SMAIC
STATE MARINE ACCIDENT INVESTIGATION COMMISSION

FINAL REPORT

114/22

Marine casualty

Towing unit – tug Odys and pontoon TRD Voyager

Loss of cargo, a shipyard crane from the deck of a towed pontoon – Baltic Sea, 24 August 2022.

July 2023

SMAIC
STATE MARINE ACCIDENT INVESTIGATION COMMISSION

The investigation of a maritime accident of the tug Odys and the pontoon TRD Voyager was conducted under the State Marine Accident Investigation Commission Act of 31 August 2012 (Journal of Laws of 2019, item 1374) as well as norms, standards and recommended procedures agreed within the International Maritime Organisation (IMO) and binding the Republic of Poland.

The objective of the investigation of a marine accident or incident under the above-mentioned Act is to ascertain its causes and circumstances to prevent future accidents and incidents and improve the state of marine safety.

The State Marine Accident Investigation Commission does not determine liability nor apportion blame to persons involved in the marine casualty or incident.

The following report shall be inadmissible in any judicial or other proceedings whose purpose is to attribute blame or liability for the accident referred to in the report (Art. 40.2 of the State Marine Accident Investigation Commission Act).

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1. Facts

On 23 August 2022, a 255-tonne, 46.8m-high shipyard crane (also called the shipbuilding crane) has been loaded onto the pontoon TRD Voyager at the port of Gdynia, Hungarian Quay. It was lashed to the pontoon's deck by a designed lashing system with a declared strength of 60 t (588.6 kN).

Five legal entities were involved in the preparation of the shipyard crane for transport from Gdynia to Szczecin, its loading from the quay and lashing onto the TRD Voyager.

Photo 1. Lashed shipyard crane on board TRD Voyager – Port of Gdynia, Hungarian Quay.

After the Certificate of Readiness for Towing had been issued and the conditions required by the regulations of the Maritime Office in Gdynia for tug units fulfilled, Gdynia Harbour Master gave permission for the unit to sail from Gdynia to Szczecin.

At 1700 LT, the towing unit consisting of the Odys in front of the unit, the towed TRD Voyager with the lashed shipyard crane, and the tug Fairplay VII on the stern, departed from the Port of Gdynia – Hungarian Quay bounded for the Port of Szczecin.

Photo 2. Towing unit: Odys, TRD Voyager with shipyard crane on deck, and Fairplay VII departing from the Port of Gdynia on 23/08/2022.

At 17:30, after passing the Gdynia breakwater line, the pilot disembarked, and after passing the GD buoy, the Fairplay VII, which was securing the stern of the pontoon, was released. On the Odys, the towing line was extended up to 330m and the sea voyage of the towing unit with the shipyard crane loaded on board the pontoon commenced.

Until 0200 LT on 24 August 2022, the Master was in charge of the tug's bridge watch and at 0200 LT the First Officer took over the duty. Due to side swell, at 0230 LT the speed of the tug had been reduced and a more favourable course of the towing unit had been selected.

At 0647 LT, the First Officer found the cargo from the towed pontoon missing. He immediately informed the Master about the situation, and at 0703 LT called the Operations Officer of the VTS Słupska Bank with a message about the loss of the cargo. After consulting the shipowner, the towing unit sailed back to the Port of Gdynia.

At 1415 LT, Border Guard officers, when towing unit was abeam of Rozewie, carried out a check on the safety of navigation of it and the state of sobriety of the crew. In three members of the crew, tests showed the presence of alcohol in the breath[1].

On 26 August 2022, the Zodiak II multi-purpose vessel of the Gdynia Maritime Office, located a sunken shipyard crane at a depth of approximately 23 m east of the TSS Słupska Bank area. The Hydrographic Office of the Polish Navy (BHMW) issued a Navigation Warning and a Virtual Navigation Marking on the position of the wrecked shipyard crane.

[1] The crew members found to have alcohol in their breath were not part of the bridge watch.

On 24 May 2023, the main structure of the crane was picked up from the bottom of the Baltic Sea using the 'Maja' floating crane and transported to Gdańsk (Photo 3 from 'Portal Trójmiasto.pl').

Photo 3. Picked up mobile part of the shipyard crane on board the Maja floating crane.

2. General information

2.1. Tug Particulars

Tug's name:	Odys
Flag:	Polish
Owner:	Fairplay Towage Polska Sp. z o.o. Sp. k.
Operator:	Fairplay Towage Polska Sp. z o.o. Sp. k.
Classification society:	PRS (Polish Register of Shipping)
Vessel's type:	tug
Call sign:	SQLU
IMO number:	7937965
GT:	329
Year and place of build:	1979 Naval Shipyard Gdynia
Engine power:	1840 kW
LOA:	35.63 m
Width:	9.34 m

Hull material:	steel
Minimum manning:	international navigation – 6 crew
	Domestic navigation – 4 crew

Photo 4. Tug Odys

2.2. Towed object TRD Voyager

Pontoon's name:	TRD-Voyager
Flag:	Polish
Owner:	Trend Projekt Sp. z o. o. Sp. k. – Mokry Dwór
Operator:	Trend Projekt Sp. z o. o. Sp. k. – Mokry Dwór
Classification society:	PRS (Polish Register of Shipping)
Vessel's type:	pontoon
Register number:	ROG/S/872
GT:	1390
Year and place of build:	2006 Stocznia Crist Sp. z o.o. Gdańsk
Engine power:	No propulsion
LOA:	60.26 m
Width:	20.00 m
Hull material:	steel

Photo 5. Pontoon TRD Voyager

2.2.1. Cargo on board TRD Voyager

The cargo on board the TRD Voyager was an Eberswalde shipyard (rail type) crane with the following technical data:

Crane weight:	255 tonnes
Lifting capacity:	20 tonnes
Max reach:	32 m
Year of manufacture:	1969
Manufacturer:	VEB Kranbau Eberswalde Germany
Crane drive:	electric
Crane height:	46 m

Photo 6. Shipyard crane on board the TRD Voyager in the Port of Gdynia at Hungarian Quay

2.3. Voyage details

Ports of call during the voyage:	Gdynia
Destination port:	Szczecin
Type of voyage:	domestic, near-coastal
Crew details (number, nationality):	6 persons (all Polish)

2.4. Marine casualty or incident information

Type:	marine casualty
Date and time of the accident:	24 August 2022 at about 0304 LT[2]
Position at the time of the accident:	φ=54°06,8'N λ=017°31,3'E
Area of the accident:	Southern Baltic – east of the TSS Słupska Bank traffic separation scheme
Nature of the water region:	territorial waters
Weather at the time of the accident:	
From Odys Logbook:	wind NNE 4°B, state of the sea 2-3

[2] LT – *Local Time*

Operational condition of the vessel at the time of the accident: towing unit (tug + pontoon) with the loaded shipyard crane.

Consequences of the accident: Loss of cargo – shipyard crane. Tug Odys was not damaged as a result of the accident, minor damages on board TRD Voyager.

2.5. Shore Services and Search & Rescue Action Information

Entities involved: Maritime Office in Gdynia (VTS Zatoka Gdańska (*Gulf of Gdańsk*), Maritime Measurement Department, Navigation Marking Division), Border Guard, Hydrographic Office of the Polish Navy (BHMW).

Means used: vessel Zodiak II, which located the sunken shipyard crane at the geographical position φ=54°56.51'N; λ=017°52.06'E, and a depth of approximately 23m.

Action by the search & rescue services: S&R units were not involved in the accident.

Actions taken: the towing unit was directed by the shipowner to the Port of Gdynia. On 24/08/2022 duty operator of the Maritime Office in Gdynia, supervising ship traffic in the TSS Słupska Bank area, warned passing vessels on VHF Ch. 73 of a navigational hazard related to the accident of loss of the cargo – shipyard crane – in the area of TSS Słupska Bank. In addition, following information on the loss of the shipyard crane, BHMW issued a Navigation Warning No. PL 203/2022. On 26 August 2022, following the location of the sunken crane, BHMW issued a new Navigation Warning and a Virtual Navigation Marking on the position of the wrecked shipyard crane.

3. Circumstances of the accident

On 18 August 2022, a preliminary documentation for the marine transport of the shipyard crane structure, regarding the stability of the pontoon with its cargo and the design of the lashing of the crane system to the pontoon deck has been prepared (LST.SRM.EBE_P00_2022.08.18). This document has been provided to the shipowner and the master of the Odys.

On 22 August 2022 at approximately 1100 LT the Master and First Officer inspected TRD Voyager. It was checked if the pontoon is equipped with an emergency tow and if it has a towing bridle for the main towing line in good condition. The have also checked if the navigation lights on the pontoon are ready to use.

On 23 August 2022, a final document showing the stability and buoyancy parameters of the pontoon and how the crane should be lashed to the pontoon deck has been prepared (LST.SRM.EBE_R01_2022.08.23).

On 23 August 2022, the shipyard crane was loaded on the TRD Voyager moored at Hungarian Quay in the Port of Gdynia. After the crane was lashed on 23 August 2022, a visual examination report on the welds was prepared. At 1610 LT the same day, Odys unmoored from the Czech Quay and approached the TRD Voyager at the Hungarian Quay. Following the inspection of the towing unit by an authorised certified surveyor, a Certificate of Readiness for Towing has been issued. This certificate contained the towing recommendations and conditions for the Master of the towing unit. The certificate was received and signed by the Master of Odys.

At 1645 LT the harbour pilot boarded the Odys and the Fairplay VII approached the stern of the pontoon to assist in its movement during harbour manoeuvres.

At 1650 LT, the Odys crew, under the supervision of the First Officer, gave the main towlines from the bow and stern of the pontoon and completed the inspection and preparation of the towed object according to the vessel's procedures contained in the form F-PS-02/2 'Inspection of towed object prior to towing'.

At 1700 LT a towing unit consisting of the tug Odys and the pontoon TRD Voyager with a shipyard crane on board unberthed from the Hungarian Quay and, assisted by the tug Fairplay VII at the stern, using short 15 metre long towlines, sailed out from Gdynia.

At 1730 LT, after passing the Gdynia breakwater line, the pilot disembarked, and after passing the GD buoy, the Fairplay VII, which was securing the stern of the pontoon, was released. On the Odys extended the towing line up to 330 m and commenced sea passage to Szczecin.

At 1855 LT the towing unit passed the GN buoy.

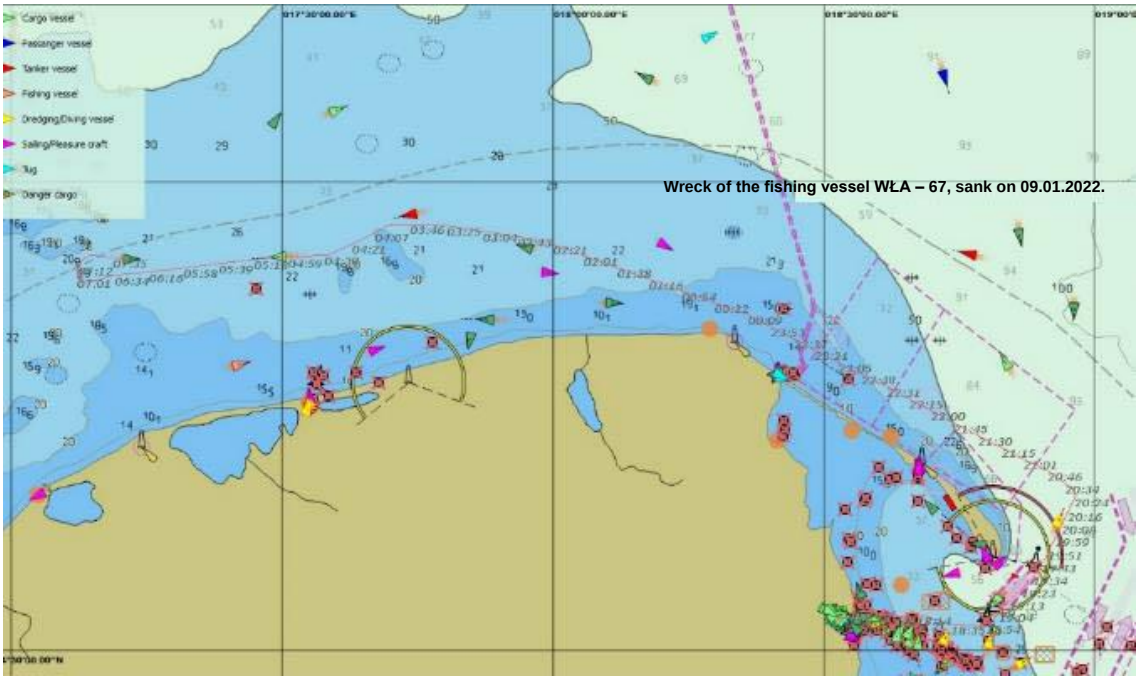


Figure 1. The route of the towing team – Odys and TRD Voyager – as recorded in the Shipping Safety Information Exchange System (SWIBŻ)

From 2000 to 0200 LT the navigational watch on the bridge was performed by the Master. The sea voyage proceeded without problems. At 0200 LT, the first officer took over the bridge watch on the position φ = 54° 55.0'N,λ = 018° 03.3'E, with the course 291°, and speed 6.5 knots. At 0230 LT, First Officer informed Master of deteriorating weather conditions and a side wave. Master came to the bridge and, after checking the weather situation, reduced the tow speed and changed a course to a more favourable one so that the swell would affect the stern of the towed pontoon. The course was changed from 291° to 265°.

According to the Master's report, at 0230 LT the shipyard crane was visible on the towed pontoon. After the aforementioned actions had been performed, Master left the bridge, and First Officer continued bridge watch. Between 0304 and 0310 LT, the shipyard crane was lost from the pontoon, as determined by the collected data of the route of the Odys and the location where the sunken crane structure by the vessel Zodiak II, on 26 August 2022, has been found.

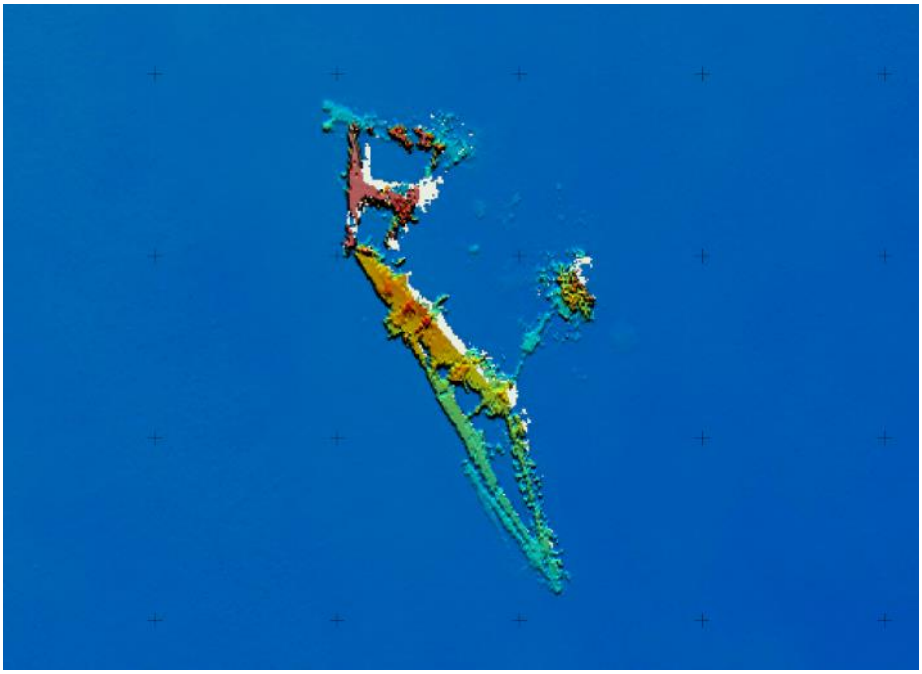


Figure 2. Sunken at the bottom of the Baltic Sea, crane lying on its side, facing SE with its arm.

The tug crew did not observe the moment the crane fell from the deck of the pontoon into the sea. At 0647 LT on position φ = 54°53.8'N; λ = 017°09.5'E, the First Officer noticed the absence of the shipyard crane on board the towed pontoon. He immediately informed the Master about this fact.

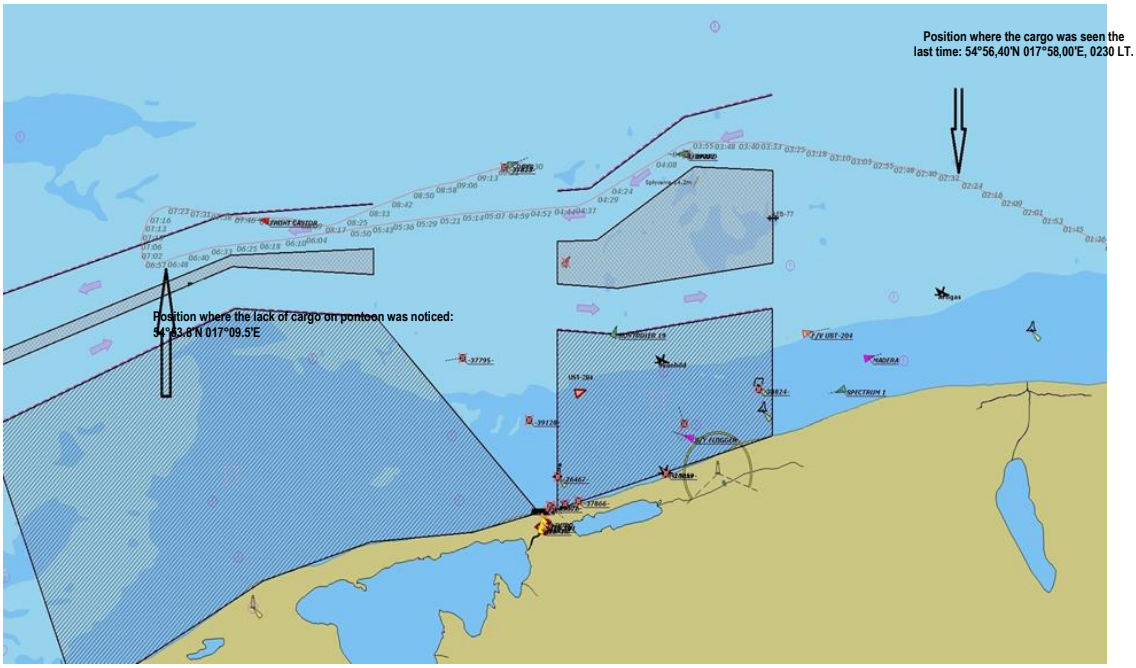


Figure 3. Position of the towing unit when it was determined that there is no cargo on board the pontoon.

At 0657 LT, the shipowner's operations inspector, having been informed of the loss of cargo, instructed the Master to sail back to the Port of Gdynia.

At 0703 LT, the First Officer on VHF Ch. 73 notified the duty officer of the VTS Słupska Bank of the loss of the shipyard crane from the deck of the towed pontoon. He reported the position and time when he noticed that the crane was missing. He was unable to determine the position and time when the cargo fell into the sea. After that, the towing unit left the traffic separation scheme TSS Słupska Bank and sailed back to the Port of Gdynia. At 2130 LT on 24 August 2022 Odys, together with TRD Voyager, safely moored at the Hungarian Quay in the Port of Gdynia.

Photo 7. View of the TRD Voyager deck when moored at Hungarian Quay in the Port of Gdynia – 25 August 2022.

On 26 August 2022, the multipurpose vessel Zodiak II, owned by Maritime Office in Gdynia, using a multibeam bathymetric system, surveyed the passage route of the towing unit and found the sunken shipyard crane on position φ =54°56,51'N; λ = 017°52,06'E.

The structure of the sunken crane, approximately 60 m high, 16 m long and 8 m wide, was located south of the Odys route, between the 14th and 15th points shown on the drawings below.

The found sunken shipyard crane was lying on its side with its arm facing SE[3]. The minimum depth above the object was 15.7 m while the depth of the area was approximately 23 m.

In May 2023, the main structure of the shipyard crane (the portal section including the rail mechanism) was picked up from the bottom of the Baltic Sea so that it would not pose a navigational hazard to deep-draught ships.

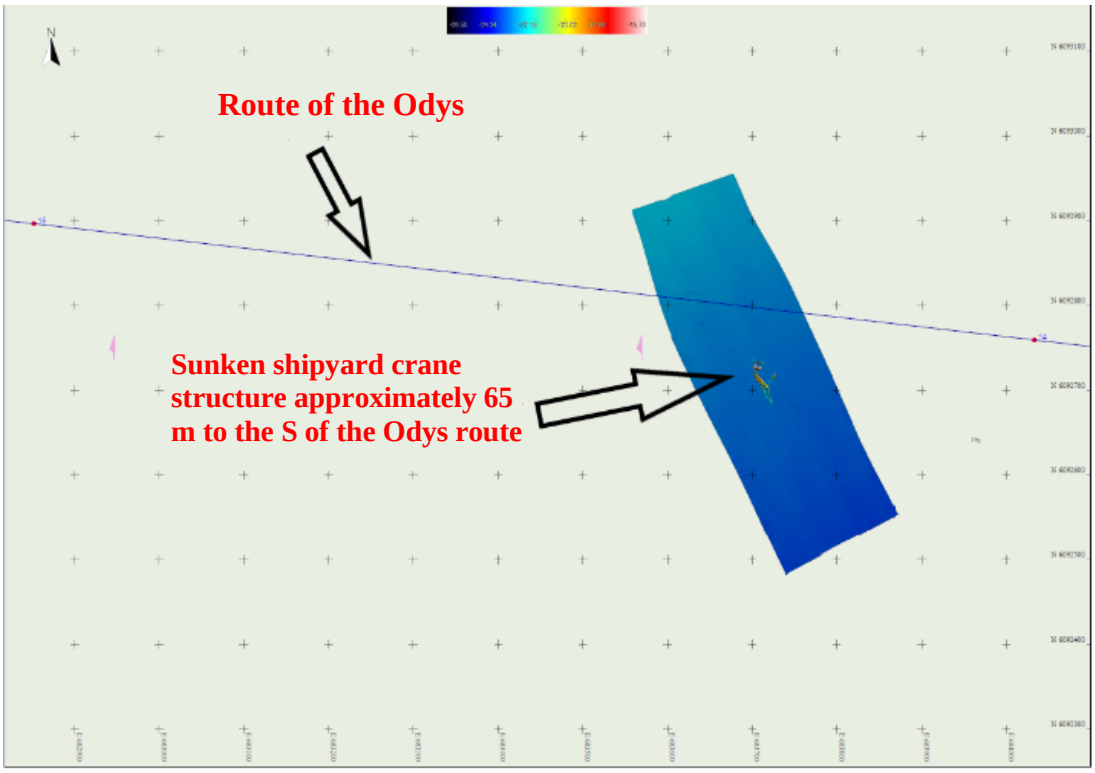


Figure 4. Position of the sunken crane – 65 m from the route of the Odys

[3] SE – south-easterly direction

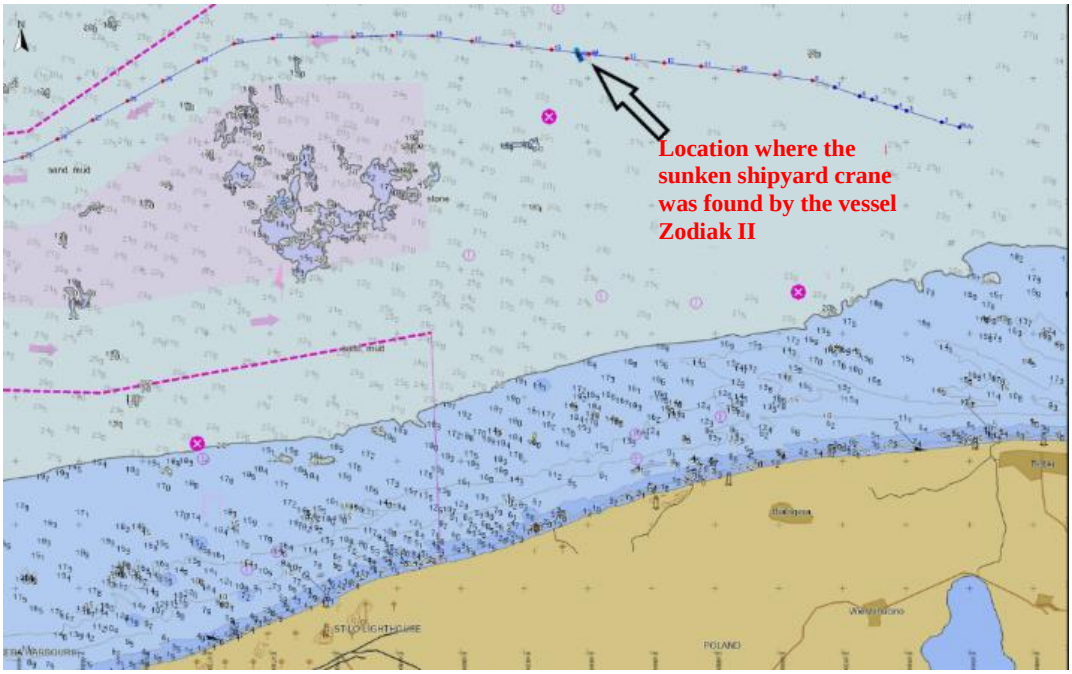


Figure 5. Location of sunken shipyard crane structure found by Zodiak II

4. Analysis and comments about factors causing the marine casualty with regard to results of investigation and expert opinions.

In maritime transport, towing operations of pontoons and barges with non-standard, large-sized cargo are higher risk operations. There is a possibility of damage or loss of the cargo, or the vessel. This requires proper calculation of the forces and moments acting on the cargo that will occur during towing. The IMO recommended method for determining the forces acting on the cargo and the practical rules for selecting a lashing system are described in the CSS Code[4], Annex 13, as well as in MSC.1/Circular.1623[5] – Amendments to the Code of Safe Practice for Cargo Stowage and Securing (CSS Code). In addition, advanced calculation methods are used, contained in standards, guidelines and regulations developed by classification societies regarding marine operations of large-sized, non-standard cargo. Such standards and regulations have been developed and made available by DNV classification society to improve safety in the design of lashing systems, planning and execution of shipping operations. These guidelines are contained in the DNV-ST-N001[6] standard and the DNV-RU-SHIP Classification Rules Pt.3

[4] CSS Code – Code of Safe Practice for Cargo Stowage and Securing
[5] MSC.1/Circ.1623 – Amendments to the Code of Safe Practice for Cargo Stowage and Securing (CSS Code).
[6] DNV-ST-N001 – *Marine Operations Standards.*

Ch.4 (2022)[7], which are based on specific examples of loads and strengths during non-standard cargo transport operations on board the ships during sea voyages, for specific assumed hydrometeorological conditions affecting the cargo.

As a result of this marine accident investigation carried out by the SMAIC, the individual fixing components were subjected to computational analysis and strength verification, checking that they met the conditions according to the methodology for calculating the forces, moments and accelerations acting on the cargo. Due to the different elasticity of the securing system components used, it was assumed for the assessment that only the main securing system has to carry the full loads, resulting from the transport of the shipyard crane, on board the pontoon. Calculations carried out by an expert in the field of securing non-standard loads in maritime transport showed that the lashing elements of the shipyard crane did not fully secure it and did not guarantee safe transport. They created the possibility of the crane falling into the sea. Calculations confirming the use of a lashing system with limited strength are included in Appendix 1.

Designed shipyard crane securing system, the methodology and compliance of the strength calculations contained therein were analysed, namely:

- Design strength of the lashing system (MSL 60 t).
- The strength of the lashing system for weather conditions recommended according to *DNV-ST-N001 (2021*).
- The strength of the lashing system for actual weather conditions during the voyage.

The Commission analysed the buoyancy and stability of the pontoon with shipyard crane on deck, as recommended in the Stability Information based on the PRS Rules for Classification and Construction of Sea-going Ships, Part IV, Stability and Subdivision. The analysis showed that TRD Voyager, with its cargo, met the stability requirements.

[7] DNV-RU-Pt.3 Ch4 (2022) – DNV Classification Regulations Vessels Part 3 Chapter 4 Cargoes.

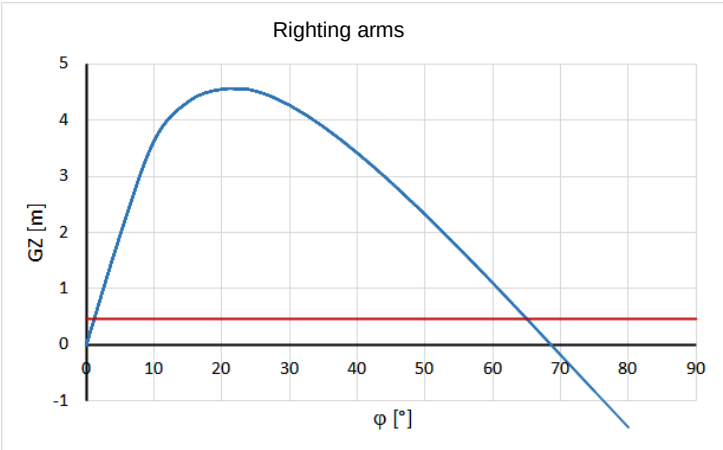


Figure 6. Righting arm curves of the TRD Voyager

		Required	Obtained	Criterion
1.	Area to the angle of maximum righting arm	0.08 m·rad	1.075 m·rad	**Fulfilled**
2.	Heel angle caused by a wind	$\varphi_{HALF\ FB}$ = 17.67°	1.2°	**Fulfilled**
3	Range of positive straightening arms	20°	68.3°	**Fulfilled**

Table 1. PRS stability criteria for pontoons

The Commission found that the pontoon had a minimal amount of ballast. Ballast water was only present in the bow section in ballast tanks No. 1 Port and Starboard.

			Masses		LCG	LCG	TCG	TCG	VCG	VCG	i_0	
			ton		meter	Moment	meter	Moment	meter	Moment	m^4	
	Light weight		**860,0**		0,96	825,6	0,00	0,0	2,60	2236		
TANKS :	**1 PS**	**188 t**	**20,0**	**11%**	**-22,4**	**-448,0**	**-7,99**	**-159,8**	**0,24**	**4,79**	**64,00**	*ballast water*
	1 SB	**188 t**	**20,0**	**11%**	**-22,4**	**-448,0**	**7,99**	**159,8**	**0,24**	**4,79**	**64,00**	*ballast water*
	2 PS (Central)	282 t	15,0	5%	-23,33	-350,0	-2,99	-44,9	0,12	1,80	0,00	
	2 SB (Central)	282 t	15,0	5%	-23,34	-350,1	2,99	44,9	0,12	1,80	0,00	
	3 PS	216 t	10,0	5%	-12,00	-120,0	-7,99	-79,9	0,10	1,04	0,00	
	3 SB	216 t	10,0	5%	-12,00	-120,0	7,99	79,9	0,10	1,04	0,00	
	4 PS (Central)	324 t	15,0	5%	-12,00	-180,0	-3,00	-45,0	0,10	1,56	0,00	
	4 SB (Central)	324 t	15,0	5%	-12,00	-180,0	3,00	45,0	0,10	1,56	0,00	
	5 PS	216 t	10,0	5%	0,00	0,0	-7,98	-79,8	0,10	1,04	0,00	
	5 SB	216 t	10,0	5%	0,00	0,0	7,98	79,8	0,10	1,04	0,00	
	6 PS (Central)	324 t	15,0	5%	0,00	0,0	-3,00	-45,0	0,10	1,56	0,00	
	6 SB (Central)	324 t	15,0	5%	0,00	0,0	3,00	45,0	0,10	1,56	0,00	
	7 PS	216 t	10,0	5%	12,00	120,0	-7,99	-79,9	0,10	1,04	0,00	
	7SB	216 t	10,0	5%	12,00	120,0	7,99	79,9	0,10	1,04	0,00	
	8 PS (Central)	324 t	15,0	5%	12,00	180,0	-3,00	-45,0	0,10	1,56	0,00	
	8 SB (Central)	324 t	15,0	5%	12	180,0	3,00	45,0	0,10	1,56	0,00	
	9 PS	104 t	5,0	5%	21	105,0	-7,99	-40,0	0,11	0,54	0,00	
	9 SB	104 t	5,0	5%	21	105,0	7,99	40,0	0,11	0,54	0,00	
	10 PS (Central)	156 t	8,0	5%	21	168,0	-3,00	-24,0	0,12	0,92	0,00	
	10 SB (Central)	156 t	8,0	5%	21	168,0	3,00	24,0	0,12	0,92	0,00	

Table 2. Ballast condition of TRD Voyager during towing according to shipyard crane sea transport documentation

Figure 7. Forward draught of the TRD Voyager

The Commission noted that the forward draught of the pontoon on departure from Gdynia was 1.20 m, which was less than the recommended 1.70 m.[8] For a wave height of approximately 1.20 m this could have caused the bow to emerge from the water. Maintaining the recommended forward draught would reduce the occurrence of bow slamming. Bow slamming[9] generates rapid changes in the resistance to motion of the pontoon and thus can create high accelerations in the longitudinal direction.

4.1. Mechanical factors

The Commission, considering that the accident of loss of the shipyard crane was not due to loss of integrity of the towing unit, and there was also no loss of stability or capsizing of the pontoon, analysed and verified the correctness of the design of the lashing (LST.SRM .EBE_R01_2022,08,24) of the crane to the pontoon deck. To verify the strength of the designed lashing system, a computational analysis of the strength of its individual components was carried out for an assumed working load of 60 tonnes. In case of exceeding the permissible

[8] The draught of the pontoon on departure from Gdynia was:
– on fwd 1.20 m
– on aft 1.60 m.
The recommended trim and draft in DNV guideline ST-N001 indicates that the minimum trim of a 60 m long pontoon should be 0.60 m to the aft and the minimum forward draft of the pontoon should be 1.7 m.
[9] Bow slamming – the impact of the bow of the ship's hull against a wave.

load, the values of the maximum safe working loads for each element of the lashing system were determined.

The limits of permissible loads for the structure attaching the crane to the deck of the TRD Voyager given below were adopted for the analysis.

Material:	Steel 235 MPa.
Yield strength limit	$\sigma yield = 23.5$ kN/cm^2,
Strength limit	fu = 41.0 kN/cm^2
• tensile forces:	$\sigma_t \leq 0.60 * \sigma yield 14.10$ kN/cm^2
• shear forces:	$\sigma_S \leq 0.40 * \sigma yield 9.40$ kN/cm^2
• compression forces:	$\sigma_c \leq 0.60 * \sigma yield 14.10$ kN/cm^2
• bending forces:	$\sigma_b \leq 0.66 * \sigma yield 15.51$ kN/cm^2
• contact stress:	$\sigma_{be} \leq 0.90 * \sigma yield 21.15$ kN/cm^2
• von Mises stress:	$\sigma_{vM} \leq 0.75 * \sigma yield 17.62$ kN/cm^2
• borehole stress:	$\sigma_{tPH} \leq 0.45 * \sigma yield 10.58$ kN/cm^2
• welds:	$\sigma_W \leq 0.30 * fu 12.30$ kN/cm^2
• Hertz:	$\sigma_W \leq 2.5 \cdot \sigma yield 58.75$ kN/cm^2
Poisson's ratio:	v = 0.3
Young's modulus – steel:	E = 20000 kN/cm^2

The calculation of the strength of the fixings did not take into account the additional elastic deformation of the shipyard crane during the pontoon roll.

4.1.1. Design of the shipyard crane lashing system

The system for lashing the shipyard crane to the pontoon deck has been prepared and fabricated according to an updated design (LST.SRM.EBE_R01_2022.08.23) approved on 23 August 2022. This system involved lashing the shipyard crane to the deck of the TRD Voyager using:

a) the main lashing system – 4 sets securing the crane chassis. The main crane lashing system used was a rigidly secured, non-adjustable initial tension, with a declared strength of 60 t (588.6 kN).

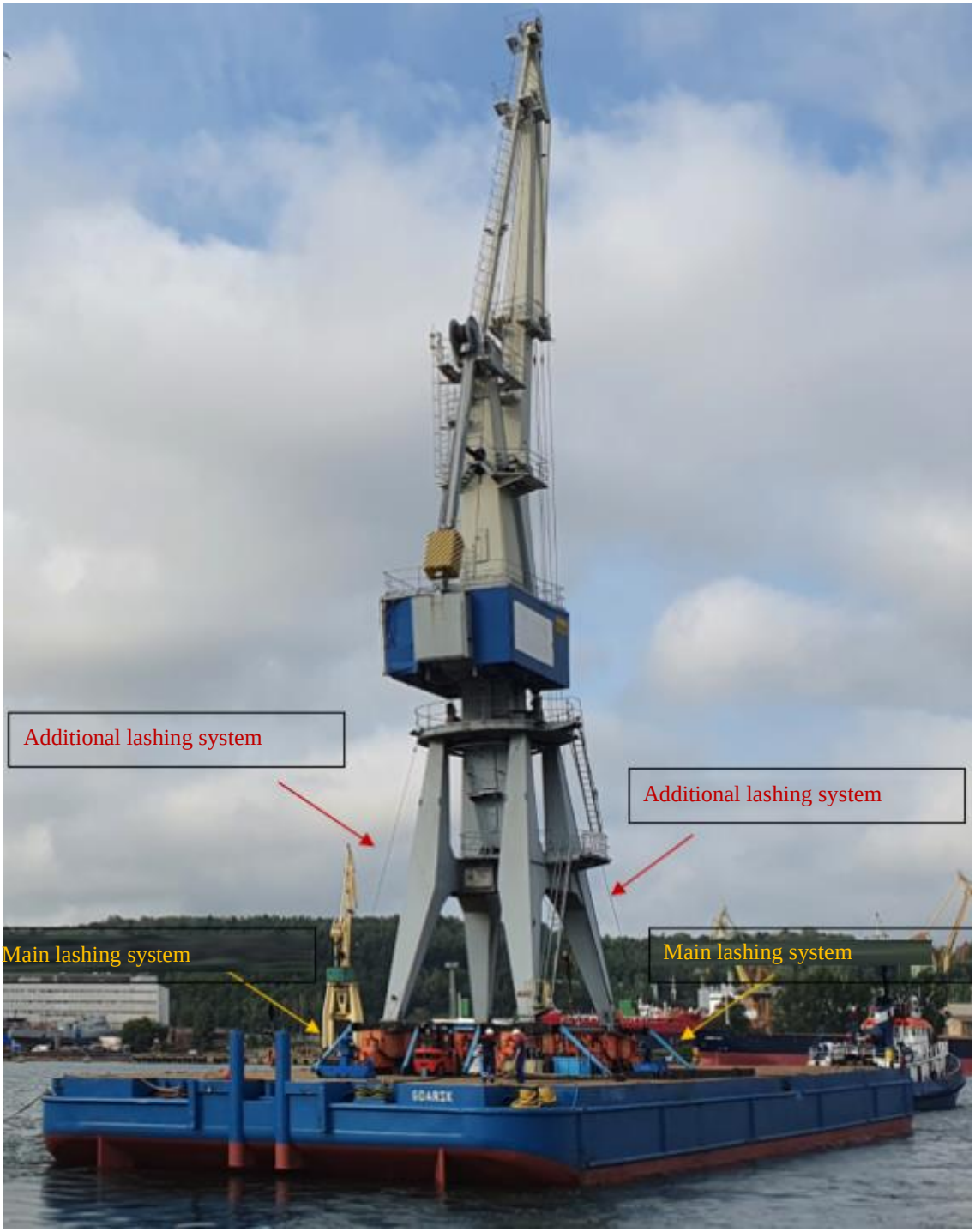


Figure 8. System for lashing the crane to the pontoon.

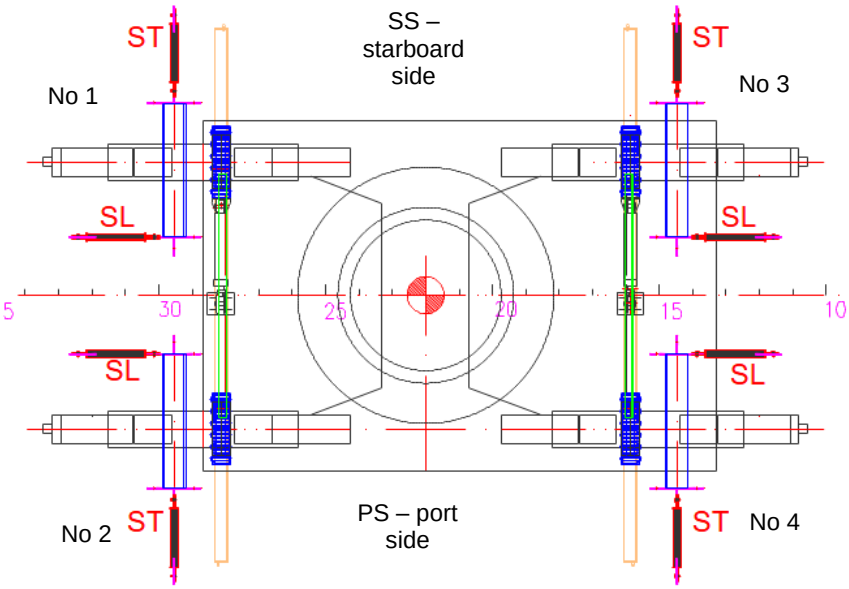


Figure 9. Main lashing system – 4 fixing sets.

b) additional lashing system – steel wires (∅ 18 mm) attached to the winches (fixed with stoppers on the deck) and the top of the crane base. The steel wires lashing system was not included in the crane fixing due to the lack of information on its strength (wires, shackles, winch fixings, winch brakes) and due to a different elastic coefficient than the crane chassis securing.

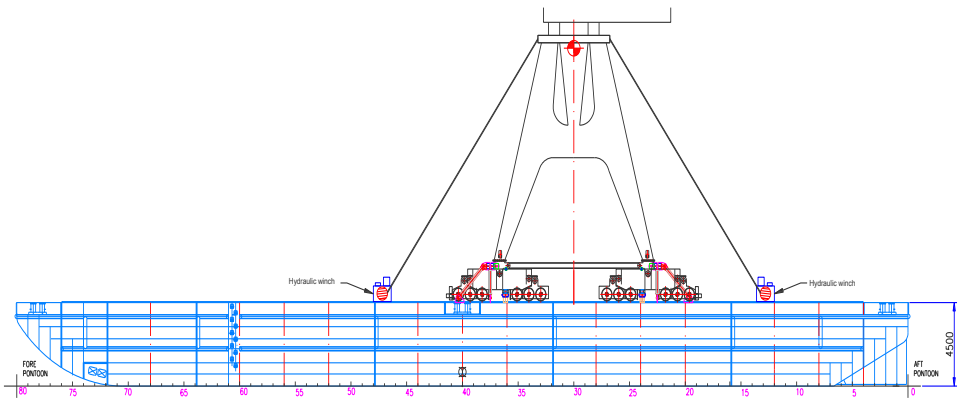


Figure 10. Additional crane lashing system (steel wire – Ø 18 mm)

c) stoppers securing the guide rails and individual components of the shipyard crane chassis.

Figure 11. Welded stoppers for lashing the chassis and guides.

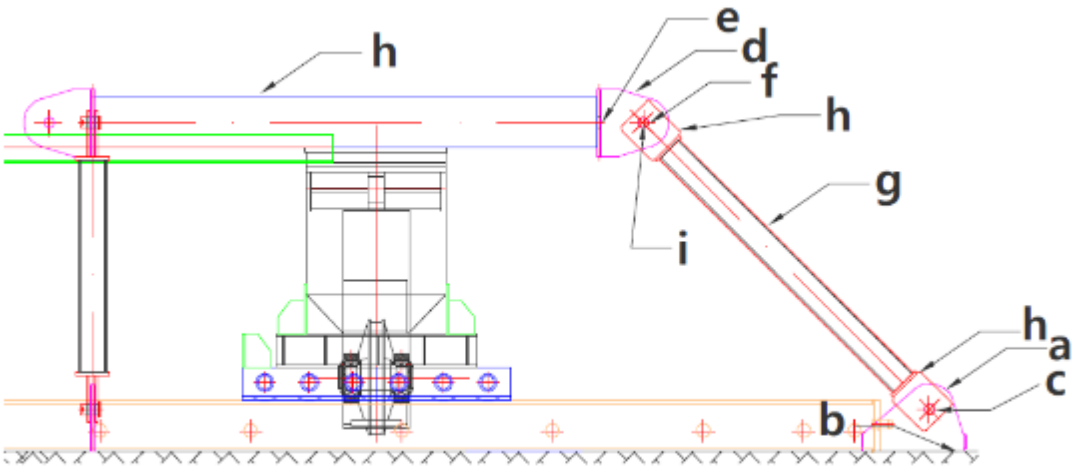


Figure 12. Design of the lashing system

Components of the main lashing system:

1. Bottom fixing plate (a)
2. Weld of the lower fixing plate (b)
3. Eye in bottom fixing plate (c)
4. Upper fixing plate (d)

5. Weld of upper fixing plate (e)
6. Eye in upper fixing plate (f)
7. Pipe (g)
8. Cheek plates in the pipe (h)
9. Eye in cheek plates (i)
10. Lashing system mounting bar (j)

After analysis of the main lashing system, the safe working load of the system was determined at 200 kN. The strength gradation of the individual lashing system components (from the weakest one) was:

1. Eye in the upper gusset – 200 kN
2. Eye in lower gusset – 200 kN
3. Plates in the pipe fixing – 212 kN
4. Weld of upper plate – 294 k
5. Eye in plates in pipe fitting – 293 kN
6. Upper plate – 353 kN
7. Weld of lower plate – 755 kN
8. Fixing of bottom plate – 795 kN

4.1.2. Strength of the lower fixing plate

The lower fixing plate of the main lashing system was welded to the pontoon shell with a 10 mm weld.

Figure 13. Lower fixing plate

The lower fixing plate and the weld of the lower fixing plate met the strength requirements under a force of 60 t (588.6 kN).

Stress calculations in the hole of the lower fixing plate showed that it exceeded the allowable working stress by 260%. The photo below shows the deformation of the plate eye and the plastic deformation of the plate. The allowable load (MSL) of the plate eye should not exceed 200 kN.

Figure 14. Figure 14: Plastic-deformed fastening hole of the lower fixing plate.

4.1.3. Strength of the upper fixing plate (beam).

The upper fixing plate was part of a horizontal beam attached to the shipyard crane chassis.

Figure 15. Upper fixing beams

Strength calculations showed that the stresses in the upper fixing plate exceeded the allowable working stress by 144%. The allowable load (MSL) of the beam should not exceed 400 kN. Below are drawings of the broken upper fixing beams.

Figure 16. Broken upper fixing beams No. 1, 2, 3 and 4.

The weld stresses of the upper fixing beams exceeded the allowable working stress by 158%. The allowable load (MSL) of the weld should not exceed 335 kN. Below is a drawing showing the remains of the damaged welds of the upper fixing beams.

Figure 17. Remains of welds of upper fixing beams No. 1, 2, 3 and 4

4.1.4. Strength of fixing pipes

The fixing pipes used met the strength requirements for the assumed loads.

Figure 18. Fixing pipes

The strength of the cheek plates, due to the forces acting in the lashing, was met with a horizontal working angle of up to 0.5°. During the voyage, the working angles of the lashing exceeded the allowable load considerably, causing the cheek plates to bend – figure below.

Figure 19. Bent cheek plates of the main lashing system.

The lashing system provides for 16 mandrels fixing the pipe section with the lower and upper plates. The mandrel can withstand loads for the Maximum Securing Load (MSL) of 60 tonnes. The mandrel was prevented from slipping out by means of a bent steel pin. The strength of the pin was tested assuming a transverse tilt angle of 0.5°. A tenfold excess of the allowable cutting force means that the pin could not block the cheeks of the pipe fitting from swinging out. The pin was sheared or pulled into the centre of the bore when the bore was enlarged.

Figure 20. Broken pin of the mandrel and torn out mandrel securing the bottom plate to the cheeks of the fixing pipe

Figure 21. Pin of the mandrel pulled out and sheared through the bent cheeks on the pipe.

4.1.5. Strength of the fixing beam

The crane's main lashing system used four beams to secure its chassis.

Figure 22. Upper fixing beams

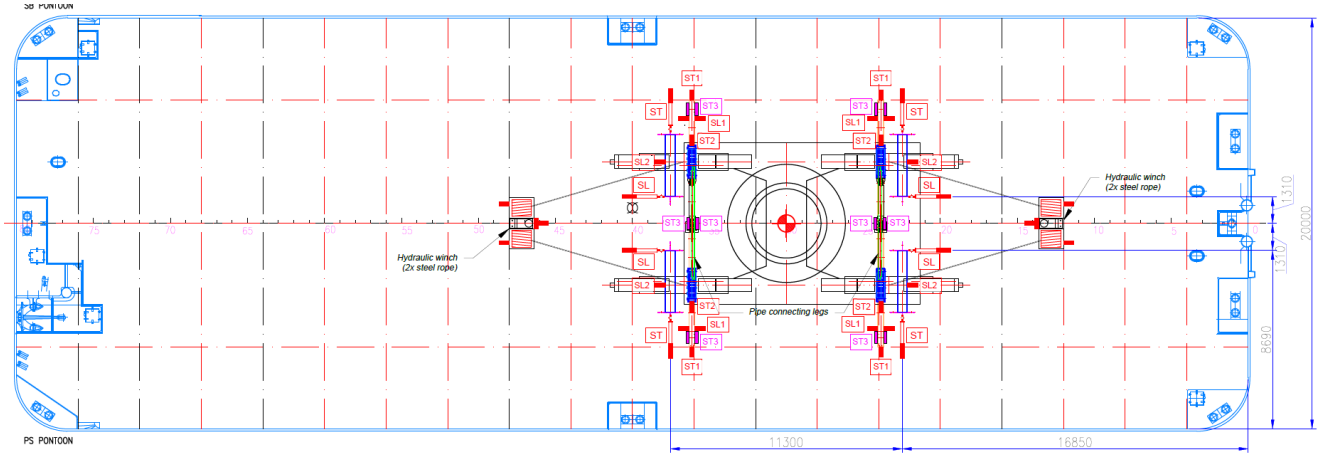


Figure 23. Layout plan of the shipyard crane and fixing beams on the pontoon

The crossbeam securing the crane chassis was welded to it using a weld with a declared dimension of 10 mm. To the fixing beams were added triangular gussets (Designation SL 2 on the fixing drawing) with dimensions: 300×300×12 mm.

Verification of the strength of the fixing beam weld, for a design load of 60 t, showed that the fixing weld did not meet the strength requirements for the design load and exceeded it by 148%.

4.1.6. Welded fixings of the lashing system.

The used shipyard crane lashing system, was a lashing based on elements of welded joints, which, after completion of the shipyard crane lashing operation, were subjected to visual testing

in accordance with PN-EN ISO 17637[10] and the welded joint assessment standard PN- EN ISO 5817[11], by a person certified to Grade 2VT. After VT testing (visual examination), protocol No. 07/08/2022 was prepared, which stated that the welded joints meet the requirements at level C (medium). The report did not include any comments on the quality of the welds, their correction or the welding discrepancies found. The photographs provided, taken before the towing unit departed for sea, show the gussets with a non-continuous weld attaching them to the crane chassis. The weld did not have the correct shape and profile, the weld surfaces were not uniform throughout, and a full weld was missing.

Figure *24. Fixing beam – additional gussets of fixing beam (incomplete lower weld)*

4.1.7. Actual strength of the lashing system

Large-sized cargo produce an additional capsizing moment through their rotational inertia relative to the ship's rotational acceleration in rolling or pitching. The additional capsizing moment is independent of where the cargo is placed on the vessel and is always positive, i.e., intensifying the capsizing moment. This phenomenon requires additional safety measures and

[10] PN-EN ISO 17637 Standard for non-destructive testing of welded joints – Visual testing of welded joints.
[11] PN- EN ISO 5817 International standard – Welding – Welded joints of steel, nickel, titanium and their alloys.
– Quality levels according to welding imperfections.

should therefore be included in the analysis of capsizing of large-sized cargo units (MSC.1/Circ.1623).

The capsizing moments taking into account the moment of inertia of the mass were calculated according to the recommendations of the Circular MSC.1/Circ.1623. The effective height of the load was assumed as 46.8 m (the height of the crane structure during transport).

The results obtained allow us to verify the lashing system for the designed accelerations of forces and moments acting on the cargo:

- The use of fixings with an actual MSL = 60 t did not allow for the effective securing of the cargo due to transverse shifting, as well as longitudinal and transverse tipping. The degree of securing against the transverse force acting on the cargo was ineffective and fulfilled in 68%. The protection against longitudinal and transverse capsizing of the cargo was ineffective and fulfilled in only 29% (longitudinal direction) and 12% (transverse direction) only.
- Lashing with verified MSL = 20 t did not secure against shifting and capsizing in either direction and met the lashing criterion in the longitudinal direction in 18% and in the transverse direction in only 7%.

Figure 25. Remains of the shipyard crane main lashing system on the pontoon after the accident.

The Commission believes that the primary cause of the loss of the crane from the TRD Voyager deck, was the use of the lashing system with limited strength. The critical factor was transverse capsizing, against which the shipyard crane was secured at only 7%. The transverse capsizing moments and the inertia of the crane's mass generated loads in the lashing system that exceeded its strength and caused plastic deformation and ultimately, rupture. This was evidenced by the bending of the cheeks on the pipes and the breaking of the mandrels' pins. The essential components of the lashing system carrying the greatest loads, were the welds connecting the upper fixing beams to the shipyard crane chassis. During its examination and visual inspection of the remains of the main lashing system on TRD Voyager, the Commission noted that the welds of the fixing beams were failed most probably as one of the first components of the entire lashing system.

4.2. Human factors

In investigating the marine casualty, the loss of the shipyard crane from TRD Voyager during towing, the Commission points to failings in the effective preparing of the crane for sea transport that were made during the design, lashing and preparation of the pontoon for sea passage with the shipyard crane on board.

Odys was manned during the towing operation by 6 crew who had the appropriate professional qualifications as required by the Safety Card. The Master had more than 30 years' experience working on tugs and the First Officer had several years' experience working on tugs in this shipowner's company.

The crew on the Odys, prior to and during the tug unit's voyage, were provided with an adequate amount of rest hours. They work on a rotational basis, two weeks on the tug and two weeks resting at home. The crew boarded the tug on 22 August 2022, and this was their first voyage, so the fatigue factor resulting from the failure to provide adequate rest hours for crew during the voyage did not arise.

The Commission notes that during the towing operation there was a lack of proper observation of the behaviour of the towed object with its cargo. The officer on the bridge did not notice the loss of the crane from the deck of the pontoon until approximately four hours after it had fallen

into the sea.[12] While the towed object was hardly visible at night due to weather conditions, passing rain and the grey colour of the crane, between 0410 and 0500 LT in the morning (navigational dawn), with good visibility prevailing, the absence of the crane on the pontoon was readily apparent.

According to the Safety Management Manual in operation at Fairplay Towage Sp. z o.o. Sp. k. the Master of the Tug, at all times during the voyage, is responsible for the vessel and crew and, in the case of acting as Master of the Tug while towing an unpowered and unmanned craft, is also responsible for the towed craft. During the night watch there was no seafarer on the bridge[13]. The officer on watch (OOW) was busy navigating the tug and did not notice the moment when the cargo was lost from the towed pontoon.

The Commission notes that the failure to accurately observe the location of the loss of cargo by the Odys, resulted in a risk to navigational safety on the approach to the eastern part of the traffic separation scheme TSS Słupska Bank for ships with a draught of 15 m and more, until the discovery of the wrecked crane by the Zodiak II two days after the accident.

The Commission, in the course of its investigation, drew attention to the fact that on the way back to the Port of Gdynia, after a sobriety check had been carried out by Border Guard officers, tests showed the presence of alcohol in the breath of three members of the crew, not connected with the navigation watch. The Commission points out that this circumstance was inconsistent with the applicable policy of Fairplay Towage Polska Sp. z o.o. Sp. k. 'zero alcohol policy' in relation to the use of drugs and alcohol, which prohibits the carrying and consumption of alcohol on board the vessel.

4.3. Organisational factors

The charter contract between the shipowner of the tug Odys and the owner of the crane Halifax P Sp. z o.o. was concluded for the service of towing the pontoon TRD Voyager together

[12] Safety Management Manual – Ship Procedure – 'Non-standard Port and Sea Towing" Item 7 – Execution of non-standard port and sea towing – 'The safety of navigation and towing operations requires a high degree of divided attention from the Master and crew of the towing vessel, as, in addition to observing the behaviour of the towed object and the tow, there is a requirement for intensified observation of the movement of other ships and navigational markings on the passed sea areas.'

[13] On a seagoing vessel, during night watch, there should be a seafarer with the OOW. In accordance with the STCW Convention (Code) 2017 Edition (Section A-VIII/2 Part 14-17 Lookout, an officer may be the sole look-out on the bridge, only during daylight hours and only if the situation has been accurately assessed to be safe for the ship taking into account visibility, weather and sea conditions, traffic density and whether the necessary attention is required when navigating in or near a traffic separation scheme.

with the loaded on it a shipyard crane from the Port of Gdynia (Hungarian Quay) to the Port of Szczecin (Repair Quay). The charter contract obliged the owner of the crane to properly prepare the pontoon with its cargo for the sea voyage, prior to the towing unit's departure from Gdynia. Both, Odys and the towed TRD Voyager had valid Safety Cards. A marine transport documentation of the crane structure had been prepared, which included stability calculations of the towed pontoon with its cargo and a lashing plan for the crane, together with strength calculations for the assumed weather conditions. The towing unit left the port on short tows with two tugs and a pilot on board, as per the conditions specified by the Gdynia Harbour Master's Office.

The Commission, based on an analysis of the design and supporting documents of the shipyard crane lashing system on board the pontoon concluded that the design of this system proved to be inadequate for the assumed hydrometeorological conditions and the planned sea passage from Gdynia to Szczecin.

The failure to assess the risk of losing the shipyard crane as a homogeneous structure in an unassembled state, when transported by sea, was inadequate and posed a risk of cargo loss during sea passage. The crane manufacturer, due to the heavy weight (255 tonnes) and the very high centre of gravity in the assembled state, recommends transporting the crane by sea in parts, after dismantling the rotating part, including the arm from the chassis gate structure (portal).

The Commission found that, according to the ship's procedure in force at the shipowner of the Odys, as contained in the Safety Management Manual, a 'Towing Plan' should have been prepared on the form F.PS-02/1 for the sea voyage from Gdynia to Szczecin and sent to the company's operations department as preparation for the towing of the marine and harbour object. According to the Safety Management Manual, the 'Towing Plan' shall illustrate the configuration of the towing unit, the configuration of the towing line and the towing method. Such a plan was not drawn up.

4.4. The influence of external factors, including those related to the marine environment, on the occurrence of the accident.

Weather conditions at the time of towing according to the Ship's Log Book, 0300 LT: wind NNE 4°B, sea state 2-3, wave height about 1.2-1.5 m. The wind was affecting the pontoon and cargo from the starboard side, the wind angle was approximately 91.5°-117.5° SS.

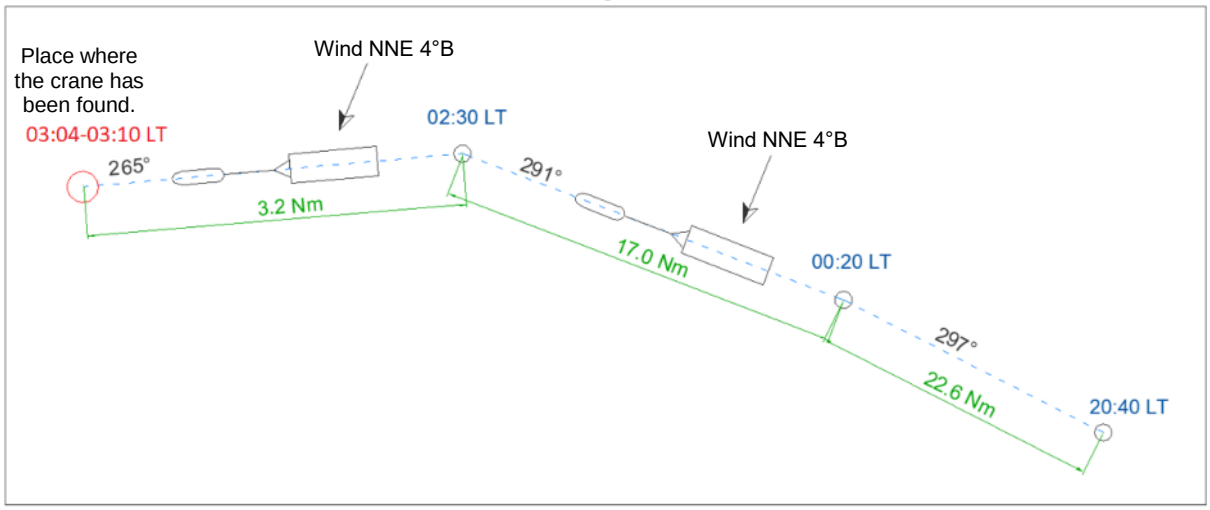


Figure 26. Courses and distances of the towing unit: Odys and TRD Voyager.

At the time of the accident of the loss of the crane from the deck, according to the data received by the Commission from the Sea Branch of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB), the weather condition on the Southern Baltic in the area of the Słupska Bank was as follows:

– north-easterly to northerly wind 3 to 5, initially with gusts of 6°B,

– sea state 3 (significant wave height from 0.9 to 1.2 m),

– good to moderate visibility,

– overcast.

Between 2100 LT on 23 August 2022 and 0200 LT on 24 August 2022, there was intermittent passing rain. The presence of an atmospheric frontal zone and towering cumulus clouds indicated the possibility of locally isolated, stronger wind gusts. Under the weather conditions (wind NE 4°B, wave approx. 1.2m) prevailing in the basin at the time of the accident, the allowable loads were exceeded several times (approx. 4 times). The external factor that contributed to the accident was the wind blowing during the night hours of 24 August 2022, generating side waves and pitching as well as rolling of the pontoon with its cargo, causing the destruction stresses to be exceeded in relation to the welded joints of the upper fixing beams, which were detached from the crane chassis. The crane fell from the pontoon deck to the port side most likely as a complete crane arm and gate (portal) structure, as evidenced by bathymetric photographs taken at the location where the wrecked crane was found.

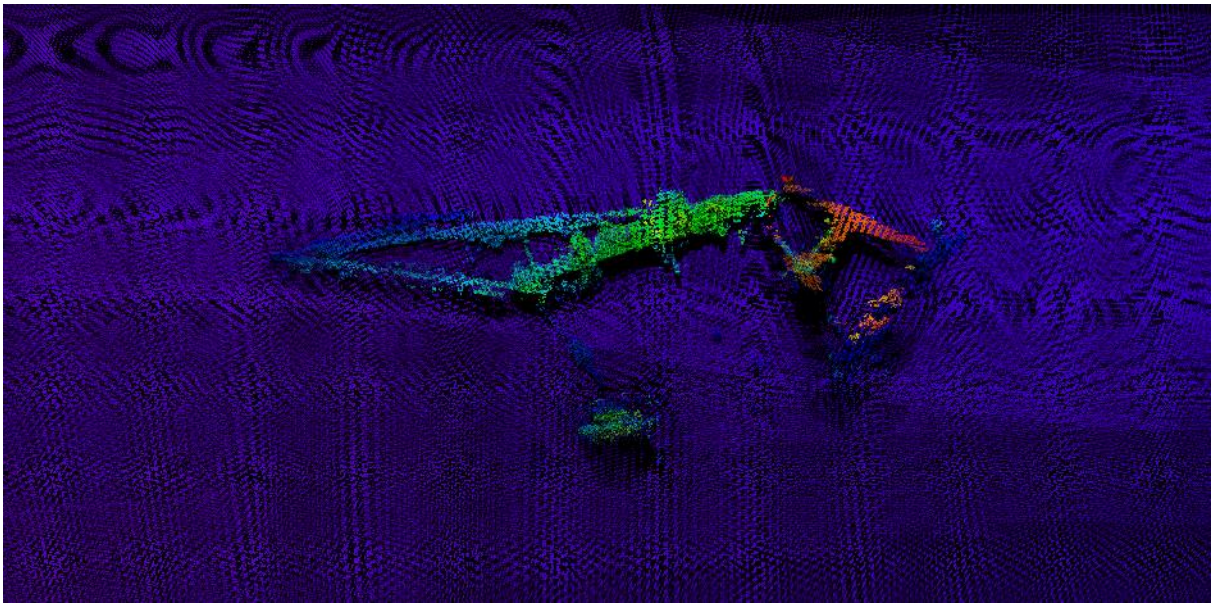


Figure 27. Found crane structure at the bottom of the Baltic Sea.

To test the strength of the crane's lashing on the pontoon, calculations were made for real weather conditions, for two cases of rolling and pitching[14], and two wave heights:

Condition I – defined for maximum pontoon sway parameters and wave height.[15]

Condition II – defined for minimum pontoon sway parameters and wave height.[16]

The rolling period for the pontoon was assumed in Condition II to be equivalent to that of a 60 m wave on the Southern Baltic. Strength analysis showed that the beam fixing weld did not meet the strength requirements for the actual loads. The loads were exceeded 3.24 times. Both the preliminary and updated design of the shipyard crane lashing included a note regarding the hydrometeorological conditions for the towing unit's sea voyage, which stated that 'the voyage should not be commenced in weather forecasts with wind speeds greater than 6°B and significant wave heights greater than 2.0 m'.

[14] The values for the pitching and rolling periods have been determined based on the regulations: DNV- RU-SHIP Pt.3 Ch.4 (2022).

[15] Weather and pontoon movement parameters, lashing strength under real weather conditions, – STATE I: Wind NNE 4°B (v = 8 m/s), Angle of the wind wave 120°, Wave height 1.5 m. Amplitude of pitching 5°. Amplitude of rolling 5°. Pitching period 5.9 s. Rolling period 3.9 s.

[16] Weather and pontoon movement parameters, lashing strength under real weather conditions – STATE II: Wind NNE 4°B (v = 8 m/s), Angle of the wind wave 120°, Wave height 1.2 m. Amplitude of pitching 2°. Amplitude of rolling 2.3°. Pitching period 5.9 s. Rolling period 6.2 s.

5. Description of Examination Findings Including the Identification of Safety Issues and Conclusions

The proper securing of a large-sized, heavy, non-standard cargo in sea transport requires careful preparation and execution of appropriate strength calculations of the securing system and securing devices, and their proper installation. If the cargo securing is based on welded steel elements, special attention should be paid to the quality of welds of large steel brackets or beams and welded stiffeners, both to the ship's deck (pontoon) and to the cargo (crane structure). The towing of a pontoon with large-sized cargoes is not a routine operation and the tug crew may not have the necessary competence and experience, regarding the lashing plan drawn up and the assessment of the correctness of its execution. In this respect, the Master of the towing team relied on the opinion of the surveyor and the issued Certificate of Readiness for Towing prepared at the request of the cargo owner, following the completion of the operation of lashing the shipyard crane to the pontoon.

Towing a shipyard crane on a pontoon required careful preparation and adequate lashing of the cargo for sea transport. To transport the crane by sea, a TRD Voyager was used, chartered for the voyage from Gdynia to Szczecin. Halifax P Sp. z o.o., which owned the crane, chartered the TRD Voyager from the pontoon owner Trend Sp. z o.o. Sp. k.

The towing service for TRD Voyager with loaded shipyard crane from Gdynia to Szczecin was contracted by the owner of the crane to the shipping company Fairplay Towage Polska Sp. z o.o. Sp. k., with which a corresponding charter contract for the sea passage was concluded. The service was a non-standard port and sea tow. The operation of transporting the crane structure from the quay to the pontoon, its loading, lashing, unloading and assembling in the Szczecin shipyard, was commissioned by the owner of the crane to Suwrem Sp. z o.o. This company, prior to loading the crane structure onto the pontoon, secured the moving parts against rotation, along with positioning, assembling the crane arms as shown on the photo below.

Photo 8. Securing a shipyard crane on a TRD Voyager in the Port of Gdynia

Suwrem Sp. z o.o. commissioned a subcontractor, LST Solutions Sp. z o.o., a company specialising in comprehensive waterborne transport and cargo operations of heavy and oversize structures, to carry out the transport of the shipyard crane from the Port of Gdynia to the Port of Szczecin. The subcontractor prepared the documentation (design) for the sea transport of the shipyard crane on board the TRD Voyager, including the system for lashing the crane to the pontoon deck, the stability calculation of the pontoon with its cargo and the results of the strength calculation of the lashing system. The contract additionally included the obligation to carry out work related to the relocation and loading of the crane from the quay to the pontoon and its lashing on the pontoon according to the design made. After the crane had been secured, a quality check of the welded joints of the lashing elements was carried out and a report on the visual examination of the welds was drawn up (Examination protocol VT[17] 07/08/22, 2022.08.23).

[17] VT – visual testing of welded joints

An independent surveyor representing J-G Marine Sp. z o.o., on behalf of the crane's owner, inspected the towing unit, and issued a Certificate of Readiness for Towing, which included recommendations to the towing unit leader (the Master of the Odys) regarding the preparation and execution of the towing, as a sea voyage, indicating that the shipyard crane is properly secured to the pontoon deck, as per the lashing design, and that the pontoon has an adequate reserve of stability. According to the certificate, the tow, the voyage of the towing unit, could take place in good and favourable local weather conditions (harbour). The wind strength should not exceed 4°B and for the entire sea voyage a maximum of 12 m/s, corresponding to 6°B and a wave height of no more than 2 m.

The crane was rigidly fixed to the deck of the pontoon, according to the designed lashing system, with the arm folded and the mechanism locked to prevent it from rotating. The voyage plan assumed that the towing unit's sea voyage will take approximately 34 hours at the speed of 6.5 knots. Marine casualty, the loss of the shipyard crane, occurred approximately nine hours after the beginning of the voyage. The crew of the tug did not observe the crane fall from the pontoon. During the voyage, the pontoon was not manned or self-propelled. Neither the integrity of the pontoon nor the tug was compromised during the voyage, the pontoon did not suffer any loss of stability or buoyancy. There was no breakage or damage to the towline. After the accident, the towing unit safely returned to the Port of Gdynia. The collapse of the crane caused minor damage to the deck of the pontoon where it fell and where the fastenings hit the deck, visible on the photo below.

Photo 9. Damage to the deck of the TRD Voyager

Any damage on board the TRD Voyager following the collapse of the shipyard crane was repaired by the charterer under the supervision of the PRS classification society.

Non-standard towing, according to the Safety Management Manual, requires the Master to comply with the shipowner's instructions and safety conditions during the towing operation. Odys had valid ship documents, a valid Safety Card issued by the Maritime Office in Gdynia and a valid Certificate of Class issued by the PRS Classification Society. The tug was operational, equipped with appropriate radio and navigation equipment as well as towing appliances and devices in good working condition. The tug was manned in accordance with the requirements of the Safety Card. The crew held the relevant diplomas and qualification certificates appropriate to their positions.

On 18 August 2022, a preliminary document was prepared for the stability of the pontoon with its cargo and the lashing system for its securing to the pontoon deck with No. (LST.SRM.EBE_P00_2022.08.18). On 23 August 2022, the final documentation for the sea transport of the shipyard crane on board the TRD Voyager with number (LST.SRM.EBE_R01_2022.08.23) was prepared, according to which this crane was lashed and secured for the sea voyage[18]. This document included stability parameters, the results of strength calculations of the lashing system and how to fix the crane to the pontoon deck. In addition, the document specified the requirements and conditions for the commencement and the sea voyage itself. The basic lashing system shown in both documents was based on the same structural elements, but the final document increased the thickness of the welds to 1 cm and added additional wire ropes for lashing and positioned additional stoppers to secure the crane chassis and the guides on which it was seated. From the material collected by the Commission and the expert opinion on the design strength of the lashing system, it appears that the possible basic cause of the shipyard crane falling overboard was the use of the lashing system with limited strength. The designed lashing system provided for a permissible securing load of 60 t. In contrast, an analysis of the strength of the lashing components shows that the MSL allowable securing load of most lashing components did not exceed 20 t. The use of components of the lashing system with strength limited to 20 t resulted in the cargo not being secured properly.

[18] The documentation for the transportation and lashing of the crane (LST.SRM.EBE_R01_2022.08.23), is based on the standards and regulations detailed in the lashing design, namely:
PRS Rules for Classification and Construction of Sea-going Ships, Part IV, Stability and Subdivision, January 2022.
International Code on Intact Stability – IS Code 2008, IMO (Resolution MSC.267(85)) adopted on 4 December 2008 and IMO amendments MSC 85/26/Add.1/Corr.3/Rev.1 – adopted on 9 December 2008; October 2018.
ABS Rules for Building and Classing Mobile Offshore Units.
Marine Operations Standard DNVGL-ST-N001.

The lashing system for the marine cargo of the custom, large-scale shipyard crane was based on welded components. The welded joints should be free of technical defects and made to a very high standard, followed by a thorough and careful VT check according to adopted standards. The simultaneous use of flexible lashing systems with welded fixing systems is not recommended, due to the very large difference in stiffness and elasticity between 'rigid welded fixing' and 'flexible fixing using wires and winches'. This results in an uneven load distribution. The Commission notes that, despite a number of conditions and requirements being met, there was a loss of the shipyard crane, some nine hours after the beginning of the sea passage (BOSP). The critical impact was probably transverse capsizing, protected against to a very low degree. In the Commission's view, the transverse capsizing moments and the mass inertia of the shipyard crane generated loads in the lashed system that exceeded their strength and created plastic deformation of the weakest components of this system, ultimately causing them to break. This is evidenced by the bending of the cheeks on the clamping pipes and the breaking of the mandrels' pins. The essential components of the lashing system carrying the greatest loads, were the welds connecting the upper fixing beams to the shipyard crane chassis. Visual inspection of the main lashing system remains on the TRD Voyager may indicate that the weld of the fixing beams failed as one of the first components of the lashing system. The loss of the crane occurred approximately 35 minutes after the First Officer and the Master changed course and speed of the tow due to wind and side wave action from the NNE direction. Deteriorating hydro-meteorological conditions, may have accelerated the loss of integrity of the lashing system, even though the weather conditions did not exceed the meteorological conditions contained in both the shipyard crane lashing design and the Certificate of Readiness for Towing. Exceeding the permissible load of the weld connecting the beam to the crane chassis by more than three times resulted in a stress nearing the destruction value, i.e., 41kN/cm². This means that with the pontoon pitching 2° and rolling 2.3°, there was a destruction of the weld connecting the fixing beam to the crane chassis. The destruction of the connection between the beam and the chassis allowed the crane to move and destroy further protection. In these conditions, with a starboard wind, the crane capsized and fell into the sea on the pontoon port side.

Photo 10. Crane guide rail element on board a pontoon from PS

On the pontoon, after the accident, parts of the lashing system with the fixing beams were left broken off.

Following an analysis of the pontoon's stability, the strength of the shipyard crane lashing system, the weather conditions, the Commission comments below on why the shipyard crane fell overboard of the pontoon, namely:

1) **comments on the design of the lashing system:**
   a. inadequate determination of the MSL of the lashing system. According to the design it was 60 t (588.6 kN), whereas from the strength analysis of the components it was determined to be only 20 t,
   b. the lashing of the shipyard crane was made as symmetrical with respect to its chassis but was asymmetrical with respect to its centre of gravity. The fixing beams were not secured symmetrically, which resulted in additional moments rotating them horizontally. No account was taken in the calculations of the additional torsional moments between the fixing beam and the crane chassis, which generated additional shear forces on the weld connecting the beam to the crane chassis (Figure. 28),

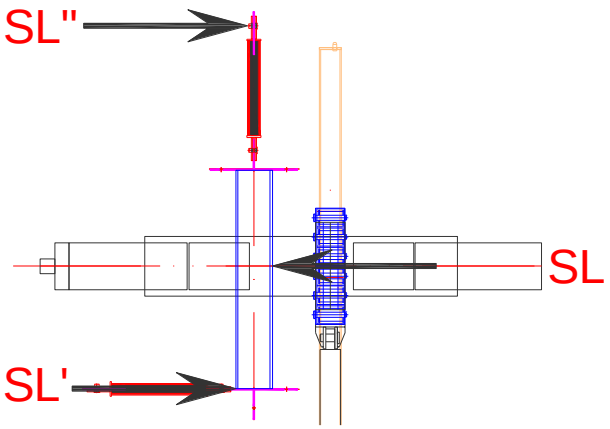


Figure 28. Torsional moment acting on the upper fixing beam.

c. steel wires attached to winches were used for additional lashing. These had a different coefficient of elasticity in relation to the chassis lashing,
d. the additional moment of inertia of the crane's mass and its effect on the lashing system was not taken into account in the design of the lashing. It caused additional stress in the weld of the beam connecting it to the crane chassis,
e. the rigid connection of the lashing system to the pontoon structure resulted in the direct transmission of loads and vibrations of the pontoon to the crane lashing system,
f. the main lashing system did not provide for a method of evenly tensioning its individual components. The use of an unevenly tensioned lashing system may have caused small movements of the load that led to the wear and tear (plastic deformation) of individual components of this system (e.g., cheeks and pins) and its further loosening,
g. securing the mandrels in the cheeks by 5-6 mm steel rod was incorrect. Locking pins with nuts should have been used. Cutting the locking pin resulted in free movement of the fixation relative to the mandrel and spreading of the cheeks which led to the mandrel being pulled out of the fixing cheeks and loosening the fixation.

2) Comments on the execution of the lashing system:

a. the plan for the placement of the stoppers lacked a definition of the critical connections and the choice of method for testing their quality,
b. the lashing system design documentation obtained lacked detailed information on the parameters of each weld and confirmation of its dimensions,

c. some of the stoppers securing the cargo were not in contact with it and there were gaps between the stoppers and the cargo (Figure 29),

Figure 29. Stoppers fixing the cargo – no contact.

d. preparation of the material for welding – none of the photographs show surface preparation (grinding) of the material before the weld was placed. The welds were welded on paint and dirt (Figure 30),

Figure 30. No visible signs of material preparation for welding.

e. there is a lack of information in the documentation about the number (length) of welds made and their continuity. The photographs show discontinuous welds or welds of variable thickness (fig. 32),

Figure 31. Lack of full weld.

f. fig. 32 shows significant differences in weld thickness. In the documents submitted after the accident there is no information about other tests of weld quality being carried out apart from the visual examination e.g., magnetic testing. There is also no confirmation of the weld thickness of the main fixing elements,

Figure 32. Differences in weld dimensions.

g. there is information in the documentation about visual testing of the welds (Protocol VT 07_08_2022_LST). The protocol does not show any objections to the welds tested. A notation was made that the surfaces should be raw or ground, but it was not defined to which welds this refers,

h. no cleaning has been made after welding (this applies to the welds connecting the fixing beams to the crane structure),

i. welds connecting the fixing beams to the crane chassis were not properly prepared for acceptance/inspection due to the slag not being removed,

j. there is no visible signs of grinding the weld ends, which is necessary to achieve weld acceptance level C (standard EN ISO 5817) (fig.33),

Figure 33. No visible signs of grinding the weld ends.

k. an additional lashing by steel wires (D = 18 mm) was placed in the final lashing plan. The steel wires were attached to the swivel section of the shipyard crane and to the hydraulic winches on deck. The hydraulic winches were fixed to the deck with stoppers. Due to the lack of information on the holding force of the winch drum, such fixing cannot be included when determining the strength of the crane lashing,

l. the transverse fixing beams were attached to the crane legs with a 10 mm weld – there is no confirmation that this weld dimension was met,

m. gussets (SL2) were attached to the fixing beams – there is no confirmation of the continuity of the welds fixing these gussets.

3) comments on the preparation of the pontoon and its cargo for the sea passage

The pontoon had a minimal amount of ballast, which meant that it did not reach the required draughts at the bow and stern (DNV ST-N001). This could have generated additional jerking of the towing rope and therefore additional acceleration of the pontoon during wave motion.

6. Safety recommendations

The loss of the shipyard crane demonstrates the importance of using advanced calculation methods for the performance of the correct lashing system according to strength calculations: forces, moments and accelerations acting on the cargo and the lashing system. Each non-standard cargo requires the design of a customised lashing system to secure it during the sea voyage.

The State Marine Accident Investigation Commission recommends that shipowners and specialist companies involved in securing non-standard cargo on ships should:

1. follow the guidelines contained in the Code of Safe Practice for Cargo Stowage and Securing (CSS Code), as amended by Annex 13 of the circulation MSC.1/Circ.1623 and the DNV-RU-Pt.3 regulations Ch4 (2022) – DNV Classification Regulations Vessels Part 3 Chapter 4 Cargoes and the standards in Marine Operations Standards in chapter DNV-ST N001, or equivalent contained in the recommendations of classification societies, on methodologies for calculating the strength of lashing of large-sized non-standard cargoes on vessels for specific conditions, in marine operations,
2. conduct training courses on the latest principles and technical standards used in securing non-standard large-sized cargoes on board the ships, for their effective application in the design of maritime operations; such training courses shall be conducted by classification societies or other organisations using their experience and insights regarding marine operations,
3. conduct consultations with manufacturers as to the recommended method of transporting non-standard marine cargo, such as: cranes, shipyard cranes, port cranes, as well as other cargo to ensure the optimum safe lashing system used in marine transport.

7. List of photos

8. List of figures

9. List of tables

10. List of abbreviations

B – Beaufort (wind scale)

BHMW – Hydrographic Office of the Polish Navy

IMGW-PIB – Institute of Meteorology and Water Management – National Research Institute

KZB – Safety Management Manual

MSL – Maximum Securing Load, determines the breaking strength of the cargo securing device

NNE– wind direction (northerly, north-easterly)

PRS – Polish Register of Shipping (classification society)

SWIBŻ – Shipping Safety Information Exchange System (serving as a platform for the distribution of information between operational services cooperating in the field of maritime safety)

VTS – *Vessel Traffic Service*

11. Information sources

Notification of the accident.

Crew hearings.

Commission's own photographs.

Materials and documents received from those involved in the operation of lashing and transporting the shipyard crane.

Materials and documents received from the owner of the shipyard crane.

Information received from the manufacturer of the shipyard crane.[19]

Documents and materials received from the owner of the Odys and TRD Voyager.

Documents and materials received from the Maritime Office in Gdynia and the Border Guard.

Expert opinion prepared by Dr. Jarosław Soliwoda, expert of the SMAIC.

12. Composition of the accident investigation team

Team leader – Tadeusz Gontarek – Member of the Commission

Team member – Marek Szymankiewicz – Secretary of the Commission

13. Załącznik 1. Projektowany system mocowania żurawia do pokładu pontonu – obliczenia wytrzymałościowe.

Obliczenia wytrzymałościowe systemu LST.SRM.EBE_R01_2022.08.23 mocowania ładunku żurawia stoczniowego na pontonie TRD Voyager.

Skróty i objaśnienia

Skrót	Jednostka	Objaśnienia
α	°	Pionowy kąt pracy mocowania
β	°	Poziomy kąt pracy mocowania
φ	°	Poprzeczny kąt przechyłu pontonu
Δ, D	t	Wyporność statku
a	mm	Grubość spoiny
AP	-	Pion rufowy
A_W	-	Powierzchnia nawiewu

[19]The Eberswalde shipyard crane was manufactured in 1969 at VEB Kranbau Eberswalde, which was privatised in 1990 and now operates under the name Kirow Ardelt GmbH as one of the largest manufacturers of cranes and harbour cranes.

BM	tm, kNm	Moment gnący
BP	-	Płaszczyzna podstawowa
c_H	-	Współczynnik wysokości
CL	-	Płaszczyzna symetrii
c_S	-	Współczynnik kształtu
FB	m	Wolna burta
FL	kN	Siła wzdłużna
FLS	kN	Siła wzdłużna zabezpieczenia ładunku
FP	-	Pion dziobowy
F_S	kN	Siła zabezpieczająca
FSC	m	Poprawka na swobodne powierzchnie cieczy
FSL	kN	Wzdłużna siła działająca na ładunek
FST	kN	Poprzeczna siła działająca na ładunek
F_T	kN	Siła poprzeczna
FTS	kN	Siła poprzeczna zabezpieczenia ładunku
F_X	kN	Siła wzdłużna
F_Y	kN	Siła poprzeczna
F_Z	kN	Siła pionowa
GM	m	Wysokość metacentryczna
GZ	m	Ramię prostujące
KMT	m	Wysokośc metacentrum poprzecznego
l	m	Długość spoiny
LC	kN	Wytrzymałość odciągu
LCB	m	Odcięta środka wyporu
LCF	m	Odcięta środka ciężkości wodnicy
LCG	m	Odcięta środka masy
ls	m	Ramię stateczności kształtu
LT	-	Czas lokalny
M	-	Śródokręcie
MML	kNm, tm	Wzdłużny moment masowy przeciwdziałający przewracaniu

MMT	kNm, tm	Poprzeczny moment masowy przeciwdziałający przewracaniu
MSL	kN, t	Maksymalna siła zabezpieczająca
MTL	kNm, tm	Moment przewracający wzdłużny
MTLS	kNm, tm	Wzdłużny moment przeciwdziałający przewracaniu
MTT	kNm, tm	Moment przewracający poprzeczny
MTTS	kNm, tm	Poprzeczny moment przeciwdziałający przewracaniu
P	N/m^2	Ciśnienie wiatru
t	m	Przegłębienie
T	m	Zanurzenie średnie
TA	m	Zanurzenie na rufie
TCG	m	Poprzeczne położenie środka masy
TF	m	Zanurzenie na dziobie
VCG	m	Wysokość środka masy
W	m^3	Wskaźnik przekroju
zw	m	Odległość pionowa środka nawiewu od wodnicy pływania

Wytrzymałość systemu mocowań

Obliczenia wytrzymałości mocowań opracowano o metody stosowane w projektowaniu konstrukcji stalowych: Norma EN 1993, *Specification for Structural Steel Buildings ANSI/AISC 360-16.*[20]

Obciążenia dopuszczalne konstrukcji

Granice obciążeń dopuszczalnych konstrukcji mocującej żuraw stoczniowy do pokładu pontonu TRD Voyager

Materiał: Stal 235 MPa

Granica plastyczności σyield = 23.5 kN/cm^2

Granica wytrzymałości fu = 41.0 kN/cm^2

- rozciąganie: σ_t ≤0.60 *σyield 14.10 kN/cm^2
- ścinanie: σ_S ≤ 0.40 *σyield 9.40 kN/cm^2
- ściskanie: σ_c ≤0.60 *σyield 14.10 kN/cm^2
- zginanie: σ_b ≤ 0.66 *σyield 15.51 kN/cm^2
- naprężenie stykowe: σ_{be} ≤ 0.90 *σyield 21.15 kN/cm^2
- naprężenia von Mises: σ_{vM} ≤ 0.75 *σyield17.62 kN/cm^2
- naprężenie w otworze: σ_{tPH} ≤ 0.45 *σyield 10.58 kN/cm^2
- spoiny σ_W ≤ 0.30 *fu 12.3 kN/cm^2
- Hertz σ_W ≤ 2.5·σyield 58.75 kN/cm^2

Współczynnik Poissona: v = 0.3

Współczynnik Younga – stal: E = 20000 kN/cm^2

Parametry projektowe systemu mocowania

System zamocowania żurawia do pokładu pontonu został przegotowany w dokumencie: *CRANE EBERSWALDE Q=20 T ON PONTOON TRD-VOYAGER SEA-FASTENING PLAN_2022_08_23*.

W celu weryfikacji wytrzymałości projektowanego systemu mocowania przeprowadzono analizę wytrzymałości jego poszczególnych elementów dla założonego obciążenia roboczego 60 t.

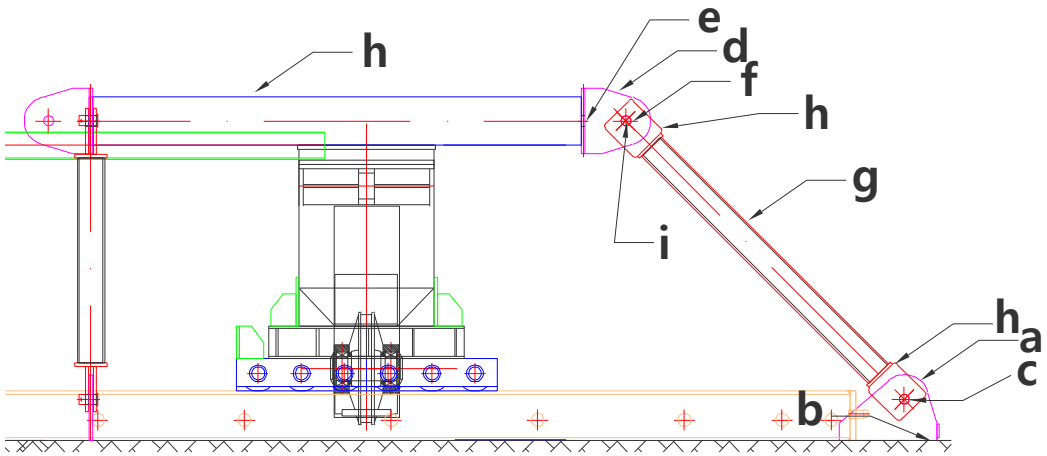
[20] Specification for Structual Steel Buildings Norm –Specyfikacja dla Stalowych Konstrukcji Budowlanych Norma z 7 lipca 2016 r. wydana przez Amerykański Instytut Konstrukcji Stalowych zatwierdzony przez American National Standards Institute- instytucja ustalająca normy techniczne w USA)

W przypadkach przekroczenia obciążenia dopuszczalnego określone zostały wartości maksymalnych bezpiecznych obciążeń roboczych dla każdego elementu systemu mocowania.

W obliczeniach wytrzymałości mocowań nie brano pod uwagę dodatkowych odkształceń sprężystych żurawia w czasie kołysania na pontonie.

Elementy składowe głównego systemu mocowania:

11. Płyta mocująca dolna (a)
12. Spoina dolnej płyty mocującej (b)
13. Oko w dolnej płycie mocującej (c)
14. Górna płyta mocująca (d)
15. Spoina górnej płyty mocującej (e)
16. Oko w górnej płycie mocującej (f)
17. Rura (g)
18. Płyty policzkowe w rurze (h)
19. Oko w płytach policzkowych (i)
20. Belka montażowa systemu mocowania (j)



Rys. Konstrukcja systemu mocowania

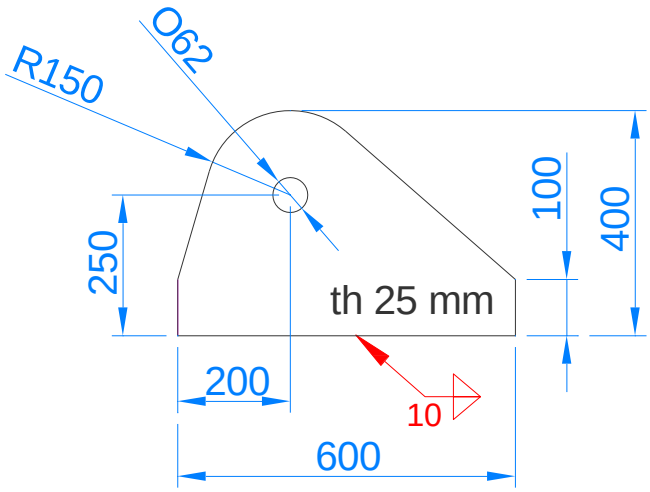
Parametry projektowe mocowania głównego:

Projektowane obciążenie robocze	MSL = 60 t, F = 588.6 kN
Współczynnik obciążenia dynamicznego	DLF = 1.12
Projektowe obciążenie dynamiczne:	Fd=F·DLF = 659.2 kN
Pionowy kąt pracy mocowania:	α =45°
Poziomy kąt mocowania:	β = 0.5°
Średnica trzpienia:	∅ 60 mm

Średnica otworu: ∅ 62 mm

Wytrzymałość dolnej płyty mocującej

Dolna płyta mocująca głównego systemu mocowania była spawana po poszycia pontonu spoiną o grubości deklarowanej 10 mm.



Rys. Dolna płyta mocująca

Parametry dolnej płyty mocującej:

Grubość płyty	a = 2.5 cm
Powierzchnia przekroju płyty	A = 150 cm^2
Wskaźnik przekroju oś poprzeczna:	Wx = 1500 cm^3
Wskaźnik przekroju oś wzdłużna:	Wy = 62.5 cm^3
Siła wzdłużna:	$F_x = F \cdot \cos(\alpha) \cdot cos(\beta)$= 416.2 kN
Siła poprzeczna:	$F_y = F \cdot \cos(\alpha) \cdot sin(\beta)$= 3.63 kN
Siła pionowa:	$F_z = F \cdot sin(\alpha)$= 416.2 kN
Średnica trzpienia:	DP = 6.0 cm
Średnica otworu:	DH = 6.2 cm
Wysokość środka otworu ponad podstawą:	h = 25 cm
Wzdłużny moment gnący:	$BM_x = F_x \cdot h$ = 416.2·25= 10405.0 kN·cm
Poprzeczny moment gnący:	$BM_y = F_y \cdot h$ = 3.63·25 = 90.8 kN·cm

Tab. Naprężenia w dolnej płycie mocującej

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Rozciąganie	$\sigma_t = \frac{F_z}{A}$	2.77	14.10	OK
2	Ścinanie x	$\tau_{sx} = \frac{F_x}{A}$	2.77	9.40	OK
3	Ścinanie y	$\tau_{sy} = \frac{F_y}{A}$	0.02	9.40	OK
4	Zginanie-x	$\sigma_{Bx} = \frac{BM_x}{W_x}$	6.94	15.51	OK
5	Zginanie-y	$\sigma_{By} = \frac{BM_y}{W_y}$	1.45	15.51	OK
6	Von Mises		12.15	17.62	OK
	$\sqrt{(\sigma_t + \sigma_{Bx} + \sigma_{By})^2 + 3 \cdot (\sigma_{sx}^2 + \sigma_{sy}^2)}$				
7	Obciążenia złożone	$\frac{\sigma_t}{\sigma_{MAX}} + \frac{\sigma_{Bx}}{\sigma_{MAX}} + \frac{\sigma_{By}}{\sigma_{MAX}}$	0.74	1.00	OK

Dolna płyta mocująca spełnia wymagania wytrzymałości przy obciążeniu siłą 60 t.

Wytrzymałość spoiny dolnej płyty mocującej

Wymiar spoiny a = 1.0 cm

Długość spoiny l = 125 cm

Powierzchnia spoiny A_W = 125 cm^2

Wskaźnik przekroju oś poprzeczna: W_x = 1333 cm^3

Wskaźnik przekroju oś wzdłużna: W_y = 143 cm^3

Tab. 1.2. Naprężenia w spoinie mocującej

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Rozciąganie	$\sigma_t = \frac{F_z}{A_W}$	3.32	14.10	OK
2	Ścinanie x	$\tau_{sx} = \frac{F_x}{A_W}$	3.32	9.40	OK
3	Ścinanie y	$\tau_{sy} = \frac{F_y}{A_W}$	0.03	9.40	OK
4	Zginanie-x	$\sigma_{Bx} = \frac{BM_x}{W_x}$	7.81	15.51	OK
5	Zginanie-y	$\sigma_{By} = \frac{BM_y}{W_y}$	0.63	15.51	OK
6	Von Mises $\sqrt{(\sigma_t + \sigma_{Bx} + \sigma_{By})^2 + 3 \cdot (\tau_{sx}^2 + \tau_{sy}^2)}$		13.09	17.62	OK
7	Obciążenia złożone	$\frac{\sigma_t}{\sigma_{MAX}} + \frac{\sigma_{Bx}}{\sigma_{MAX}} + \frac{\sigma_{By}}{\sigma_{MAX}}$	0.78	1.00	OK

Spoina dolnej płyty mocującej spełnia wymagania wytrzymałości przy obciążeniu siłą 60 t.

Wytrzymałość otworu w płycie dolnej

Dynamiczne obciążenie robocze: Fd = 659.2 kN

Średnica trzpienia D_P = 6.0 cm

Średnica otworu: D_H = 6.2 cm

Grubość płyty: t = 2.5 cm

Powierzchnia styku z trzpieniem: $A_{BE} = \frac{\pi}{4} \cdot D_P \cdot t = 11.78$ cm^2

Powierzchnia ścinania: $A_{SPF} = 2 \cdot A_{SP}$ = 60 cm^2

Powierzchnia przekroju nad otworem: A_{SP} =30 cm^2

Powierzchnia przekroju A-A: $A_{A\text{-}A}$ = 82.2 cm^2

Tab.1.3. Naprężenia w otworze dolnej płyty mocującej

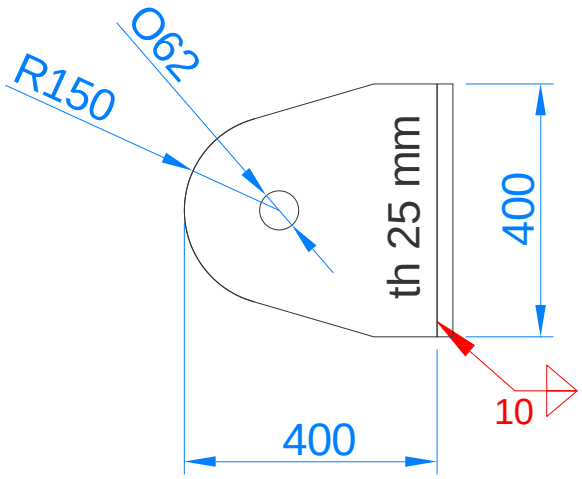
Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium	34 % MSL 200 kN
1	Naprężenie stykowe	$\sigma_{BE} = \frac{Fd}{A_{BE}}$	55.96	21.50	**Not OK**	19.03
2	Ścinanie	$\tau_{sp} = \frac{Fd}{A_{SPF}}$	11.00	9.40	**Not OK**	3.74
3	Rozciąganie A-A	$\sigma_{tAA} = \frac{Fd}{A_{AA}}$	8.02	10.58	OK	2.73
4	Hertz		99.59	58.75	**Not OK**	58.07
	$\sigma_H = \sqrt{\frac{Fd \cdot E \cdot (D_H - D_P)}{\pi \cdot (1 - v^2) \cdot t \cdot D_H \cdot D_P}}$					
	W ostatniej kolumnie powyższej tabeli przedstawiono dla maksymalne MSL, dla którego element mocowania spełnia wymagania wytrzymałości					

Naprężenia w otworze dolnej płyty przekraczają dopuszczalne naprężenia robocze (260%). Na zdjęciu poniżej pokazano zdeformowanie oka płyty i plastyczne odkształcenie płyty. Dopuszczalne obciążenie (MSL) oka płyty nie powinno przekraczać 200 kN.

Wytrzymałość górnej płyty mocującej

Górna płyta mocująca jest elementem poziomej belki przymocowanej do podwozia żurawia. Wymiary górnej płyty mocującej określono na podstawie dokumentacji zdjęciowej wykonanej podczas instalacji mocowania na pontonie. Wymiary płyty (400×300×25 mm).

W planie mocowania (LST.SRM.EBE_R01_2022.08.23) płyta górna posiada inne wymiary niż podane w specyfikacji (300×300×25 mm).



Rys. Górna płyta mocująca

Parametry górnej płyty mocującej:

Grubość płyty	a = 2.5 cm
Powierzchnia przekroju płyty	A = 100 cm^2
Wskaźnik przekroju oś poprzeczna:	W_z = 666.7 cm^3
Wskaźnik przekroju oś pionowa:	W_y = 41.7 cm^3
Odległość środka otworu od podstawy:	h = 25 cm
Kąt pionowy mocowania:	α = 45°
Kąt poziomy mocowania:	β = 0.5°
Siła wzdłużna:	$F_x = F \cdot \cos(\alpha) \cdot cos(\beta)$= 416.2 kN
Siła poprzeczna:	$F_y = F \cdot \cos(\alpha) \cdot sin(\beta)$= 3.63 kN
Siła pionowa:	$F_z = F \cdot sin(\alpha)$= 416.2 kN
Pionowy moment gnący:	$BM_z = F_z \cdot h$ = 416.2·25= 10405.0 kN·cm
Poprzeczny moment gnący:	$BM_y = F_y \cdot h$ = 3.63·25 = 90.75 kN·cm`

Tab. Naprężenia w górnej płycie mocującej

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium	69% MSL 400 kN
1	Rozciąganie	$\sigma_t = \frac{F_x}{A}$	4.16	14.10	OK	2.87
2	Ścinanie – z	$\tau_{sx} = \frac{F_z}{A}$	4.16	9.40	OK	2.87
3	Ścinanie – y	$\tau_{sy} = \frac{F_y}{A}$	0.09	9.40	OK	0.06
4	Zginanie- z	$\sigma_{Bz} = \frac{BM_z}{W_z}$	15.61	15.51	Not OK	10.77
5	Zginanie – y	$\sigma_{By} = \frac{BM_y}{W_y}$	2.18	15.51	OK	1.50
6	Von Mises	*	23.10	17.62	**Not OK**	15.94
7	Obciążenia złożone	**	1.44	1.00	**Not OK**	0.99

*) $\sqrt{\left(\sigma_t + \sigma_{Bz} + \sigma_{By}\right)^2 + 3 \cdot \left(\sigma_{sz}^2 + \sigma_{sy}^2\right)}$

**) $\frac{\sigma_t}{\sigma_{MAX}} + \frac{\sigma_{Bz}}{\sigma_{MAX}} + \frac{\sigma_{By}}{\sigma_{MAX}}$

W ostatniej kolumnie powyższej tabeli przedstawiono dla maksymalne MSL, dla którego element mocowania spełnia wymagania wytrzymałości

Naprężenia w górnej płycie mocującej przekraczają obciążenia dopuszczalne naprężenia robocze (144%). Dopuszczalne obciążenie (MSL) płyty nie powinno przekraczać 400 kN.

Wytrzymałość spoiny górnej płyty mocującej

Grubość spoiny	a = 1.0 cm
Długość spoiny	l = 80 cm
Powierzchnia przekroju	A_W = 80 cm^2
Wskaźnik przekroju oś poprzeczna:	W_z = 533.3 cm^3
Wskaźnik przekroju oś pionowa:	W_y = 58.5 cm^3

Odległość środka otworu od podstawy:	h = 25 cm
Kąt pionowy mocowania:	α = 45°
Kąt poziomy mocowania:	β = 0.5°
Siła wzdłużna:	$F_x = F \cdot \cos(\alpha) \cdot cos(\beta)$= 416.2 kN
Siła poprzeczna:	$F_y = F \cdot \cos(\alpha) \cdot sin(\beta)$= 3.63 kN
Siła pionowa:	$F_z = F \cdot sin(\alpha)$= 416.2 kN
Pionowy moment gnący:	$BM_z = F_z \cdot h$ = 416.2·25= 10405.0 kN·cm
Poprzeczny moment gnący:	$BM_y = F_y \cdot h$ = 3.63·25 = 90.75 kN·cm`

Tab. Naprężenia w spoinie

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm²]	Wartość wymagana [kN/cm²]	Kryterium	57% MSL 335kN
1	Rozciąganie	$\sigma_t = \frac{F_x}{A_W}$	5.20	14.10	OK	2.96
2	Ścinanie – z	$\tau_{sz} = \frac{F_z}{A_W}$	5.20	9.40	OK	2.96
3	Ścinanie – y	$\tau_{sy} = \frac{F_y}{A_W}$	0.05	9.40	OK	0.03
4	Zginanie- z	$\sigma_{Bz} = \frac{BM_z}{W_z}$	19.51	15.51	Not OK	11.12
5	Zginanie – y	$\sigma_{By} = \frac{BM_y}{W_y}$	1.55	15.51	OK	0.88
6	Von Mises	*	27.76	17.62	Not OK	17.46
7	Obciążenia złożone	**	1.73	1.00	Not OK	0.98

*) $\sqrt{(\sigma_t + \sigma_{Bz} + \sigma_{By})^2 + 3 \cdot (\tau_{sz}^2 + \tau_{sy}^2)}$

**) $\frac{\sigma_t}{\sigma_{MAX}} + \frac{\sigma_{Bz}}{\sigma_{MAX}} + \frac{\sigma_{By}}{\sigma_{MAX}}$

W ostatniej kolumnie powyższej tabeli przedstawiono dla maksymalne MSL, dla którego element mocowania spełnia wymagania wytrzymałości

Naprężenia w spoinie górnej płycie mocującej przekraczają obciążenia dopuszczalne naprężenia robocze (158%).

Dopuszczalne obciążenie (MSL) spoiny nie powinno przekraczać 335 kN.

Wytrzymałość otworu w górnej płycie mocującej

Dynamiczne obciążenie robocze: Fd = 659.2 kN

Średnica trzpienia $D_P = 6.0$ cm

Średnica otworu: $D_H = 6.2$ cm

Grubość płyty: t = 2.5 cm

Powierzchnia styku z trzpieniem $A_{BE} = \frac{\pi}{4} \cdot D_P \cdot t = 11.78$ cm^2

Powierzchni ścinania: $A_{SPF} = 2 \cdot A_{SP} = 60$ cm^2

Powierzchni przekroju nad otworem: $A_{SP} = 30.0$ cm^2

Powierzchni przekroju A-A: $A_{A\text{-}A} = 62.5$ cm^2

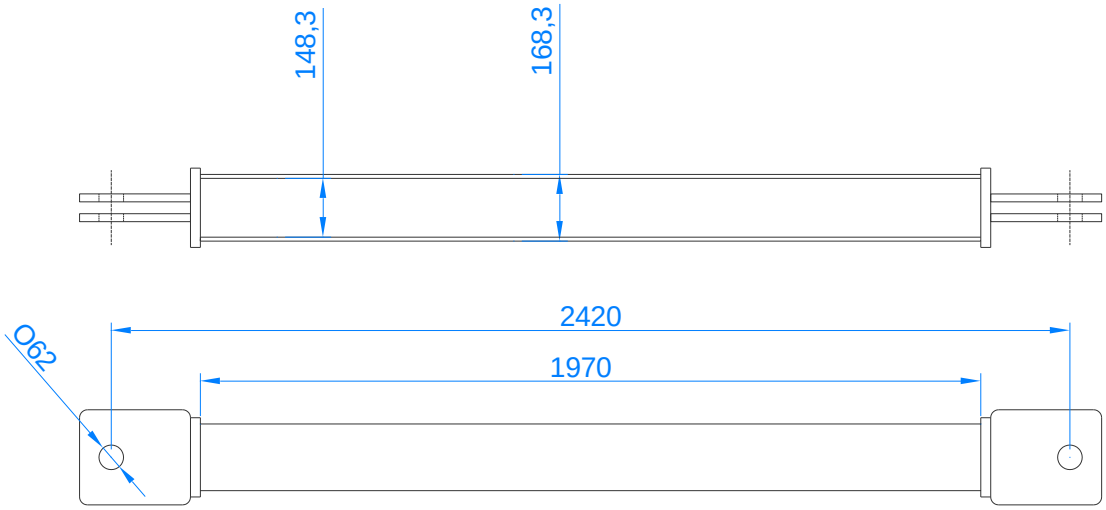
Tab. Naprężenia w oku płyty

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium	33% MSL 200 kN
1	Naprężenie stykowe	$\sigma_{BE} = \frac{Fd}{A_{BE}}$	55.96	21.50	**Not OK**	18.47
2	Ścinanie	$\sigma_{sp} = \frac{Fd}{A_{SPF}}$	10.99	9.40	**Not OK**	3.63
3	Rozciąganie A-A	$\sigma_{tAA} = \frac{Fd}{A_{AA}}$	10.55	10.58	**OK**	3.48
4	Hertz	*	99.59	58.75	**Not OK**	57.53
	*) $\sigma_H = \sqrt{\frac{Fd \cdot E \cdot (D_H - D_P)}{\pi \cdot (1-\nu^2) \cdot t \cdot D_H \cdot D_P}}$					
	W ostatniej kolumnie powyższej tabeli przedstawiono dla maksymalne MSL, dla którego element mocowania spełnia wymagania wytrzymałości					

Naprężenia w otworze dolnej płyty przekraczają dopuszczalne naprężenia robocze (260%).

Dopuszczalne obciążenie (MSL) oka płyty nie powinno przekraczać 200 kN.

Wytrzymałość rury mocującej



Rys. Rura mocująca

Parametry rury mocującej:

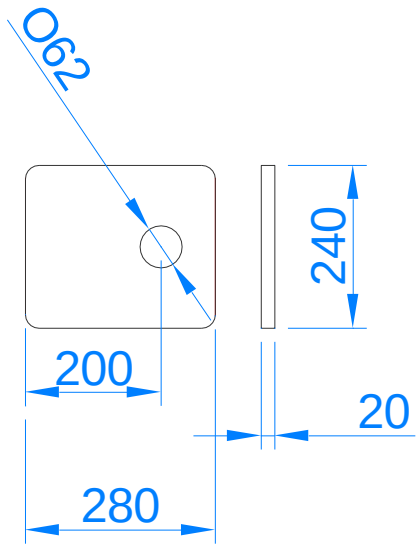
Średnica rury	D = 16.83 cm
Powierzchnia przekroju	A = 49.73 cm
Poprzeczny wskaźnik przekroju:	W_y = 185.9 cm^3
Siła wzdłużna:	$F_x = F \cdot \cos(\alpha) \cdot cos(\beta)$= 416.2 kN
Siła poprzeczna:	$F_y = F \cdot \cos(\alpha) \cdot sin(\beta)$= 3.63 kN
Siła pionowa:	$F_z = F \cdot sin(\alpha)$= 416.2 kN
Poprzeczny moment gnący:	$BM_y = F_y \cdot l = 3.63 \cdot 242 = 878.5$ kN·cm`

Tab. Obciążenia w rurze.

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Rozciąganie	$\sigma_t = \frac{F}{A}$	11.84	14.10	**OK**
2	Zginanie – y	$\sigma_{By} = \frac{BM_y}{W_y}$	4.72	15.51	**OK**
3	Von Mises	$\sqrt{(\sigma_t + \sigma_{By})^2}$	16.56	17.62	**OK**

Użyta rura spełniała wymagania wytrzymałości dla założonych obciążeń.

Wytrzymałość płyt policzkowych rury



Rys. Płyty policzkowe

Parametry płyt policzkowych:

Kąt odchylenia poprzecznego policzków 0.5°

Powierzchni przekroju: $A = 40\ cm^2$

Poprzeczny wskaźnik przekroju: $W_y = 150.48\ cm^3$

Siła poprzeczna: Fy =31.4 kN

Poprzeczny moment gnący: $BM_y = F_y \cdot = 31.4 \cdot 20 = 628\ kN \cdot cm$

Tab. Naprężenia w płytach policzkowych rury.

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm²]	Wartość wymagana [kN/cm²]	Kryterium
1	Rozciąganie	$\tau_t = \frac{F}{2A}$	7.36	14.10	OK
2	ścinanie	$\tau_s = \frac{Fy}{A}$	0.78	9.40	OK
3	Zginanie -y	$\sigma_{By} = \frac{BM_y}{W_y}$	4.17	15.51	OK
4	Von Mises	$\sqrt{(\tau_t + \sigma_{By})^2 + 3 \cdot \tau^2}$	11.61	17.62	OK

Wytrzymałość płyt policzkowych ze względu na siły działające w mocowaniu była spełniona przy poziomym kącie pracy do 0.5°.

W czasie rejsu kąty odchylenia pracy odciągu przekraczały znacznie dopuszczalne obciążenie, co powodowało wyginanie płyt policzkowych.

Wytrzymałość otworów w płytach policzkowych rury

Dynamiczne obciążenie robocze: Fd = 659.2 kN/2 = 329.6 kN

Średnica trzpienia: D_P = 6.0 cm

Średnica otworu: D_H = 6.2 cm

Grubość płyty: t = 2.0 cm

Powierzchnia styku z trzpieniem: $A_{BE} = \frac{\pi}{4} \cdot D_P \cdot t = 9.42$ cm^2

Powierzchni ścinania: $A_{SPF} = 2 \cdot A_{SP}$ = 19.6 cm^2

Powierzchni przekroju nad otworem: A_{SP} = 9.8 cm^2

Powierzchni przekroju A-A: $A_{A\text{-}A}$ = 35.6 cm^2

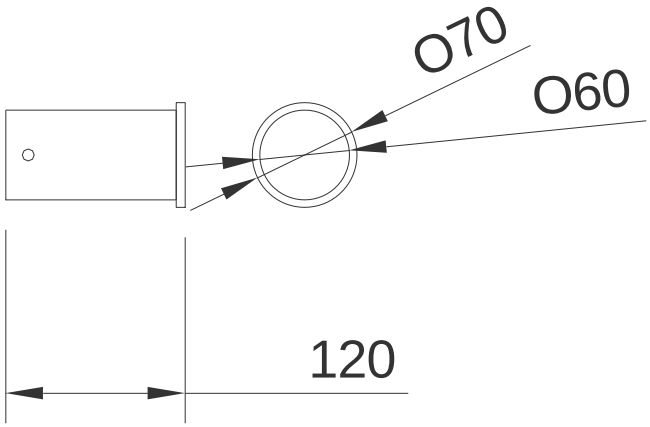
Tab. Naprężenia w otworze mocującym trzpienia

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium	55% MSL 323kN
1	Naprężenia stykowe	$\sigma_{BE} = \frac{Fd}{A_{BE}}$	34.99	21.50	**Not OK**	20.99
2	Ścinanie	$\tau_{sp} = \frac{Fd}{A_{SPF}}$	16.82	9.40	**Not OK**	10.09
3	Rozciąganie A-A	$\sigma_{tAA} = \frac{Fd}{A_{AA}}$	9.26	10.58	OK	2.73
4	Hertz		78.73	58.75	**Not OK**	58.39
	$\sigma_H = \sqrt{\frac{Fd \cdot E \cdot (D_H - D_P)}{\pi \cdot (1 - v^2) \cdot t \cdot D_H \cdot D_P}}$					
W ostatniej kolumnie powyższej tabeli przedstawiono dla maksymalne MSL, dla którego element mocowania spełnia wymagania wytrzymałości						

Naprężenia w otworze płyt policzkowych rury przekraczają dopuszczalne naprężenia robocze (179%). Dopuszczalne obciążenie (MSL) oka płyty nie powinno przekraczać 323 kN.

Wytrzymałość trzpienia i zawleczki trzpienia

W systemie mocowania przewidziano 16 trzpieni mocujących cześc rurową z płytami dolnymi i górnymi.



Rys. Trzpień mocujący

Materiał:	Stal S355
Średnica trzpienia:	∅ 60 mm.
Powierzchnia przekroju:	A = 28.27 cm^2
Siła ścinająca:	F = 588.6 kN
Naprężenie ścinające:	τ = 10.41 kN/cm^2 < naprężenie dopuszczalne 13.8 kN/cm^2

Trzpień wytrzymuje obciążenia dla MSL mocowania 60 t

Trzpień był zabezpieczony przed wysunięciem za pomocą zawleczki giętej ze stali.

Wytrzymałość zawleczki została sprawdzona przy założeniu kata odchylenia poprzecznego 0.5°.

Średnica:	d = 0.5 cm
Powierzchnia przekroju:	A = 0.20 cm^2
Poprzeczny moment gnący:	$BM_y = F_y \cdot l = 3.63 \cdot 242 = 878.5$ kN·cm
Shearing force:	Fy =31.4 kN

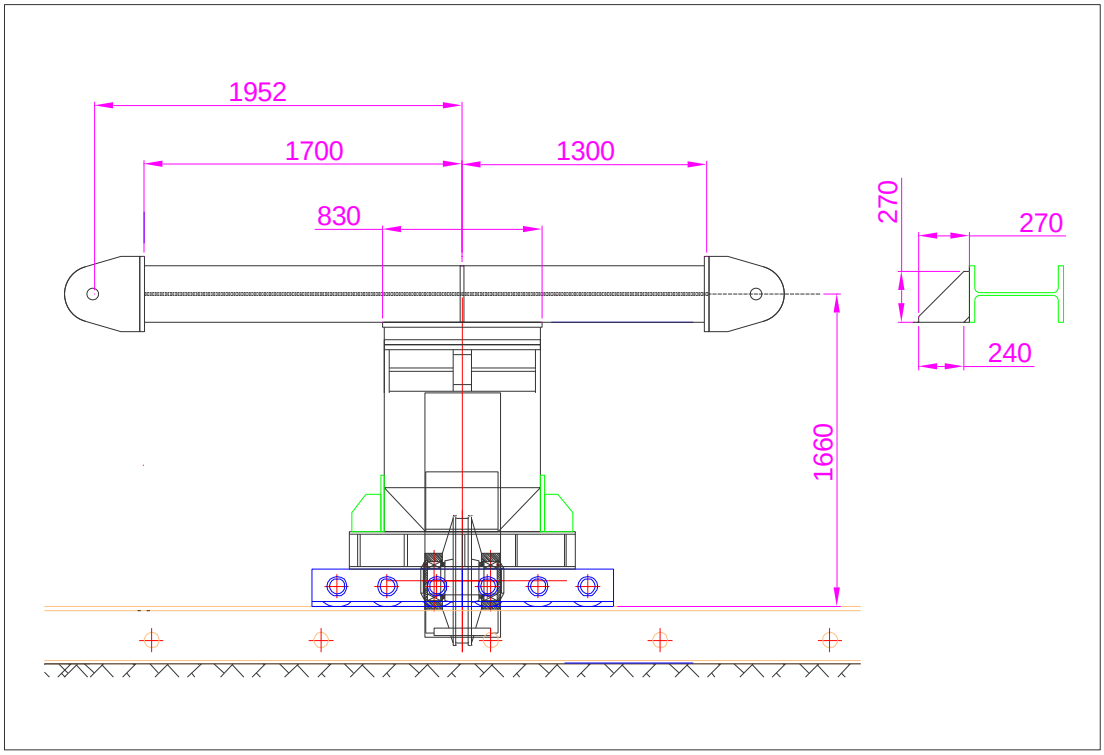
$$\sigma_{sp} = \frac{Fy}{A_{SPF}} = \frac{31.4}{0.20} = 157\ kN/cm^{\,2}$$

Dziesięciokrotne przekroczenie wartości dopuszczalne siły tnącej oznacza, że zawleczka nie mogła zablokować rozchylania się policzków mocowania rurowego. Zawleczka mogła być ścięta lub wciągnięta do środka otworu jeśli otwór był powiększony.

Po przeprowadzonej analizie głównego systemu mocowania określono bezpieczne obciążenie robocze systemu na 200 kN

Wytrzymałość belki mocującej

W głównym systemie mocowania żurawia użyte były cztery belki mocujące jego podwozie.

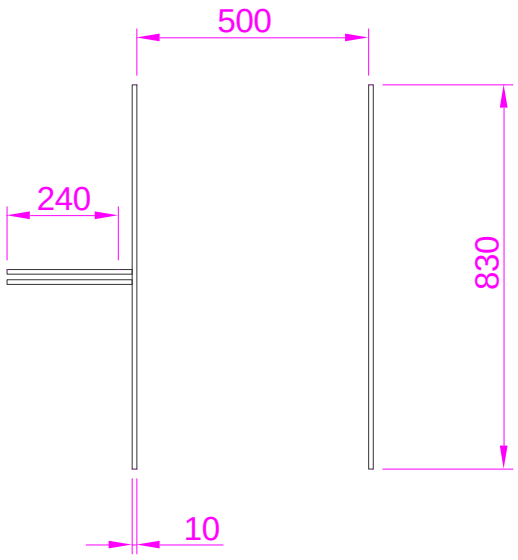


Rys. Poprzeczne belki mocujące

Belka poprzeczna mocująca podwozie żurawia została zespolona z podwoziem żurawia za pomocą spoiny o deklarowanym wymiarze 10 mm.

Do belek mocujących dołożono węzłówki trójkątne (Oznaczenie SL 2 na rysunku mocowania) o wymiarach: 300×300×12 mm.

Tab. Parametry wytrzymałości spoiny belki mocującej

Wymiary		
Grubość spoiny	a	10 mm
Długość spoiny ciągłej	l	214 cm
Powierzchnia spoiny	A_W	214 cm^2
Wzdłużny wskaźnik przekroju spoiny	Wl	5015 cm^3
Poprzeczny wskaźnik przekroju spoiny	Wt	2296 cm^3
Wskaźnik przekroju na skręcanie	WO	4980 cm^3
Wzdłużny wskaźnik przekroju całej konstrukcji mocującej	WL	464270 cm^3
Poprzeczny przekroju całej konstrukcji mocującej	WT	226709 cm^3

Projektowe siły i momenty działające na spoinę łączącą belkę z podwoziem żurawia zostały obliczone dla obciążenia projektowego 60 t.

Siła całkowita przenoszona przez cały system mocowania MSL = 60 t w każdym z kierunków:

- Siła wzdłużna: 1664.8 kN
- Siła poprzeczna: 1664.8 kN
- Siła pionowa: 3329.6 kN

Momenty gnące działające na 1 belkę:

- Wzdłużny: 62.43 kNm
- Poprzeczny: 62.43 kNm
- Moment skręcający belkę: MT = 707.55 kNm

Tab. Weryfikacja wytrzymałości spoiny belki mocującej dla obciążenia projektowego 60 t

Nr.	Parametr wytrzymałości	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Ściskanie	$\sigma_t = \frac{2 \times F_V}{A}$	3.33	14.10	OK
2	Ścinanie wzdłużne	$\tau_{sx} = \frac{F_L}{A}$	1.94	9.40	OK
3	Ścinanie poprzeczne	$\tau_{sy} = \frac{F_T}{A}$	1.94	9.40	OK
4	Skręcanie	$\tau_{St} = \frac{M_T}{W_O}$	14.20	9.40	Not OK
5	Zginanie wzdłużne	$\sigma_{Bx} = \frac{BM_x}{W_x}$	1.24	15.51	OK
6	Zginanie poprzeczne	$\sigma_{By} = \frac{BM_y}{W_y}$	2.72	15.51	OK
7	Von Mises		26.09	17.62	**Not OK**
	$\sqrt{(\sigma_t + \sigma_{Bx} + \sigma_{By})^2 + 3 \cdot (\tau_{sx}^2 + \tau_{sy}^2 + \tau_{st}^2)}$		148%		

Spoina mocująca nie spełnia wymagań wytrzymałości dla obciążenia projektowego (148%) .

Mocowanie żurawia zgodnie według zaleceń DNV-ST-N001

Przyspieszenia

Parametry ruchów pontonu w podróży z Gdyni do Szczecina oparte o przypadek 6 (Case 6) zaleceń *DNV-ST-N001, 2021, Table 11-1 Default motion criteria (ASD/WSD approach)*:

- Rodzaj podróży: nieograniczona czasowo (34.5 godz.)
- Długość pontonu mniejsza od 76 m (L = 60.0 m)
- Szerokość pontonu mniejsza od 23.0 m (B = 20.0 m)
- Stosunek L/B większy od 2.50 (3.00)
- Współczynnik pełnotliwości kadłuba CB > 0.90 (0.92)
- Okres kołysań wzdłużnych i poprzecznych 10s
- Amplituda kołysań wzdłużnych i poprzecznych 25°

- Nurzanie z przyspieszeniem 0.2 g
- Wiatr: 14.3 m/s
- Wysokość metacentryczna: GM' = 21.433 m
- Współczynnik tarcia: $\mu_F = 0.1$

Przyspieszenia obliczono wg. Przepisów DNV dla założonych powyżej parametrów ładunku. Przyspieszenia i siły nie zawierają komponentu oddziaływania fal na przewożony ładunek. Komponent sił związany z wiatrem jest przewymiarowany. W rzeczywistości siła działania wiatru jest mniejsza.

Otrzymane wyniki przyspieszeń są takie porównywalne jak przedstawiono w Raporcie LST.SRM.EBE_R01_2022.08.23.

W obliczeniach sił i momentów przyjęto współczynnik niepewności masy ładunku 1.06. Masa ładunku przyjęta do obliczeń 254.4 t (2495.7 kN)

Do analizy przyjęto, że ładunek jest zabezpieczany tylko przez system mocowania (8 szt.).

Pionowy kąt pracy mocowania $\alpha = 45°$.

Siły zabezpieczające ładunek określono dla obciążenia roboczego mocowania MSL 60 t (według Raportu LST.SRM.EBE_R01_2022.08.23).

W obliczeniach nie uwzględniono dodatkowych stoperów spawanych pomiędzy konstrukcją podwozia żurawia a pokładem pontonu ze względu na brak informacji o długości i grubości spoin, jak również niepewności, co do ich jakości.

Tab. Przyspieszenia działające na ładunek

Przyspieszenia całkowite (ruch pontonu i działanie wiatru)			
Kierunek	**Oznaczenie**	**Wartość**	
		g	m/s²
Wzdłużne	a_l	0.506	4.964
Poprzeczne	a_t	0.832	8.162
Pionowe maksymalne	a_{vmax}	1.238	12.145
Pionowe minimalne	a_{vmin}	0.694	6.808

Wytrzymałość systemu mocowania

- Wartości sił przesuwających i momentów przewracających wykonano w oparciu o metody zawarte w CSS Code Anex 13 (MSC.1/Circ.1623).
- Wartości sił zabezpieczających i momentów zapobiegających przewracaniu wykonano w oparciu o metody zawarte w CSS Code Anex 13 (MSC.1/Circ.1623).
- Współczynnik bezpieczeństwa przyjęto SF = 1.35.
- Obliczenia stopnia zabezpieczenia ładunku wykonano dla projektowanego MSL mocowań 60 t (LC = 436.0 kN) i uzyskanego z analizy wytrzymałości mocowania MSL = 20 t (LC = 145.3 kN).
- Wartości sił i momentów są wyliczone dla całego systemu mocowania.
- W obliczeniach uwzględniono działanie wiatru, nie uwzględniono oddziaływania wody na pokładzie.

Ładunki wielkogabarytowe wytwarzają dodatkowy moment wywracający przez ich bezwładność obrotową w stosunku do przyspieszenia obrotowego statku w kołysaniach poprzecznych lub wzdłużnych. Dodatkowy moment przewracający jest niezależny od miejsca umieszczenia ładunku na statku i zawsze dodatni, czyli intensyfikujący moment przeradzający. Zjawisko to wymaga dodatkowych środków zabezpieczających i dlatego powinno być uwzględnione w analizie przewracania wielkogabarytowych jednostek ładunkowych (MSC.1/Circ.1623).

<u>Dodatkowy poprzeczny moment bezwładności masy</u>

Dla ładunku o szerokości (w) i wysokości (h), gdzie ($w^2 + h^2$) > 50 m^2, do zwykłego momentu przewracającego Fy · a należy dodać dodatkowy moment wywracający k · J wynikający z bezwładności obrotowej ładunku.

Wartość masowego momentu bezwładności została określona z zależności:

$$J = m \cdot \left(\frac{w^2 + h^2}{12}\right) \; [tm^2]$$

gdzie:

k – zwrotne przyspieszenie kątowe: $k = \frac{36 \cdot GM}{B^2} \left[\frac{1}{s^2}\right]$,

B – szerokość jednostki, [m],

GM – wysokość metacentryczna, [m].

Dodatkowy wzdłużny moment bezwładności masy

Dla ładunku o długości (l) oraz wysokości (h), gdzie ($l^2 + h^2$) > 50 m^2, do zwykłego momentu przewracającego Fx·a należy dodać dodatkowy moment wywracający k · J wynikający z bezwładności obrotowej ładunkowego.

Wartość masowego momentu bezwładności została określona z zależności:

$$J = m \cdot \left(\frac{l^2 + h^2}{12}\right) [tm^2]$$

gdzie:

k – zwrotne przyspieszenie kątowe: $k = \frac{25}{L} \left[\frac{1}{s^2}\right]$

L – długość jednostki, [m].

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie (MSL 60 t)

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła działająca na ładunek	FSL	1262.8	FST	2076.34
Siła zabezpieczająca od mocowań i tarcia	FLS	1418.2	FTS	1418.2
Stopień zabezpieczenia		112%		68%
Kryterium	**Zabezpieczenie skuteczne**		**Zabezpieczenie nieskuteczne**	

Tab.Momenty działające na ładunek i momenty przeciwdziałające przewracaniu (MSL 60 t)

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Moment przewracający	M_{TLF}	17300.4	MTTF	28446.6
Moment przewracający bezwładności	M_{TLI}	85338,5	M_{TTI}	92412,2
Całkowity moment przewracający	M_{TL}	**102638,9**	M_{TT}	**120858,8**
Moment przeciwdziałający przewracaniu	MTLS	29388.3	MTTS	14774.2
Stopień zabezpieczenia		29%		12%
Kryterium	**Zabezpieczenie nieskuteczne**		**Zabezpieczenie nieskuteczne**	

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie (MSL 20 t)

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła działająca na ładunek	FSL	1262.8	FST	2076.34
Siła zabezpieczająca od mocowań i tarcia	FLS	472.7	FTS	472.7
Stopień zabezpieczenia		38%		23%
Kryterium	**Zabezpieczenie nieskuteczne**		**Zabezpieczenie nieskuteczne**	

Tab. Momenty działające na ładunek i momenty przeciwdziałające przewracaniu (MSL 20 t)

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Moment przewracający [kNm]	M_{TLF}	17300.4	MTTF	28446.6
Moment przewracający bezwładności [kNm]	M_{TLI}	85338,5	M_{TTI}	92412,2
Całkowity moment przewracający [kNm]	M_{TL}	**102638,9**	M_{TT}	**120858,8**
Moment przeciwdziałający przewracaniu	MTLS	18456.1	MTTS	8388.7
Stopień zabezpieczenia		18%		7%
Kryterium	**Zabezpieczenie nieskuteczne**		**Zabezpieczenie nieskuteczne**	

Momenty przewracające uwzględniające moment bezwładności masy zostały obliczone według zaleceń rezolucji MSC.1/Circ.1623 Amendments to the Code of Safe Practice for Cargo Stwage and Securing (CSS Code)[21]. Efektywną wysokość ładunku przyjęto 46,8 m (wysokość konstrukcji żurawia w czasie transportu)

Wytrzymałość mocowania dla rzeczywistych warunków pogodowych

Ocenę wytrzymałości przeprowadzono dla warunków pogodowych panujących na akwenie rejsu. Dane uzyskano z Dziennika Okrętowego holownika Odys oraz prognoz pogodowych na dzień rejsu. Analizę wytrzymałości mocowania żurawia na pontonie przeprowadzono dla dwóch przypadków kołysań poprzecznych i wzdłużnych pontonu oraz dwóch wysokości fal. Wartości okresów kołysania wzdłużnego i poprzecznego zostały określone na podstawie przepisów: DNV-RU-SHIP Pt.3 Ch.4 (2022).

Stan I został określony dla maksymalnych parametrów kołysania pontonu i wielkości fali. Stan II został określony dla minimalnych parametrów kołysania pontonu i wielkości fali. Okres

[21] MSC.1/*Circ.*1623 Amendments to the Code of Safe Practice for Cargo Stowage and Securing (CSS Code) Załącznik do Kodeksu Bezpiecznych Praktyk Sztauowania i Mocowania Ładunków (Kodeks CSS) – określa międzynarodowy standard prawidłowego sztauowania i zabezpieczenia ładunków w celu promowania bezpieczeństwa na morzu, jak i podczas załadunku i rozładunku.

kołysania poprzecznego dla pontonu został przyjęty w stanie II, jako równoważny okresowi fali o długości 60 m na Bałtyku Południowym.

Kąty kołysania wzdłużnego i poprzecznego określono na podstawie wysokości i długości fali.

Parametry pogodowe i parametry ruchów pontonu wytrzymałości mocowania w rzeczywistych warunkach pogodowych, – STAN I:

- Wiatr NNE 4°B (v = 8 m/s)
- Kąt kursowy fali wiatru 120°·
- Wysokość fali 1.5 m
- Amplituda kołysania wzdłużnego 5°
- Amplituda kołysania poprzecznego 5°
- Okres kołysań wzdłużnych 5.9 s
- Okres kołysań poprzecznych 3.9 s

Parametry pogodowe i parametry ruchów pontonu wytrzymałości mocowania w rzeczywistych warunkach pogodowych – STAN II:

- Wiatr NNE 4°B (v = 8 m/s)
- Kąt kursowy fali wiatru 120°·
- Wysokość fali 1.2 m
- Amplituda kołysania wzdłużnego 2°
- Amplituda kołysania poprzecznego 2.3°
- Okres kołysań wzdłużnych 5.9 s
- Okres kołysań poprzecznych 6.2 s

Tab. Przyspieszenia działające na ładunek STAN I i STAN II

Przyspieszenia całkowite (ruch pontonu i działanie wiatru)					
Kierunek	**Oznaczenie**	**Wartość**			
		STAN I		**STAN II**	
		g	m/s^2	g	m/s^2
Wzdłużne	a_l	0.280	2.747	0.115	1.130
Poprzeczne	a_t	0.502	4.925	0.128	1.252
Pionowe maksymalne	a_{vmax}	1.271	12.469	1.230	12.062
Pionowe minimalne	a_{vmin}	0.721	7.073	0.769	7.546

W poniższych tabelach przedstawiono analizę obciążeń w głównym systemie mocowania dla istniejących warunków pogodowych oraz dla wyznaczonego bezpiecznego obciążenia roboczego (MSL = 20 t).

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie STAN I

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła działająca na ładunek STAN I	FSL	698.8	FST	1252.8
Siła zabezpieczająca od mocowań i tarcia	FLS	652.7	FTS	652.7
Stopień zabezpieczenia		93%		52%
Kryterium	**Zabezpieczenie nieskuteczne**		**Zabezpieczenie nieskuteczne**	

Tab. Momenty działające na ładunek i momenty przeciwdziałające przewracaniu STAN I

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Całkowity moment przewracający	M_{TL}	94911,9	M_{TT}	109575.9
Moment przeciwdziałający przewracaniu	MTLS	18961.4	MTTS	8590.9
Stopień zabezpieczenia		20%		8%
Kryterium	**Zabezpieczenie nie skuteczne**		**Zabezpieczenie nieskuteczne**	

Dla założonych kołysań wzdłużnych i poprzecznych o wielkości 5° mocowanie jest całkowicie nieskuteczne.

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie STAN II

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła działająca na ładunek	FSL	287.0	FST	318.4
Siła zabezpieczająca od mocowań i tarcia	FLS	664.7	FTS	664.7
Stopień zabezpieczenia		232%		209%
Kryterium	**Zabezpieczenie skuteczne**		**Zabezpieczenie skuteczne**	

Tab. Momenty działające na ładunek i momenty przeciwdziałające przewracaniu STAN II

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Całkowity moment przewracający	M_{TL}	89275,6	M_{TT}	96774.8
Moment przeciwdziałający przewracaniu	M_{TLS}	19864.5	M_{TTS}	8952.1
Stopień zabezpieczenia		22%		9%
Kryterium	**Zabezpieczenie nieskuteczne**		**Zabezpieczenie nieskuteczne**	

Dla założonych kołysań wzdłużnych 2° i poprzecznych o wielkości 2.3° mocowanie jest nieskuteczne w odniesieniu do momentów przewracających.

Zastosowany system mocowania o rzeczywistym MSL 20 t nie zabezpieczał ładunku w rzeczywistych warunkach pogodowych dla przewracania w żadnym z kierunków.

Wytrzymałość spoiny mocującej belkę do podwozia żurawia

W poniższych tabelach przedstawiono analizę obciążeń spoiny belki mocującej do podwozia żurawia dla założonych stanów I i II.

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie – STAN I

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła całkowita działająca na ładunek	F_L	698.8	F_T	1252.8
Siła tarcia	F_F	179.9	F_F	179.9
Siła działająca na mocowanie	F_L’	518.9	F_T’	1073.8

Tab. Momenty przewracające działające na ładunek – STAN I

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Całkowity moment przewracający	M_{TL}	94911,9	M_{TT}	109575.9
Moment masowy przeciwdziałający przewracaniu	M_{ML}	13495.3	M_{MT}	5398.1
Moment działający na mocowanie	M_{TL}’	81416.6	M_{TT}’	104177.8

Moment skręcający belkę: MTo = 220.53 kNm

Tab. Weryfikacja wytrzymałości spoiny belki mocującej dla obciążenia projektowego rzeczywistego – STAN I

Nr.	**Parametr wytrzymałości**	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Ściskanie od momentu wzdłużnego	$\sigma_{tl} = \frac{M_{TL}'}{W_L}$	17.54	14.10	Not OK
2	Ściskanie od momentu poprzecznego	$\sigma_{tt} = \frac{M_{TT}'}{W_T}$	45.95	14.10	Not OK
3	Ścinanie wzdłużne	$\tau_{sx} = \frac{F_L'}{A}$	0.61	9.40	OK
4	Ścinanie poprzeczne	$\tau_{sy} = \frac{F_T'}{A}$	1.25	9.40	OK
5	Skręcanie	$\tau_{So} = \frac{M_{TO}}{W_O}$	1.11	9.40	OK
6	Zginanie wzdłużne	$\sigma_{Bx} = \frac{BM_x}{W_x}$	0.39	15.51	OK
7	Zginanie poprzeczne	$\sigma_{By} = \frac{BM_y}{W_y}$	1.75	15.51	OK
8	Von Mises		65.70	17.62	Not OK
$\sqrt{(\sigma_{tl} + \sigma_{tt} + \sigma_{Bx} + \sigma_{By})^2 + 3 \cdot (\tau_{sx}^2 + \tau_{sy}^2 + \tau_{st}^2)}$					
			Not OK	**373%**	

Tab. Siły działające na ładunek i siły zabezpieczające przesuwanie – STAN II

	Wzdłużne [kN]		Poprzeczne [kN]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Siła całkowita działająca na ładunek	F_L	287.0	F_T	318.4
Siła tarcia	F_F	192.0	F_F	192.0
Siła działająca na mocowanie	F_L'	95.0	F_T'	126.4

Tab. Momenty przewracające działające na ładunek – STAN II

	Wzdłużne [kNm]		Poprzeczne [kNm]	
	Oznaczenie	Wartość	Oznaczenie	Wartość
Całkowity moment przewracający	M_{TL}	89275.6	M_{TT}	96774.8
Moment masowy przeciwdziałający przewracaniu	M_{ML}	14398.4	M_{MT}	5759.3
Moment działający na mocowanie	M_{TL}'	74877.2	M_{TT}'	91015.5

Moment skręcający belkę: MTo = 161.5 kNm

Tab. Weryfikacja wytrzymałości spoiny belki mocującej dla obciążenia projektowego rzeczywistego – STAN II

Nr.	**Parametr wytrzymałości**	Wzór	Wartość uyskana [kN/cm^2]	Wartość wymagana [kN/cm^2]	Kryterium
1	Ściskanie od momentu wzdłużnego	$\sigma_{tl} = \frac{M_{TL}'}{W_L}$	16.13	14.10	Not OK
2	Ściskanie od momentu poprzecznego	$\sigma_{tt} = \frac{M_{TT}'}{W_T}$	40.15	14.10	Not OK
3	Ścinanie wzdłużne	$\tau_{sx} = \frac{F_L'}{A}$	0.44	9.40	OK
4	Ścinanie poprzeczne	$\tau_{sy} = \frac{F_T'}{A}$	0.59	9.40	OK
5	Skręcanie	$\tau_{So} = \frac{M_{TO}}{W_O}$	0.81	9.40	OK
6	Zginanie wzdłużne	$\sigma_{Bx} = \frac{BM_x}{W_x}$	0.07	15.51	OK
7	Zginanie poprzeczne	$\sigma_{By} = \frac{BM_y}{W_y}$	0.83	15.51	OK
8	Von Mises	*	57.21	17.62	Not OK
*) $\sqrt{(\sigma_{tl} + \sigma_{tt} + \sigma_{Bx} + \sigma_{By})^2 + 3 \cdot (\tau_{sx}^2 + \tau_{sy}^2 + \tau_{st}^2)}$					
			Not OK	**324%**	

Spoina mocująca belkę nie spełnia wymagań wytrzymałości dla obciążeń rzeczywistych. Obciążenia są przekroczone 3.24 razy.