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.

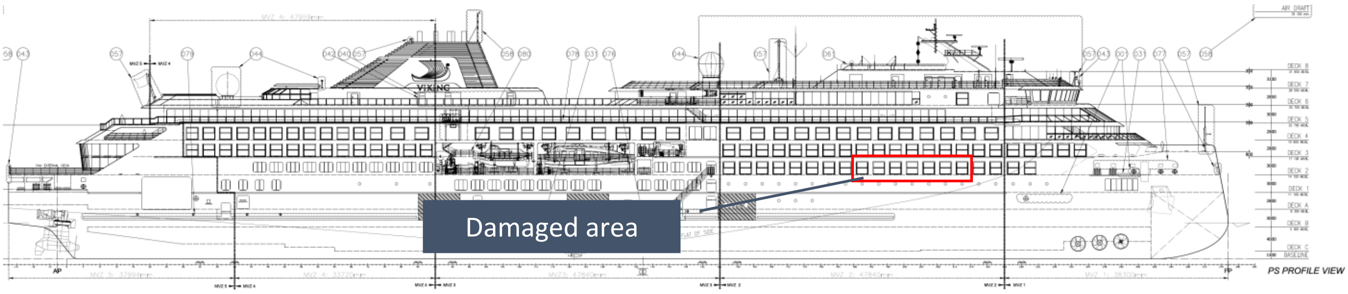


Figure 5-1: General arrangement and profile of starboard side where the damaged area is shown. Note that, although this figure shows the starboard side, the damage occurred on the port side, which has the same profile as the starboard side.

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.

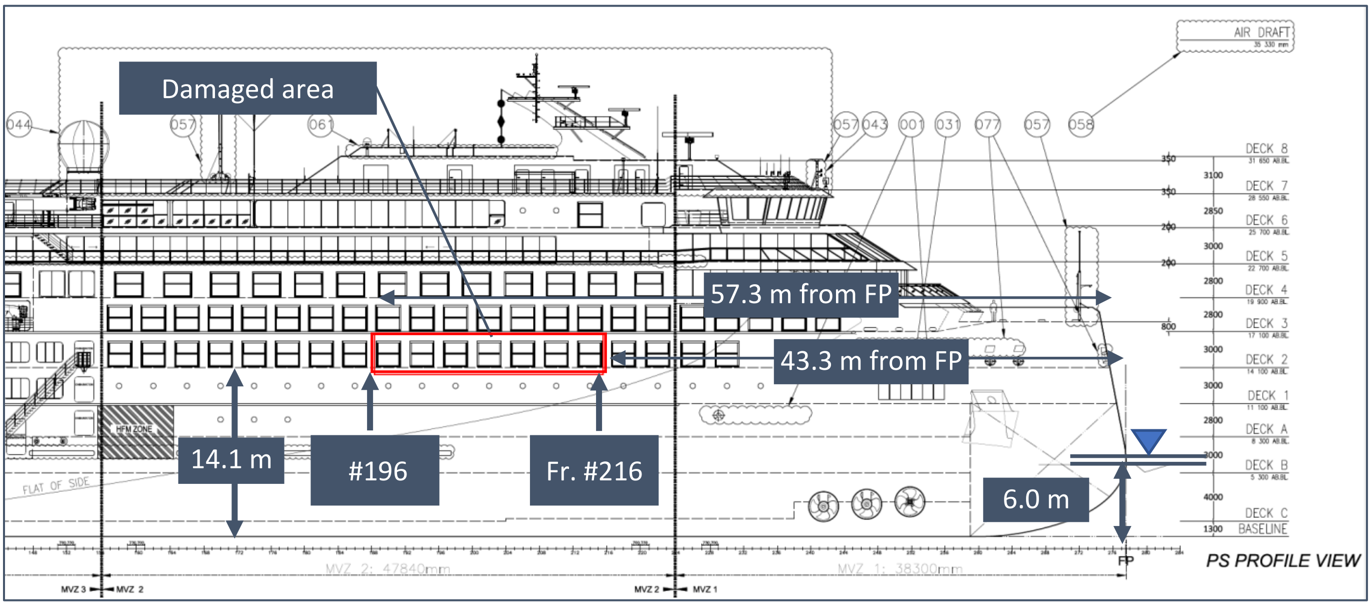


Figure 6-1 Illustration of damaged area – illustrated from starboard side on the drawing

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.

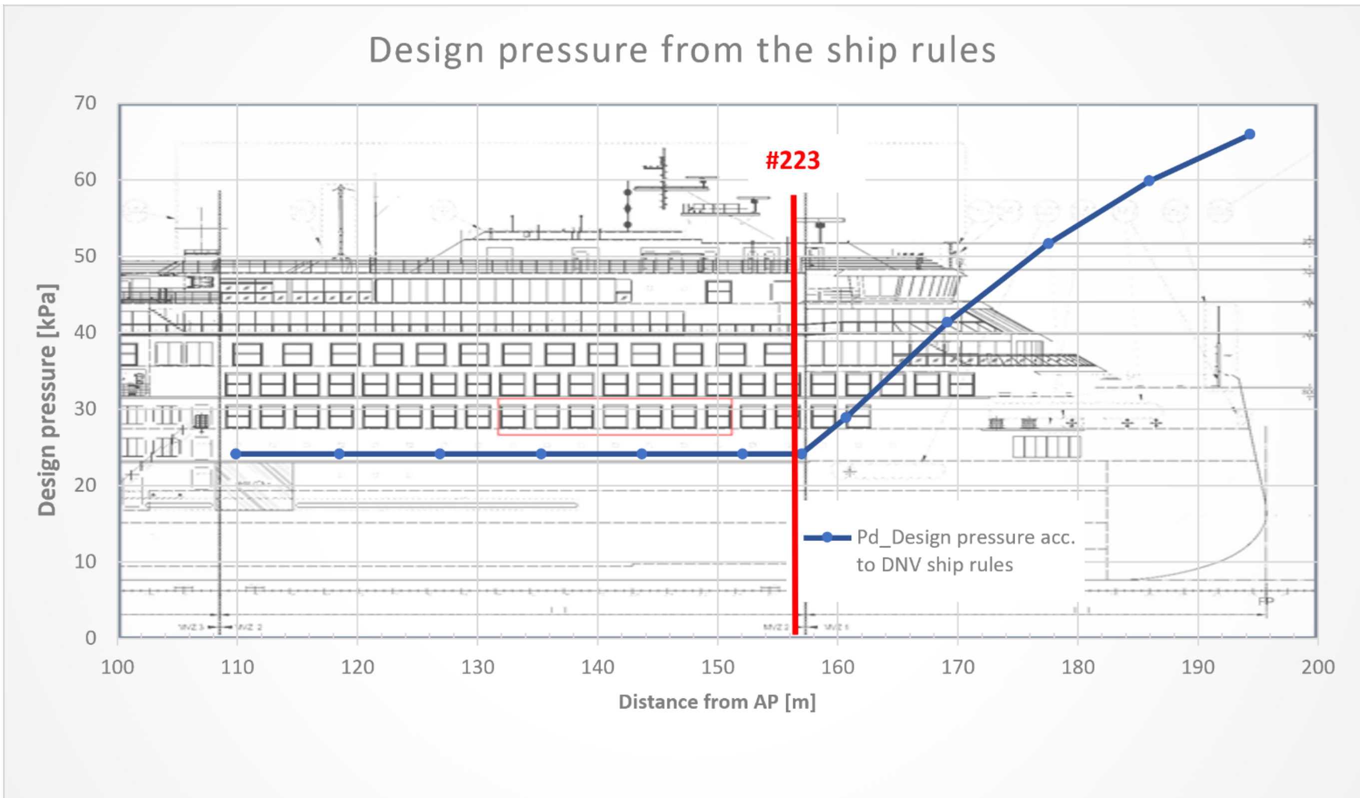


Figure 8-3 Rule pressure for the ship's side.

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.

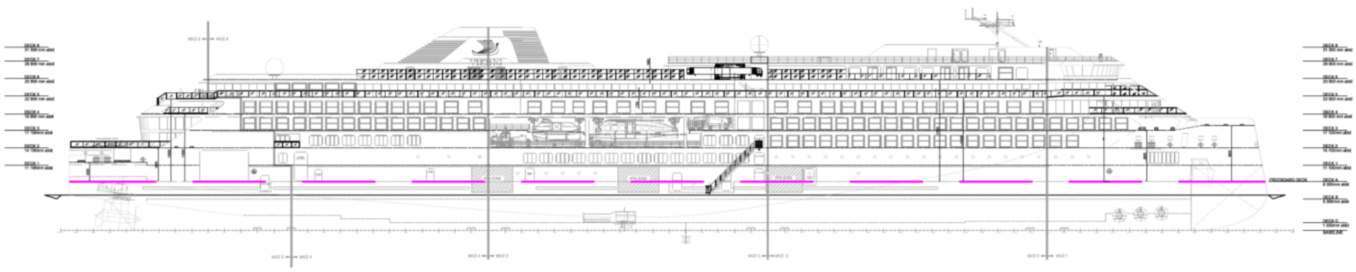


Figure 9-1 Freeboard drawing

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.

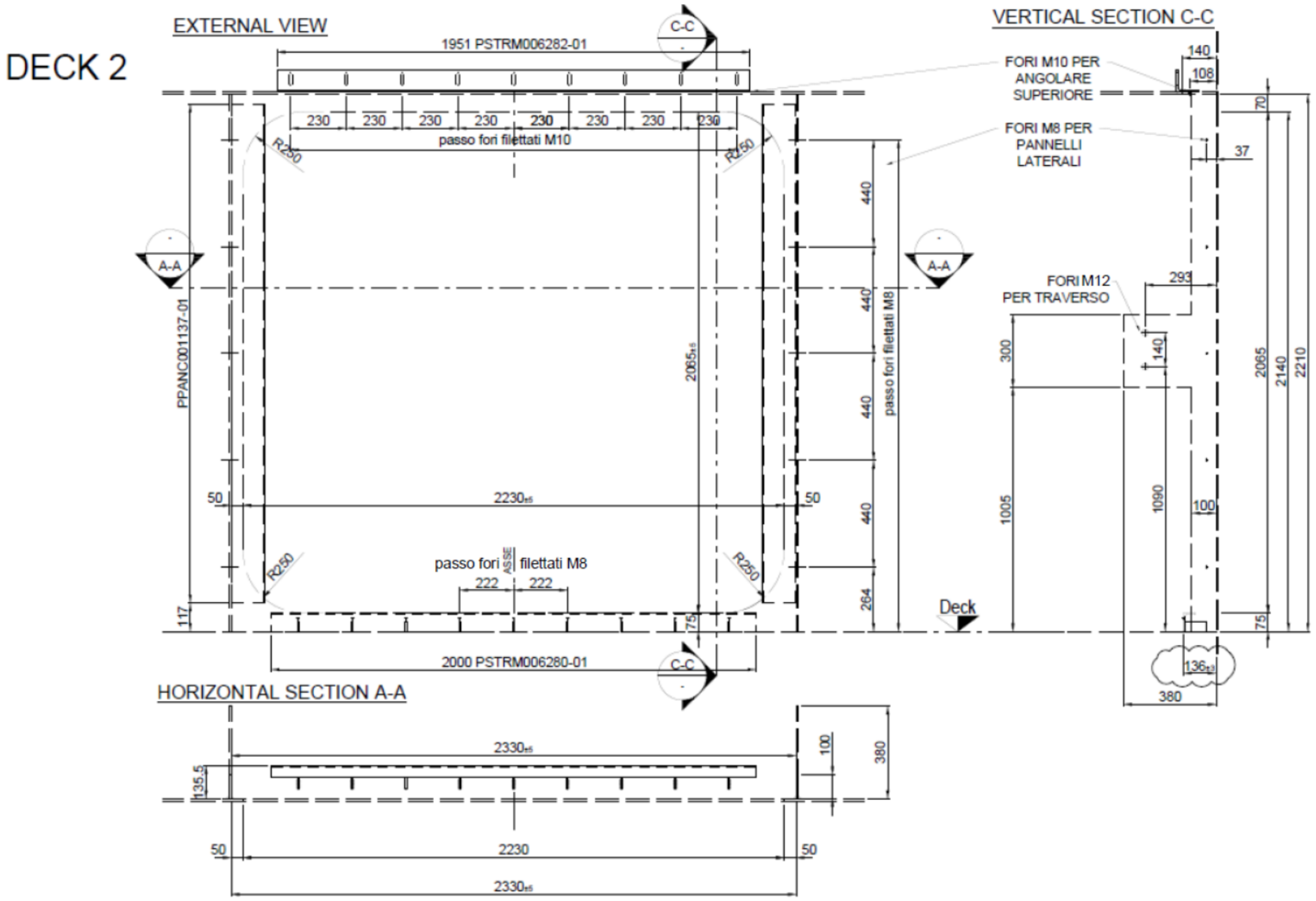


Figure 9-2 Screw fixing, deck 2

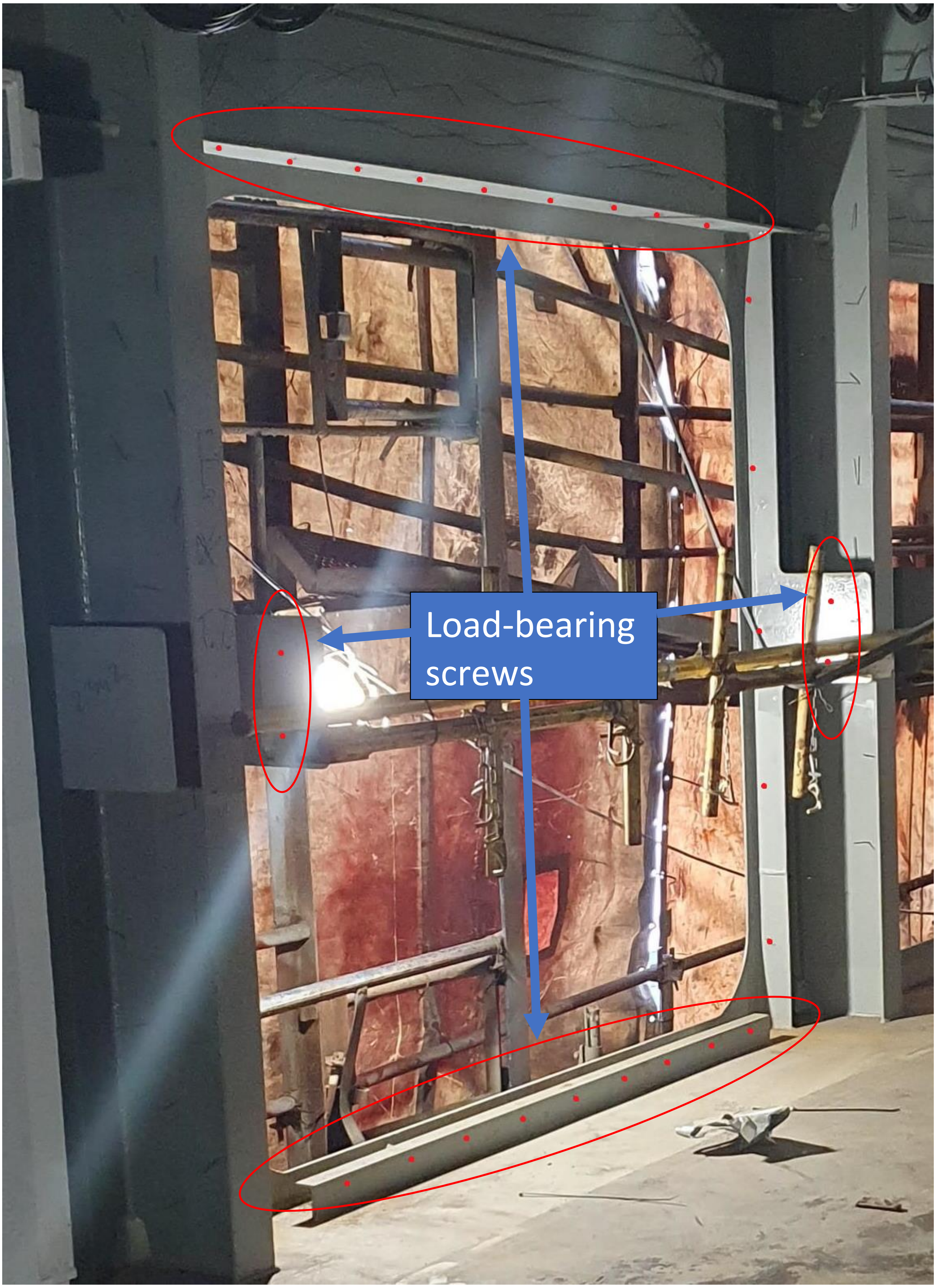


Figure 9-3 Screws fastening. The red dots show the location of the screws. The load-bearing screws are highlighted.

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.

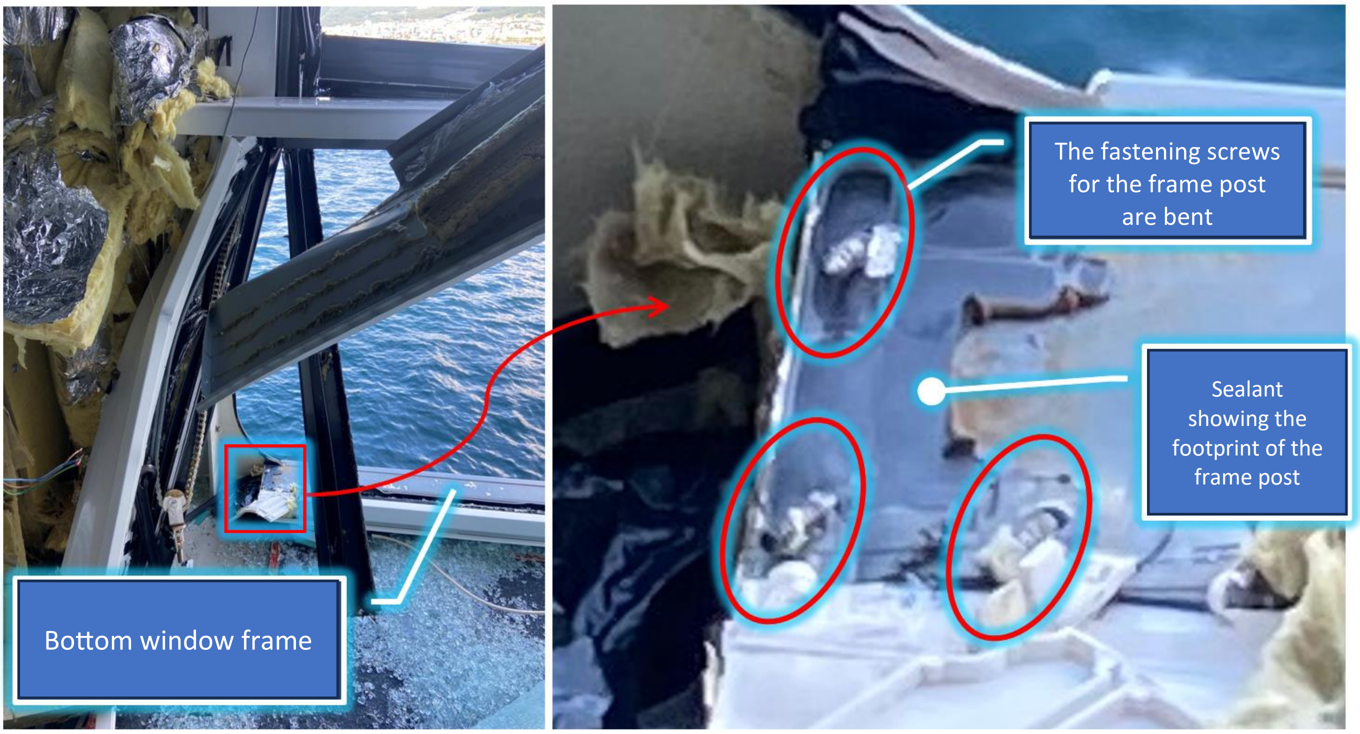


Figure 9-6 The weakest point of the window frame

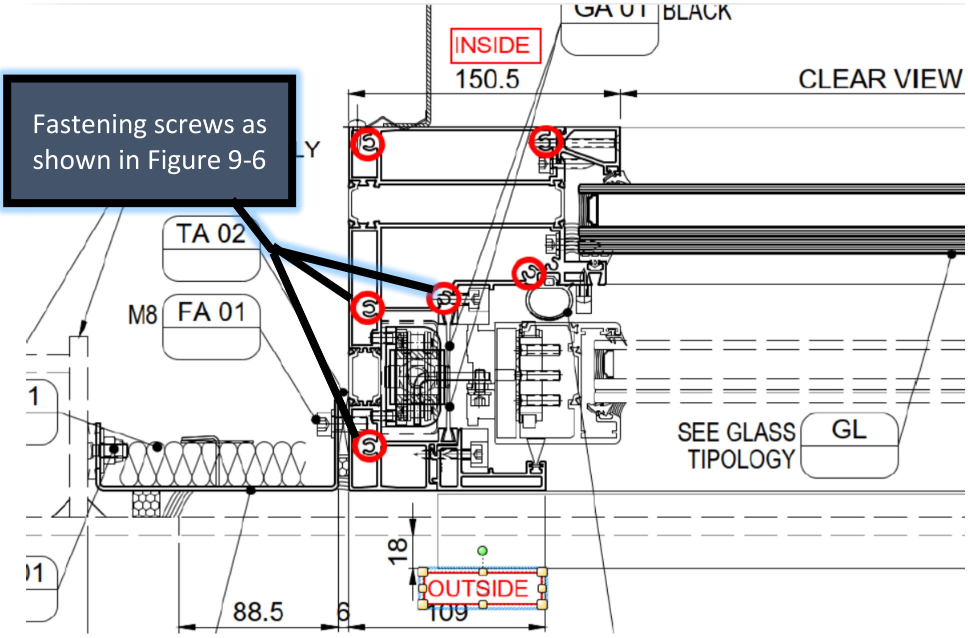


Figure 9-7 Fastening screws for the window frame seen from above

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.

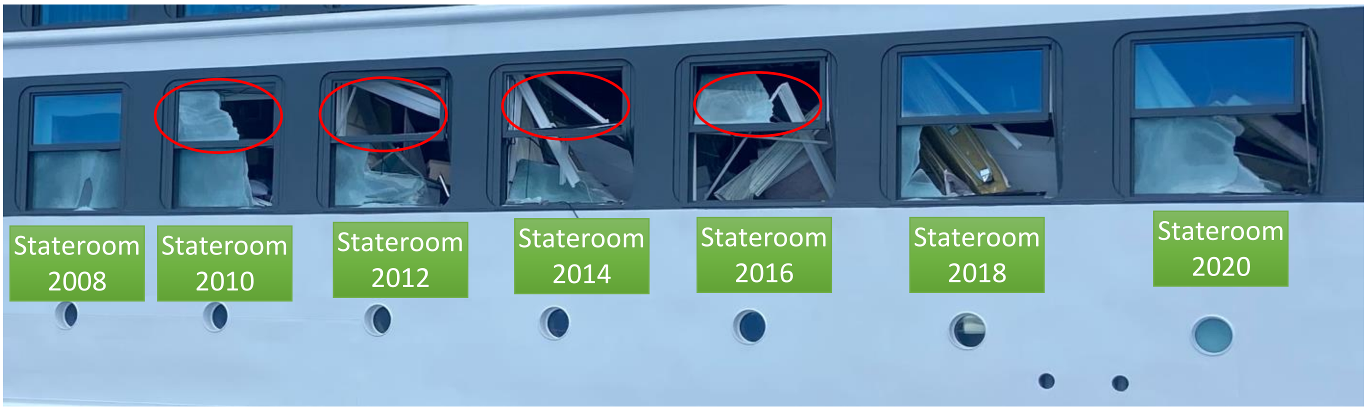


Figure 9-8 Overview photo showing the damaged staterooms on deck 2.

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.

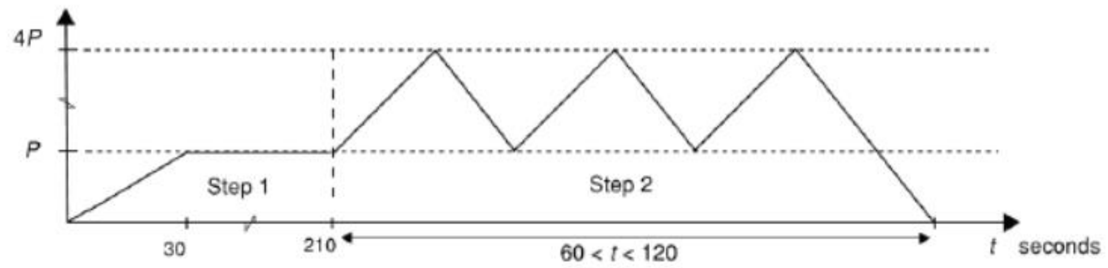
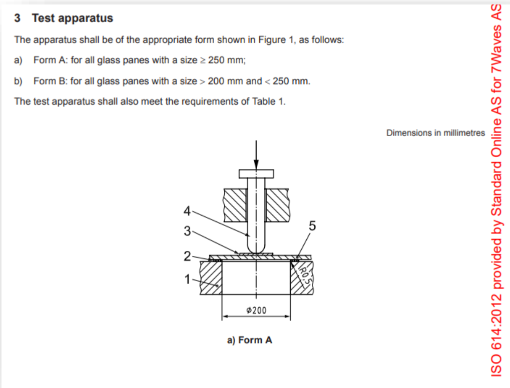


Figure 2 Test sequence for glass pane and framing

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].



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

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.

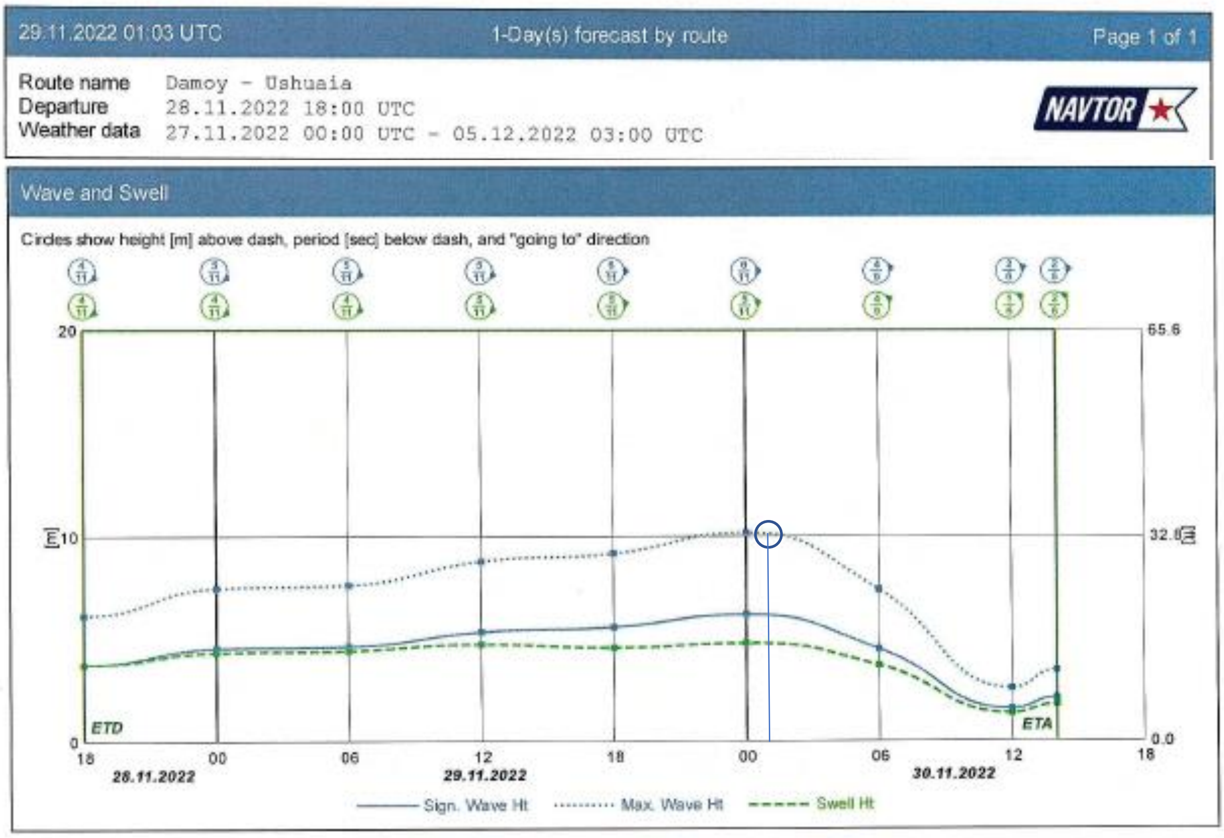


Figure 11-1 Transcript from the ship's route planning station for the voyage Damoy–Ushuaia [16]. The blue circle shows the time when the accident occurred (01:35 UTC)

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.

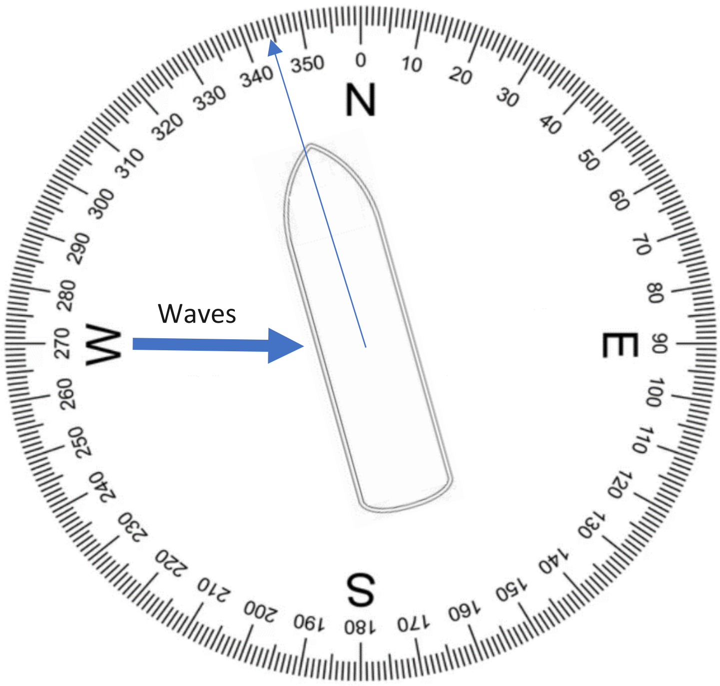


Figure 11-2 Relative wave direction

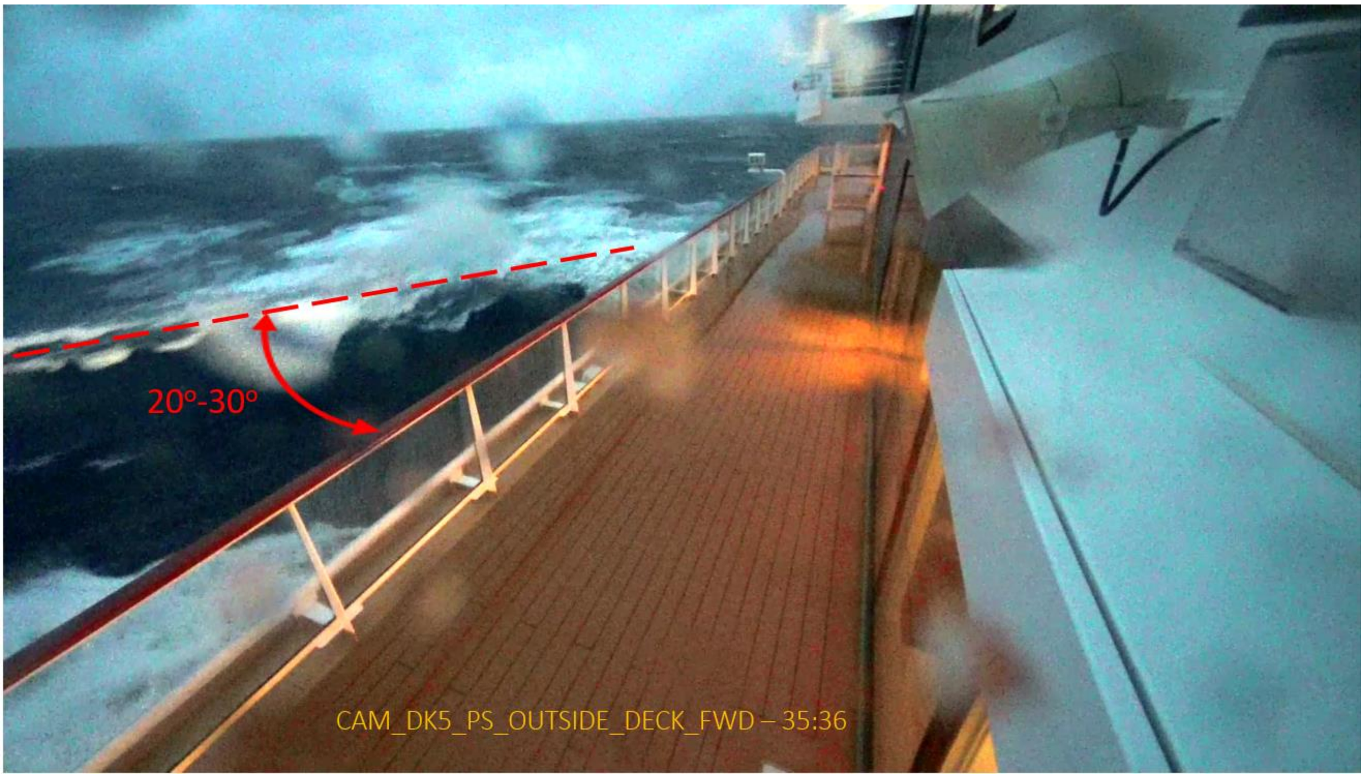


Figure 11-3 Footage from a CCTV camera on deck 5, port side at frame #162, immediately before the impact (02:35:36 UTC+1).

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.

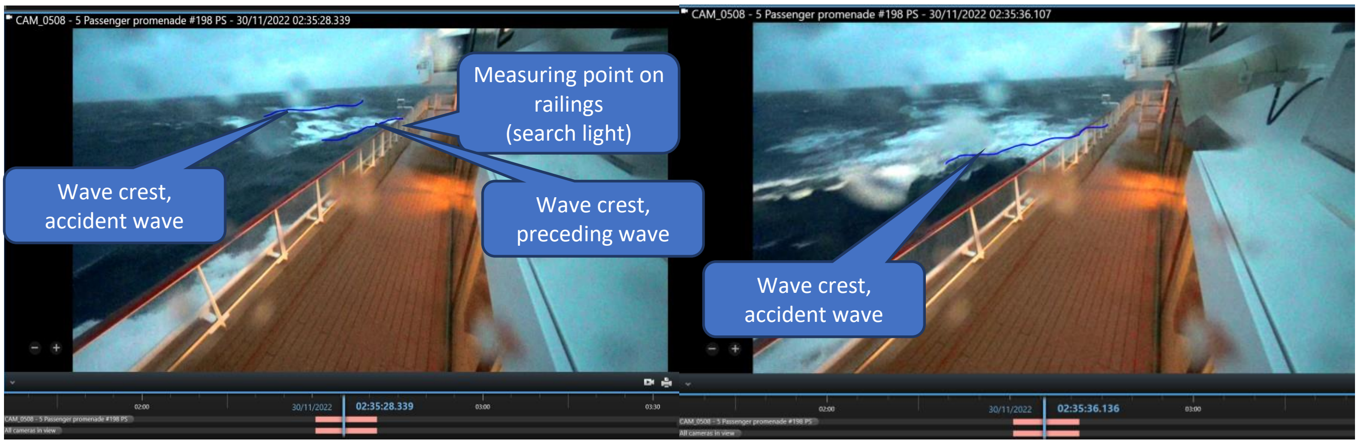


Figure 11-5 CCTV footage from frame #198, deck 5, port side. The measuring point is the search light mounted on the railing.

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.

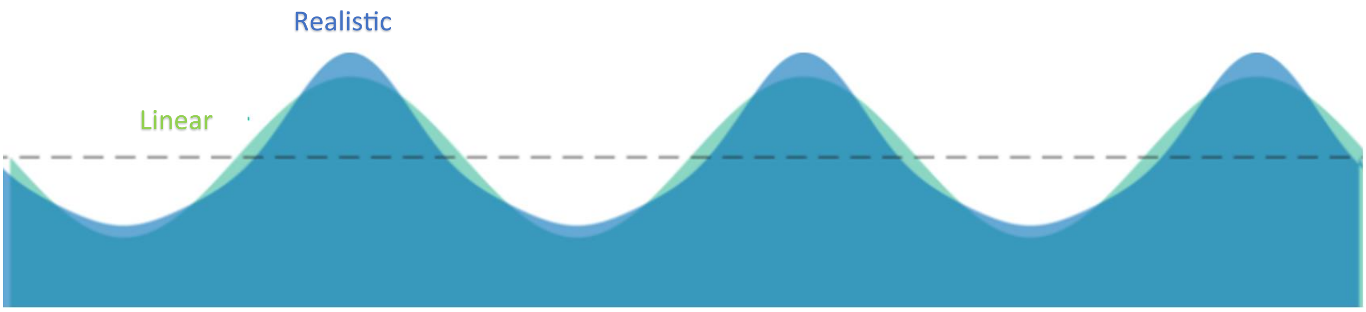


Figure 11-6 Comparison of linear and realistic wave. The realistic wave has a higher crest and a shallower trough.

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.

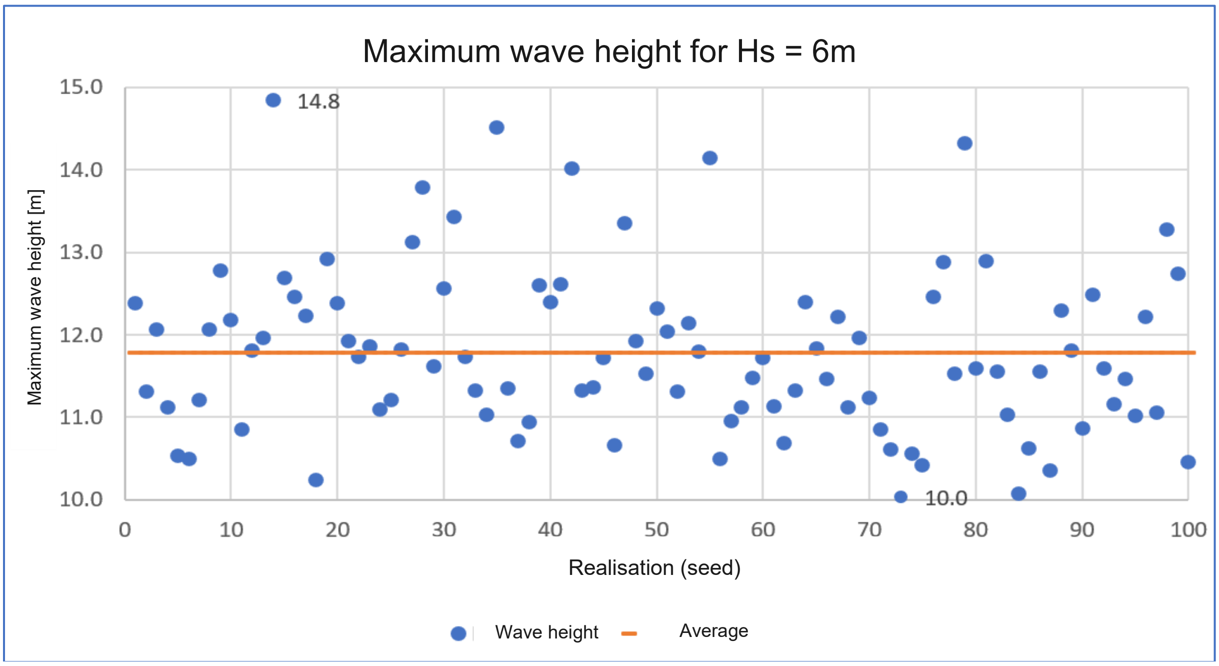


Figure 11-7 Maximum wave height from wave simulations for Hs = 6 m

[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.

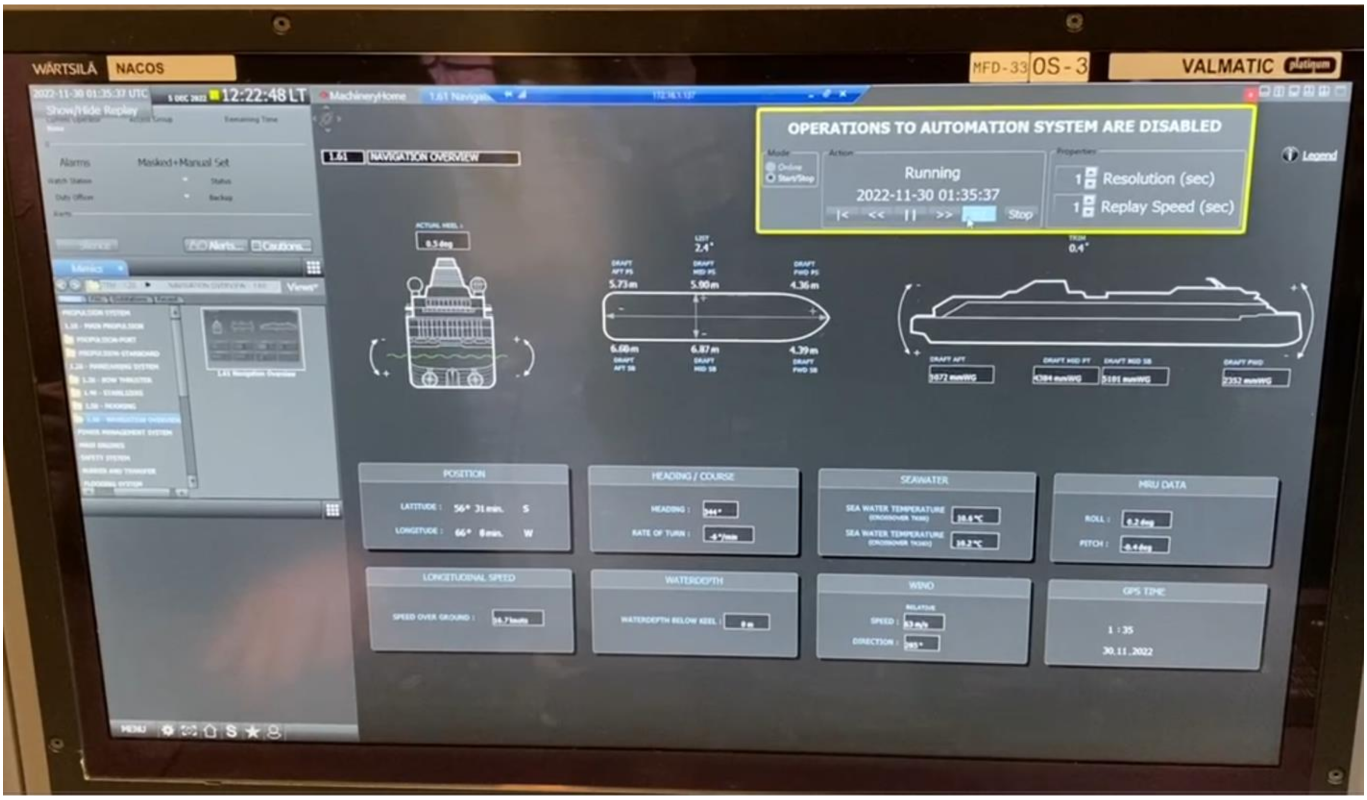


Figure 12-1 Machinery log.

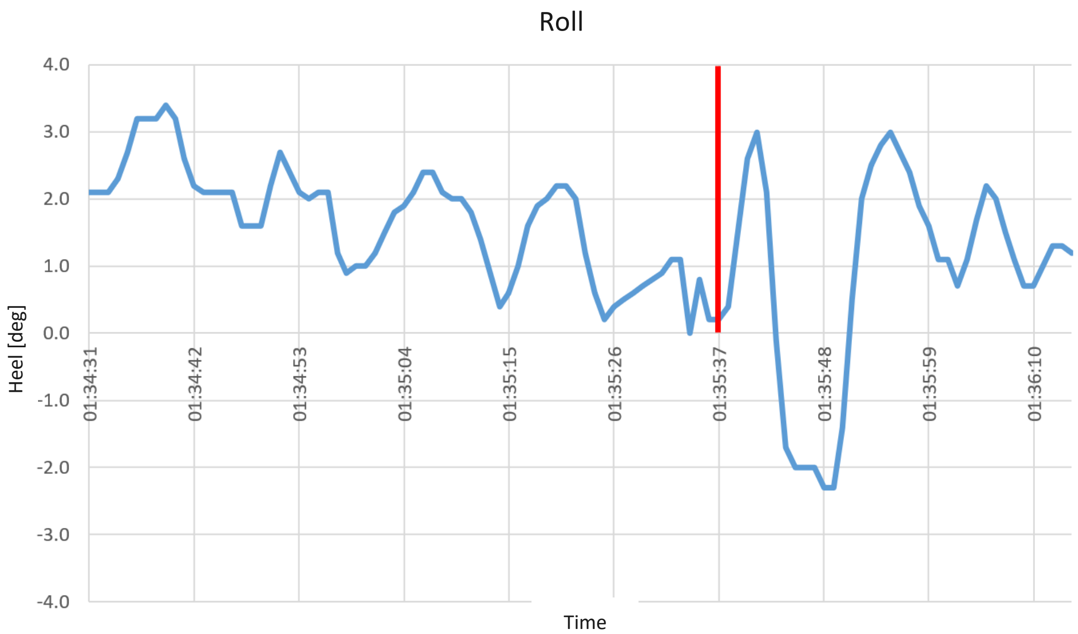


Figure 12-2 Roll movement after the accident. The wave strikes at 01:35:37. The positive angle is a starboard heel.

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.

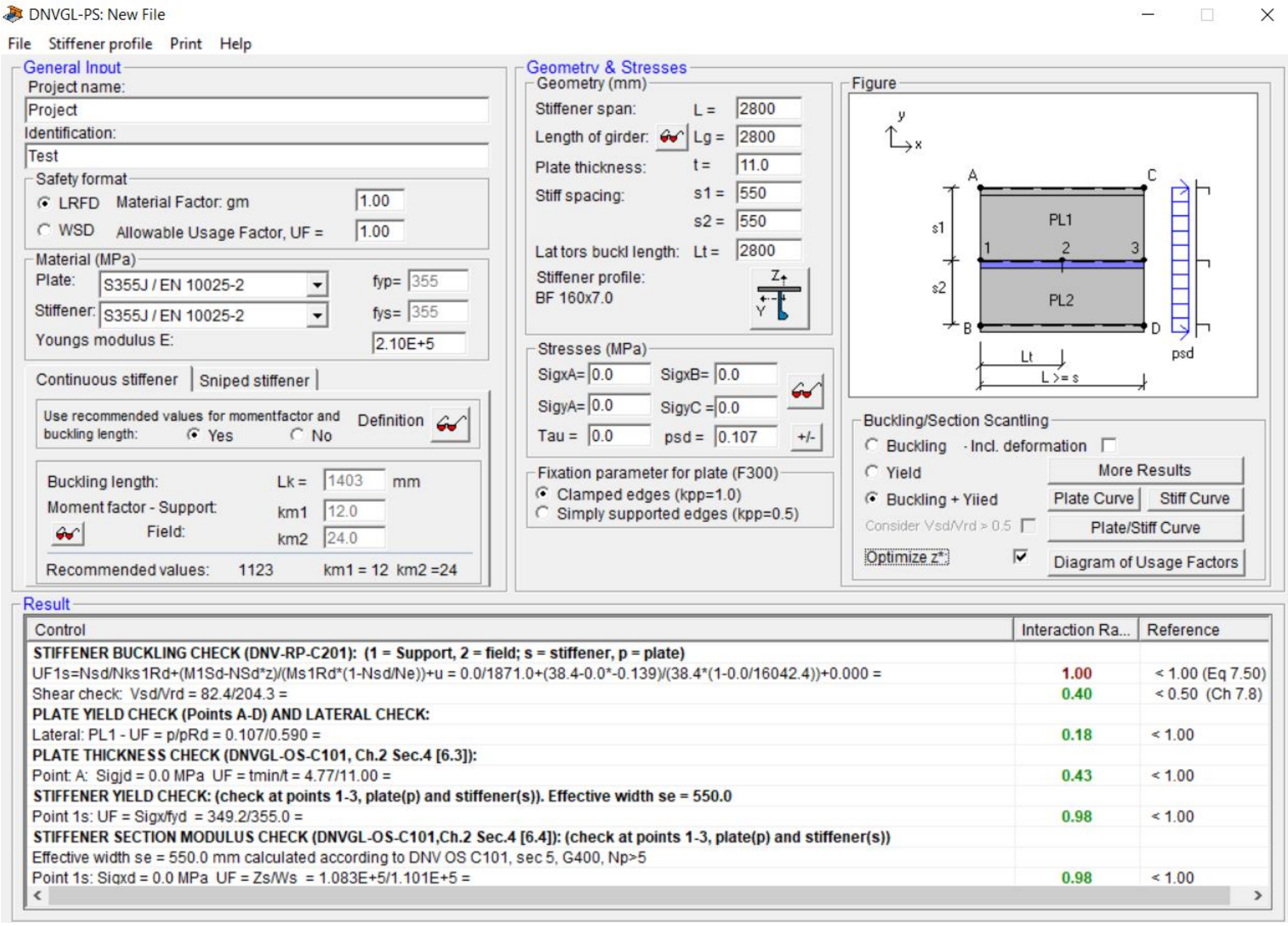


Figure 14-2 Calculation of maximum pressure in Stipla

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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.