the ship's main dimensions and general arrangement. The next part of the rules deals with the definition and calculation of loads the design is intended to withstand. When designing ships not subject to sailing restrictions, a predefined set of wave data is used that is supposed to cover all highest expected loads a ship may encounter during its service life (25 years).

For ships, this is what is known as the North Atlantic 'scatter diagram' with a 25-year return period (exceedance probability of 10^{-8}). More detailed information about the wave 'scatter diagram' is available in DNV-RP-C205 Environmental conditions and environmental loads, Appendix C, Table C-2 in [4]. The wave data in DNV-RP-C205 is based on the IACS Rec.34 Standard Wave Data for Direct Wave Load Analysis. The scatter diagram is defined by a wave period Tz and a significant wave height Hs and form a contour. The highest significant wave height (Hs) in a 25-year contour is, Hs = 16.1 m (for more details about the calculation, see Sec.3 [3.6.2.1] and Table C-4 in [4]). Sea states with the highest wave heights are typically dimensioning for global forces, while steep sea states along the contour with considerably lower wave heights and shorter wave periods is dimensioning for local forces as bow slamming or green sea on deck.

The requirements described in the ship rules for the dimensioning of e.g. windows against external pressure are governed by where on the ship the window is located. The design pressure increases forward towards the bow and down towards the waterline. The magnitude of the hydrodynamic sea pressure is calculated based on what are known as equivalent design waves (EDW). EDW are a set of regular waves intended to represent the design loads a ship can be exposed to in operation.

If, for example, the window is placed far enough aft and above the waterline, the rules will result in such low hydrodynamic sea pressures that they will not be dimensioning in this position. In such cases, the rule uses a minimum pressure (P_{SI}) instead that is based only on the wave and block coefficients; see DNVGL-RU-SHIP Pt. 3 Ch. 4 Sec. 5.

8. RULES FOR CALCULATING PRESSURE ON THE SHIP'S SIDE AND WINDOWS

There are two formulas for calculating the design pressures of the windows along the hull, of which the highest design pressure shall be dimensioning:

1. P_W
2. P_{SI}

P_W was developed with regard to a 25-year return period where all sea states and directions have been considered. It also includes an operational factor (also known as the seaman's factor) that takes the heading into account. This is typically dimensioning for the bow of the ship. Pw is dimensioning for the parts of the ship that through conventional wave loads of ship, will be exposed to pressure forces from the waves. This includes the hull below the waterline, as well as the structure above the waterline where the waves are expected to reach. In the bow, loads from bow impact/slamming are generally dimensioning. These loads are especially developed to consider high loads (including loads from breaking waves) that can be expected in rough seas directly from ahead.

P_{SI} is the minimum design pressure for the external sides of superstructures and is based on experience and shipbuilding practices. It does not include any kind of wave analysis or the operational factor; see also Chapter 13.

Neither P_W nor P_{SI} takes breaking waves into account.

In accordance with the rules, the windows on deck 2, which sustained damage, were located so far aft and so far above the waterline that the wave pressure was no longer dimensioning, i.e. $P_{SI} > P_W$. As a result of the windows' location, the minimum pressure rule shown in Figure 8-1 was applied. This formula is not based on an EDW, but is based on experience and shipbuilding practices.

The windows and steel structure of the ship's side (hull) on deck 2 were therefore dimensioned according to the Rules for Ships [3], DNVGL-RU-SHIP Pt. 3 Ch. 4 Sec. 5 [3.3][1] as shown in Figure 8-1:

3.3 Sides of superstructures

3.3.1 The design pressure for the external sides of superstructures, in kN/m^2, shall not be taken less than:

$$P_{SI} = 3C_W(C_B + 0.7) - 2(z - T_{sc})$$

but shall not be less than:

— 0 kN/m^2 for direct strength analysis according to Ch.7
— 2.5 kN/m^2 for other cases.

Figure 8-1 Rule pressure as described in Pt. 3 Ch. 4 Sec. 5 [3.3]

[1] DNVGL-RU-SHIP, Part 3 Hull, Chapter 4 Loads, Section 5 External Loads

This is the minimum pressure referred to in 7.2.

The formula specify that pressure should be calculated for the sides of the superstructure and provide a static design pressure based on the vertical position (z) relative to maximum draught (Tsc), the shape of the ship (Cb), and the wave parameter (Cw) in the ship rules, where the latter is derived from the North Atlantic scatter with a 25-year return period. By superstructure is meant the parts of the structure that are located on the freeboard deck and extend from the starboard to the port side. The design pressure and other design parameters for the windows are given in Figure 8-2.

Figure 8-2 Design parameters for the windows.

8.1 Verification of design pressure

In order to verify the design pressure calculation, a separate analysis was run in the ship design tool Nauticus Hull to determine the value of external pressure on the ship hull between deck 2 and 3. Nauticus Hull was also used by the shipyard to calculate the design pressure on 'Viking Polaris' during the design phase.

Forward of frame #223, the design pressure is calculated based on design waves for the oncoming sea, which results in increased design pressure requirements; see Figure 8-3. The results of the study are shown in Table 8-1 and show good correlation between the pressures. The study therefore concludes that the design pressure used for the design and testing of the windows and fixings were calculated correctly in accordance with the ship rules.

Input:							
X-position, LCP [Frame No.]	#154	#166	#178	#190	#202	#214	#226
Y-position, LCP [mm]	11750	11750	11750	11750	11750	11750	11750
Z-position, LCP [mm]	14180	14180	14180	14180	14180	14180	14180
Select position for load application	Superstructure, side	Superstructure, side	Superstructure, side	Superstructure, side	Superstructure, side	Superstructure, side	Superstructure, side
Select associated PSM (if applicable)	<------->	<------->	<------->	<------->	<------->	<------->	<------->
Select compartment 1	External	External	External	External	External	External	External
Select compartment 2	No compartment	No compartment	No compartment	No compartment	No compartment	No compartment	No compartment
Load scenario	-All-	-All-	-All-	-All-	-All-	-All-	-All-
Superstructure:							
Superstructure/Deckhouse Tier no.	3	3	3	3	3	3	3
b1 [m]	23.5	23.5	23.5	23.5	23.5	23.5	23.5
B1 [m]	23.5	23.5	23.5	23.5	23.5	23.5	23.5
zw [m]	14.18	14.18	14.18	14.18	14.18	14.18	14.18
Machinery casing	☐	☐	☐	☐	☐	☐	☐
Results:							
Information							
Design cases for Comp. 1	P_SI	P_SI	P_SI	P_SI	P_SI	P_SI	ExtremeSea_SD, SEA-1,...
Design pressure, P, for Comp.1 [kN/m2]	24.1	24.1	24.1	24.1	24.1	24.1	28.9
Design cases for Comp. 2							
Design pressure, P, for Comp.2 [kN/m2]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max static+dynamic design press. [kN/m2]	24.1	24.1	24.1	24.1	24.1	24.1	28.9
Max static design press. [kN/m2]	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 8-1 Design pressure for damaged area from ship rules, calculated using Nauticus Hull.

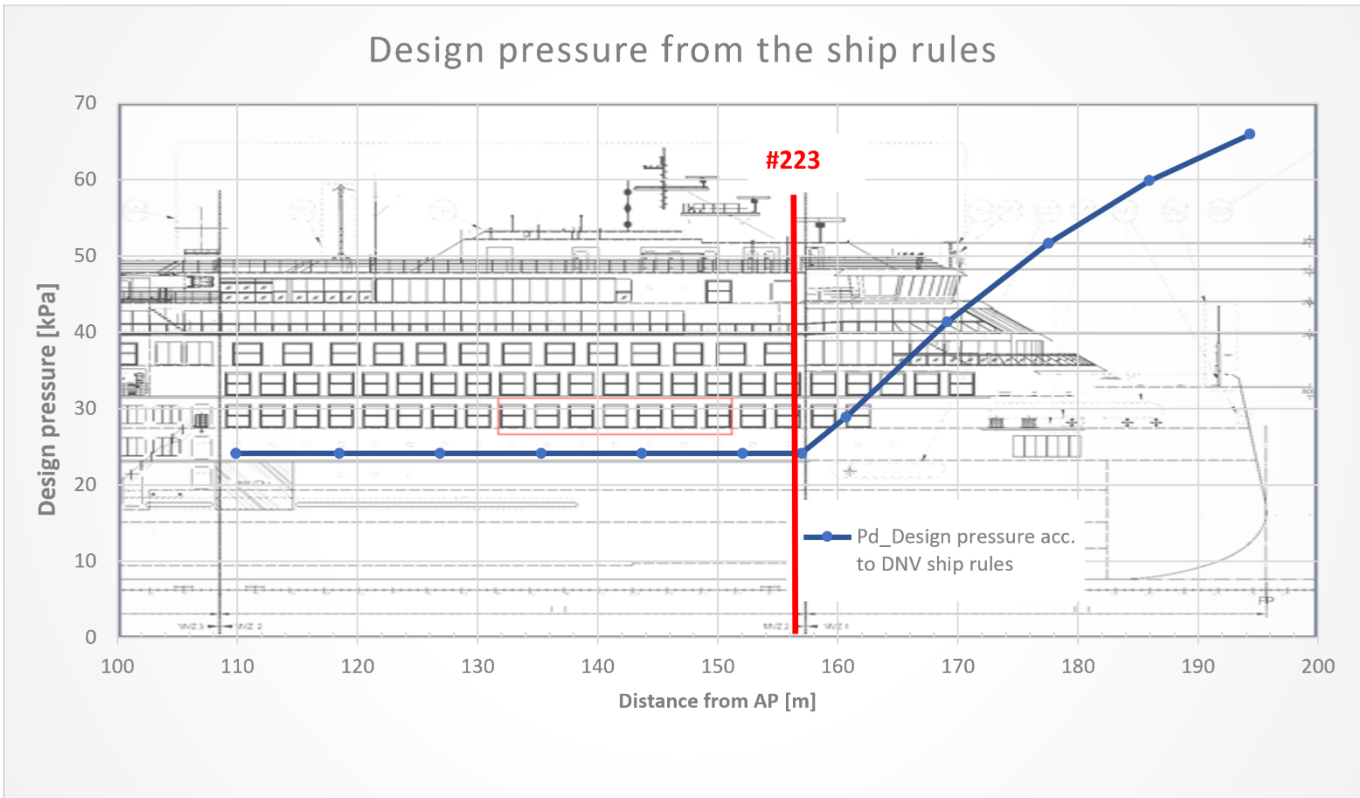


Figure 8-3 Rule pressure for the ship's side.

8.2 Other methods of calculating pressure from wave impact

The rule pressure used to calculate the design pressure for the windows (see Table 8-1) is, as mentioned, a minimum pressure partly based on empirical data.

There are other methods, based more on wave kinematics, for calculating the pressure from a wave breaking against a vertical surface (such as the windows of 'Viking Polaris'). These methods are based on the main parameters of the incoming wave, such as height, length and steepness. These methods are described in, e.g., DNV's Recommended Practice [4], and in other literature for the design of ships and offshore structures, such as

[8]. What these methods have in common is that, when using wave parameters from the time of the accident, they will give a significantly higher pressure than the rule pressure used to design the windows in the affected area on 'Viking Polaris'.

9. DESIGN BASIS FOR WINDOWS

9.1 Rules and regulations for windows

9.1.1 General information

Ship rules for windows are decribed in DNVGL-RU-SHIP Pt. 3 Ch. 12 Sec. 6[2] and DNVGL-RU-SHIP Pt. 5 Ch. 4 Sec. 2[3]. The rules provide guidance on the location of windows, their thickness and the type of glass that should be used, fixings and testing of windows, including the frame. The ship rules that apply to the windows concerned can be summarised in the following points:

- Windows must not be fitted below the freeboard.
- The thickness of the glass shall be dimensioned in accordance with the ship rules, Pt. 3 Ch. 12 Sec. 6 [4].
- Toughened or toughened laminated safety glass must be used.
- The glass pane must be supported along all sides.
- Windows with a glass pane larger than 1m^2 are not covered by known standards and must therefore be tested in accordance with the ship rules, Pt. 3 Ch. 12 Sec. 6 [6.1].

9.1.2 Location of windows

Restrictions on the location of weather-resistant windows are based on the International Convention of Load Lines (ICLL). ICLL sets standards to protect the parts of the vessel that contribute to buoyancy from being flooded, and is thus not linked to the probability of wave impacts.

ICLL and DNV's ship rules state that windows must not be fitted below the freeboard or on the superstructure that contributes to buoyancy on deck 1. The freeboard of 'Viking Polaris' is on deck A (8,300 mm above the keel), as shown in Figure 9-1, and deck 1 is 11,100 mm above the keel. The windows relevant to this investigation are located above the freeboard on deck 2 and thereby comply with DNV's ship rules.

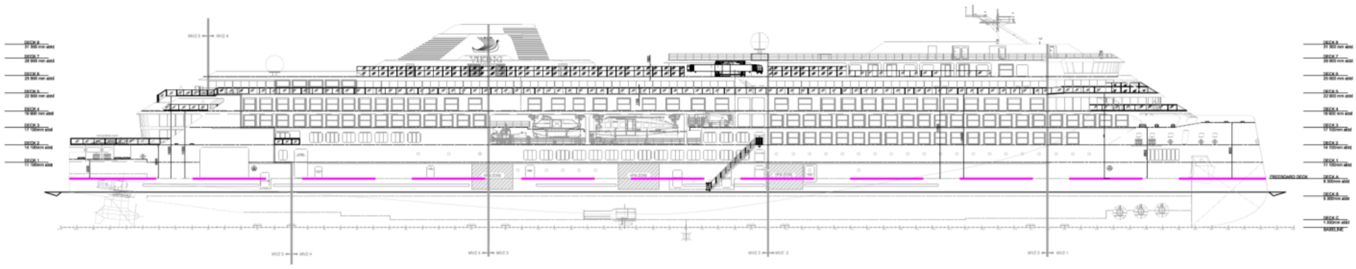


Figure 9-1 Freeboard drawing

9.1.3 Glass thickness

The requirements to minimum glass thickness for ship windows originates from ISO standard number 21005 "Thermally toughened safety glass panes for windows and side scuttles". Most IACS class societies, including DNV, use this standard in their rules. The glass itself is generally designed with a safety factor of 4 compared with the surrounding steel; see Table 5 in [9]. That means that the formula for required glass thickness presented below includes a safety factor of 4. The safety factor of 4 applies to static load application and means that the glass should be able to withstand four times the design pressure in a full-scale static pressure test. This safety factor is intended to take into account the different material properties of glass and steel. Among other things, glass is brittle and will break whereas steel will be deformed and absorb the energy from a breaking wave.

[2] DNVGL-RU-SHIP, Part 3 Hull, Chapter 12 Openings and closing appliances, Section 6 Windows, side scuttles and skylights
[3] DNVGL-RU-SHIP, Part 5 Ship types, Chapter 4 Passenger ships, Section 2 Hull, 6 Glass structure

The rules for design pressure on the ship's side are based on static pressure and does not take into account impulse loads from breaking waves. A breaking wave that hits the ship's side will produce an impulse load whose pressure may exceed the static design pressure without the material breaking. Whether the material will break depends on the properties of the material combined with the characteristics of the impulse load such as maximum pressure and duration.

The ship rules state the required thickness, t_r, for a single layer of glass as:

$$t_r = \frac{b}{200}\sqrt{\beta P}$$

where:

t_r = required thickness
b = shortest length of the window, which is 928 mm
β = factor equal to 0.6 depending on window size (1,800 mm x 928 mm)
P = design load in kPa

For laminated safety glass, the total equivalent thickness, t_e (in mm), shall be in accordance with the following formula; see Pt. 3, Ch. 12, Sec. 6 [4.1.3]:

$$t_e = \sqrt{\frac{\sum_{i=1}^{n} t_i^3}{t_{max}}} \geq t_r$$

where:

n = number of laminated layers, which is 2
t_i = thickness of each layer in mm
t_{max} = the largest thickness of n layers in mm
t_e = equivalent thickness of laminated toughened safety glass in mm, which must not be less than 10 mm.

Laminated double-layer safety glass is used in the windows in question, and SOMEC has designed the glass thickness according to the required thickness (see formula for t_r), but not in accordance with equivalent thickness (see formula for t_e). The ship rules allow for the possibility of deviating from the formula for t_e if tests are performed in accordance with Pt. 3, Ch. 12, Sec. 6 [5]. Of these tests, item 4 (see Figure 10-2), where the glass is tested with a 4 x P pressure, has not been performed. Instead, SOMEC has documented that the double-layer safety glass that was used is as strong as single-layer glass in accordance with EN 1288-3 (see pp. 104–111 in [10]) and therefore designs according to the formula for t_r. In principle, this should not affect the safety level, because SOMEC has proven that the double-layer glass used is just as strong or stronger than single-layer glass.

Whether the EN 1288-3 test provides the same safety level for the laminated glass as the test described in Pt. 3, Ch. 12, Sec. 6 [6] item 4) is uncertain, however, especially because SOMEC assumes that the characteristic breaking strength of the monolithic glass is 120 MPa, while the ship rules that refer to ISO 11336-1 [9] assume a breaking strength of 160 MPa for calculation of minimum thickness of monolithic glass (formula 5 and Table 5 in ISO 11336-1). If SOMEC had used 160 MPa, the laminated glass would have been weaker than the monolithic glass for 10 + SG + 8 mm and 12 + SG + 12 mm, while the result would be unchanged for 6 + SG + 6 mm glass. The glass thicknesses calculated by SOMEC and the pertaining results are given in [10].

Laminated glass	Static force [N] that results in breakage			Status	
		Monolithic glass			
	4-point test (EN 1288-3)	120 MPa	160 MPa	SOMEC	7Waves
6 + SG + 6 mm	7,547	5,184	6,912	Approved	Approved
10 + SG + 8 mm	15,027	11,664	15,552	Approved	**Not approved**
12 + SG + 12 mm	24,984	20,736	27,648	Approved	**Not approved**

Table 9-1 Static breaking strength of laminated glass compared with monolithic

The difference in static load that results in breakage for the lower windows that shattered at a glass thickness of 10 + SG + 8 mm is 525 N. Although these results show non-conformity with the rules, and the fact that, without this non-conformity the window would have a higher strength, the outcome of the accident would still be the same, because the actual pressure applied by the wave far exceeded the design pressure. The weakest point on several of the lower windows was the vertical post. Even if the glass had a higher strength, the vertical post would have yielded and subsequently pulled the window with it and shattered the window as the frame post was pushed into the stateroom, and the outcome of the accident would have been the same.

9.1.4 Mounting of window pane to window frame

The ship rules Pt. 3, Ch. 12, Sec. 6 [5.1.3] require an overlap of at least 10 mm or $b/75$ mm between the glass pane and the window frame, where b is the shortest length of the window. b is 804 mm for the upper and 928 mm for the lower windows. The overlap does not have to exceed 20 mm. That means that the minimum requirement is an overlap of 11 mm for the upper and 13 mm for the lower windows.

The overlap on the windows in question is 15 mm (upper) and 23 mm (lower), which is in accordance with the ship rules.

9.1.5 Mounting of window frame to hull

Metallic window frames may be bolted or welded to the ship structure in accordance with the ship rules Pt. 3 Ch. 12 Sec. 6 [5.1].

The spacing between the screws fastening the window frame to the ship structure must not exceed 150 mm. The windows in question were attached with different types of screws that were also spaced at different intervals. The spacing between the load-bearing screws varied between 222 mm and 230 mm. The capacity of the window fixings, including frame, bolts and stiffeners, are evaluated by class society to be in accordance with the applicable rules through the equivalence principle stated in Pt.1 Ch.1 Sec.1 [2.5.9], by performing a strength test of the complete installation. The fixing of the screws is shown in Figure 9-2 and Figure 9-3. The load-bearing screws are highlighted in Figure 9-3. The remaining screws hold a thin aluminium profile with low load-bearing capacity and are therefore not considered load-bearing.

No damaged or broken load-bearing screws were found for the windows studied in this report. It can therefore be concluded that the load-bearing screws were of sufficient strength. This has also been verified by a full-scale pressure test as explained in section 10.2.

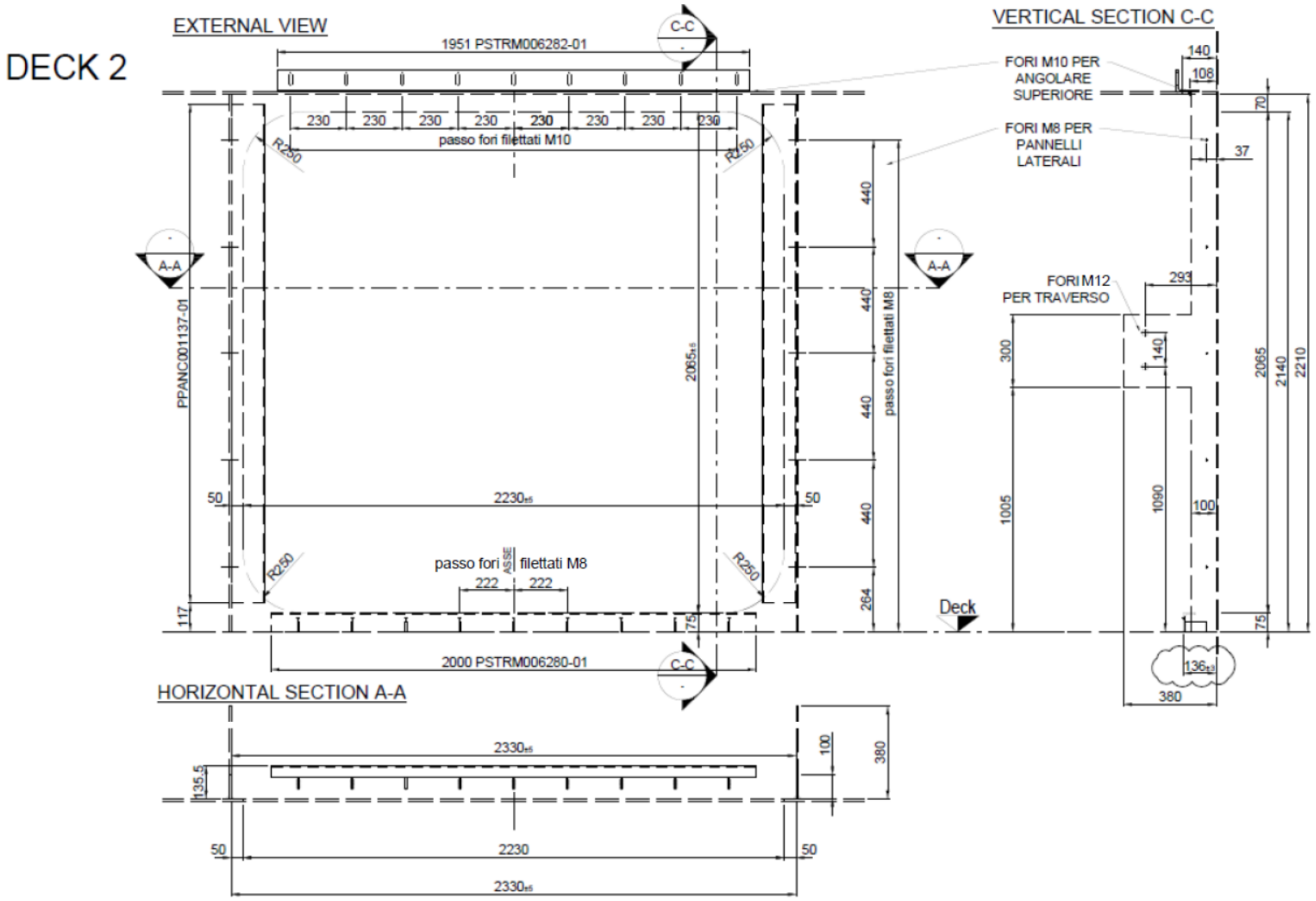


Figure 9-2 Screw fixing, deck 2

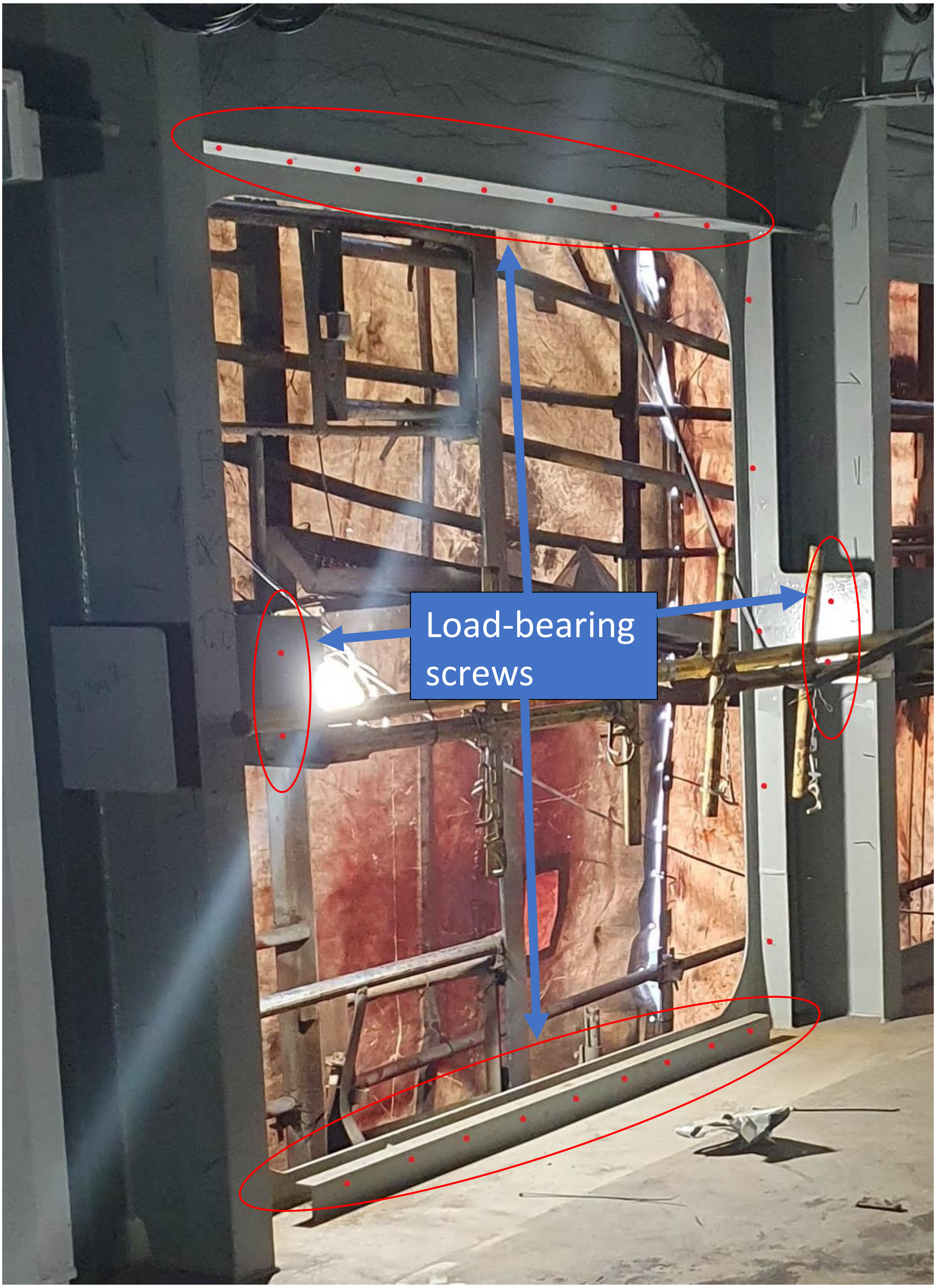


Figure 9-3 Screws fastening. The red dots show the location of the screws. The load-bearing screws are highlighted.

9.2 Failure modes

9.2.1 Lower windows, staterooms 2012, 2014, 2016, 2018 and 2020

In five of seven staterooms (2012, 2014, 2016, 2018 and 2020), the aft frame post has been knocked in; see Figure 9-4 and Figure 9-5. For these windows, it can be concluded that the frame post was knocked in while pulling the shortest (aft) side of the window pane with it, thereby shattering the glass. That means that the frame yielded before the pane, and that the pane shattered as a result of high pressure and inadequate support from the frame post.

Figure 9-4 Overview photo showing the damaged staterooms on deck 2. We can see that the aft frame post is damaged on five of the seven damaged windows.

Figure 9-5 Window of stateroom 2014

Figure 9-6 shows a close-up photo of the aft frame post. We see that three of six fastening screws are bent as a result of the frame post being pushed into the stateroom. The six fastening screws used to attach the frame post are shown in Figure 9-7.

The full-scale pressure test that was carried out (see section 10.2) showed that the frame was able to withstand a test pressure of 40 kPa. The windows and frames for these staterooms had a design pressure of 24.4 kPa. The fact that the frame withstood a higher pressure but yielded first suggests that the pressure has been higher than 40 kPa and thus far higher than what the window was designed for. If the frame post had been attached to the hull with load-bearing screw, it would have been able to withstand the pressure from the wave. As the pressure from the wave far exceeded the design pressure, however, the window would in any case have been shattered.

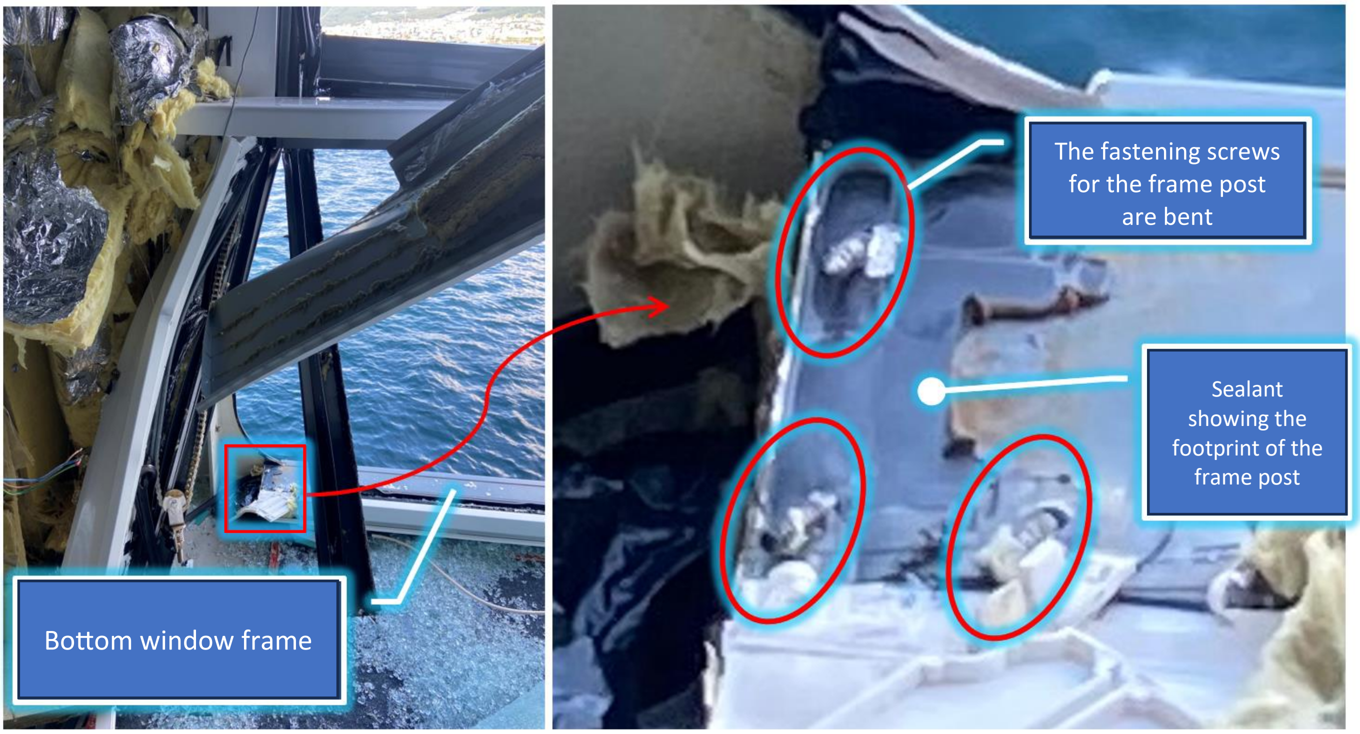


Figure 9-6 The weakest point of the window frame

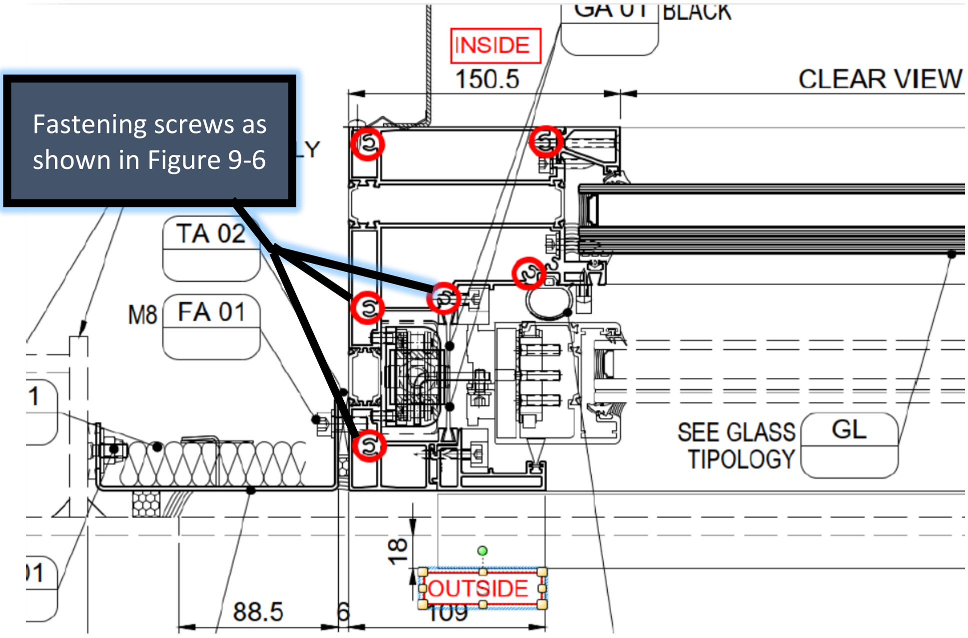


Figure 9-7 Fastening screws for the window frame seen from above

9.2.2 Upper windows, staterooms 2010, 2012, 2014 and 2016

Figure 9-8 shows the four upper damaged windows, where the frame is still intact. This means that the glass was the weakest point of these windows, and not the frame as was the case for the lower windows.

Based on these findings, we can conclude that the pressure has been higher than the glass was able to withstand.

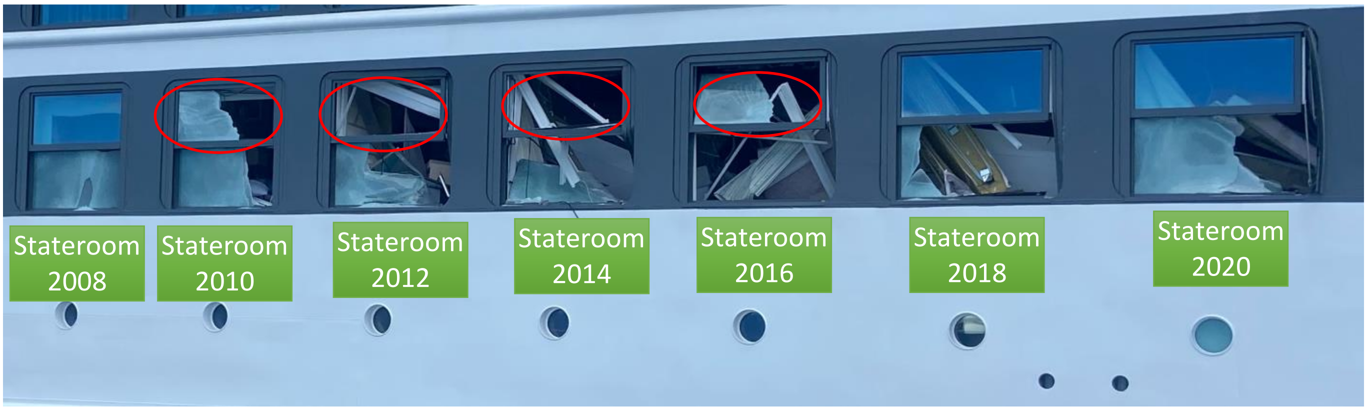


Figure 9-8 Overview photo showing the damaged staterooms on deck 2.

9.2.3 Lower windows, staterooms 2008 and 2010

On the lower windows in staterooms 2008 and 2010 (see Figure 9-9), the frame is still intact, while the pane has shattered. In that respect, they differ from the lower windows in the other staterooms, where the aft frame post was pushed in, taking the window pane with it. For the lower windows in staterooms 2008 and 2010, the pane was the weakest point. It has not been possible to find an explanation as to why the frames are intact on these panes, while the aft frame posts of the remaining lower windows have been knocked in.

Based on these findings, we can conclude that the pressure has been higher than the glass was able to withstand.

Figure 9-9 Overview photo showing the damaged staterooms on deck 2.

9.3 Summary of failure modes

- The pressure was higher than 40kPa for the lower windows in staterooms 2012, 2014, 2016, 2018 and 2020, where the frame posts were knocked in.
- The glass panes were the weakest point in lower staterooms 2008 and 2010 and upper staterooms 2010, 2012, 2014 and 2016.

10. TESTS PERFORMED DURING THE DESIGN PHASE

10.1 General information

There are no uniform requirements in recognized international rules for ships for testing of windows, but it is generally required that recognized standards are used. The rules for Viking Polaris, in this case apply DNVGL-RU-SHIP, Pt.3 Ch.12 Sec.6 [1.1.5], therefore require full scale testing. These windows were tested because the window area exceeded 1 m2 in addition to the window fixings was of a new design and not standard.
The investigation of the window design testing shows that all required tests had been performed and approved.

The requirements for certification and testing in the rules for the windows concerned can be summarised as follows:

- Special full-scale test because the windows are larger than 1 m^2
- The glass must be tested in accordance with EN 1288-3 because is not in accordance with the thickness requirements in the ship rules
- The glass must be in accordance with ISO 21005 and tested in accordance with ISO 614
- Hose test to verify that windows are weathertight
- Impact test of balcony railings (applies to passenger ships)

10.2 Full-scale pressure test

The test was performed in accordance with the ship rules Pt. 3 Ch. 12 Sec 6 [6.2] items 1–3. The test was performed on a hydrostatic test bench by statically applying the design pressure (35.4 kPa) over a period of 5 minutes. This corresponded to the design pressure of the forward window in stateroom 2000, which was also the strongest on deck 2. Figure 10-1 shows a photo from the test.

The purpose of the test is to verify that the window, including the frame and fixings, is able to withstand the design pressure. This means that the test is performed with an arrangement identical to that installed on the ship.

The test was approved and is documented in [11].

SOMEC has, on its own initiative, increased the pressure applied during the test to 40 kPa in order to test the windows' residual capacity [10]. The test was positive, as no visible damage or deformations were registered.

Figure 10-1 Static pressure test. Photo from window manufacturer SOMEC

10.3 Pressure test of the glass

For windows fitted below an elevation of 22.7 m from the keel (below 1.7 Cw from the waterline), the ship rules dictate that the glass shall be tested under a varying pressure load at four times the design pressure. The varying pressure test is described in the ship rules Pt. 3 Ch. 12 Sec 6 [6.2] and is shown in Figure 10-2. Note that item 4) concerns this test, while items 1–3 are covered in section 10.2.

The purpose of the test is to verify that the glass has sufficient strength (without the frame and fixing).

This test has not been performed. Instead, the glass has been tested using a 4-point bending test (EN 1288-3) that verifies the strength of the glass. The conclusion following the EN 1288-3 test was that the laminated glass is as strong as monolithic (single-layer) glass. The test was approved and is documented in [10]. Whether EN 1288-3 provides the same safety level as the test described in Pt. 3 Ch. 12 Sec 6 [6.2] item 4 (see discussion in section 9.1.3) is uncertain, but this has not been a decisive factor in relation to the accident.

6.2 Test arrangement

1) The glass pane together with its framing shall be supported with an arrangement identical to that on board the actual ship.
2) The test pressure shall be applied uniformly over the entire glass surface.
3) Step 1: Increase test pressure to the design pressure as defined in Ch.4 Sec.5 [3.5] within 30 seconds and maintain the pressure for 3 minutes. No leakage, no signs of structural damage to frame or glass pane retaining structure and no signs of glass pane detaching from retaining structure shall be visible.
4) Step 2*: Perform 3 loading/unloading cycles between test pressure P and 4xP within 60 sec < t < 120 sec before reducing the test pressure to zero. The glass pane shall show no signs of damage.

   In case of leakage, damage to the framing structure, glass pane detaching from the frame or visible damage, the test shall be repeated.

   *Note: Step 2 is not required for windows located in superstructure and deckhouse sides from 1.7 C_w above WL at scantling draft.

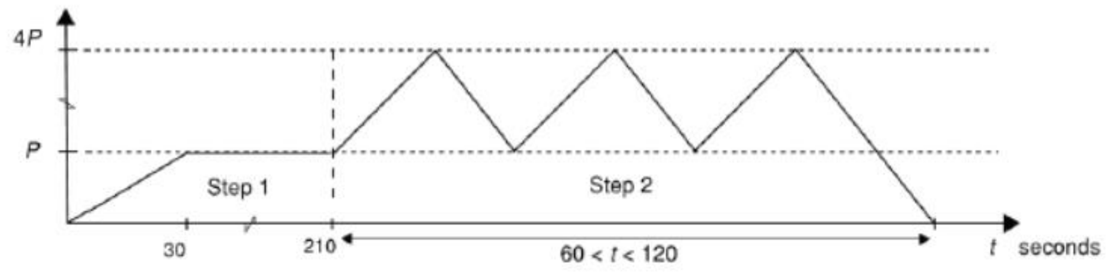


Figure 2 Test sequence for glass pane and framing

Figure 10-2 Excerpt from the ship rules. Test requirements from Pt. 3 Ch. 12 Sec 6 [6.2]

10.4 Punch test

A punch test has been performed in accordance with ISO 614. This test is relevant for toughened safety glass used for ship windows, and checks the local strength of the glass. The test is performed by placing a piece of glass over a flat ring. A punch is then placed over the centre of the flat ring. Finally, the punch is pressed against the glass to a specified design force to test its local strength. The force increases by 1 kN/s [12]. The test was approved and is documented in [10].

3 Test apparatus

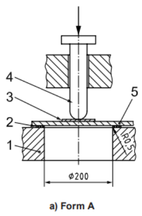
The apparatus shall be of the appropriate form shown in Figure 1, as follows:

a) Form A: for all glass panes with a size ≥ 250 mm;

b) Form B: for all glass panes with a size > 200 mm and < 250 mm.

The test apparatus shall also meet the requirements of Table 1.

Dimensions in millimetres



a) Form A

Report No: N1422DC5
Rev.01

Survey extent and result

Survey extent:
Punch test acc. ISO 614 and visual inspection witnessed by undersigned.

Survey result:
Without objection

Report
THIS IS TO CONFIRM THAT undersigned surveyor to DNV GL on attended works for the purpose of surveying of toughened glasses punch as follows:

FORMATOR WORKING ORDER : 2020-2335
HULL: 906
LOT: 5
CLIENT: SOMEC ORDER OF20010011

Figure 10-3 Details from the punch test

10.5 Hose test

High-pressure jetting of the joint between the window frame and the pane performed to test the weathertightness of the windows. The hose test is described in the ship rules Pt. 3 Ch. 12 Sec 6 [6.4] and shown in Figure 10-4. The test was approved and is documented in [13].

6.4 Hose testing

Hose testing as per Pt.2 Ch.4 Sec.2 shall be performed after installation to verify the weathertight performance of the window.

Figure 10-4 Excerpt from the ship rules. Test requirements from Pt. 3 Ch. 12 Sec. 6 [6.4]

10.6 Impact test

An impact test has been performed in accordance with EN 12600 using a 50 kg impactor and a drop height of 1.2 m. Details about the test are documented in [14]. The requirements for the test are described in the ship rules [6], Pt. 5 Ch. 4 Sec. 1 [5.1.5] and are relevant for glass balcony railings. These windows become like balcony railings in the lowered position. The test was approved and is documented in [15].

IMPACT TEST: Somec followed the standard described in the European Norm EN ISO 12600, with an impactor of 50 kg. Specification asked for a drop height of 450 mm. A further test to 1200 mm of drop height was passed, even if not mandatory for the specs.

Impact test: Witnessed and good result

- Method:
  - See separate NTQ approved procedure, acc. to EN12600 standard. We decided to try class 1 height, i.e. up to 1200 mm, only for OBW closed, but requirement is only 450 mm
- Criteria for NTQ:
  - No cracking or breaking of glass at 450 and 1200 mm height drop, for both OBW closed and half closed
- Result:
  - No cracking or breaking of glass

Ungraded

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Figure 10-5 Impact test

11. WEATHER AND WAVE CONDITIONS

11.1 Background

The part of the study that concerned the weather and wave conditions aimed to:

1. study the accident wave and its key parameters
2. determine whether the wave was within what the ship was designed to withstand.

Based on the weather forecast [16], the wave state at the time of the accident was characterised by the following significant and maximum wave height and associated wave period (H_S = 6 m, H_{MAX} = 10 m, T_P = 11 s). Figure 11-1 shows a transcript from the ship's route planning station.

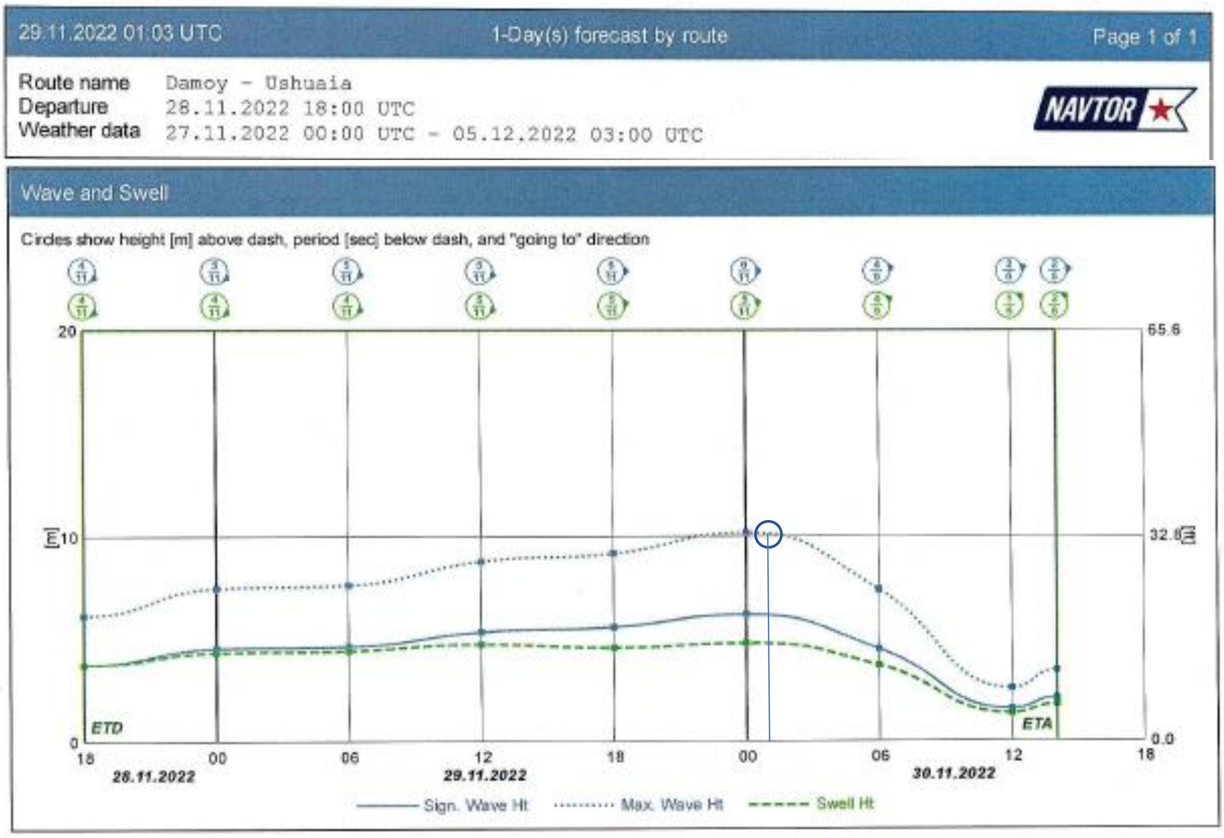

Figure 11-1 Transcript from the ship's route planning station for the voyage Damoy–Ushuaia [16]. The blue circle shows the time when the accident occurred (01:35 UTC)

Reports from the ship's crew [17] during the relevant time period confirm that the wave forecast matched the wave height observed from the bridge, but the wind was reported to increase as the evening progressed, with gusts of 60–76 knots.

Based on the weather forecast, the forecast wave conditions were within what the ship was designed to withstand (sea states with a 25-year return period; see also section 7.2). It is thus not obvious that the ship was struck by an abnormally large wave it was not designed to withstand.

A more detailed investigation into the characteristics of the accident wave follows below.

11.2 The accident wave

From the description of the accident, it has been reported that a single bang was heard as the wave hit and broke the windows on deck 2 [17]. Furthermore, it has been reported that all the damage was caused by this one wave [17]. It is therefore referred to as the 'accident wave'.

The ship did not have any wave measuring instruments on board, such as a wave radar or similar. Our investigation is therefore based on:

- The weather forecast
- Observations from CCTV footage

To be able to characterise the accident wave, our focus has been on finding and quantifying:

- Wave direction relative to the ship's heading
- Wave height and wave period

11.3 Relative wave direction

The weather forecast at the time of the accident predicted waves from 270 degrees (from the west). According to the Voyage Data Recorder (VDR), the ship's heading was 344 degrees immediately before the accident. This gives a wave direction relative to the sea state of 74 degrees to port relative to the ship length; see Figure 11-2. This wave direction is supported in part by observations from the CCTV cameras shown in Figure 11-3. However, the footage appears to show a somewhat smaller angle, and the relative wave direction is therefore estimated to approximately 60–80 degrees to port, which means beam sea.

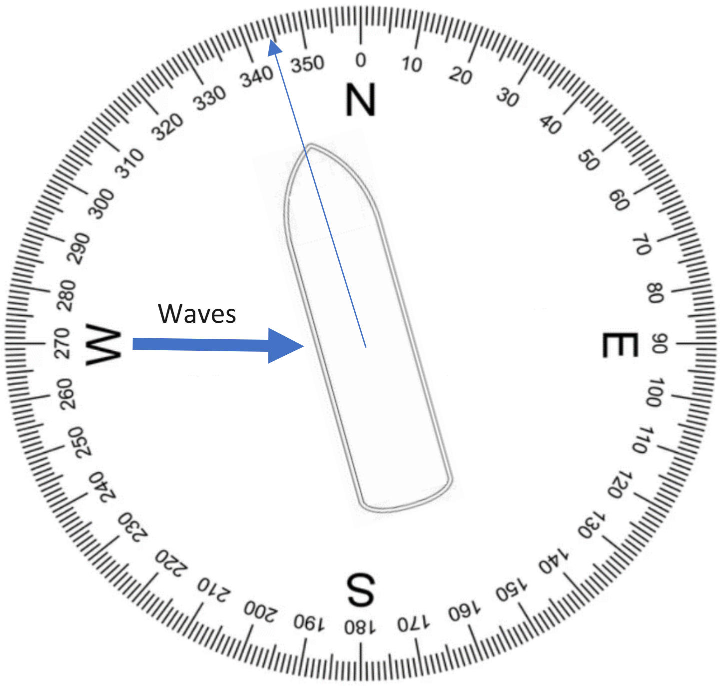

Figure 11-2 Relative wave direction

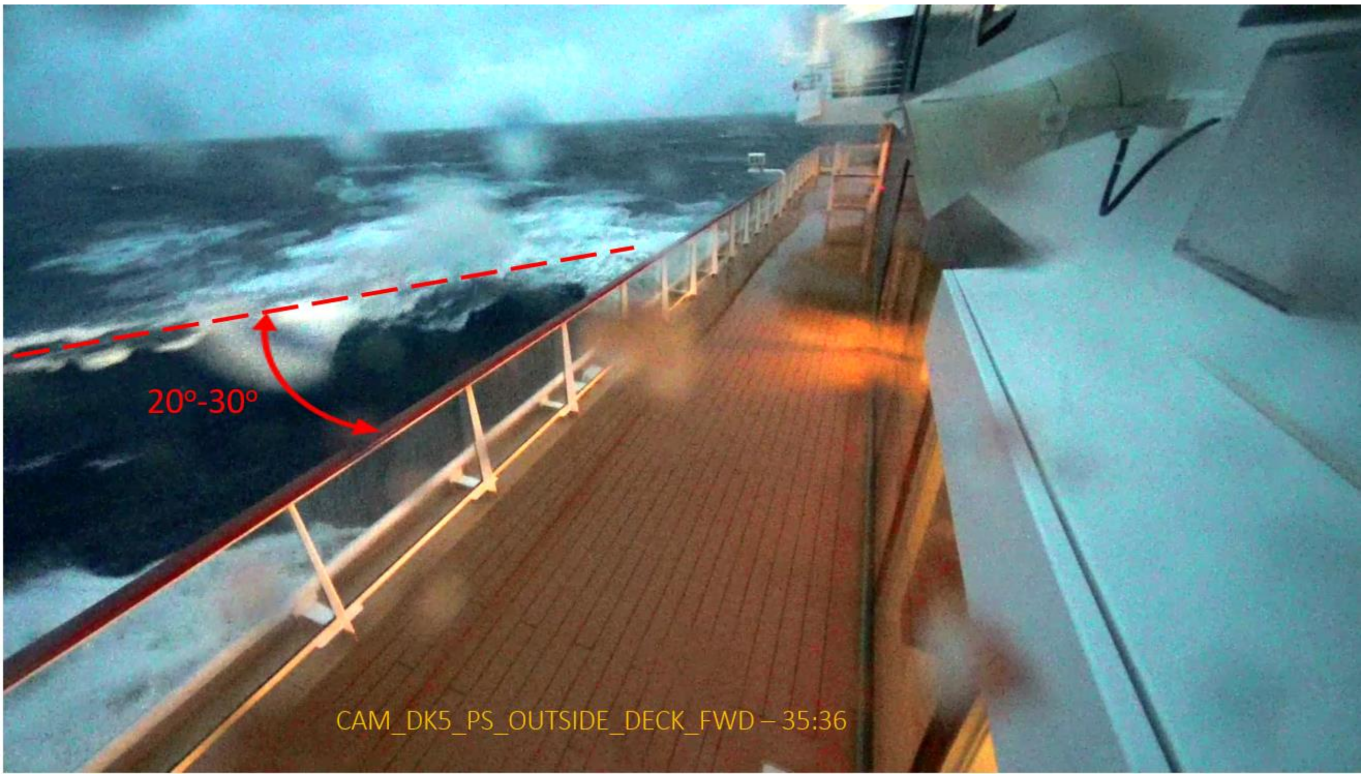

Figure 11-3 Footage from a CCTV camera on deck 5, port side at frame #162, immediately before the impact (02:35:36 UTC+1).

11.4 Wave period

From the CCTV footage, it appears that the wave broke just before or as it struck the ship. Waves can break either because strong winds or an opposing current make the crest unstable [18], and/or because of the height/length ratio (wave steepness) [8]. Breaking waves are more common in a developing sea state (when the wave height and wind speed are still increasing) and when the sea is choppy (shorter waves).

Figure 11-4 CCTV footage from the bridge showing the time interval between the preceding wave and the accident wave, measured from the bow mast.

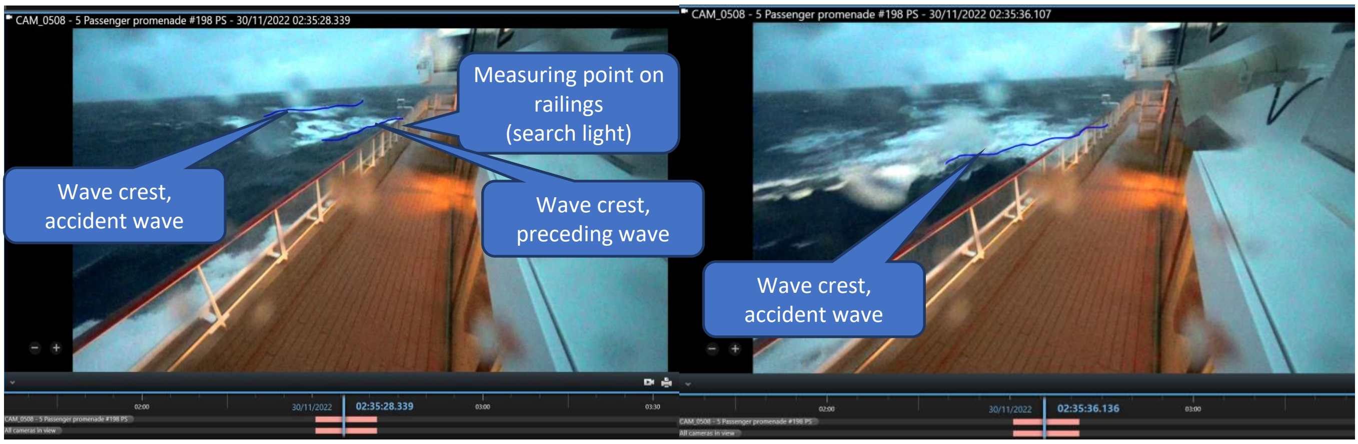

Figure 11-5 CCTV footage from frame #198, deck 5, port side. The measuring point is the search light mounted on the railing.

Figure 11-4 shows the crest of the preceding wave passing approximately at the measuring point of the bow mast at 2:35:20:9 and the crest of the accident wave passing approximately the same point at 2:35:29:9, which gives a wave encounter period of 9.0 seconds.

Figure 11-5 shows the crest of the preceding wave passing the area around the rack at 2:35:28:3 and the crest of the accident wave passing approximately at the measuring point at 2:35:36:1, which gives a wave encounter period of 7.8 seconds.

Based on the above, it is reasonable to assume an average of these values, i.e. that it took approximately 8.5 seconds for the ship to pass both wave crests.

11.5 Wave height

The following methods have been used to estimate the maximum wave height in the prevailing sea state:

1. Assessing the wave height based on the distance from the waterline to the shattered windows and CCTV
2. Carrying out wave realisations to find probable maximum wave heights; see calculations in Appendix A.

1. Wave height based on distance from waterline to damaged area

The distance from the waterline to deck 3, where the windows were undamaged, is 11 m (no damage to windows was found above deck 2). This means that the crest height must have been less than 11 m, because CCTV footage shows that the ship moved into a trough just before the impact.

Because of nonlinear effects, some waves have a crest that is higher than their trough is deep, and it can be assumed that the crest is up to 20% higher than the amplitude of a regular wave; see asymmetry factor in [4]. This phenomenon is shown in Figure 11-6, where a linear wave is compared with a realistic (nonlinear) wave.

Based on a crest height of 11 m and an asymmetry factor of 1.2, we can conclude that the size of the accident wave was less than (11 m/1.2*2) 18.3 m.

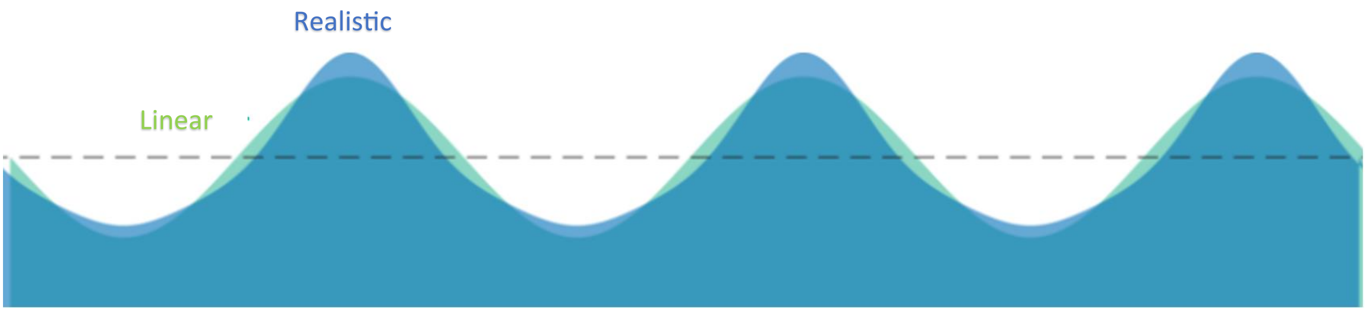

Figure 11-6 Comparison of linear and realistic wave. The realistic wave has a higher crest and a shallower trough.

2. Wave height based on wave realisations

Wave realisations have also been performed to estimate a probable wave height range. The following has been done to estimate probable wave height:

- The JONSWAP[4] wave spectrum has been assumed with Hs = 6–7 m and Tp = 11 seconds. γ = 1.8 for Hs = 6 and γ = 2.6 for Hs = 7 m.
- A total of 100 different 3-hour wave realisations have been carried out, providing 100 observed maximum wave heights.
- The tenth smallest of 100 observed maximum waves is used as the lowest probable wave.
- The ninetieth biggest of 100 observed maximum waves is used as the highest probable wave.

The results of the simulations for Hs = 6 m are shown in Figure 11-7. The results of the simulations are given in Table 11-1.

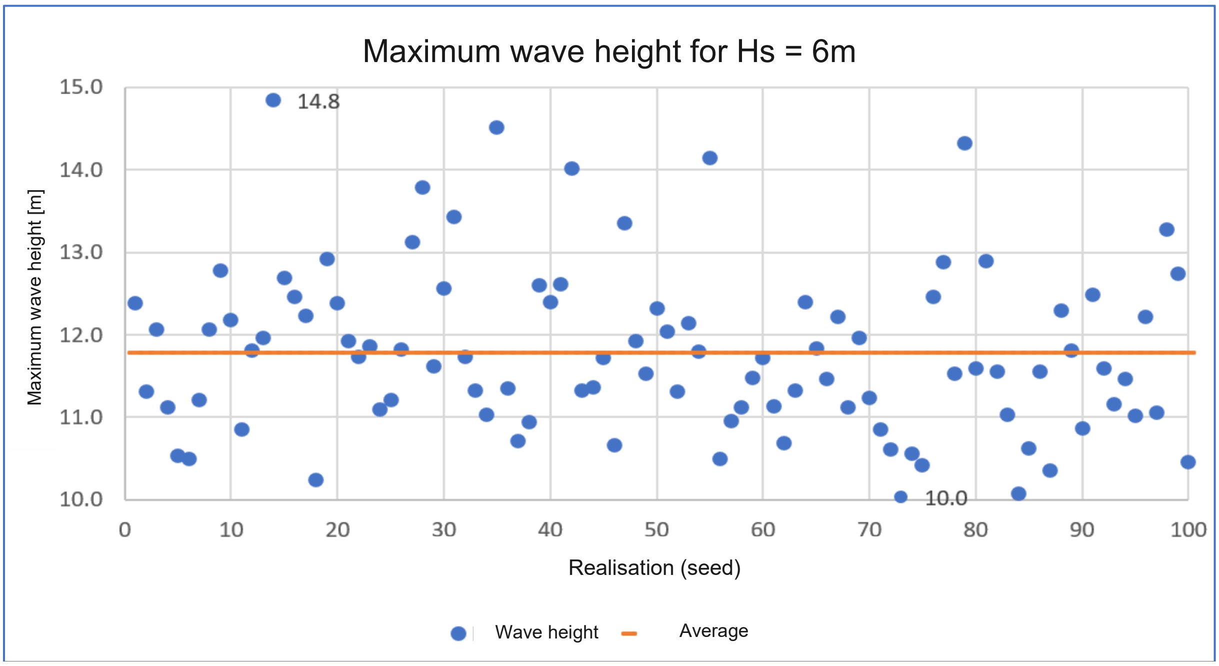

Figure 11-7 Maximum wave height from wave simulations for Hs = 6 m

[4] Joint North Sea Wave Project

Hs [m]	Maximum wave height [m] given percentile	
	10%	90%
6	10.6	12.9
7	12.6	15.7

Table 11-1 Maximum wave height

From Table 11-1 we can see that the tenth smallest maximum wave of the 100 realisations with Hs = 6 m is calculated to 10.6 m, while the ninetieth biggest is 12.9 m.

Based on calculated wave realisations, it is probable that the wave height was between 10.6 and 15.7 m.

11.6 Wave climbing

It is probable that the incoming wave has been enlarged compared with an undisturbed wave due to the phenomenon of 'wave climbing' and surface elevation from the wake. It has not been possible to quantify this effect.

11.7 Summary of wave height

In summary, the calculations of the height (H) of the accident wave show that:

1. An estimate based on distance from waterline to damaged area suggests H < 18.3 metres
2. Estimate based on wave realisations: H = 10.6–15.7 metres

On this basis, we draw the following conclusion:

1. The wave height was probably between 10.6 and 15.7 m.
2. The wave was probably smaller than 18.3 m.

12. ASSESSMENT OF MACHINERY LOG

An assessment has been made of the ship's rolling motion after it was struck by the accident wave. The assessment was made on the basis of data from the ship's machinery log, which can be seen in Figure 12-1. Roll values from the MRU have been entered in an Excel sheet to allow us to assess how the ship rolled before and after the accident. The values were then visualised in the graph show in Figure 12-2.

The accident wave struck the ship on the port side at 01:35:37 (UTC). The accident wave can be characterised as an impulse load that sets the ship in motion and leads to a maximum angle of heel of 3.0 degrees to starboard 4 seconds after the impact, i.e. at 01:35:41. Then, the ship rolled to port with a maximum impact of -2.3 degrees after 11 seconds (at 02:35:48), before it rolled back to starboard with an angle of heel of 3.0 degrees after 18 seconds (at 01:35:55).

It took 'Viking Polaris' a few seconds to get full roll motion towards starboard after the impact of the accident wave (impulse load). We also see that the ship rolls with her own natural period until the movements have been dampened out. This is as expected.

There was a constant angle of heel of 1–2 degrees to starboard when the accident occurred. This is based on an average of the roll measurements.

'Viking Polaris' is equipped with stabiliser fins that dampen the roll motion, and we see that these fins dampen most of the roll motion after 30 seconds.

There has been uncertainty about the coordinate system used for the roll angles. Based on CCTV footage and the roll response in Figure 12-2, we conclude that a positive angle of heel means that the ship lists to starboard and that the starboard side inclines. This is the opposite of the coordinate system shown under 'actual heel' in the machinery log in Figure 12-1.

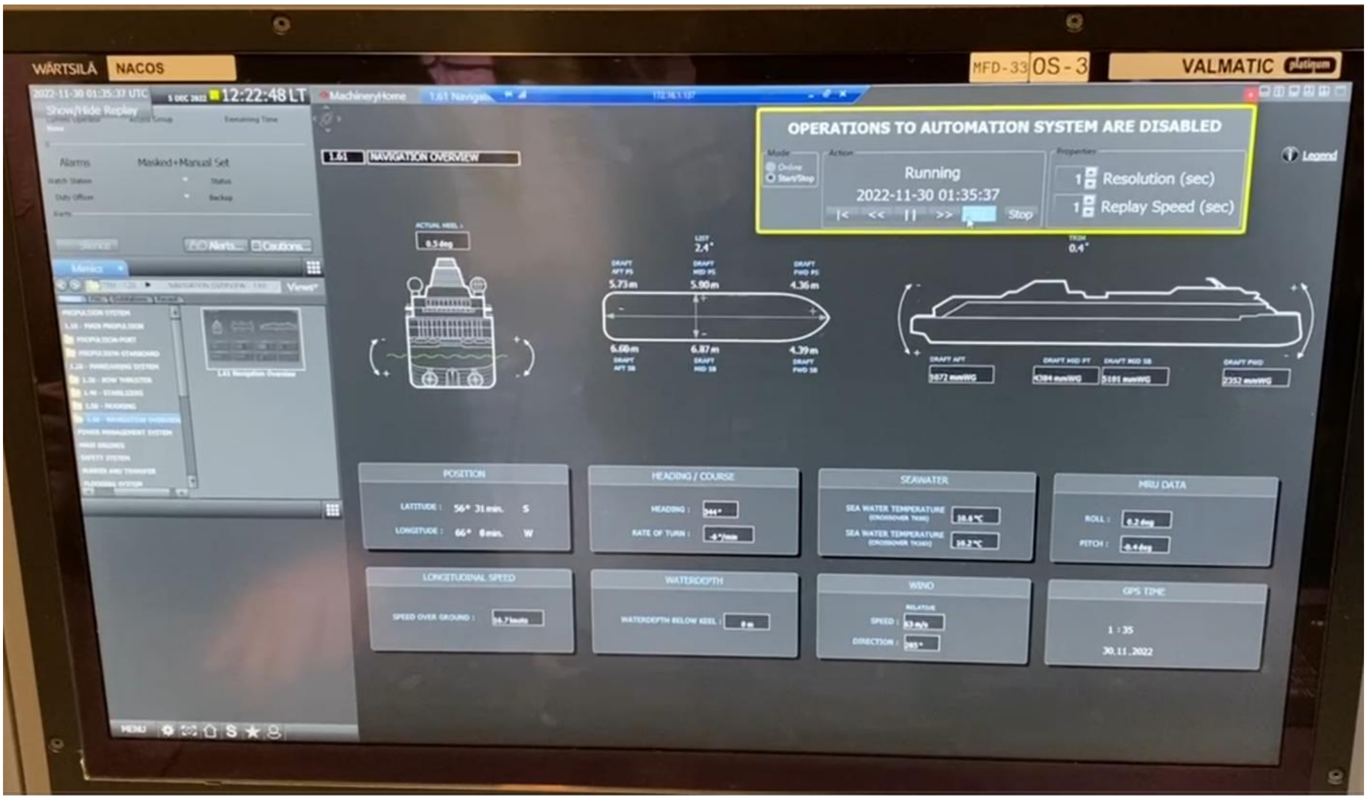

Figure 12-1 Machinery log.

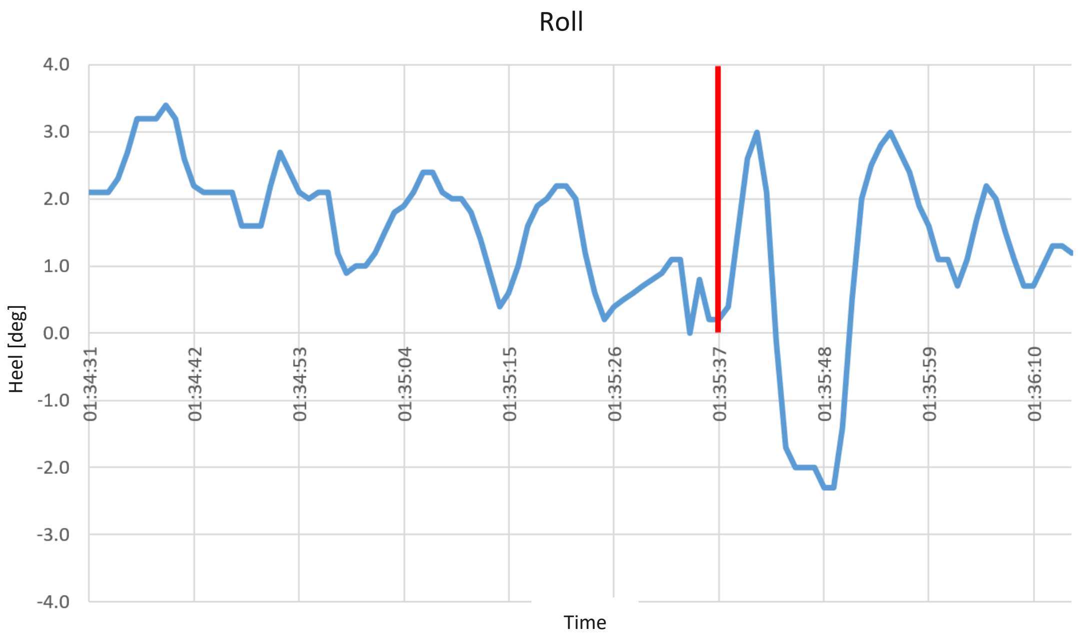

Figure 12-2 Roll movement after the accident. The wave strikes at 01:35:37. The positive angle is a starboard heel.

13. ASSESSMENT OF SEAMANSHIP

The ship rules rely on the assumption of 'good' seamanship. That means that they assume that seamanship will comply with applicable practice, which means to avoid storms, change course or voluntarily reduce speed based on the prevailing weather conditions [19].

The assumption of good seamanship is also reflected in the design phase when direct calculations of the rule loads are carried out in accordance with [19]. If directly calculated loads are applied, the loads must be adjusted by factors that, among other things, take account of the fact that seafarers change their course based on the weather forecast, and these factors are reflected in several of the formulas described in the ship rules. Examples of such factors are f_R (operational factor) and f_β (heading correction).

The design pressure calculation (P_{SI}; see Figure 8-1) used for the relevant windows on board 'Viking Polaris' does not include an explicit seaman's factor or wave analysis because of the location of the windows on the ship. Since the design pressure is not reduced by an explicit seaman's factor, we must assume that the windows should be able to withstand a sea state which is within the 25-year contour. That means that the sea state during the voyage was within the ship rules.

14. CAPACITY OF SURROUNDING STEEL

An assessment of the capacity of surrounding steel has been made to attempt to provide an upper estimate of the pressure caused by the accident wave. The hull steel plates just below the windows shows no signs of damage or deformation. It is therefore assumed that the maximum pressure this steel can withstand will therefore provide an indication of the upper interval of the pressure at the time of the accident.

The steel withstands more than the windows because it is dimensioned based on a minimum thickness requirement that provides greater strength than the local pressure requirement. This enables the steel plate to withstand greater pressure than the windows. The ship rules also contain minimum thickness requirements for glass, as explained in section 9.1.3, where a safety factor of 4 is used.

Stipla version 2.3 has been used to establish a rough estimate of the maximum static pressure the surrounding steel can withstand. A stiffened integrated panel is modelled in Stipla with plate thicknesses and stiffener profiles in the area shown in Figure 14-1. Then the pressure was increased to maximum capacity. The calculations performed in Stipla are shown in Figure 14-2.

The calculations show that the maximum static pressure on the surrounding steel can withstand is estimated to withstand 107 kPa. This indicate that the pressure from the accident wave must have been in the order of magnitude of 107 kPa, but greater than the test pressure of the frame of 40 kPa. It cannot be ruled out that the maximum slamming pressure has been greater than 107kPa over a very short period since the calculations are based on static pressure load.

Figure 14-1 Undamaged steel. The maximum pressure these plates can withstand has been calculated in Stipla.

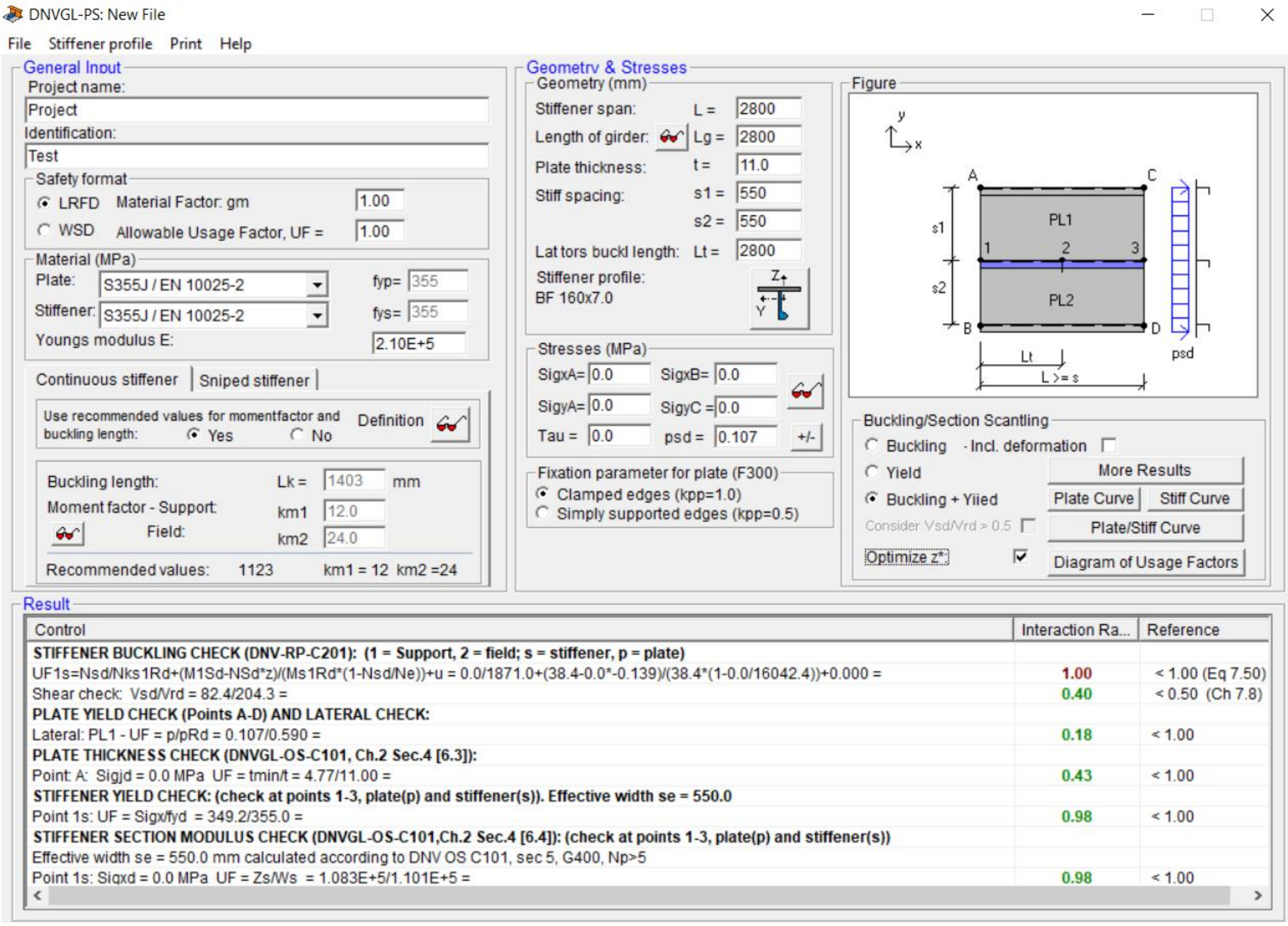

Figure 14-2 Calculation of maximum pressure in Stipla

15. BIBLIOGRAPHY

[1] Petroleumstilsynet, "Granskingsrapport etter hendelse med fatalt utfall på COSLInnovator 30. desember 2015. dok:418005005," Petroleumstilsynet, Stavanger, 2016.

[2] F. B. f. t. I. o. M. A. (FEBIMA), "Report on the investigation into a fatal accident on board vlcc ARAFURA near Cape Horn with the decease of two crew members on September 11th, 2021.," FEBIMA Doc 004987, Vooruitgangstraat 56 – B1210 Brussels – Belgium, 2021.

[3] DNV, "DNVGL-RU-Ship, Skipsregler," January 2018.

[4] DNV, "DNV-RP-C205 Environmental conditions and environmental loads," September 2021.

[5] DNV, "DNVGL-RU-SHIP-Pt3 Hull," January 2018.

[6] DNV, "DNVGL-RU-SHIP-Pt5 Ch. 4 Passenger ships," January 2018.

[7] T. U. Berntzen, "Email fra DNV til SHK "Viking polaris - spørsmål"," DNV AS, 20/02/2023 .

[8] O. Faltinsen, Sea Loads on ships and offshore structures, Cambridge University Press, 1990.

[9] "ISO 11336-1:2012".

[10] SOMEC, "RM0198-004-GEN-001".

[11] SOMEC, "CM0186-TEST-002 Static test".

[12] "ISO614," 2012.

[13] SOMEC, "CM0186-TEST-004 Hose test".

[14] SOMEC, "906-515-2500.pdf".

[15] Vard, "906-515-2500.pdf".

[16] NAVTOR, "1 Day Forecast by route, Damoy-Ushuaia," NAVTOR, 28.11.2022 18:00 UTC.

[17] SHK, *Oppstartsmøte - 7WAVES, Undersøkelse av ulykke om bord Viking Polaris,* PPT, Statens Havarikommisjon (SHK), 16.02.2023.

[18] T. Garrison, "Essentials of Oceanography, sixth edition", Belmont, CA: Brooks/Cole, 2012.

[19] DNV, "DNV-CG-0130 Wave loads," October 2021.

[20] O. ltd., "Orcaflex Version 11.3," Orcina ltd, November 2022. [Online]. Available: https://www.orcina.com/orcaflex/specification/.

APPENDIX A: GENERATION OF RANDOM WAVE TRAIN, MAXIMUM WAVE HEIGHT

Generation of random wave trains to find the maximum wave height.
The random wave trains for wave height are generated using the analysis software Orcaflex [20] for a Jonswap wave spectrum with the following parameters:

Hs = 6.0 m
Tp = 11.0 s
Y = 1.8

The wave height of irregular waves is calculated as the sum of the number of wave components (N = 10,000)

$$\zeta = \sum_{j=1}^{N} A_j \sin\left(\omega_j t + \epsilon_j\right)$$

where Aj, ωj and εj are wave amplitude, angular frequency and random phase angle of wave component j, respectively.

The wave amplitude Aj is calculated from the wave spectrum S(ω) as shown below:

$$\frac{1}{2}A_j^2 = S(\omega_j)\Delta\omega$$

where Δω is a constant difference between consecutive frequencies.

The phases associated with each wave component are pseudo-random. OrcaFlex uses a random number generator and the user-defined seed to assign phases. The sequence is repeatable, which means that the same seed will always give the same phases and consequently precisely the same wave train. The specified duration of each sea state is three hours and the wave direction is 0 degrees. The wave height at the origin is recorded.