Investigation Report

C4/2009M

M/S SILJA EUROPA (FIN), Breaking of the Starboard Rudder Shaft in the Aland Archipelago on 22 November 2009

This is an abridged version of the comprehensive investigation report available in Finnish.
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SUMMARY

M/S SILJA EUROPA (FIN), BREAKING OF THE STARBOARD RUDDER SHAFT IN THE ALAND ARCHIPELAGO ON 22 NOVEMBER 2009

The M/S SILJA EUROPA was on her way from Stockholm to Turku on 22 November 2009 when irregularities in the manoeuvring of turns began to occur west of Sottunga at approx. 15:17. There were approx. 1660 persons onboard the vessel. At 15:40 it was decided that the vessel would be manoeuvred to a nearby extension of the shipping channel, and the Master was called to the navigating bridge. He started to manoeuvre the vessel by using thrusters and succeeded in stopping the vessel in the extension. The vessel was later taken to the Airisto open sea with tug assistance. There a diver concluded that the difficulties in manoeuvring were caused by the breaking of the vessel's starboard rudder shaft.

On the basis of the analysis completed in the investigation, it can be concluded that the rudder shaft broke at approx. 15:10. The breaking of a rudder shaft does not cause any direct indication on the navigating bridge; the failure can be detected only indirectly by observing the vessel's motion state, its changed manoeuvring behaviour and the manoeuvring variables. The bridge crew noticed manoeuvring irregularities in the first major turn after the failure from approx. 15:17 onwards. The voyage was continued and the bridge crew grew gradually aware of the gravity of the situation as they got more observations of the manoeuvring difficulties. The breaking of a rudder shaft is, however, highly unusual so it was not even considered to be the reason for the manoeuvring difficulties. The situation was so unclear that it took time for the bridge crew to gather observations before the decision to interrupt the voyage was made. Even if it took time to understand the severity of the situation and the voyage was continued with reduced manoeuvrability, the crew, who had in simulator training got readiness to steer a vessel with irregular behaviour, managed to keep the vessel in the fairway and finally to stop her in a safe manner.

In the docking after the accident in 2009 it was found out that the starboard rudder shaft had broken because of bending fatigue stresses. The extensive corrosion on the pintle bearings housing of both rudders had been repaired with cast epoxy filling in the docking in 2004. The corrosion had caused in the pintle bearings a significant empty space, a transverse free play, which might have made the rudder shafts bend more than intended. In the docking in 2009 it was discovered that the cast epoxy filling had disappeared entirely of the starboard side pintle bearing thus the large transverse free play was now only on this rudder. The changing stresses generated by the rudder forces on the shaft then considerably exceeded the design values. In scheduled traffic rudder forces recur similar each service period. The stresses caused by these forces depend, however, on the transverse free play of the pintle bearing. When the free play increases, the stress in the rudder shaft grows.

Three factors working simultaneously made the bending fracture of the rudder shaft possible. The two most important of these are anything but common. Firstly, in the production stage a sharp, 0.3-mm-deep notch was left on the starboard shaft and, secondly, there was sustained galvanic corrosion in the bearing housings caused by the structure of the pintle bearings. These two to-

gether would have been enough to cause the failure, but the breaking process was significantly accelerated by a third factor, i.e. the resonant vibration of the rudder.

The fatigue breakage developed in 17 years in three stages. *In the first stage* the housing of the pintle bearings of both rudder shafts corroded because of galvanic corrosion. This was made possible by the structure of the housing, in which a bronze bush and the cast steel of the housing were in contact without any insulation. After the housing had corroded around the bushes, they could rotate. The rotation wore the corrosion rust and this accelerated significantly the increase of free play. Because of the corrosion, the transverse free plays of the pintle bearings had for quite a while been manifold when compared with the rated value, which had caused the stresses in the rudder shafts to be higher than normally. The first stage of the process used a large part of the fatigue life of the starboard shaft, up to 85% on the basis of the calculations made in connection with the investigation.

The corrosion was not detected until in the docking in 2004. The pintle bearing housing was repaired by filling the corroded space with cast epoxy and the bearing bushes were replaced with new ones. Additionally, the hull areas (the surface of the cast iron) around the upper bearings of the rudder shafts were inspected from outside. The hairline cracks of the early fatigue breakage then possibly existing in the rudder shafts were impossible to be detected, because the inspection did not include the rudder shafts.

In the *second stage* of the process, the corrosion of the pintle bearing housings continued after the installation of cast epoxy, but the process was slower because of the insulating effect of the epoxy. In the docking in 2007 the epoxy still looked intact.

In the third stage the cast epoxy of the starboard pintle bearing broke entirely. The bush came loose and could now rotate in the housing due to the axle rotation. Therefore a large free play was generated in the pintle bearing for the second time, the stresses in the rudder shaft became high and the shaft broke. According to the calculations, the third stage only took a couple of days.

The Safety Investigation Authority of Finland recommends to *Bureau Veritas and other classification societies* that the measuring methods concerning clearances be specified and the method be entered into the inspection report of the classification society, and that the reparation history of a vessel be used as the basis for deciding whether a more detailed inspection of the steering gear is in order. In addition, it is suggested that classification societies consider adding an inspection of a removed rudder shaft at specified regular intervals in their rules. The use of cast epoxy when repairing a pintle bearing must be a temporary solution and the reason for the need for repair must established in order to plan and realise a correct repair method.

It is recommended to the shipping company that simulator training should be developed further in such a way that the preparedness of the trainees to work out and analyze in a systematic way a situation in which the maneuvering systems of the vessel do not function in a normal way will improve. The objective must be the development of gathering data to support the decision-making on whether a voyage should be interrupted or continued.

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Figure 1. M/S SILJA EUROPA.

FOREWORD

The M/S SILJA EUROPA was on her way from Stockholm to Turku on 22 November 2009 when irregularities in the manoeuvring of turns began to occur west of Sottunga. At approx. 15:40 the vessel had to switch to emergency steering, but it did not help. Propellers and thrusters were then used to steer the vessel, and she could be stopped in a channel extension between Långholmskobben and Rönnskär. In the open sea of Teili the vessel was steered clockwise along an ellipse-shaped route while waiting for tug assistance. The tugboat UKKO, which the Master had ordered to assist, accompanied the SILJA EUROPA to Tervi anchorage, where a diver discovered that the starboard rudder shaft was broken. The vessel arrived in Turku on 23 November at 16:46 assisted by the tugboats UKKO and KRAFT. The vessel was taken to a dock in Riga, where she was discovered to be too large for the dock. From Riga she was moved to Gdansk, to Remontowa S.A. shipyard. The SILJA EUROPA returned to traffic on 19 December 2009.

After receiving information about the accident, the Safety Investigation Authority of Finland (hereafter referred to as “the SIA”) decided on 24 November 2009 to initiate an investigation and appointed Chief Marine Safety Investigator Martti **Heikkilä** investigator-in-charge. D.Sc.(Tech.) Sauli **Ahvenjärvi**, Lic.Sc.(Tech.) Olavi **Huuska** and Chief Engineer Ari **Nieminen** were appointed as investigators. M.Sc.(Tech.) Ville **Grönvall** was appointed as a member of the Investigation Commission on 27 September 2011. M.Sc.(Tech.) Jorma **Salonen** and M.Sc.(Tech.) Markku **Hentinen** from the Technical Research Centre of Finland have acted as experts.

The breaking of a rudder shaft is a very rare type of an accident. When the investigation was started, there was no technical basic material on similar incidents, which meant that the technical background of the incident and the whole operation history of the vessel had to be studied in detail in order to prevent similar incidents in the future. The investigation became more demanding than usually, and the investigation plan had to be specified several times. It was possible to assess (extrapolate) the evolution of the first stage of the failure, which had developed slowly in the course of more than ten years, with the help of the vessel’s voyage data recorder (VDR) and its recording covering one month. Studying the repair technique with epoxy, the breakage of the repair and the fatigue process leading to the breaking of the rudder shaft has been a demanding undertaking.

The SIA has exchanged information and discussed with the shipping company, the Maritime Safety Department of the Regulation and Oversight at the Finnish Transport Safety Agency (former Maritime Administration) and the classification society Bureau Veritas which had classed the vessel.

Statements of the Investigation Report. The final draft of the Investigation Report was sent on 27 August 2012 for statements according to the 28§ of the Safety Investigation Act (525/2011) to the Finnish Transport Safety Agency, to the classification society, to the shipping company and the bridge team. Statements were received in due course from the Finnish Transport Safety Agency, from the classification society, from the shipping company and from one member of the bridge team. A summary compiled on the basis of the statements is attached to the Investigation Report. The statements were considered when finalizing the Investigation Report.

The sources used in the investigation are filed at the Safety Investigation Authority.

The abridged version of the Investigation Report has been translated into Swedish and English by Minna Bäckman.

1 EVENTS AND INVESTIGATIONS

1.1 Main information about the vessel

The information is based on the vessel's drawings, on the marine casualty report of 7 December 2009 and on the interviews with the vessel's officers. The home port and registration port of the vessel is Mariehamn, Finland. The vessel is owned by Tallink Autoexpress Ltd, Limassol, Cyprus, and it is operated by Silja Line Ltd., Helsinki, Finland. The maximum number of passenger is 3,123, and the vessel was built on the Jos. L. Meyer Werft shipyard in Papenburg in Germany in 1993. The classification society is Bureau Veritas.

1.1.1 General information

Tonnage:	Gross tonnage: 59,914 Net tonnage: 41,309
Overall length/Length L_{pp}:	201.78 m/171.6 m
Breadth:	32.00 m
Draught:	6.80 m
Speed:	22.50 knots

1.1.2 Manning

The deck and engine crew of the vessel consisted of 41 persons and there were 245 members in the service personnel. The navigational watch consisted of a mate as Officer of the Watch (OOW) and a route pilot[1]. Both officers had a Master Mariner Certification of Competency. The OOW also had pilot exemption certificate for the fairway in question. The change of watch of route pilots on the 22 November 2009 took place at 15:32, after which the First Officer of the vessel acted as the route pilot.

A Watchkeeping Engineer holding the competency of an engine attendant was acting as the officer in charge of the engineering watch in the engine control room. In addition, there was a Motorman acting as an engine room watch in the engine control room.

1.1.3 Navigating bridge and bridge equipment

The vessel operated on the Turku-Långnäs-Stockholm-Mariehamn-Turku line, and the route was programmed into the autopilot of the integrated navigation system. The autopilot turns rudders and the speed is adjusted by the machinery control handle (KaMeWa) which changes concurrently the speed of rotation and pitch of propellers. The automatic steering system receives position information from the satellite navigator and compares this information to the information about the intended route and then makes necessary adjustments. Manual steering is mainly in use during port operations when also thrusters can be used. To make port manoeuvring more effective, there was a Jastram-rotor installed to the rudder.

[1] Route pilot is a mate of the vessel, who is a holder of a Finnish Pilot Exemption Certificate for the fairway in question.

There are normally two persons on the bridge, an OOW and a route pilot. Their positions are in the front part of the bridge, Figure 2. The radar and the so-called conning-display[2] at the steering positions at the front are the most important displays (Figure 8). These displays are also located at the side steering positions on the sides of the navigating bridge. In addition, there are displays for example for rudder angles above the window and in the ceiling. The monitoring on the bridge mainly focuses on the radar and especially its predictor[3], which shows a prediction of the vessel's movements. According to the normal praxis, only momentary information is available on the displays, except for depth information.

Navigational equipment

The vessel has two independent integrated navigation systems of the type Atlas Nacos 25-2 Integrated Bridge System, which includes for instance the following radars: 2 Atlas 9600 X-band radars, 2 Atlas 9600 S-band radars. Automatic steering equipment consists of 2 ATLAS TRACKPILOT devices.

Figure 2. View from the navigating bridge, the vessel's steering positions. The picture was taken on 24 November 2009 in Turku. The red arrows point to the radar displays (one of them is hidden behind the chair) and the yellow arrows indicate the conning displays. The route pilot's chair (main steering) is in the middle, the OOW's chair (monitoring navigator) is to the right and to the left is the Master's chair. The white arrow indicates the control console of the hydraulic accumulators of the steering gear, the levers on the right and left side.

[2] Conning Display, the centralised display of the vessels' alarm, safety and information system is integrated to the bridge system. Important information related to navigation and the control of the vessel is gathered on the display, in one place. The information includes the vessel's position, speed, course, rudder angles, turning speed, wind data, depth of water. Typical alarms include e.g. the following: radar target is too close, the vessel is outside the set route limits, manoeuvring alarms, problems in navigation lights, compass failure, alarms from machine automation, etc. Alarms can be acknowledged one at a time or centralised.

[3] The predictor of the vessel's motion state shows the vessel's position at a given time and a prediction of its movement after a selected short time (e.g. one minute) when the prevailing motion state parameters remain unchanged.

1.1.4 Propulsion machinery

The propulsion machinery includes two Kamewa outward rotating controllable pitch propellers. One propeller is run through reduction gear by two MAN B&W 6L58/64 diesel engines á 7950 kW 428 1/min. The reduction gear also runs the shaft generator. The diameter of the propellers is 5.0 metres and the speed of rotation range is 100–143 1/min when the shaft generator is switched to 130 1/min. The distance of the centre of the root of the propeller blade from the centre of the rudder shaft is approx. 3.5 m. Figure 3a.

1.1.5 Rudders and other manoeuvring equipment

The starboard (SB) rudder shaft of the vessel broke, but there were also damages in the port (BB) rudder[4]. Therefore the steering gear is described fairly extensively.

Figures 3a and 3b present the placing of the vessel's rudders. In addition, there are four tunnel-type thrusters on the vessel, three in the bow and one at the stern.

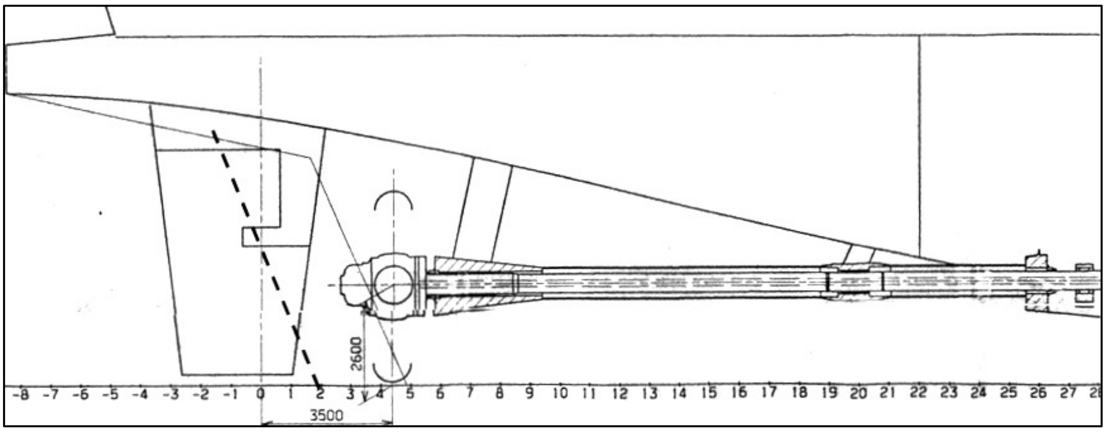


Figure 3a. The propeller-rudder arrangement of the SILJA EUROPA. The stern fin was extended already in the summer of 1993 (broken line). This assessment has been made on the basis of a photograph taken in Gdansk on 2 December 2009.

[4] Abbreviations SB for starbord and BB for port have been used in the report according to the Finnish shipbuilding practice.

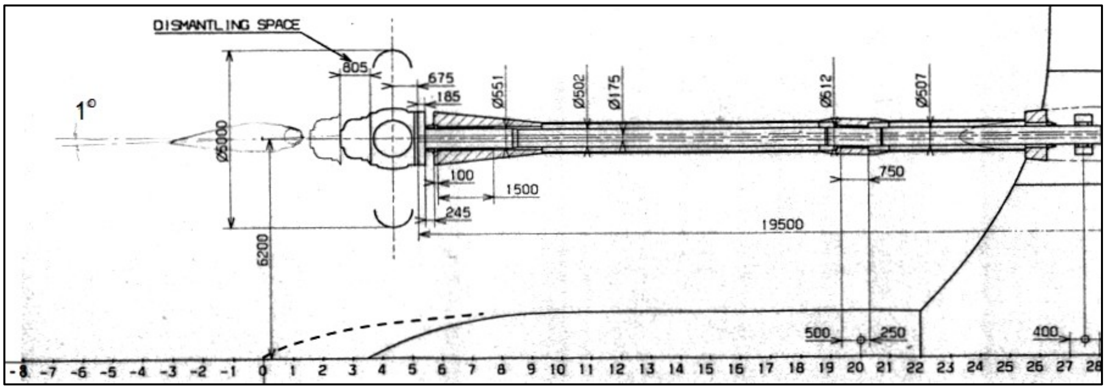


Figure 3b. The propeller-rudder arrangement of the SILJA EUROPA. The frame spacing is 800 mm.

Rudders.[5] There are two horn rudders[6] on the vessel, Figure 4. The surface of the rudder blade is approx. 20 m^2 and the rudder weighs[7] approx. 21 tons. The rudders are aligned behind the propellers and turned one degree inwards, Figure 3b. After the commissioning of the vessel in 1993, it was discovered that it was advisable to improve its manoeuvring properties, for instance course stability. The rudders had been extended approx. 30 cm and a thruster had been added to the bow already before the delivery. The vessel was docked in August 1993 in Vuosaari. Bilge keels were then added, the stern fin was extended, a thruster was mounted in the stern and a bow fin in the bow and the capacity of the steering wheel pumps was increased.

The rudder is mounted from its upper part to the conical lower part of the rudder shaft by using an interference fit. From its upper part the rudder shaft is mounted to the steering gear with a hydraulic coupling. The rudder is mounted lower down to the conical lower part of the pintle shaft by using a similar crimp connection. The upper part of the pintle shaft has been bearing-mounted to the rudder horn.

The rudder horn is a steel-cast component, which continues streamlined above the rudder and meets the hull of the vessel. It is partly plate structure and in places it reaches inside the hull (see for instance Figure 4). The aft part of this structure forms a so-called ice knife, which protects the rudder when the vessel is reversing in ice. The rudder horn receives the majority of the bending forces directed to the rudder and in that way also directed to the rudder shaft, and because of this the stresses on the rudder shaft stay within the permissible limits. This requires that the pintle bearing is intact, in which case the rudder horn reduces the bend of the rudder shaft to a minor one.

There are two plain bearings in the rudder of the SILJA EUROPA: the grease-lubricated bearing of the rudder shaft (upper bearing), Figure 5a, and the sea water-lubricated bearing (pintle bearing) of the pintle shaft located in the rudder horn, Figures 5b and 5c.

[5] Steering gear plans in PDF format were obtained from the shipping company.

[6] There are several ways to mount horn rudders. Another common rudder type is a so-called spade rudder, in which there is no horn.

[7] The weight stated in the drawing of the rudder. In the investigation the weight has been interpreted as a lifting weight obtained when dismounting the rudder. In that case the weight included the pintle shaft, but it did not cover the rather small parts of the rudder plating which are removed in connection of the dismounting.

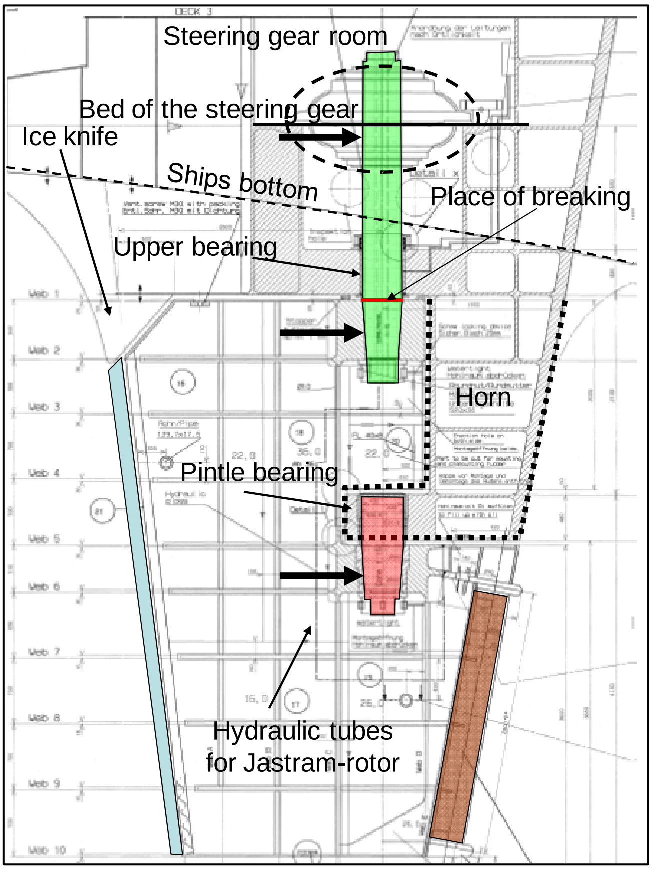


Figure 4. The rudder. The green colour indicates the rudder shaft, the red colour the lower shaft (pintle shaft, lower spindle), the brown colour the Jastram-rotor and the blue colour the extension of the rudder which was added already before the vessel was delivered. The thick arrows show the interference fits. The dotted line indicates the rudder horn, which joins closely the hull of the vessel through the streamlined intermediate structure. The steering gear has been circled with a broken line. Diagonal lines have been used to indicate the casting.

On the forward edge of the rudder, underneath the horn, there was a hydraulically driven Jastram-rotor till the docking in 2009. The rudder is turned by a rotary vane type steering gear Tenfjord SR 782, the nominal torque of which is 800 kNm and the maximum angle 2 x 68 degrees. The turning speed 2 x 35 degrees is 28 s with one pump and 14 s with two pumps.

Both bearings are plain bearings, the material of which is bronze. The response surface at the point of the bearings on both shafts consists of a stainless-steel liner, which is fastened by using a crimp connection. An essential requirement for the functioning and durability of the rudder is that the bearing clearances[8] are correct to begin with and that they remain within permissible limits during the usage.

Rudder bearings. A tightening nut, connections for high pressure oil, the breaking point of the shaft and draughts have been marked in the picture showing the *upper bearing*. The materials are the same as in the pintle bearing, Figure 5b.

8 Bearing clearance is the difference between the inner diameter of the bearing and the outer diameter of the shaft. Half a clearance is the possible free play of a shaft assuming that the centres of the shaft and bearing concur and that the possible worn points are symmetrical. The free play of a shaft increases when the clearance grows, and it increases more if an empty space in generated between the bronze bush and the steel of the housing because e.g. corrosion.

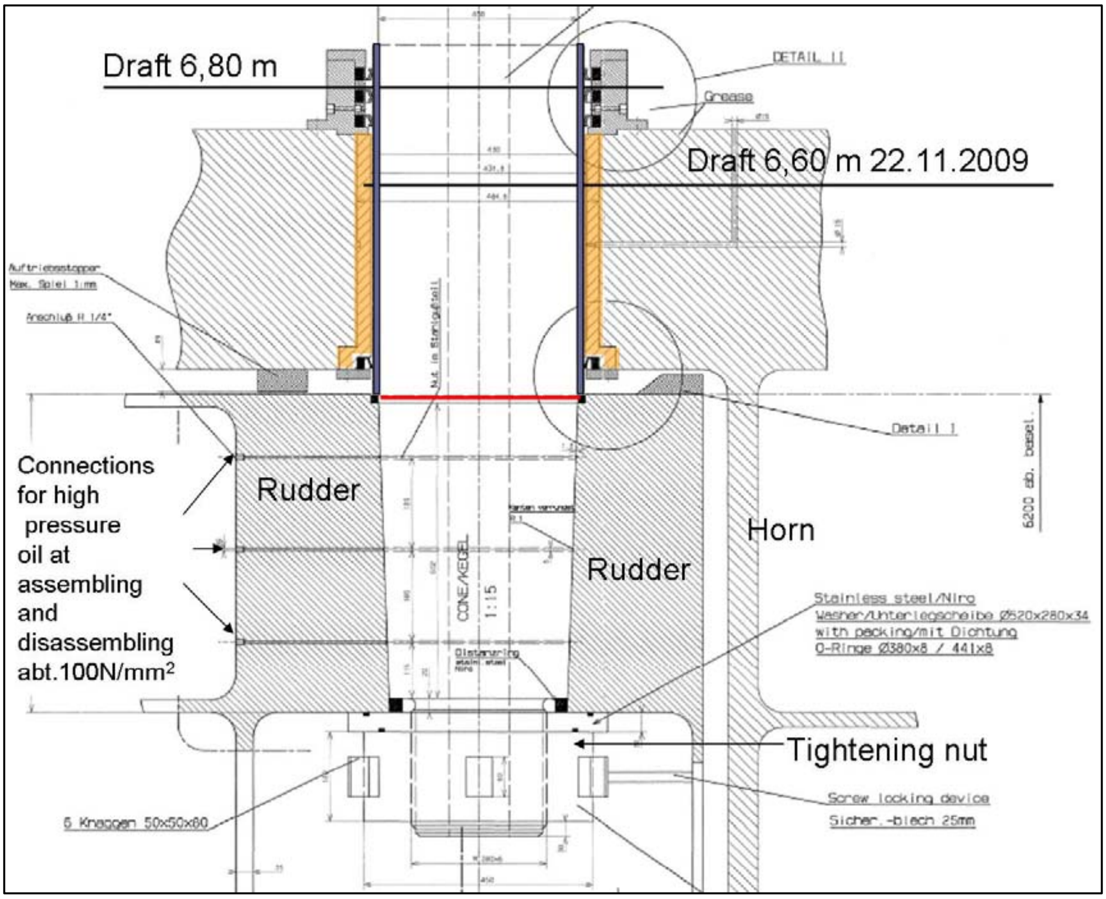


Figure 5a. A drawing of the upper bearing of the rudder. The taper connection of the rudder shaft to the rudder can be seen in the drawing. The bronze bush has been indicated with orange colour, the stainless steel liner with blue-grey. The bearing clearance is 1.8 mm (431.8–430.0). The breaking point of the SB rudder shaft has been indicated with red colour (at the point where the cone changes into a cylinder). Diagonal lines have been used to indicate the casting.

A lower limit, an upper limit and a control limit have been set for **bearing clearances** in the classification society rules. The limits depend on the diameters of the rudder shaft and the pintle shaft. For the shafts of the SILJA EUROPA these limit were approx. 1.4 mm, 5 mm and 4 mm. The clearances are measured in connection with dockings in accordance with the classification society rules and the bronze bushes are, when necessary, replaced with new ones. In practice the bronze bushes are replaced if the clearance clearly exceeds 2 mm. With normal clearances and ordinary rudder forces the rudder shaft does not touch the bronze bush of the upper bearing, which means that the wear of the upper bearing is minor.

The diameter of the straight part of the *pintle shaft* is 432 mm, and the thickness of the stainless steel liner mounted to it by using a shrink-fitting is 24 mm, Figure 5b. The length of the shaft is approx. 1.3 metres and it weighs 1.2 tons. The thickness of the upper part of the bronze bush was originally 26.5 mm and of the lower part 25 mm. There was a notch in the middle of the bush as well as one in the housing to help the fitting and staying in place of the bush. From the top the bush was secured against torsion and rising with six screws, which had even been welded to the casting. The height of the housing and bush is 480 mm. It is worth noticing that the cast steel of the bearing housing is in direct contact with the bronze bush in a sea water environment (galvanic couple).

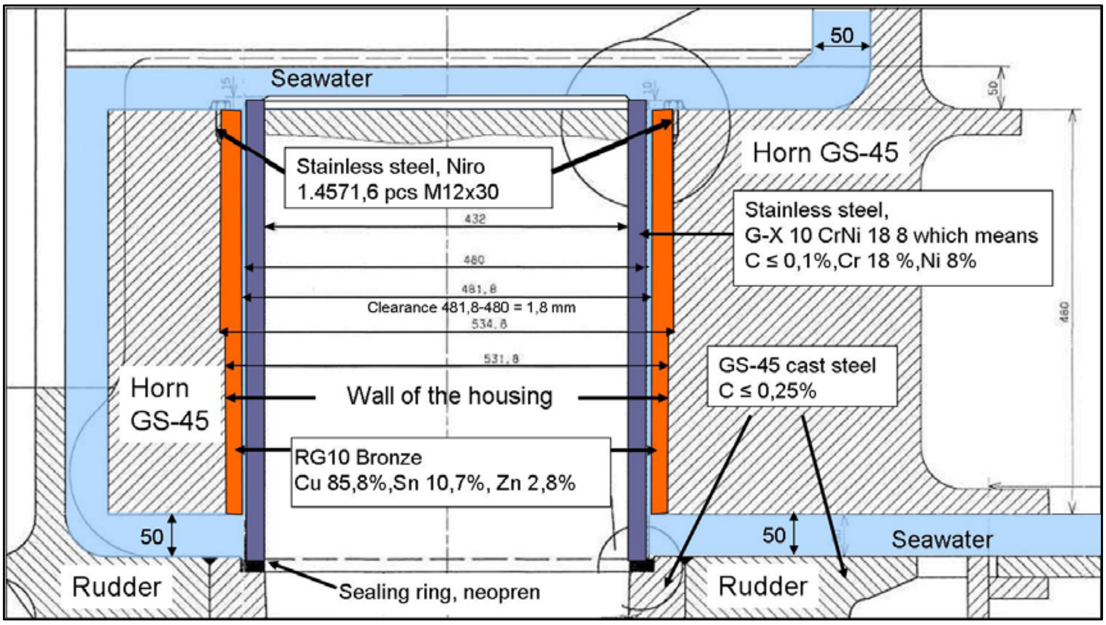


Figure 5b. The original drawing of the pintle bearing, added with e.g. information about the materials. The bronze bush has been indicated with orange colour, the stainless steel liner with blue colour. The bearing clearance is 1.8 mm (481.8–480). It is to be noted that the bronze in the bush and the cast steel in the horn are in contact with each other in seawater without insulation (galvanic couple).

In the connection with the docking in 2004, corrosion of the housing was repaired by using cast epoxy filling and at the same time new bronze bushes were installed, Figure 5c. In order to centre the bushes when the epoxy was cast, hexagonal socket-head screws reaching to the wall of the housing were used. They remained there after the casting had been completed. This structure formed by the epoxy and screws broke in 2009. It is worth noticing that the cast steel of the bearing housing was in direct contact with the bronze bush, now through screws (galvanic couple).

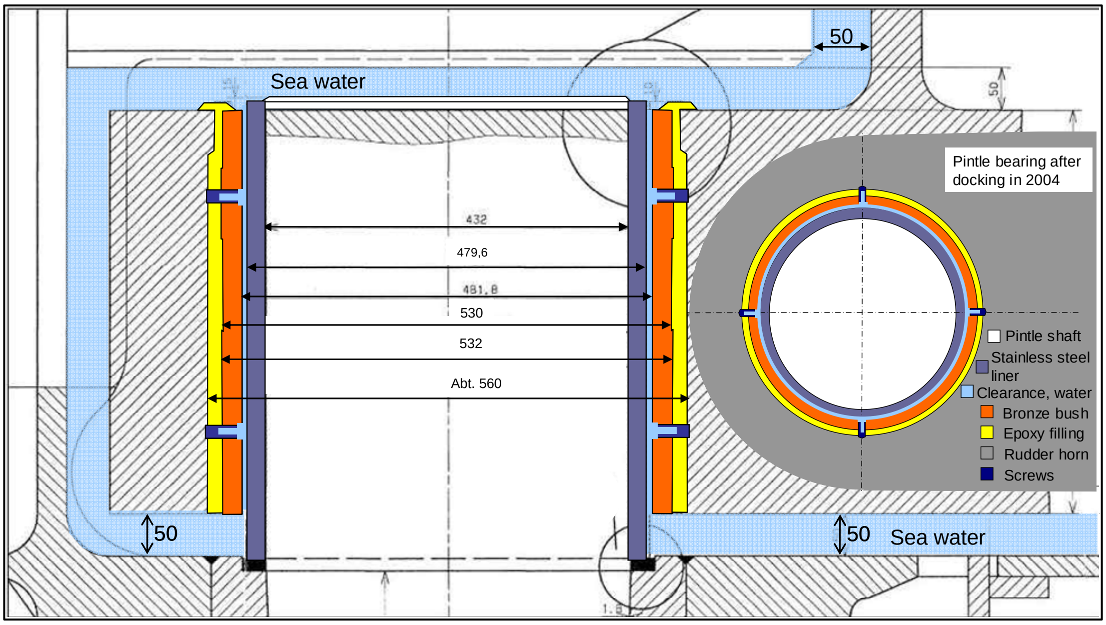


Figure 5c. *The structure completed in the 2004 repair. In order to centre the new bush during the epoxy casting, hexagonal socket-head screws were used (altogether 8 screws). The clearances returned to normal. The hex sockets filled with sea water.*

Rudder shafts. The length of a rudder shaft is approx. 3.5 metres and it weighs approx. 3.1 tons, Figure 6. The rudder shaft is made of non-alloy steel CK 22 N, which had been forged and anneal-normalised. The material had a classification certificate, according to which it fulfilled the standards set on it. The diameter of the rudder shaft is 400 mm. The strength properties of the shaft were normal and corresponded with the vessel's ice class[9]. The thickness of the liner installed by using shrink-fitting was 15 mm. For the hydraulics of the Jastram-rotor, a 120-mm-diameter hole had been drilled in the middle of the shaft. The hole only caused a minor reduction in the strength of the shaft.

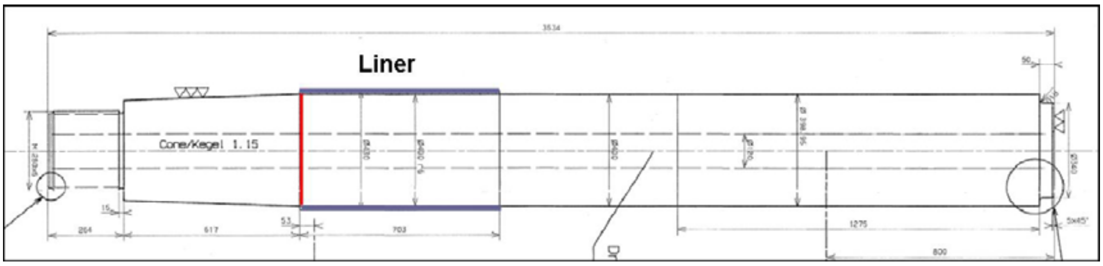


Figure 6. *Rudder shaft. The liner made of stainless steel is indicated with blue-grey. A 120-mm-diameter hole was drilled through the rudder shaft for the hydraulic pipes of the Jastram-rotor. Red colour has been used to indicate the breaking point of the SB rudder shaft.*

9 The speed of the vessel was over 20 knots. In that case only the speed defines the dimensioning of the shaft. According to the classification drawing, the breaking strength is 470 N/mm^2 and the yield strength 270 N/mm^2.

1.1.6 Corrosion protection

In addition to the paint work, the vessel has active and passive corrosion protection. Passive, local protection for the rudder is provided by zinc anodes (5-7 for each side of the rudder, the number of the anodes as well as their places have varied).The active, hull protecting system is provided and maintained by SAVCOR Consulting Inc. Anodes were added in connection with the docking in 1997. This protection is intended for large surfaces, and it probably cannot prevent local corrosion if the place in question has favourable conditions for galvanic corrosion caused e.g. by unfavourable material contacts[10]. The rudder had been earthed[11] to the hull of the vessel.

1.1.7 Passengers and cargo

When the accident occurred, the vessel carried 1373 passengers and 1133.1 tons of ro-ro cargo. The cargo included dangerous goods.

1.2 Accident voyage[12]

The chart drawing below (Figure 7) presents the route of the accident voyage near the Långnäs in the Aland Archipelago at the time when the rudder failure developed. It is presumed that the SB shaft broke in the position indicated by the red arrow. The black arrow points to the position where the vessel was stopped and steered off the channel, to “a pocket”.

[10] Discussions with the manufacturer of the system in Mikkeli on 28 April 2010.
[11] Active corrosion prevention can be made this way to reach also the surfaces of the rudders.
[12] Discussions with the bridge team and Master and VDR-data including listening to the registered discussions on the bridge. The voice registration is partly of so bad quality that every now and then the conversations are hard to follow.

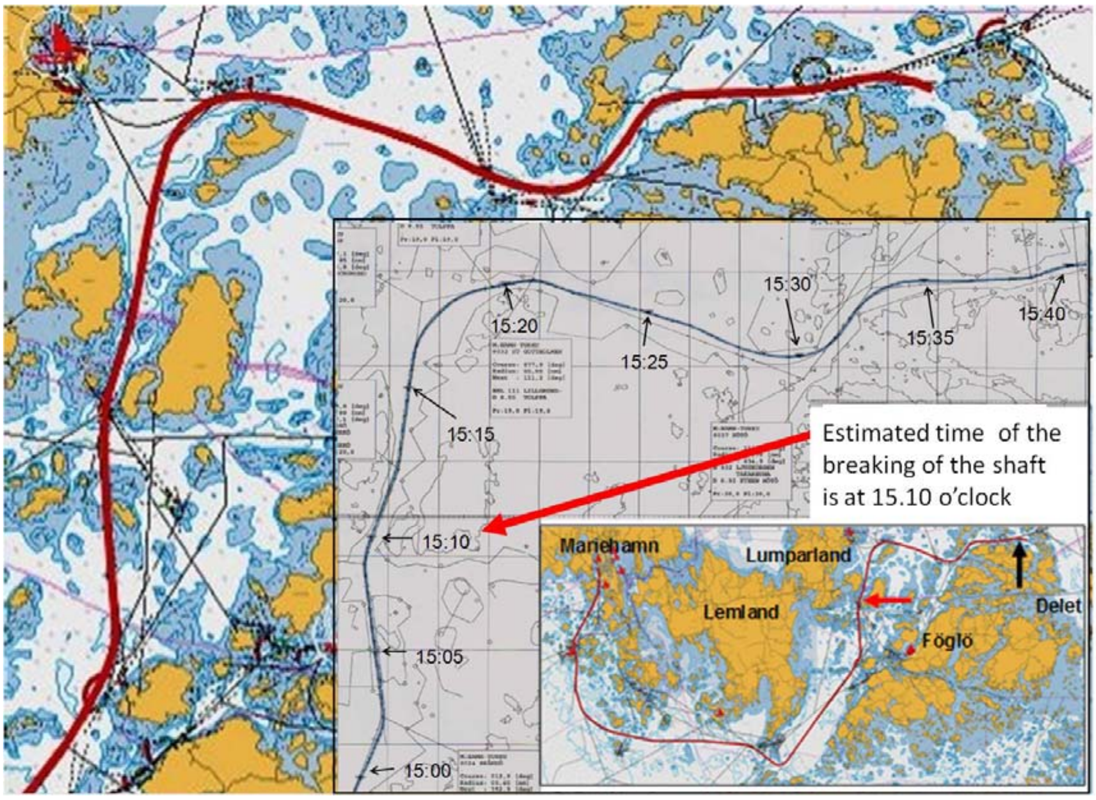


Figure 7. The accident voyage at Långnäs. It is presumed that the SB shaft broke at the point indicated by the red arrow. The vessel was stopped at the position indicated by the thick black arrow. The channel from Mariehamn to the open sea area at Teili includes several bends and narrow and shallow sections.

Events on the voyage The vessel had departed from Stockholm on 22 November 2009 on schedule. A couple of days earlier, irregularities had been observed in the manoeuvring. It was estimated on the vessel that strong wind had played some part in fact that the vessel occasionally took turns too gently or too sharply. The gusty wind, 18 m/s, was thought to be the reason also for the irregularities observed during a turn near Marienhamn, Finland, on 21 November.

On 22 November 2009 it was again noticed during a starboard turn after 15:15 at Långnäs that the vessel behaved in an atypical manner while in automatic steering. This irregular behaviour was taken under discussion on the navigating bridge. On the basis of the analysis completed in the investigation, the rudder shaft broke at approx. 15:10.This starboard was the first major turn after the breaking of the rudder shaft (approx. seven minutes had passed after the failure). Large rudder angles caused wondering and lead to minor course alterations in the autopilot. At 15:21:07-15:22:22 the automatic steering used unusually large rudder angles (30 degrees), Figure 8. The angles were noted on the bridge; however neither the numerical values of the large rudder angles nor their duration were discussed. The irregular steering behaviour was not analysed – the observations remained unconnected statements. The conversation ceased for approx. five minutes when the M/S FJÄRDVÄGEN was overtaken.

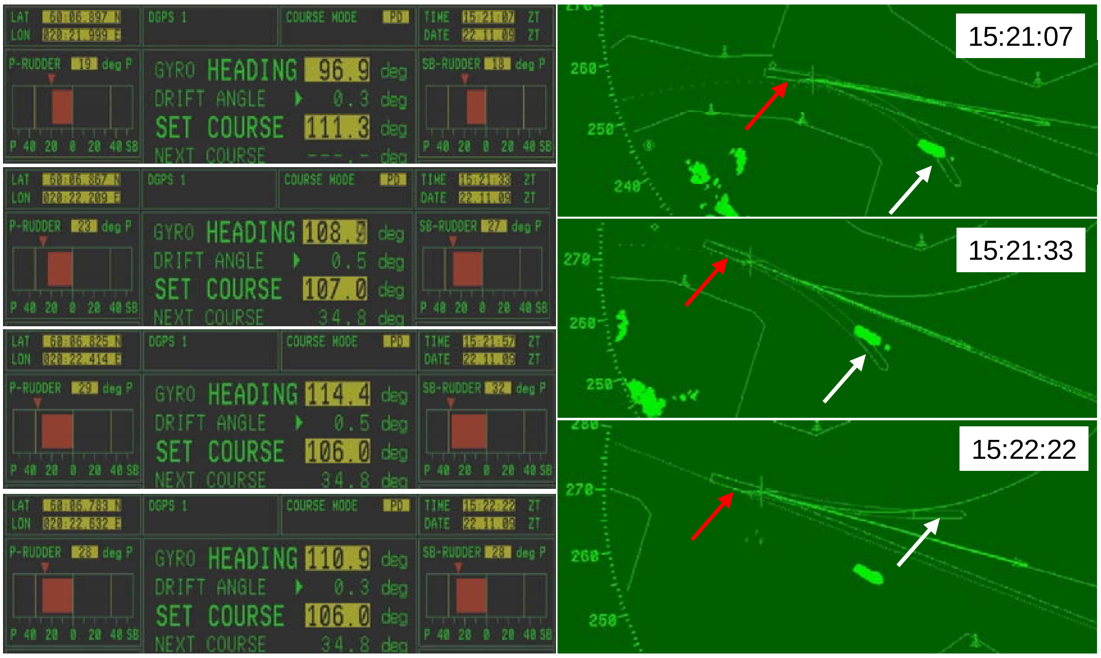


Figure 8. Large rudder angles used in the counter rudder after a turn to starboard commenced at 15:20 (Figure 7) shown on the conning-display (to the left) and corresponding picture of the radar display (to the right); the rudders are turned to port: BB rudder angle on the left and SB rudder angle on the right. In the radar pictures the position estimated by the predictor after a minute has been marked with a white arrow and the vessel's position at that particular moment with a red arrow. The green radar echo close to the white arrow is the M/S FJÄRDVÄGEN.

The overtaking of M/S FJÄRDVÄGEN at 15:25–15:29 was started by using the autopilot. The SILJA EUROPA appeared to behave normally when proceeding right ahead. One may notice a small permanent shift to the right in the registered rudder angles during the overtaking. At the end of the overtaking, a change-over to manual steering was made for the first time at 15:27. The rudder was turned momentarily 30 degrees to the left in order to start the next S-turn's first turn to port. The turn went in a proper way; however one had to use rudder angles of about 20 degrees to the left during nearly the whole turn.

At this moment the route pilots were to change watch. The second route pilot, who had arrived at the bridge, was informed about the manoeuvring observations and that using manual steering was connected with the overtaking of the FJÄRDVÄGEN. The steering behaviour of the vessel raised some discussion; it was mentioned that the vessel is steering poorly.

During the straight part of the S-turn the autopilot was used and the watch change could be carried out at 15:32[13]. Now one began to compile earlier observations and the analysis of the situation was gradually begun. The second route pilot was informed that the steering had worked properly up to the turn commenced at 15:15. The second route pilot

[13] It is not possible to carry out the watch change when using hand steering.

changed to the manual steering immediately after the first turn to starboard was commenced. He made a comment after this first turn he navigated at 15:35:22, that it was not possible to stop the yaw of the vessel properly by using counter rudder. The problems continued in the following minor port turn, and the route pilot suspected that there was a failure in the display indicating rudder angles. At this stage, approx. 20 minutes after the manoeuvring problems had been noticed; suspicions were for the first time raised about the manoeuvring problems being in the vessel herself and not being caused by environmental factors. After this, a normal traffic report was transmitted to the Archipelago VTS; the irregular behaviour of the manoeuvring equipment had not generated any clear need to interrupt the voyage.

At approx. 15:38 it was noticed that the vessel did not turn or turned poorly to port. After the small turn to port using the autopilot, a minor corrective course alteration was made to starboard. The autopilot made effort to counter the turn and took 20–30 degrees to port, but the vessel continued turning and first the manual steering and then the emergency steering was taken into use. At 15:40:07 the route pilot decided to steer the vessel to a nearby channel extension. He used the main engines in opposite directions and then full astern. The Master was called to the bridge at 15:40:45 and he stopped the vessel in an extension of the channel. The Archipelago VTS was informed at 15:44:05 that the vessel was having technical problems.

The functioning of the steering was later tested and the vessel could proceed to the open sea area of Teili, where the vessel was steered clockwise along an ellipse-shaped route without disturbing other traffic while waiting for tug assistance. A diver arrived with the tug, and he later concluded, after the weather had improved, that the starboard rudder shaft was broken. The vessel arrived in Turku almost twenty-four hours late.

All the most important variables present at the time of the breaking of the shaft have been compiled in Figure 9.

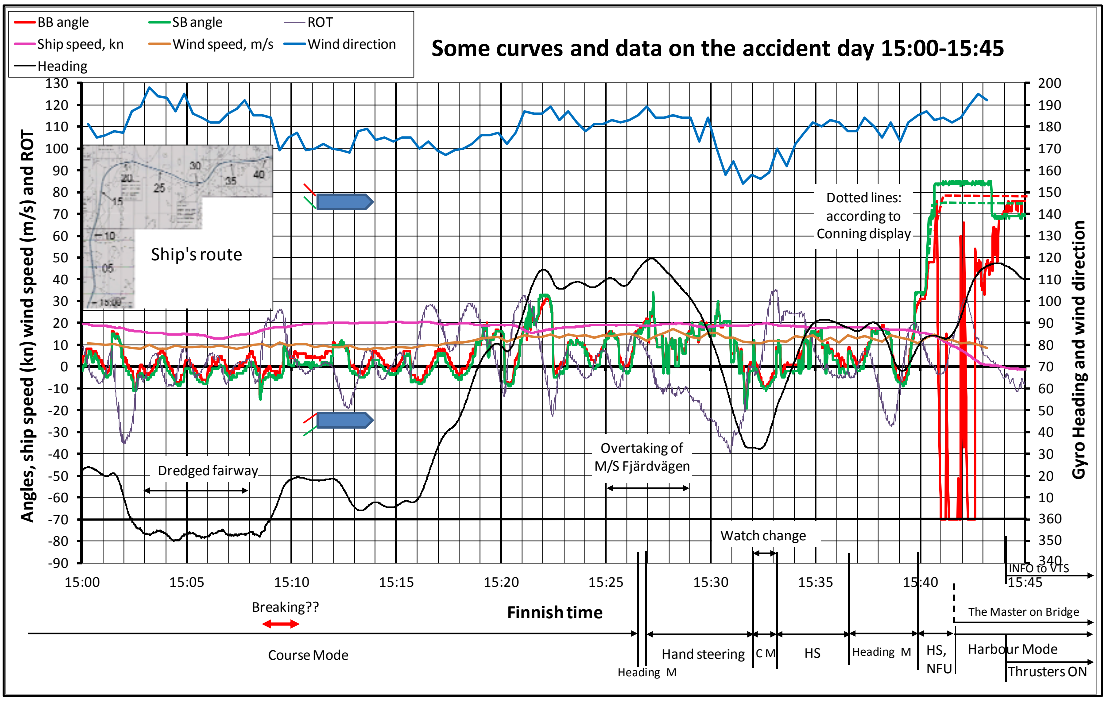


Figure 9. Information about the proceeding and steering of the vessel at the time of the accident. ROT stands for Rate Of Turn (the turning speed of the vessel, degrees per minute); Heading is the direction of the bow. After the breaking of the rudder shaft, SB-rudder angle equals to the angle of the angle indicator; the factual angle of the rudder remains unknown.

1.3 Damages to the vessel

The SB rudder shaft was broken. The rudder blade had fallen and it was leaning on the rudder horn as well as on the hydraulic pipes of the Jastram-rotor (the thick grey line), Figure 10a. The rudder angle of the broken rudder was 45 degrees to the left during the diver's innspections.

An expert from the Technical Research Centre of Finland identified the cause as *a fatigue breakage* on the basis of how the fracture plane of the shaft looked like, Figure 10b.

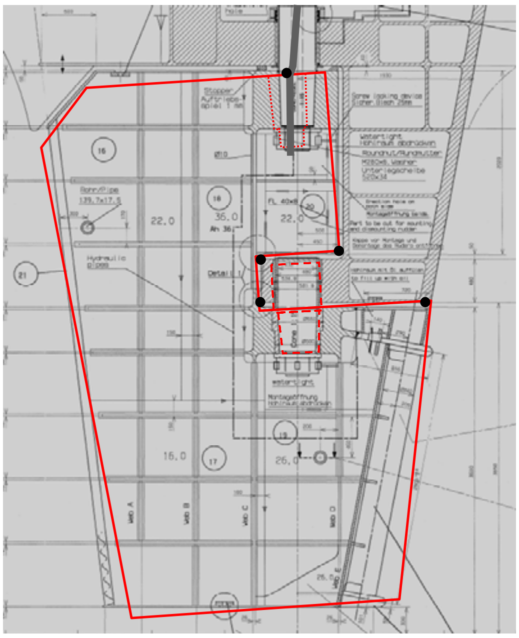


Figure 10a. An estimation of the position of the SB rudder (if the rudder is midships) after the rudder shaft was broken. It was inclined approx. 3-4 degrees lengthwise. The black spots illustrate the possible supporting spots after the rudder shaft was broken.

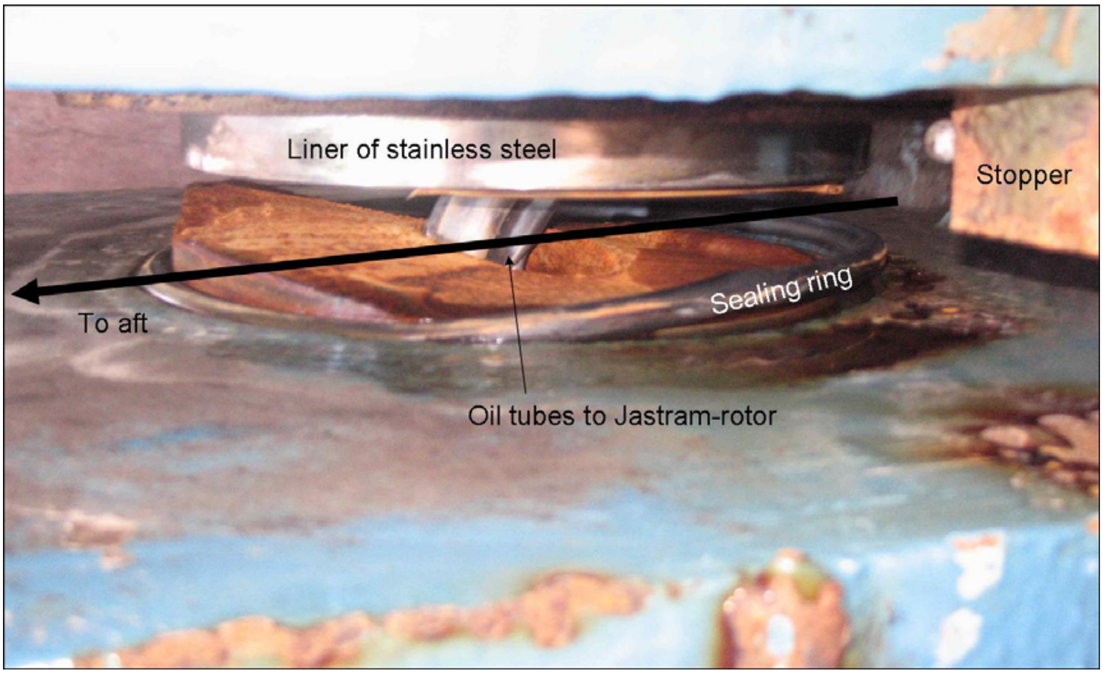


Figure10b. The broken SB rudder shaft photographed in Riga on 28 November 2009. The rudder had dropped downwards approx. 5 cm and moved a little bit afterwards. The tubes going to the Jastram-rotor can be seen in the middle of the picture. The rudder is midships and the arrow points to the stern.

The epoxy filling cast in the 2004 repair as well as the screws had disappeared altogether from the SB side and partly from the BB side. The bronze bush of the SB side pintle bearing had dropped 130–140 mm and was now leaning to the rudder, Figure 11.

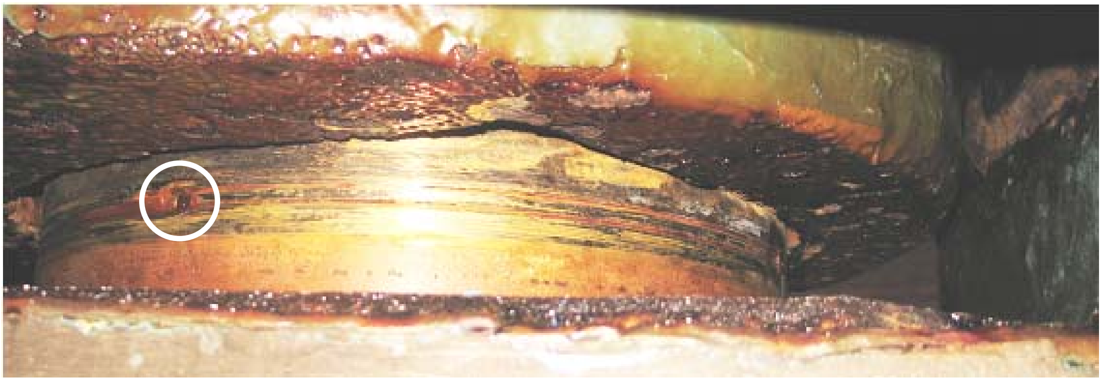


Figure 11. SB pintle bearing photographed on 2 December 2009 in such a way that the gap from which the epoxy has disappeared is visible. The inner side, the direction of the bow is to port. One of the installation screws of the bush has been marked with a white circle.

One of the screws used in connection with the installation of the epoxy casting in 2004 can be seen as broken in Figure 11. The screw area of the bush has become visible when the rudder has fallen down the distance allowed by the gap above the horn. In addition, several fretting cracks were discovered in the upper part of the cone and several cracks were found in the rudders and rudder horns. The surfaces of the rudders have corroded in places, Figures 12 and 13.

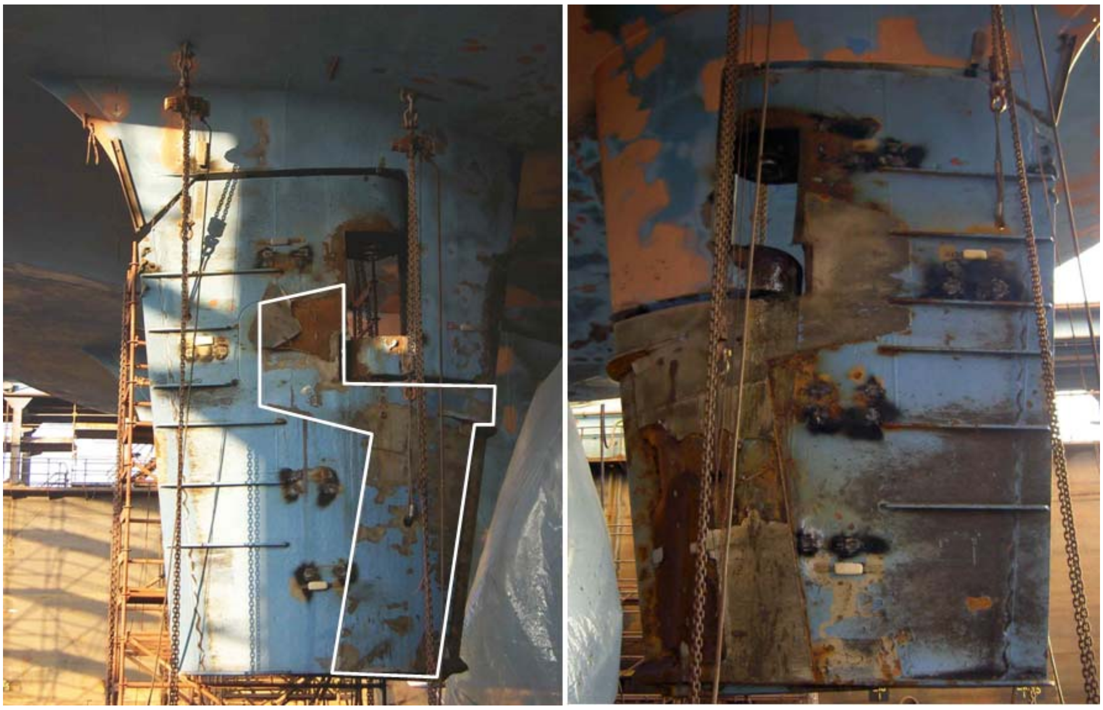


Figure 12. SB rudder in Gdansk on 3 December 2009. The picture to the left shows the outside, the picture to the right the inside. On the area indicated by the white line there was a coating made of stainless steel plate on both surfaces of the rudder.

The area coated with stainless steel plate has been indicated by the white line in Figure 12. There was coating on all the four surfaces. The state of the rudder had been quite similar even earlier.

Both horns had severe corrosion caused by cavitation on the side of midships. The upper part of the corroded places were so deep that the durability of the horn was jeopardized, Figure 13.

Figure 13. Cavitation corrosion in the rudder horn. BB to the left (photo taken on 3 December 2009), SB to the right (photo taken by the Finnish Transport Safety Agency on 4 December 2009), both on the side of midships.

1.4 Rescue and alerting activities

No alert was given, and the Archipelago VTS was informed of the situation. A passenger had informed the MRCC of the situation; the MRCC contacted the vessel. The Master estimated that the situation did not require any other rescue activities in addition to tug assistance; the vessel was manoeuvrable and seaworthy. The Master did not deem it necessary to start evacuating the passengers because the vessel was intact and it was possible to steer it. The passengers were informed of the situation and how it evolved.

1.5 Accident safety investigation

The damage, *the breaking of the SB rudder shaft* causing an emergency situation took place in a narrow and winding channel with busy traffic. There were altogether approx. 1660 persons onboard the vessel and also cargo classified as dangerous. Reduced manoeuvrability in the middle of demanding turns may result in the vessel drifting off the channel with high speed and in a grounding or collision. It should, however, be noted that one of the two rudders is only one of the several appliances used in the manoeuvring of the vessel.

It is very rare that a rudder shaft breaks. This has not happened in Finland, and the classification societies had information about only two incidents like this[14]. Rudder shafts are not removed for inspection during dockings[15]. On the basis of the aforementioned, it has been deemed necessary to execute a very extensive safety investigation. The in-

[14] Det Norske Veritas, Casualty Information 2/00, corrosion had been stated as the reason for the breaking. E-mail from Bureau Veritas on 31 May 2011; the shaft had broken when the vessel was operational.

[15] The rules of Bureau Veritas state among other things, that visible parts of rudder shaft are inspected regularly. If considered necessary by the Surveyor, the rudder is to be lifted or the inspection plates removed for the examination of pintles. (Statement of Bureau Veritas on Draft Report, appendix 1 of the investigation report). Note that those paragraphs include nothing about the removing of the rudder shaft.

vestigation was also first of its kind, which means that there was no model available for it nor was there any ready idea on the possible causes which led to the incident.

The contents of the safety investigation comprised the following:

1. Finding out the history of the vessel and the measures taken concerning the rudders.
2. Collection and analysis of VDR data.
3. Examination of the rudder and its parts after the accident.
4. Evaluation of the forces having an effect on the rudders.
5. Determination of the fatigue life of the rudder shafts.
6. Assessment of the handling of the accident situation.
7. Evaluation of the production and repair processes of the rudder.

The descriptions of these topics and the results are presented in Chapters 1.5.1–1.9 of this investigation report.

1.5.1 History of the vessel and its rudders

On the basis of the information received on the operating of the vessel, the steering gear had not had extra stresses caused e.g. by a ground touching. Instead, ice loads had strained the rudder in the wintertime.

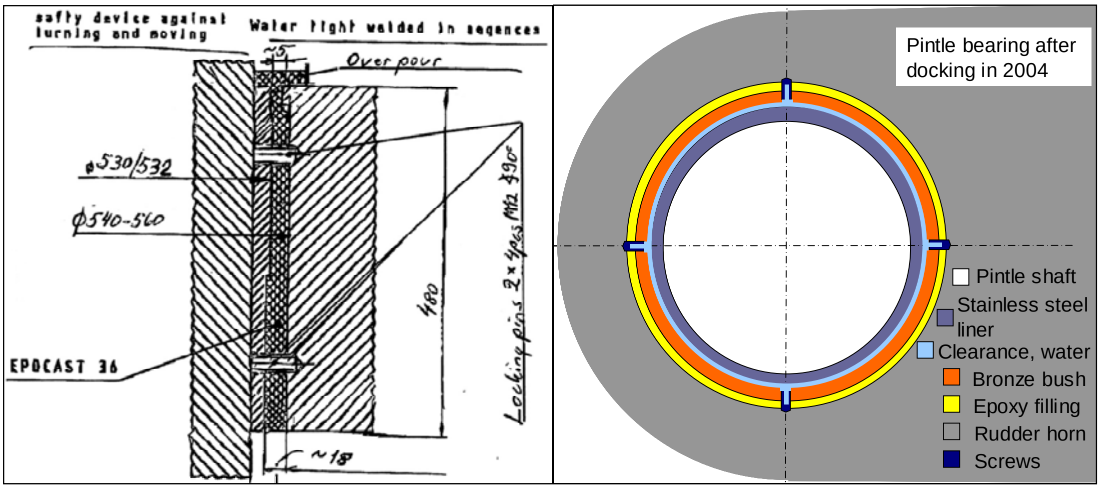
Table 1. The distribution of the vessel's routes 1993–2004 and 2004–2009.

	1993–2004		2004–2009	
Route	**months**	**%**	**months**	**%**
Turku-Mariehamn-Stockholm	54	26.9	0	0
Helsinki-Mariehamn-Stockholm	0	0	1.5	0.7
Helsinki-Stockholm	22	10.9	0	0
Turku-Mariehamn/Långnäs-Stockholm	36	17.9	39.5	19.7
Turku-Mariehamn/Långnäs-Kapellskär	37.5	18.7	10.5	5.2
TOTAL	149.5	74.4	51.5	25.6

The dockings and the inspections, the maintenance and reparations of the steering gear during the vessel's 17-year-long operating history have been established in the investigation. The dockings in connection of which the clearances were measured can be seen in Table 2. The results from clearance measurements are presented in Figure 15. This abridged version of the investigation report only presents in detail the measures in connection with the 2004 and 2007 dockings, because the repairing of the pintle bearing in 2004 had a significant effect on the breaking of the SB rudder shaft and because the state of the repair was examined in 2007. The docking in 2009 is mainly illustrated with the help of pictures.

Turku Repair Yard 30.8–8.9.2004. The vessel had with her new slabs for the bronze bushes of the pintle bearing probably because of the increased clearances detected in the 2002 docking[16]. The bronze bushes of the pintle bearings of both rudders had dropped approx. 50 mm. All clamping screws from the upper edge had disappeared. It was discovered that the clearances had increased and that they now exceeded the limit allowed by the classification society. The clearance measurement was carried out in such a way that the wear on the pintle shaft and on (the inner surface of) the bronze bush were measured. The whole extent of corrosion was probably not detected in the clearance measurements. It was discovered by measuring the opening of the pintle bearing housing[17]. The opening proved to be too large for only the bush. The opening was not circular. Because of the short time reserved for the docking, such a solution was proposed to settle the matter which could be realised time-wise. A surface welding of the housing and reaming after that were not an option. It was decided that the corrosion was to be filled with Epocast-brand cast epoxy, which is commonly used when mounting machineries, Figures 14a and 14b. The repair shipyard had previously not used this repair method for vessels of SILJA EUROPA- size.

The planning of the epoxy casting took a couple of days and the planning was done by exchanging execution schemes by fax between the supplier of the epoxy material, the performer of the epoxy casting and the shipping company. At the same time a representative from the classification society was conferred. It has not come to the investigators' knowledge that the strength and durability of the repair would have been assessed by calculations.



Figures 14a and b. Casting drawing of the epoxy mass (a, to the left) and a cross cutting of the pintle bearing (b, to the right) in the 2004 docking. The hex sockets of the screws have been drawn in the picture. The sockets filled with water.

16 In the work order list of the shipping yard, number 5100 was: "replacing of the SB/BB bearings of the rudder pins by dismounting the rudders".

17 A specialist from Kvaerner Masa Yards completed the measuring as well as the alignment of the shaft.

After dropping 50 mm the bronze bush had rotated in the housing for so long that an approx. 7-mm edge had formed in the upper part at the height of 50 mm. The opening of the horn was made somewhat more even and larger by grinding. Three holes were made in the upper part for the epoxy casting. The bronze bushes of both pintle bearings were badly worn and they were replaced with new ones which did not have only one notch but several approx. 1 mm notches, see Figures 23a and 23b. Both surfaces of the bushes had probably been machine-tooled (ground) and they had not been cleaned.

Epoxy mass (Epocast 36[18]) was cast in the hole between the bronze bush and the housing from above in such a way that a brim was formed, Figures 14a and 14b and 5c. There was a counterpart at the bottom during the casting. For centring the bronze bush, hexagonal socket-head screws going through the bush and epoxy were used, see Figures 14a and 14b.

The classification society wrote the Memorandum No 5, which meant that the repairing was meant to be permanent and made known to the shipping company.

The hull areas (the surface of the cast iron) around the upper bearings of the rudder shafts were inspected from outside with magnetic powder[19]. No damages were detected; however new sealings of the upper bearings were installed. The inspection did not include the rudder shafts.

Turku Repair Yard 21–25.1.2007. The clearances were measured and found out to fulfil the requirements but the rudder was fully turned inwards and the measuring results are thus not comparable. Classification society's surveyor has told that he checked the condition of the lower edge of the pintle bearing by using a pocketknife, a mirror and his finger. Because of the cramped space, the inspection reached 270–300 around the bearing. The epoxy casting seemed to be intact, there were no visible cracks and nothing came loose when the knife was used.

Remontowa, Gdansk, 30.11–18.12.2009. The SB rudder shaft was broken and cracks were discovered in the upper part of the conical part of the BB rudder shaft. Cracks were also discovered on the rudders, on the rudder horn and above the rudder horn. The epoxy was entirely missing from the SB side pintle bearing, from the BB side bearing partly. When loosening the BB side bronze bush, some of the epoxy remained attached to the housing.

The pintle bearing housings were repaired by surface-welding several layers in the hole. Finally, the inside was reamed to meet the dimensions of the new bronze bush and the outside was sanded down.

[18] H.A.Springer marine + industrie service GmbH trade name. Two-component. In distinction from corresponding products which are spread, the term "cast epoxy" is used. If there is no danger of confusion, the short form "epoxy" has also been used.

[19] Inspection protocoll, Inspecta Oy 2.9.2004 about inspection by magnetic powder. Surface condition "cast, pre-cleaning by sandblasting".

1.5.2 Bearing clearances and the free play of the pintle bearing

Bearing clearance (in brief clearance) stands for the difference of the inner diameter of the bush and the diameter of the shaft. The free play of the pintle bearing is formed by half of a clearance added with the possible free play allowed by the gap between the outer surface of the bush and the wall of the housing. The gap can be caused e.g. by corrosion.

Clearance measurements are normally carried out while the rudder is midships lengthwise and transversally on four points on the lower edge of the bearing. The distance between the points is 90 degrees ("aft-fore" longitudinal and "SB-BB" crosswise). **The technique used when measuring the clearance** carries great significance as to the reliability and interpretation of the results. *A feeler gauge* is used to determine the dimensions of the gap between the liner and the bush (stainless steel and bronze) at the measurement point at the lower edge of the bearing. The clearance is the total of the gaps measured from opposite sides.

Another common technique for the measuring clearances is *jacking or lifting tackle*. The rudder is pushed by using a jack (or pulled by using a tackle) till the stainless steel bush touches the bronze bush, i.e. the movement ends. The dislocation is read in the dial gauge. The total of the dislocations measured in the opposite directions constitutes the clearance.

Pintle bearing. The measurement results and the time intervals between the dockings are presented in Table 2. The pintle clearances have most often been measured at the lower edge of the bearing by using a feeler gauge, but jacking may also have been used. In most cases there is no certainty about the measurement technique. The techniques presented in the table are the investigators' assumptions which are based on the held discussions. The measurement techniques presumed certain are marked with grey.

Table 2. The dockings of the vessel and the measuring of the pintle bearing clearances[20]. As to the years 2004 and 2009, the measurement results are shown both before and after the repairing.

Date	Docking interval, months	Pintle clearances				Shipyard	Docking duration, days	Measuring technique
		BB-pintle		SB-pintle				
		crosswards	longitudinal	crosswards	longitudinal			
1.9.92		1.90	1.80	1.80	1.80	Meyerwerf		feeler gauge
3.9.93		1.80	1.95	1.80	1.95	Vuosaari/Kotka Shipyard	8	feeler gauge
16.1.95	16.4	2.05	1.80	2.15	1.65	Turku Repair Yard	5	jack/f-gauge
5.9.95	7.6	1.95	1.85	1.95	1.80	Vuosaari/Kotka Shipyard	5	feeler gauge
1.9.97	23.9	***2.20***	*2.00*	***1.25***	*1.35*	Turku Repair Yard	5	feeler gauge
18.1.00	28.6	2.15	2.10	2.60	2.00	Finnyards, Rauma	11	jack/f-gauge
4.9.02	31.5	3.25	3.40	3.30	3.20	Helsinki Repair Yard	6	feeler gauge
4.9.04	24.0	4.32	4.02	4.57	3.82	Turku Repair Yard		bush-shaft
8.9.04		2.57	2.20	2.44	2.20	Turku Repair Yard	10	bush-shaft
25.1.07	28.6	***1.30***	-	***1.60***	-	Turku Repair Yard	5	feeler gauge
4.12.09	34.3	4.43	3.80	3.42	2.13	Remontowa, Gdansk		bush-shaft
17.12.09		1.80	1.80	1.80	1.75	Remontowa, Gdansk	20	bush-shaft

[20] Italics has been used to indicate unreliable measurings, and the ones indicated with bold have been included in the picture.

The measured pintle bearing clearances crosswise and some limit values for the clearance have been presented in Figure 15. It has not been possible to verify the comparability of the clearance measurements made at different points of time in the investigation. In practice the bronze bushes are replaced if the clearance clearly exceeds 2 mm.

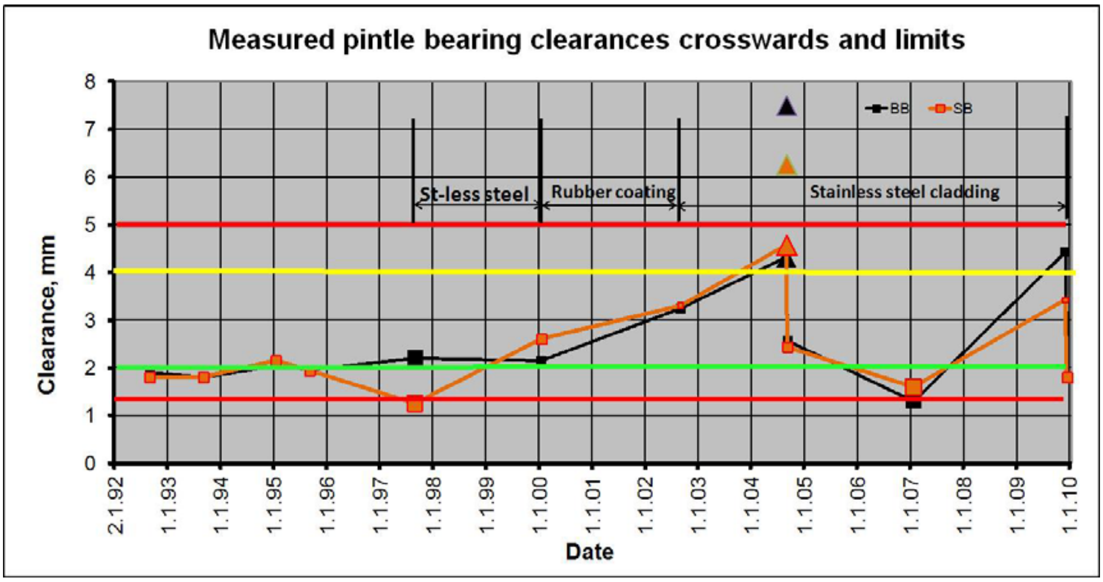


Figure 15. *Pintle clearance measurements, corresponds with Table 2. The measurements in which the rudder has been turned to the side are indicated with a larger square. The highest clearance measurement results have been obtained as the difference between the inside diameter of the bronze bush and the diameter of the pintle shaft, so they are the most accurate results. The green line presents a common, acceptable clearance of 2 mm, the yellow line the action limit of the classification society and the red line the absolute lower and upper limits for the dimensions corresponding to those of the SILJA EUROPAs rudder shaft. The time intervals for the different coatings have also been shown.*

From the point of view of the bending of the rudder shaft, *the corrosion of the pintle bearing* had a crucial impact in the SILJA EUROPA case. The corrosion multiplied the deflection made possible by the clearance. The corrosion was caused by galvanic corrosion. The corrosion almost stopped after the 2004 reparations. In Figure 16 the corrosion has been presumed so extensive that the bush has dropped. The situation was like this when the vessel came to the dock in 2004. The theoretical amount of the pintle shaft to move horizontally is henceforth referred to as *free play.* It varies at the different height of the pintle bearing and at the different points on the bearing race. The pintle shaft moves crosswise approx. 8 times per second, which makes the water move in the clearance and in the corroded space (and after 2004 in the hex sockets of the screws) thus accelerating the corrosion.

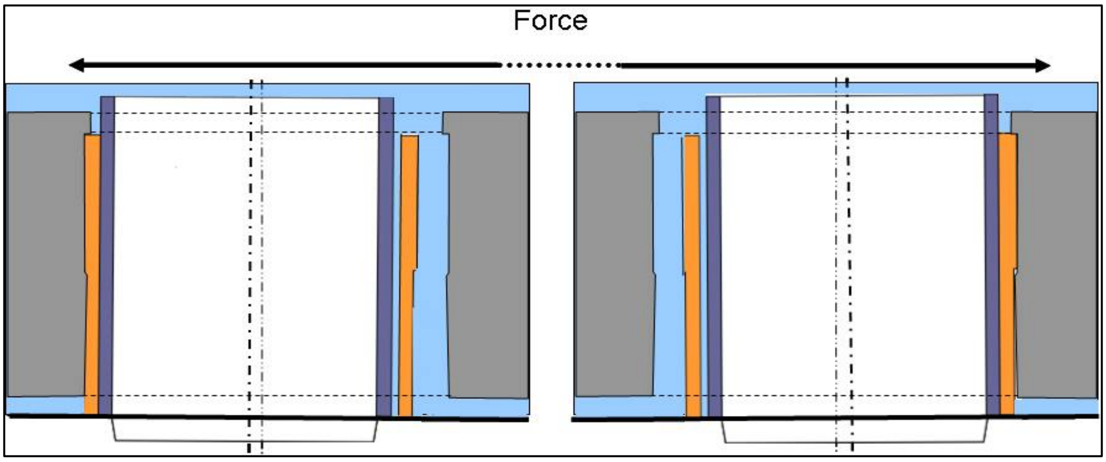


Figure 16. The pintle bearing seen from astern. On the left the rudder shaft has bent to port and on the right to starboard. The pintle shaft and the dropped bush move ±15 mm from one side to the other because of the corrosion of the housing. At the same time the rudder tilts. The height of the housing is 480 mm and the diameter of the bearing is 533 mm.

When the oval form of the cross cutting of the pintle housing and the inequalities of the surfaces are taken into consideration, we reach the concept of "***net free play***" giving a realistic free play.

By combining the measurement results presented above and the estimates on the progress of the corrosion, the investigation has come to the following view on the development of the net free play of the pintle bearings, Figures 17a and 17b. Broken lines have been used to indicate the estimated uncertainty area.

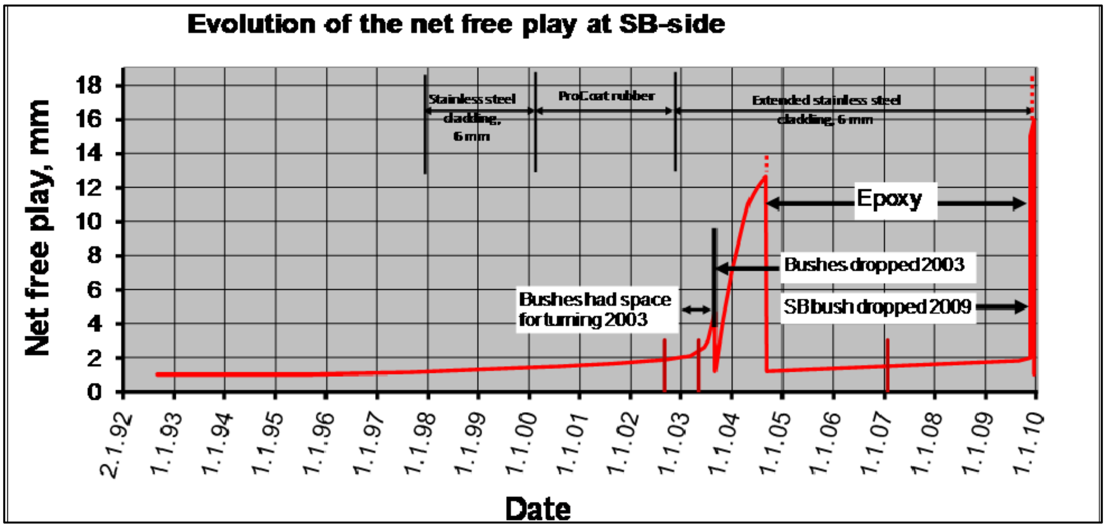


Figure 17a. An estimate on the evolution of the ***net free play*** *of the SB pintle bearing. When the bush dropped in 2009, it is presumed that there was still epoxy left in its place. When the epoxy disappeared, the net free play increased erratically. The broken line shows the maximum estimate. The dockings in 2002, 2003 (clearances not controlled) and 2007 (the clearance measurement was not comparable) have been indicated with a brown vertical line.*

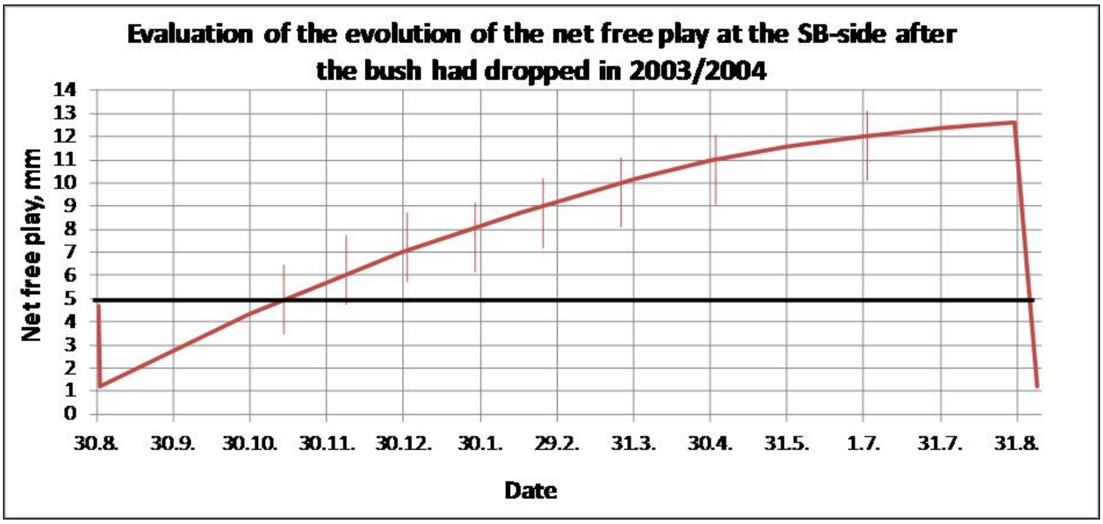


*Figure 17b. An estimate on the development of **net free play** specified on the basis of Figure 17a. The vertical lines in the figure have been used to assess the duration of each net free play over 5 mm with the interval of one mm. It has been estimated in the investigation that the BB bush might have dropped a bit earlier.*

Figure 17b presents also the approximate limit value of the net free play (about 5 mm) specified on the basis of fatigue calculations. Below this net free play limit the cyclic stress is at fatigue limit[21].

The most important structures of the pintle bearings defined on the basis of measurements carried out crosswise at different points of time are presented in Figure 18.

[21] Fatigue limit, used in fatigue damage assessment, is the limiting value of experimentally for various materials determined cyclic stress at which a failure occurs as number of cycles becomes very large, more than one million in case of steel. Many materials, e.g. aluminum do not have fatigue limit.

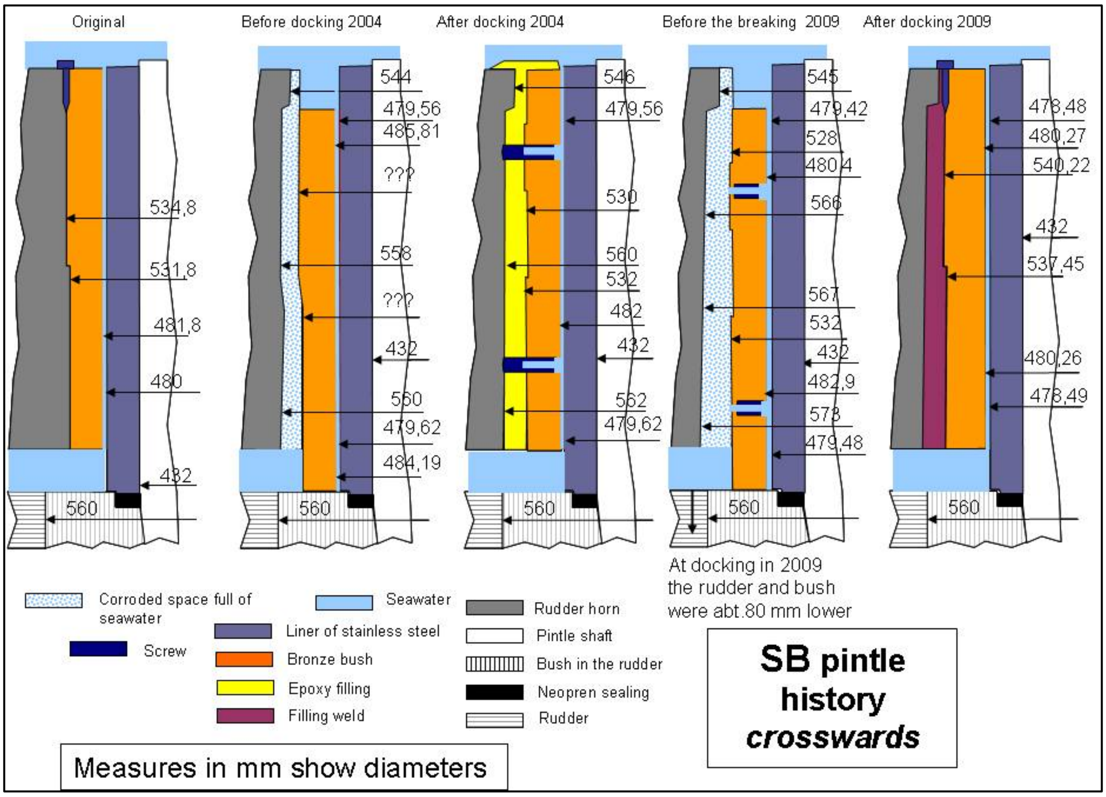


Figure 18. Some crosswise measurement results of the SB pintle bearing.

When compiling the picture it was presumed that the bend at the wall of the housing, which was caused by the notch of the bush, was grinded off in 2004 and the wall was made more even also elsewhere in which case approx. 1-2 mm of material was removed.

Until approx. **the summer of 2003**, the free play slowly increased merely due to corrosion. After that the bushes might have rotated, in the beginning a little and finally full revolutions. The rotation wore the corrosion rust and this accelerated significantly the increase of free play. In the end there was so much room around the housing that the bushes dropped.

When the bush dropped, the net free play in Figure 17a decreased to the size of the half of the clearance, because there was a counter notch for the bush in the wall of the housing. The bushes were still rotating, which kept the growth rate of the free play high. At a later point the wear became somewhat slower because when the free play was larger, only the highest rudder forces caused so large bend that the bush of the pintle bearing could touch the wall of the housing. The net free play was 12–13 mm at its largest.

The SB bronze bush dropped because of the further corrosion of a couple of millimetres which had evolved by **the year of 2009** and because of the breaking of the screws. The free play remained, however, small, because there was probably still cast epoxy in certain places in the housing. After the epoxy had come off entirely, the free play increased **abruptly to the value of 16–18 mm (clearance 32–36 mm).**

In Gdansk the situation was restored to correspond with the original structure in such a way that the thickness of the bronze bush was increased to approx. 2.5 mm, its inside diameter was machined to 480.3 mm and the thickness of the pintle bearing to 478.5 mm.

1.5.3 The free play of the pintle bearing and the stresses to the rudder shaft

The effect of the free play on the bending stress of the rudder shaft has been examined approximately with the help of the beam model of the rudder, Figure 19. The critical point of the rudder shaft is in the lower part of the upper bearing, where the stress is at its highest and where the breaking takes place.

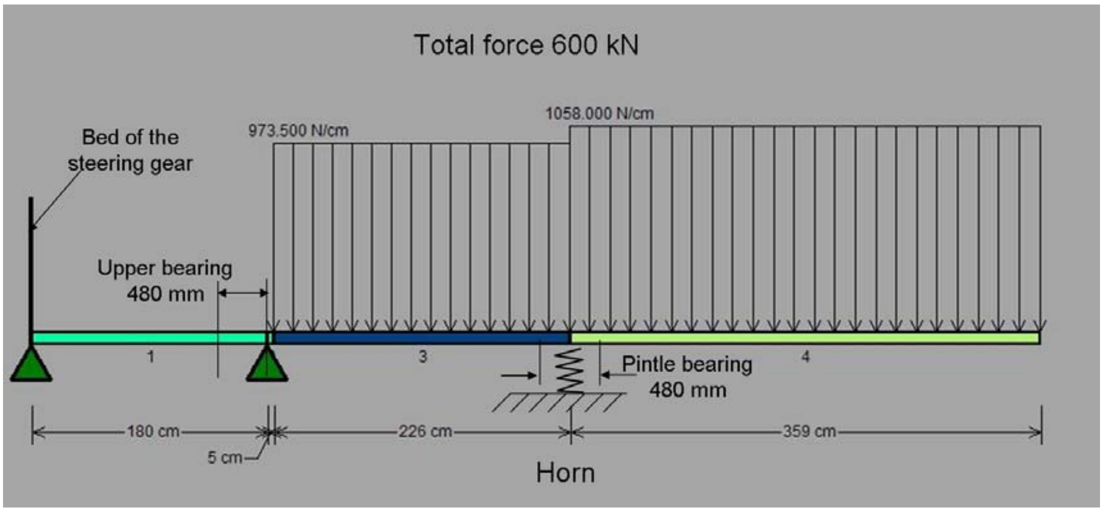


Figure 19. The beam model used in the study of the rudder. The different parts of the beam have been shown with different colours, because the second moment of inertia and the section modulus of the different parts are different. The mounting is of the pin support type at the steering gear thus fulfilling the requirements of the classification society. In reality the mounting was somewhat stiffer.

Figure 20 shows how the bending stress of the rudder shaft depends on the bending force. The blue, thick curve corresponds with the situation in which the beam formed by the rudder shaft and the rudder bends as a cantilever beam, without the support provided by the rudder horn. When the yield strength of the rudder is exceeded, the situation becomes approximate and therefore there are two limit curves in the figure[22]. The point in which the horn begins to support has also been marked in the figure with the interval of one millimetre of the net free play. The increase of the stress along with the increase of force slows down when the horn enters the picture.

[22] The duration of the maximum stresses of rudder shaft caused by the changes in the forces bending the rudder is so short that the stress can exceed the yield strength obtained from a standard drawing test.

The design force corresponding with the design formulae of the classification society is approx. 1,700 kN. In the figure the situation has been shown only till 1000 kN, because very high forces are rare exceptions.

It is presumed that torsional stress only depends to a small extent on the clearances of the pintle and upper bearings, which means that its relative proportion decreases as the bending stress increases. The mean torsional stress is approx. 3-5 N/mm^2 to each 100 kN of the rudder force.

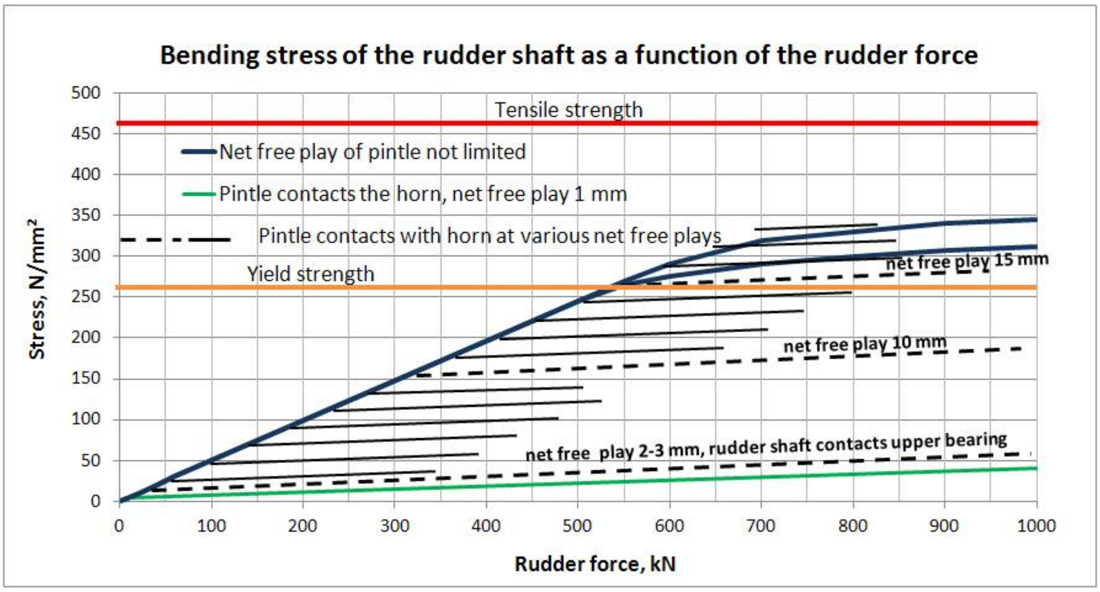


*Figure 20. The dependence of the **bending** stress of an **intact** rudder shaft on the rudder forces with different net free plays of the pintle bearing. The stress increases when the rudder force increases in accordance with the blue, thick curve until the pintle bearing leans on the horn. After that the stress increases slowly. After the stress exceeds the yield strength, the situation is so undefined that only estimated limit curves have been presented.*

At the point of the upper bearing, the rudder shaft is affected by a shearing force. The stress generated by the shearing force is minor when the pintle bearing is in working order. In practice, even with large net free plays for the pintle bearing the decisive factor is the combined stress which is formed by torsion and bending and which has been used in the calculations.

1.5.4 Collection and analysis of the VDR data

The VDR equipment has registered three kinds of information: numerical information registered with the interval of one second, pictures from the Conning display registered with the interval of 25 seconds and from the radar display with the interval of 15 seconds, and the discussions on the bridge as well as the communication with the vessels in vicinity and with the VTS. This information has been used for the following purposes:

- The simulation model for steering was used to calculate the rudder forces[23]. These forces were used to determine the quantity and direction of the forces bending the rudder shaft. The bending forces combined with the speeds and revolutions were used as the basis for frequency statistics.
- The changes in the rudder angles, the turning speed and the position of the vessel a couple of hours before the vessel was stopped were compared to the corresponding information from the same point of the route a couple of weeks before the accident when the shaft could still be presumed to have been intact. This was done in order to try to estimate the breaking time and position of the shaft.
- The vessel’s position information was used to determine the vessel's route during the couple of hours before it was stopped and to draw the route on a chart template. The result was compared to the intended route[24].
- The picture and voice registrations were used to assess the activities of the bridge personnel.

Three intervals were chosen to be used to describe the whole history of the vessel:

1. From Mariehamn to the Teili open sea area till 21.20 on 22 November 2009.
2. From Mariehamn to Stockholm and back to Mariehamn 21–22 November 2009.
3. A couple of voyages from Turku to Stockholm and back with the interval of approx. two weeks on 29 October – 1 November 2009 and 8–11 November 2009.

The history information presented in the curves compiled on the basis of the VDR data was not available on the bridge; the displays only presented data one moment at a time.

1.5.5 Investigation of the rudders – the factors leading to fatigue failure

The rudder shafts, the bronze bushes of the pintle bearings with their screws and pieces of epoxy were sent to the Technical Research Centre of Finland for more detailed investigation. The main part of the research of metallic parts carried out by the Technical Research Centre of Finland is available in the report[25] which is filed at the Safety investigation Authority of Finland. A magnetic particle testing was carried out on the rudder shafts. The outer surface of the fractured surfaces of the broken rudder shaft was examined at the Technical Research Centre of Finland by using a stereo microscope, and

[23] Simulco Oy
[24] Simulco Oy
[25] Technical Research Centre of Finland, report VTT-R-0222-10.

metallographic test samples were made of the shaft and then studied by using a light microscope. Cracks found on the broken shaft outside the breaking point were opened and the opened fractured surfaces were studied by using a scanning electron microscope (SEM). The composition of the material of the broken shaft was defined by using an optical emission spectrometer. The hardness of the steel used in the shafts, of the bronze bushes and of the mounting screws used in 2004 was measured and the hardness of the material used in the pintle bearing housing was assessed in the Vickers units. Two test bars were made on the broken shaft and tensile strength tests were carried out on them. The most important findings are compiled below.

Fractured surfaces. When studying the fractured surfaces of the broken shaft (Figure 21), a 0.3-mm sharp-corned notch was found at the point where the cone turns into cylinder (Figure 22). It is estimated that the notch carried a significant notch effect which weakened the fatigue endurance. This point around the shaft mainly follows smoothly the brim of the fractured surface. *Arches portraying the progress of the breakage*, stopping marks ("growth rings") caused by bending fatigue can be seen on the surfaces. On the basis of the appearance of the fractured surface it could also be concluded that the final stage of the breaking had been *a cleavage fracture*[26] and that the SB rudder had been turned a couple of degrees inwards at the time of the breaking.

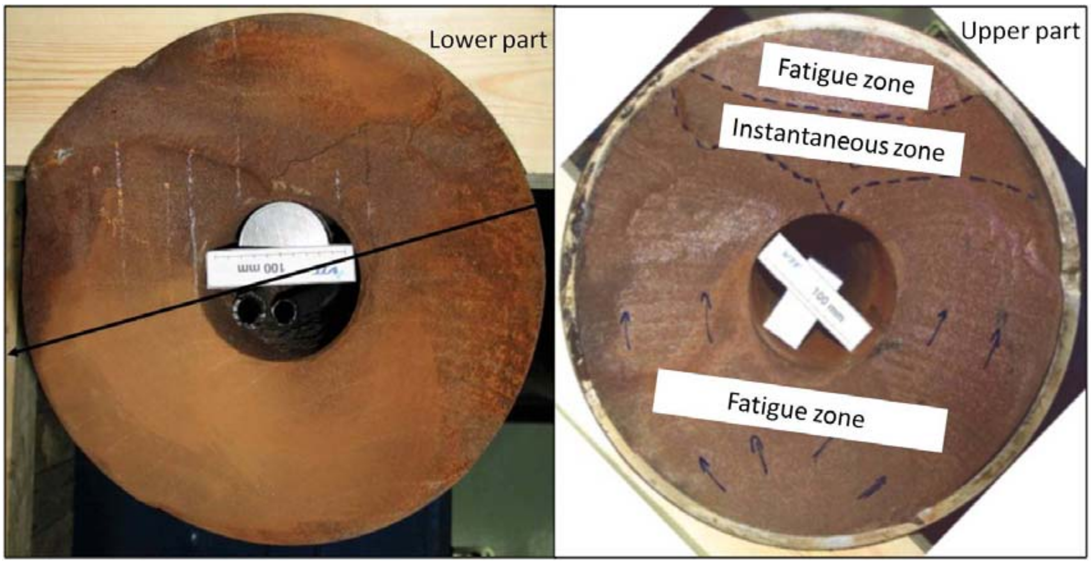


Figure 21. The upper part of the broken shaft to the right and the lower part to the left. There is still a liner made of stainless steel on the upper part on the shaft. The limits of the fatigue and final breaking have been drawn on the upper part. The direction to the aft when the rudder is midships has been marked on the lower part. An attempt has been made to place the halves in a position corresponding one another. Pictures by the Technical Research Centre of Finland.

[26] A cleavage fracture is a sudden brittle failure, which is affected by temperature, notches, weld joints, loading rate and the susceptibility of steel to suffer from a cleavage fracture (measured with a toughness test in order to determine the grade of steel). Once a breakage has started, it does not stop unless there is a significant change in the circumstances.

According to the casting mould assessment by the Technical Research Centre of Finland, the notch point of the BB shaft corresponds to Figure 22 after the 0.2 mm machining performed in Gdansk. *It has not been possible to find out the shape of the original notch.* It cannot be excluded that there was a similar sharp notch in the BB shaft as there was in the SB shaft. The corresponding point on the extra shaft close by, which was then brought into use, is shown to the right in Figure 22.

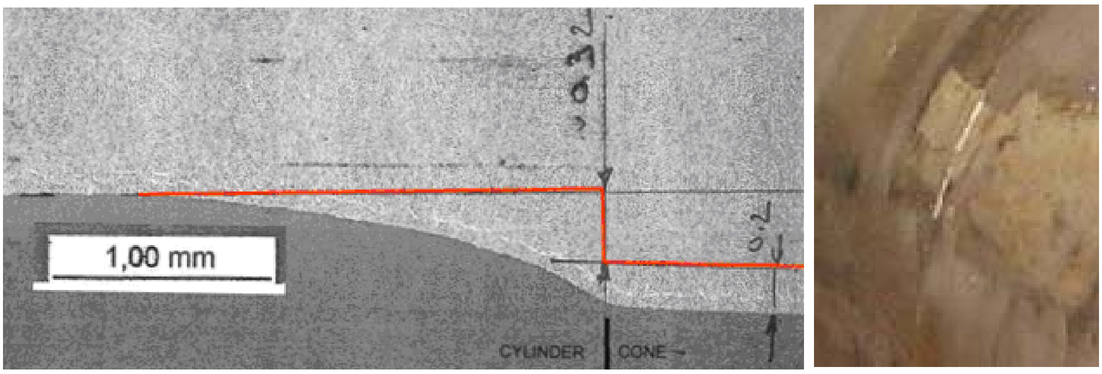


Figure 22. To the left the profile of the "intact" (BB) rudder shaft at the point of the notch (modified on the basis of the report by the Technical Research Centre of Finland) and to the right the notch point of the extra shaft. 0.2 mm was machined off the cone of the "intact" shaft so it is uncertain what the original profile of the notch looked like. The red line shows the profile of the broken shaft.

There was a thicker point on the upper edge of the pintle bearing housing at the height of approx. 50 mm; it was approx. 10 mm thick. There were three dents of the width of approx. 40 mm there. The thicker point (without the dents and somewhat lower) was already there in the 2004 docking. It is presumed that it was generated by the dropped bronze bush as it wore the corrosive waste which had been accumulated in the housing when the bush rotated, Figures 23a and 23b.

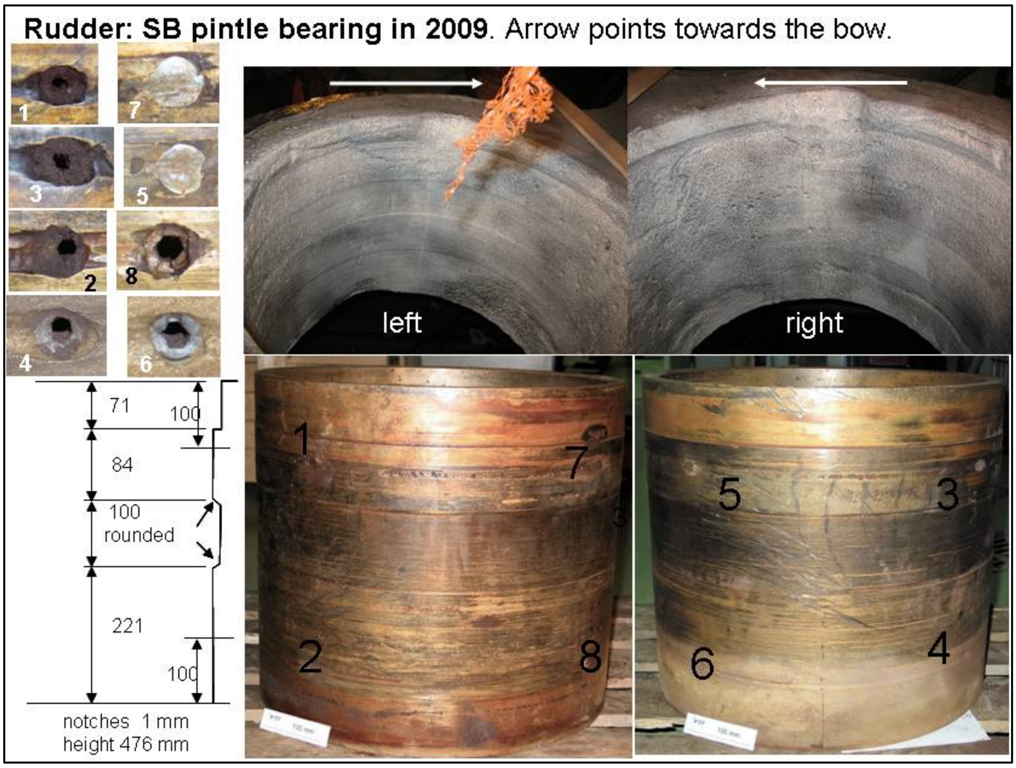


Figure 23a. The SB pintle bearing. Pictures of the housing by the shipyard, of the bush by the Technical Research Centre of Finland.

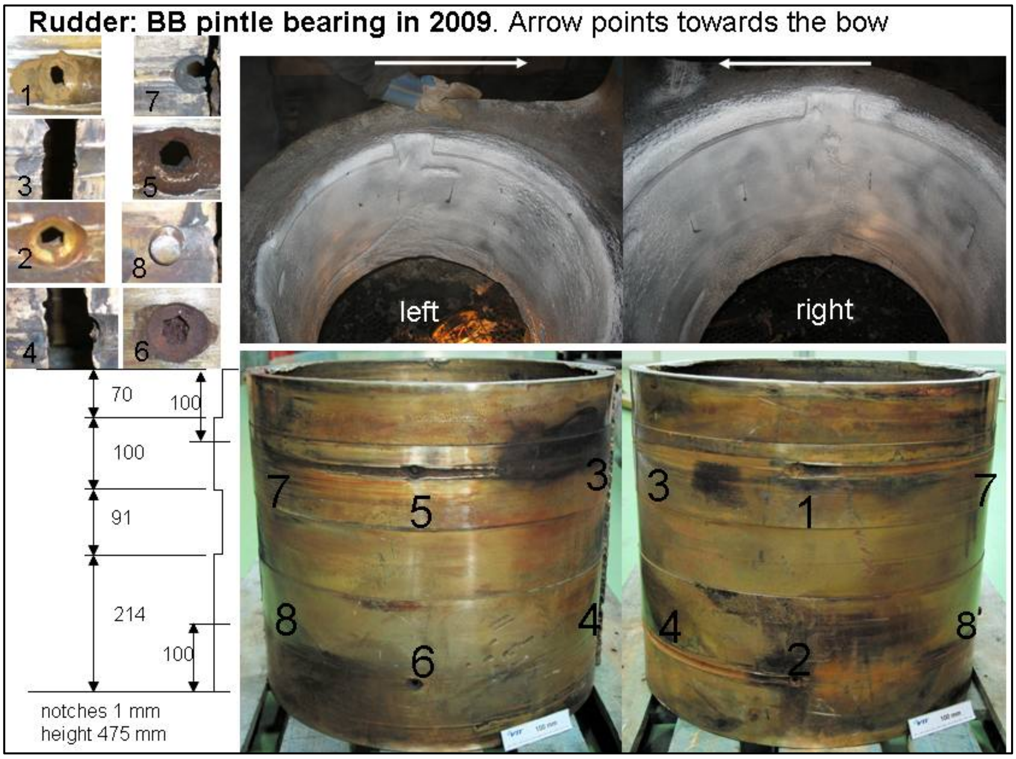


Figure 23b. The BB pintle bearing. Pictures of the housing by the shipyard, of the bush by the Technical Research Centre of Finland.

On the wall of the SB housing one may notice tracks corresponding to the notches of the bush, which tells about the rotation of the bush after the epoxy fell off. Scratches generated by the screws are visible on the wall of the housing and on the outer surface of the bush.

In the BB pintle bearing the cast epoxy remains mainly in its place. At the lower part of the pintle bearing the epoxy has come off from an area of approx. 120 degrees, at some points from the depth of over 20 cm. Figure 24 shows the gaps between the epoxy and the bush and between the epoxy and the housing.

Figure 24. Epoxy which has partly come off on the BB pintle bearing. The thin gaps between on one hand the epoxy and the housing and on the other hand between the epoxy and the bronze bush are clearly visible. Picture taken on 3 December 2009.

The surfaces of the bushes on the side of the cast epoxy were found to be smooth except the scratches mentioned above. The bushes had been centred with screws for the duration of the casting of the epoxy without any particular removal of the machining liquid, which made the adhesion between the epoxy and the bush weak. This also led to the possibility that water could enter between the bush and the epoxy quite soon after the docking in 2004.

Flamecutting had to be used in order to remove the BB bronze bush even though it had had room to rotate. Apparently the screws stopped it from dropping off. Both bushes have rotated at some point, evidently against the epoxy. Pieces of screws have probably stuck in the cast epoxy and grooved the bush, Figures 23a and 23b.

The screws. Hexagonal socket-head screws M16 had been used during the installation of bushes in 2004 in order to keep the bush in the correct position during the casting of the epoxy. The screws penetrated the bush and the epoxy and reached the wall of the housing, where a hollow had been made possibly for the screws.

Properties of the cast epoxy. In connection with the dismounting of the bush, it was possible to put aside some pieces of the cast epoxy. Two pieces were sent to the Technical Research Centre of Finland for a more detailed study. In addition, the Centre got epoxy and hardening agent for performing a test casting from the company which had done the casting[27]. The values received from the test pieces have for the main part been close to the values given by the manufacturer, and the casting as such can be regarded as successful.

1.5.6 Corrosion of the pintle bearing

The structure of the vessel's pintle bearing is unfavourable considering the danger of galvanic corrosion, because bronze is unprotected in a seawater electrolyte in immediate contact with cast iron, Figures 5a, 5b and 25.

Only the lower edge of the pintle bearing is shown in the figure; the corresponding point on the upper edge on the SILJA EUROPA was unprotected but shown protected in the alternatives.

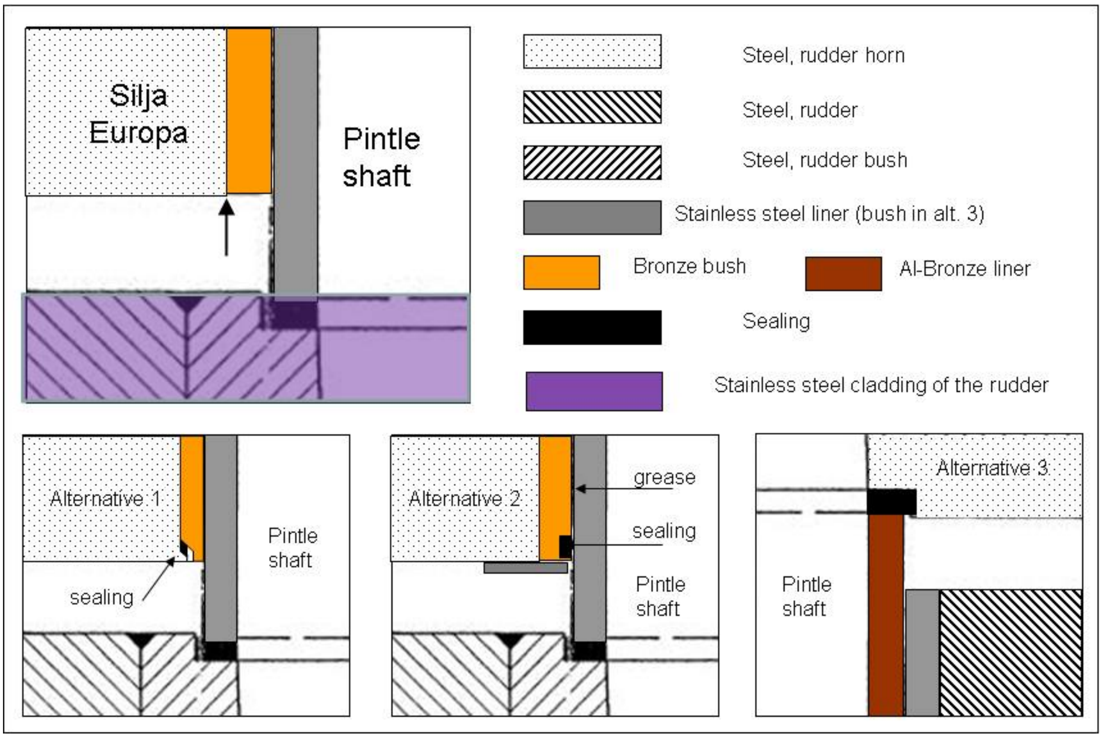


Figure 25. The structure of the lower edge of the pintle bearing of the SILJA EUROPA and alternative structures used on other vessels. The extent of the coating of the SILJA EUROPA's rudder has been presented in Figure 12. Alternative 1 is the one most commonly used, for instance on the SILJA SERENADE and the SILJA SYMPHONY.

[27] Technical Research Centre of Finland, report VTT-S-09524-10.

1.5.7 Rudder vibration

In addition to the rudder force generated by the steering, the rudder is also affected by forces generated by propeller wash. The combined effect of these forces bends the rudder. Rudder forces change slowly in the course of a few seconds. On the other hand, the forces attributable to the propeller change rapidly when the propeller rotates. The change repeats during one revolution as many times as there are blades in the propeller. This is described by propeller blade frequency which depends on the speed of rotation and number of blades. The propeller blade frequency of the SILJA EUROPA is 6.7–9.5, Figure 26. The rudder is a beam, which has a natural frequency depending on the structure. If it happens to be the same or close to the propeller blade frequency, the transverse movement of the rudder becomes stronger because of resonance.

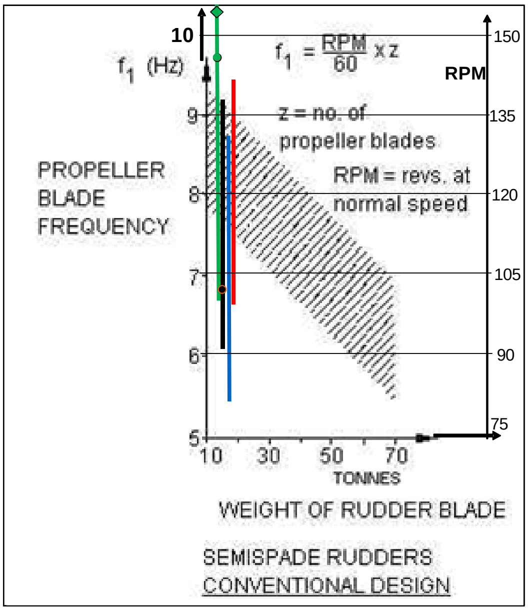


Figure 26. The natural frequency of an intact horn rudder as the function of the weight of the rudder blade. The RPM range of the SILJA EUROPAs propeller has been marked with red. The figure also shows the situation on three other vessels. The diamond indicates the RPM of the propeller when the shaft generator is in use. The circles show the most commonly used RPM. The dangerous RPM range has been indicated with lines. The original picture by Det Norske Veritas has been modified ("Semispade rudder of conventional design" is same as horn rudder).

The increase in the transverse movement of the rudder increases the stresses directed to the rudder shaft. The dangerous range of the propeller revolutions for a horn rudder has been shown in Figure 26[28]. The propeller blade frequency range of the SILJA EUROPA has been marked with red colour. The information on three similar vessels has been added in the picture. The normal range of propeller revolutions varies between 100–143 1/min.

On the basis of the calculations made at the Aalto University (Helsinki University of Technology) it has been possible to assess the cyclic force generated by the propellers which bent the rudder shaft. According to the estimate, the strength of the force is approx. 180 kN and it generates a bending cyclic moment[29] of approx. 885 kNm. According to the results by the Aalto University, the natural frequency of an intact rudder is

[28] The figure is based on a damage report by Det Norske Veritas 3/9, which describes a crack in a rudder. It had probably been caused by the blade frequency coming to the dangerous frequency band (indicated with lines) illustrated in the picture. The sister ship did not suffer from this kind of a damage; there were three blades in her propeller, i.e. one blade less which means that the blade frequency had dropped by 25%.

[29] The point of application of the cyclic force is lower than the resultant of the rudder force.

6-7 Hz and of a damaged rudder 2-3 Hz. The ratio of the specific frequencies has been estimated to approx. 2.5 in the investigation. In the calculations by the Aalto University the speed of the vessel was 22.7 knots. With other speeds the forces can be changed in relation to the square ratio of speeds. The force and moment mentioned above are scaled to correspond to the registered statistics of the ship's speed (table 3).

The significance of resonance depends on the speed of rotations which is used, on how close one is to the natural frequency of the rudder. For approx. 30% of the time the speed of rotations seems to be in the dangerous range of 135–112.5 Hz.

1.5.8 Cavitation of the rudder

It has become clear from the docking reports that cavitation damage to rudder had been repaired in connection with each docking. This extent of cavitation is typical for horn rudders. The strength of cavitation increases when the propulsion power in relation to the propeller surface increases. 800 kW/m^2 has been suggested as the limit value[30], on the SILJA EUROPA the value was 810 kW/m^2.

1.6 Fatigue process of the rudder shafts

Before the accident occurred, the vessel had been in traffic for almost 17 years. Let us presume that there are 350 operating days per year and 22 operating hours per day. These assumptions give us a cycle of stress 17x350x22x3600x8 = 3.8 billion when the propeller excitation is 8 Hz. In addition, according to the simulation calculations made in the investigation, there are a couple of hundred significant slow changes per day in the rudder force. Due to the large number of stress variations, the strength of the rudder shaft and of also other parts of the steering gear has to be studied from the point of view of fatigue in this failure situation.

An adequately reliable theoretical control of the fatigue phenomenon is difficult for the time being. In practice a dimensioning taking fatigue into account and a fatigue failure study must be based on simplified theory, experimental results, tables and curves. The same procedures have been applied in this case but to the other direction: the fatigue life of the broken part has been assessed.

In the case of the SILJA EUROPA, many complex factors related to fatigue calculations as well as inaccuracies in the initial data prevail. On the other hand, this has made it possible to select the initial data in such a way that the SB shaft broke. The results are indicative and present one possible course of the fatigue process.

The evaluation of the breaking caused by the fatigue of the rudder shaft can be divided into the following subtasks:

1. Determining the forces affecting the rudder and thus also the rudder shaft and determining the most important factors affecting these forces and reciprocal correlations between these factors.

[30] Rudder Cavitation part, Proceedings of 25th ITTC (International Towing Tank Conference) – Volume II, page 495, Fukuoka.

2. Determining the frequency distribution of the forces of different magnitudes *per day*. It has been presumed that there are not very large differences between the days. Multiplying the days gives fatigue periods of different durations. The influence of ice has been taken into consideration separately.
3. Conversion from force distributions to stress distributions.
4. Determining the fatigue endurance of the rudder shaft (Wöhler curve).
5. Cumulative fatigue calculations (Miners summation).

1.6.1 Active forces and rudder shaft stresses

Bending forces. The bending force directed to the rudder consists of two components: of the rudder force directed to the rudder which for a few seconds remains almost constant, i.e. *stationary*, and of the cyclic, i.e. *non-stationary* force generated by propeller wash which depends on the vessel's speed and the speed of rotation of the propellers and which changes several times per second. Even the stationary force varies and generates so-called slowly alternating cyclic stress, Figure 27a.

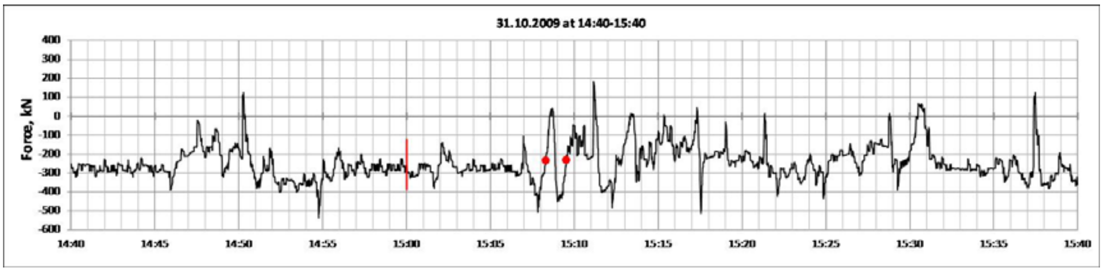


Figure 27a. A force bending the rudder from the period of one hour, 14:40–15:40, on 30 October 2009.

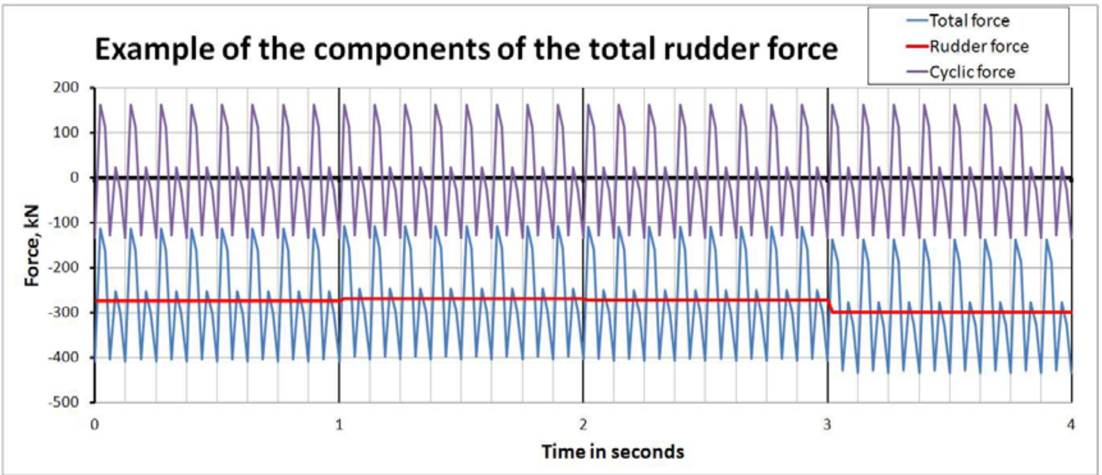


Figure 27b. A principle model of the force stressing the rudder. The force consists of the stationary rudder force and of the non-stationary force which changes at the frequency of approx. 8 Hz caused by the rotating propeller. The smallest interval on the horizontal scale corresponds with the propeller rotation of 90 degrees when the speed of rotation is 120 1/min. The figure is an excerpt from the previous figure starting at 15:00 and showing an interval of 4 seconds.

One so-called slow period has been marked in the figure with red dots. How these two forces add up[31] when the vessel's speed is 20.14 knots is shown in Figure 27b for the duration of four seconds starting at 15:00 (the red line in Figure 27a).

When the free play of the pintle bearing increased, the situation became more complex, because at times the pintle bearing hit the wall, and at times not. The natural frequency of the rudder is different in these situations. The situation becomes more complex by the fact that the pintle bearing may sometimes come loose from the wall because of the cyclic force. Seawater acting as lubricator damped the movement.

In addition to the bending stress, the rudder shaft is at the same time affected by the rapidly changing torsional stress, by the shear stress caused by the bending and by the compressive stress in the cone part. At the critical point the increasing effect which the bearing stress has on the mean stress is relatively highest when the bending stresses are small. The fatigue calculations have been carried out at the critical point by summing the stresses in two ways: bending+torsion and bending+torsion+compression.

Operating in ice has been taken into consideration in such a way that the number of the stationary large changes has been somewhat increased from the values in the autumn of 2009.

1.6.2 Design principles used by classification societies

The rated value of the rudder force is determined on the basis of the classification society rules. This gives the upper limit of the force. In the case of the SILJA EUROPA, the design force is approx. 1,700 kN and the design torque approx. 600 kNm.

The classification calculations of Bureau Veritas in 1991–1993 had been made using the 1987 rules. The result then was an overall rudder force of 1,412 kN. According to the recheck calculations made by the classification society, the dimensioning was correct[32].

1.6.3 Simulated static forces

The stern shape and dimensions, rudder and propeller arrangement and the wake of the vessel used in the simulation model correspond to those of the SILJA EUROPA. The distribution of the absolute value of the simulated rudder forces during one day grouped in 100 kN ranges of force can be seen in Table 3.

[31] The non-stationary force calculated by the Aalto University, corresponding with the speed of 22.7 knots, has been altered (by using the square ratio of speed) to correspond with the vessel's speed of 20.14 knots at the particular moment without any other corrections.

[32] An e-mail forwarded by the Finnish office of Bureau Veritas on 12 November 2010. In the 1987 rules the calculation formula of force was different from the present one.

1.6.4 Combining static and cyclic forces

Simulated static forces as such are available for further calculations. Instead, the cyclic force calculated by the Aalto University has to be changed to correspond with the speed of the vessel and to how close the actual RPM is to the RPM equivalent to the natural frequency of the rudder. The cyclic force modified in this way by the resonance effect is added to the static force.

Because of this, the speed has been divided into four groups and the speed of rotations into three groups in each 100 kN range of force. The ranges of force have been chosen on the basis of the absolute value of the static force. These groupings have been considered adequate and to correspond with the approximate nature of the initial values and the entire calculations procedure. At the same time the calculating has been simplified.

There is an example in Table 3 of the grouping made concerning these three variables. For instance in the most dangerous range of propeller revolutions 115–135 1/min (marked with grey colour) there are 41 one second occurrences per day for the power range 400–500 kN in the speed range of 15–18 knots. Altogether there are 86,401 occurrences, which equals with the number of seconds in a day +1. The squares in which there are 0 occurrences have been left out from further calculus. The coloured squares show the force ranges in which the pintle bearing does not touch the wall of the housing and in which the natural frequency of the rudder is 2.5 Hz. The table is based on data from 9-10 November 2009.

Table 3. The number of occurrences in 24 hours grouped by using three variables.

RPM range	below 115 RPM							115-135 RPM							over 135 RPM						
force range / speed range and coeff.	0-100	100-200	200-300	300-400	400-500	500-600	600-700	0-100	100-200	200-300	300-400	400-500	500-600	600-700	0-100	100-200	200-300	300-400	400-500	500-600	600-700
below 10 kn/ 0.10	11469	153	0	0	0	0	0	8868	682	333	131	51	35	1	3	0	0	0	0	0	0
10-15 kn/0.33	1659	761	47	0	0	0	0	3045	6540	230	9	1	0	0	105	1370	253	13	2	0	0
15-18 kn/0.56	62	196	76	0	0	0	0	342	3366	875	92	41	0	0	300	4890	4000	221	25	0	0
over 18 kn/0.74	0	34	2	0	0	0	0	31	336	520	55	13	0	0	273	4069	26626	4029	161	5	0
total	13190	1144	125	0	0	0	0	12286	10924	1958	287	106	35	1	681	10329	30879	4263	188	5	0

The cyclic force has the peak value of 345 kN appearing eight[33] times per second according to the calculations made by the Aalto University, and this corresponds with the vessel's speed of 22.7 knots. There are thus 691,200 peak values per day. In the table there is a speed range specific coefficient calculated from the square ratio of speed. The peak value must be multiplied with this coefficient. In addition, the coefficient which depends on the speed of rotations in two cases of free play at pintle bearings must also be taken into consideration: the pintle bearing does not touch the housing (net free play large, the natural frequency of the rudder 2.5-3 Hz) and the net free play minor (the pintle bearing touches the housing, the natural frequency of the rudder 8 Hz). The result has been reduced further by 25 % on the basis of the statement in the Aalto University report claiming that the force in the calculations is too large because the rudder is stiff.

[33] The rotation speed of the propeller has been approximately 122 1/min, so that the blade frequency of 8 Hz is appropriate.

1.6.5 Conversion of forces into stresses

Force distribution has to be changed into cyclic stress distribution. It and the Wöhler curve of the rudder shaft make it possible to evaluate the fatigue life of the shaft.

One possible method is to change the stress variations to be such that the average value is zero. In the case of the SILJA EUROPA, the stress variations are divided into quick ones taking place 8 times per second and into slowly changing ones, which change with the interval of as much as several tens of seconds. In practice, the loading has been random. For example the interval in Figure 27a indicated with red circles forms one slow period.

Transformation to cyclic stresses has been made using the principle presented in Figure 28. The average value of cyclic stress prevailing in the situation has been determined first. This value was caused by the non-stationary propeller force. After this it has been transformed to be such that the mean stress is zero by using the Goodman formula.

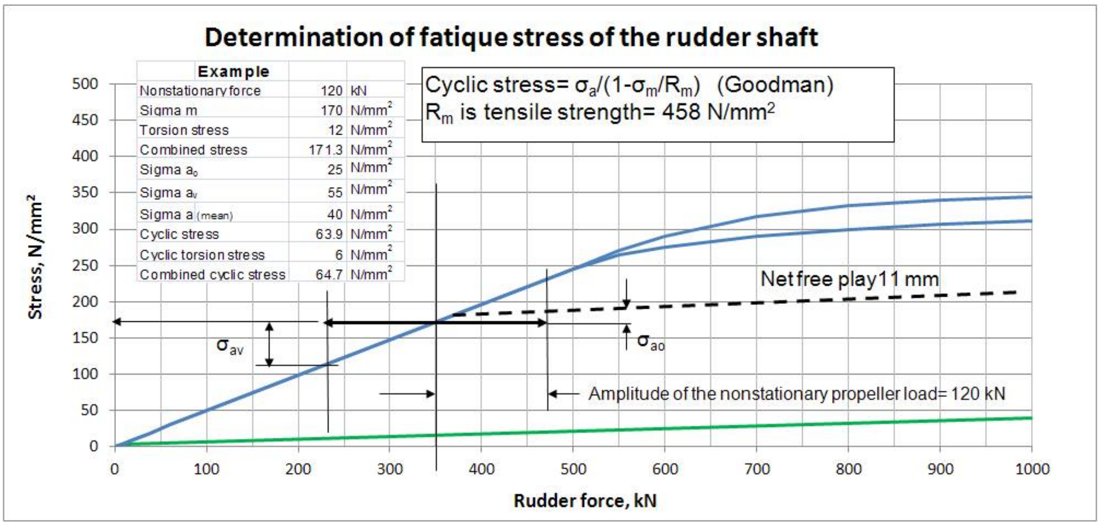


Figure 28. Goodman's formula applied to determine the cyclic stress with zero mean value used in fatigue calculations. The figures in the example do not in any way correspond with the situation of the SILJA EUROPA. The force range in the example is 300–400 kN, and 120 kN has been chosen as the amplitude of the non-stationary force in the example. The effect of torsional stress is minor.

A new table was generated through these stages, which has cyclic stresses corresponding with the cells in Table 3. After this it was possible to calculate the number of cyclic stress occurrences in each stress interval by using a stress step of 50 N/mm^2. When the pintle bearing is in working, the rudder horn carries most of the load, and the static and cyclic stresses of the shaft are small. The situation was like this in the first years till 2004, and after the cast epoxy had been installed, almost till the failure.

This procedure was repeated with all significant free plays with and without the compressive stress in the cone: by 2004, with 5-12 mm free plays with the interval of one millimetre and in the autumn of 2009, with over 16 mm free play. Compressive stress shortens the operating life of the shaft to some extent.

1.6.6 Assessing the fatigue endurance of rudder shafts

Assessing the fatigue endurance of the rudder shaft is based on the Wöhler curve, Figure 29. The curve illustrates how many cyclic stress (more than ca 1,000) or strain/compression changes (under ca 1,000) of a certain magnitude the material endures. The estimated basic curve of the rudder shaft, black, is the starting point. Normal corrections caused by the quality of the surface and the size of the object have been made to it and the result is the green curve. If there is a notch, cracks or similar in the object under stress, the fatigue endurance decreases. The effect of the notch can be taken into account e.g. by using the so-called effective notch fatigue concentration factor. When the effect of the 0.3 mm sharp notch in the SB shaft is taken into consideration, the outcome is the red curve.

As can been seen in Figure 29, steel has the kind of characteristic that under a certain stress limit, the object can withstand practically an unlimited number of stress variations. The alternating stresses under this limit are in the range of so-called *fatigue limit*, and there is usually no need to take them into consideration in fatigue endurance calculations.

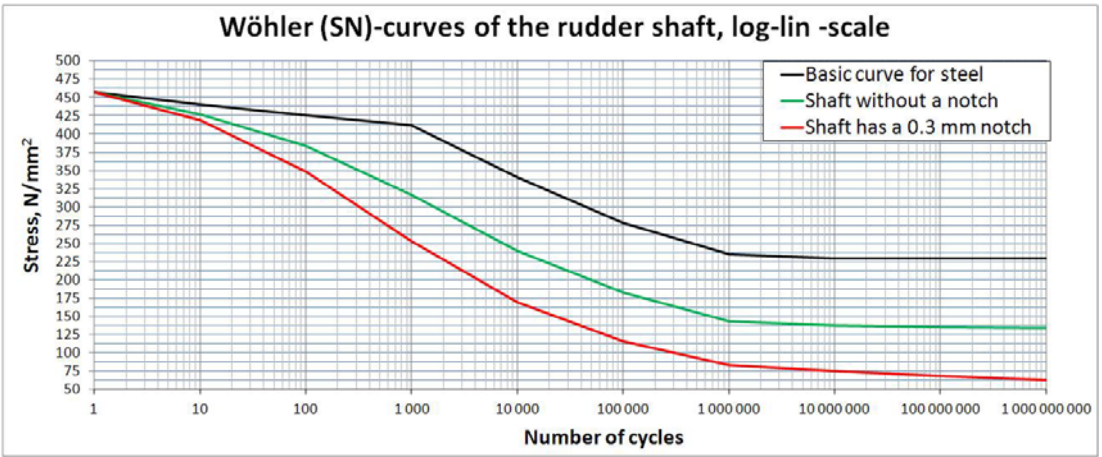


Figure 29. The basic curve of the fatigue endurance of steel (black) and the estimated fatigue endurance curves of the rudder shafts, Wöhler i.e. SN curves when the mean stress is zero. The horizontal scale is logarithmic.

When the cyclic loading is random, the Wöhler curves can be even lower e.g. the situation is even worse than presented above. Attempts have not been made to estimate this.

1.6.7 Estimating the operating lives of the rudder shafts

The part **Miner's theory** plays in this procedure is referred *to as cumulative fatigue damage rule*. It is used to find out how large part of the fatigue life of the shaft a certain cyclic stress range consumes. The consumed parts of all cyclic stress ranges are added up, and according to a common praxis, the total must be under 1 so that the structure can bear the alternating load in question.

Such a combination of variables has been found by trial and error in the calculation procedure that the observations and measured results can be explained. Even the slightest change in the SN curve has an especially strong impact on the results. Also by adjusting the magnification factor of the non-stationary force depending on the propeller revolutions and the vibration damping factor it is possible to adjust the results (the damping of the vibration has been estimated to be quite high). The fact that fatigue endurance becomes somewhat weaker as the mean stress increases (the Wöhler curve settles down) has not been taken into consideration in the procedure. The results presented here do not include the effect of compressive stress. When compressive stress is taken into account, the fatigue life of the shaft becomes somewhat shorter.

Normal clearances. The calculations show that without corrosion the shafts would have withstood and the fatigue would not have shortened the service life.

Shaft without a notch, but the pintle bearing corrodes. The shaft would have withstood its entire service life the corroding pintle bearing with the net free play of 12 mm. With a net free play of 16 mm the shaft would have withstood less than two years. The impact of the fretting phenomenon has not been taken into consideration in these estimates. The phenomenon starts to appear when the net free plays are large, but it has not been possible to estimate its impact on the service life. It is not excluded that the service life can become shorter than what has been presented above.

Accident event, i.e. the shaft with the notch

Calculation 1993–2004. After the net free play grew over 5 mm, the fatigue endurance of the shafts began to decrease. The majority, approx. 85%, of the fatigue life of the SB shaft had been used by the 2004 docking. This means that if the situation had continued more or less similar as it had been in the past 11 years, there might have been approx. two years left of the fatigue life. If the situation had continued as it was during the last two months prior to the docking, there would have been one year fatigue life left, but because of the accelerating growth of the crack, the time might have been considerably shorter, i.e. a couple of months. These estimates on the fatigue life are only indicative. The fatigue life was for the main part shortened by the non-stationary force of the propeller at the frequency of approx. 8 Hz. Only with the net free play of 11–12 mm did the slow force changes become significant.

The fatigue life of the BB shaft did not shorten because the stress remained below the fatigue limit.

Calculation 2004–2009. Most of the time, the stresses were minor, and the fatigue life left did not shorten because the net free play was 1 mm (the clearance remained normal as the cast epoxy was at least partly in its place). The calculation goes through the same stages as described above, but now as the epoxy had disappeared, the free play was so large that the natural frequency of the rudder was almost all the time 2.5 Hz; so, the slow changing forces were in main role. The stress increased to the yield strength of steel with a 550 kN rudder force. At its maximum the stress may have exceeded the yield strength, to stresses 300–350 N/mm^2 with high steering forces, in which case the horn took some of the load (if the net free play was approx. 18 mm). In that case a study of fatigue strain should be included in the fatigue study. This has not been deemed necessary, and it is concluded that with the actual loading, the remaining fatigue life of the SB shaft was consumed in 1-2 days.

The fatigue life of the BB shaft did not shorten, because the clearance remained within permissible limits (the majority of the cast epoxy was in its place).

1.7 Estimate on the reliability of the calculation procedure used in the investigation

Even when the initial data is reliable, the calculation of the fatigue life of a structure includes more uncertainty than static dimensioning. In the case of the SILJA EUROPA, there are significant factors in the initial data which increase uncertainty. The final result, i.e. the breaking of the rudder shaft, is, however, known. This fact was utilised when selecting the variable values to be such that the desired final result was attained. The same final result can be reached even with other combinations of variables; other options have not been considered to replace the combination used in the investigation.

One starting point for the calculation is the Wöhler (SN) curve which describes the fatigue limit of the rudder shafts. The curves used in the investigation are approximate, and even small changes in them have a strong effect on the final result. In addition, it has to be noted that the Wöhler curves used in the calculations are based on fatigue tests done in air. In this case the rudder shaft has been protected by sealing and surrounded by seawater, but the sealing has not necessarily been waterproof. Because of this, the impact of seawater might have had a lowering effect on the Wöhler curve, i.e. the fatigue life of the shaft is poorer in water than in air. The impact cannot, however, be estimated.

The second uncertain factor is the rudder vibration and the amount of magnification (estimation of the damping factor) in resonance with the non-stationary propeller excitation or near to resonance. The third uncertain factor is the magnitude of the natural frequency of the rudder, which is based on the calculations by the Aalto University and on the approximate statistics of Det Norske Veritas. The calculation method of the magnitude of the non-stationary force also contains simplifications. In addition, the dropping times of the bushes are estimates.

The reliability of the static stresses of the rudder shaft and the simulated steering forces is better. It is believed that the VDR data is reliable enough. The estimate on the progress of corrosion is based on the measured diameters and on general corrosion rate data.

The applied cumulative fatigue damage rule procedures, i.e. the Goodman's formula to determine the equivalent cyclic stress with zero mean value and finally Miner's rule do not apply well to this case (random load variation, changing mean stress, at times a long period of very low stress, occasionally mean stresses exceeding the yield strength at the final stage).

In spite of these limitations, the investigators are of the opinion that the correct process description of the incident has been found in the investigation.

1.8 Rules and regulations guiding the operations

According to the classification society rules, the classification of a vessel must be renewed with the interval of five years (class renewal survey). In this time the vessel must be docked twice, and for instance the steering gear must be inspected. A note on the inspection must be entered into a protocol, to which the inspector can attach a memorandum on the defects which do not affect the validity of the class certificate. Rudder shafts are not removed for inspection during dockings. The Classification Society does not have rules or instructions on the corrosion protection of the rudder or on the repair method of the pintle bearing because these are not Class items[34].

Alerts. International instructions, for example the Radio Regulations, define the Master's right but not his/her duty to transmit a distress or urgency message in an emergency situation. In the Finnish legislation the Maritime Act and the Vessel Traffic Service Act oblige the Master to report on an incident or accident, but there is no obligation to transmit a distress message.

The quality systems and instructions of the shipping company

At the time of the incident, the MPM (Marine Planned Maintenance) service system was in use on the vessel. The MPM had replaced the AMOS system which had been in use earlier. The information in the AMOS system had been transferred to the new system. The maintenance information on the rudders and rudder gear include information on the clearance measurements and replacements of bearings done by the repair shipyard in connection with the dockings. The preventive maintenance plan does not include measures on the rudder or pintle shafts.

The ISM guidelines of the vessel contain all the instructions pertaining to the operating of the vessel in electronic format. On the bridge there is a so-called yellow book, which contains instructions for different emergency situations, e.g. emergency steering measures. Instructions for normal operations can be found in the so-called green book.

[34] Bureau Veritas comments on Draft Report dated on 27th August 2012, Silja Europa <38J418>:"*Corrosion protection is not a Class item. The Classification rules are not designed, intended or required to include repair methods."*

A vessel-specific BRM procedure was in use on the vessel. The objective of the procedure is to develop the steering procedures used by the bridge personnel in order to secure the safety of the vessel. Training on the steering of the vessel is given 1-2 days yearly on the basis of the BRM[35] modules. Three modules are completed by using a simulation model and after this the outcome of the activities is analysed. The modules may include e.g.: failure chains, situational awareness, bridge personnel as a team, communication, voyage planning, emergency situations.

The shipping company has trained in ship simulator the control and analysis of various abnormal situations and equipment failures regularly starting in the late 90’s. These simulations have included also BRM-trainings.

[35] The international STCW convention of 1978 and its subsequent amendments (Convention on Standards of Training, Certification and Watchkeeping for Seafarers) includes a voluntary ”Code B” instruction on watch-keeping when navigating and suggests that shipping companies introduce BRM, Bridge Resource Management.

2 ANALYSIS

The breaking of a rudder shaft is a very rare accident especially when it occurs without an external ground touching etc. In order to prevent a similar failure from occurring again, the technical backgrounds of the incident were comprehensively explored in the investigation. The objective was to explain the damaging of the rudder shafts, a three-stage process which had developed in the course of 17 years.

In the first stage the fatigue breakage process was so slow that the far-advanced galvanic corrosion of the pintle bearing leading to the fatigue breakage was not detected until in connection with the 2004 docking, 11 years after the vessel's commissioning. The hair crack possibly existing in the rudder shaft and later evolving into a fatigue breakage was not detected in the inspections carried out in 2004. (See 1.5.1, Turku Repair Yard 30.8–8.9.04).

In the second stage the process was stopped by using cast epoxy repair, but its causes were not eliminated. The cast epoxy broke in the course of five years. In the third stage, after the cast epoxy had disappeared entirely, the development of the fatigue breakage continued and the SB shaft broke in a few days.

2.1 Factors contributing to the breaking of the SB shaft

A sharp, 0.3-mm-deep notch (Figure 22) in the SB shaft significantly reduced the fatigue endurance of the shaft and was the most important factor leading to its breaking. The notch in the rudder shaft had for unknown reason been left sharp. **Galvanic corrosion in the pintle bearing** (Figure 25) is, in the investigators' view, another main factor leading to the failure. However, galvanic corrosion alone would not have been sufficient to cause the prolonged fatigue process of the rudder shaft. The simultaneousness of these factors caused **the durability of the shaft to be weaker than presumed and its stresses exceeded the rated values in two stages.** These factors differed entirely from the normal ship building practice.

The choice of materials in the pintle bearing made corrosion, which was not contained structurally, possible. These hidden defects had remained in the vessel when it was planned and built, and at no point were they noted nor regarded as dangerous. These defects had passed the control at the building shipyard, and neither the classification society nor the supervision of the buyer had paid attention to these details. The first mentioned defect caused a process (the increase of the net free play) due to which the static and fatigue loading of the shaft occasionally considerably exceeded the normal values.

As long as the bearing clearances remain within permissible limits, the rudder horn supports the rudder, which means that the mean and cyclic stresses are so small combined even with the corresponding torsional stresses that they clearly fall below the static design stress and the calculated fatigue limit of the material of the rudder shaft.

Classification society rules do not define how clearances should be measured[36]. The initial stage of the corrosion in the pintle bearing housing cannot be detected with the commonly used feeler gauge measuring. The rudder shaft is not removed for inspection at specified intervals during the dockings. Inspecting them would require more extensive dismounting of steering gear, which would lengthen the docking time. The schedules for dockings are very tight because of costs, and this has an effect on the method selected for the repairs. The docking interval is sometimes lengthened to the maximum permitted by the class, in which case even a slow process may evolve too far.

There might have been discontinuity in the transfer and use of data from the results of the inspections because of changes of the personnel in the classification society and in the shipping company in 2004. In addition, the owner of the vessel had changed several times.

Resonance phenomenon and the vibration of rudders. The structure of rudders on this type of car passenger ferries and the optimal propeller revolutions range lead to the fact that blade frequency resonance cannot be avoided altogether. Of the vessels compared (Figure 26), the SILJA EUROPA was most badly in the dangerous zone The resonance vibration of the rudder accelerated the effect of the notch and corrosion.

Rudder vibrations caused by resonance mainly stress the rudder and rudder horn, and damage to them is usually checked and they are easy to repair. The cracks in the rudders and rudder horn of the SILJA EUROPA prove that the vessel's rudders occasionally vibrated strongly. In severe problems caused by resonance the structure is altered in such a way that the natural frequency of the rudder is changed. Blade frequency can sometimes be altered by replacing the propeller with another one which has a different number of blades.

The rudder vibrations of the SILJA EUROPA would not have become a problem for the rudder shaft if the free play of the pintle bearing had remained within the permissible clearances (max. free play 2.5 mm). The most dangerous net free play is between approx. 7–10 mm. With small free plays leaning on the rudder horn prevents high stresses (large bends) and with large free plays the rudder acts mainly as a spade rudder, in which case there is no resonance.[37]

After the vessel had been completed, she had problems with course stability. These problems were reduced in connection with the 1993 docking. However, the steering of the vessel still requires, more than normally, small rudder angles when manoeuvring straight ahead. The problems caused by the interaction of the rudders and propellers, the cavitation and vibration of the rudder, remained unaltered and were continuously the cause of rudder repairs in connection with the dockings.

Cavitation may have accelerated the corroding of the pintle bearing of the SILJA EUROPA. Especially the outer surface of the pintle bearing housing corroded so badly that it had been repaired in connection with the previous dockings by using surface welding.

[36] Bureau Veritas comments on Draft Report dated on 27th August 2012, Silja Europa <38J418>: *"The Classification Rules are not designed, intended or required to include instruction on methods of measurements."*

[37] The excitations considered here are at 8 Hz. Slow force changes become more dangerous with the increasing net free play.

When also the inside of the housing corroded, the durability of the structure of the housing began to become questionable.

2.2 Main phases of the analysis

It has been found out in the investigation that in all three abovementioned stages of the fatigue process observations have been made on the pintle bearing clearances. A massive corrosion in the pintle bearing housing was discovered in the 2004 docking. It was repaired by using cast epoxy and replacing the bushes.

In spite of the observation made on the considerable corrosion of the housing in the 2004 docking, the reasons for these findings were not investigated. Therefore the contributing factors hidden in the background were not discovered. In 2009 these factors caused the rudder shaft to break due to a fatigue breakage. The fatigue failure could evolve undiscovered.

The approach applied in the analysis is presented in Figure 30. The topics marked with a red broken line have been analysed in more detail in 2.2.2 and 2.4.2.

The 1st phase of the fatigue breakage process – the beginning and the developing	The 2nd phase of the fatigue breakage process – the cast epoxy repair and its breakage		The 3rd phase of the fatigue breakage process– the breaking of the rudder shaft
1993–2004	Docking 2004*	2004–2009	2009**
The observations and measures			
The observations The clearance has increased in the 2002 docking.	Surprising corrosion in the pintle bearing housing and the bush was dropped. The free play of the pintle bearing 12 – 13 mm.	The clearance was within the set limits in the 2007 docking.	The steering difficulties of the vessel on 22 November 2009.
Measures Rules, measuring method routine-like and varying The clearance measurements (in connection) with the dockings	The cast epoxy repair. No time to analyse the factors leading to the damage and to plan a permanent repair.	2007 different kind of clearance measurement; the condition of the cast epoxy was checked only superficially	The voyage was interrupted and the vessel later docked.
Hidden factors			
Development of the fatigue failure (1993–2009) 1. The corrosion prone construction of the pintle bearing *(which made the galvanic corrosion of the pintle bearing possible and caused a large net free play in the pintle bearing)* 2. The notch in the SB rudder shaft *(the fatigue life of the SB rudder shaft decreased considerably)* 3. The rudder forces and resonance vibrations of the rudder, which generated cyclic stresses *(because of the large net free play the cyclic stresses exceeded clearly the rated values of the shaft; the shaft was weaker than planned because of the notch)*			
The progress of the fatigue failure The slow start of the corrosion of the pintle bearing. The net free play of the pintle shaft increased to 12–13 millimetres by 2004. The fatigue failure starts to develop. The majority of the fatigue life of the rudder shaft was spent by the year 2004.	The progress of the fatigue failure stopped along with the cast epoxy repair and the development of corrosion became effectively slower.	The cast epoxy used in the repair starts to break slowly. Further corrosion in the bearing housing. The breaking of the epoxy became faster and it broke off entirely.	The epoxy has disappeared completely and the free space of the pintle bearing increased to 16–18 millimetres. The fatigue breakage process continued. The rudder shaft broke.

Figure 30. The main topics of the analysis. Phases 1-3 of the fatigue breakage process, the observations and measures taken in the different phases and the factors which remained hidden in the course of the process. Two topics analysed later in more detail have been marked with broken lines in the figure:

**) the analysis of the planning and realisation of the cast epoxy repairing completed in the 2004 docking and the effects of the repair (2.2.2) and*

***) the factors related to the control of the vessel after the rudder shaft had broken (2.4.2).*

2.2.1 Repair method and its implications

The docking time was planned to be so short that a quick solution had to be found. The alternative which could be realised fastest, the use of EPOCAST 36 cast epoxy, was chosen from the different alternatives; a person who could do the job and was approved by the classification society was in the region. Casting had the advantage that the housing did not have to be machined; it was enough that the rust and worst roughness were removed. By casting it was possible to fill entirely the gap of varying dimensions located between the bush and housing.

The repair operation altered the structure of the pintle bearing decisively, Figures 5b and 5c and Figures 14a and 14b. The new bronze bush was centred for the duration of the casting with hexagonal socket-head screws, which were left in their places. An epoxy brim appeared in the upper edge of the pintle bearing. In the new bronze bush there were several approx. 1 mm notches against the cast epoxy. Several screws were screwed so deep into the bush that the hex socket came through the bush which reduced the durability of the screw when it became stressed.

There was no time for thorough planning: an exchange of faxes began between the supplier of the cast epoxy, the founder and the shipping company on 31 August, and the casting of one pintle bearing took place already on 2 September. The cast epoxy can be compared with a medicine: it cured the ailment but did not remove the malady. Using cast epoxy created a new, latent risk factor: the risk caused by the breaking of cast epoxy and the consequences of this. In addition, the structure contained the hexagonal socket-head screws as extraordinary parts.

2.2.2 Assessment of the 2004 repair method

On the SILJA EUROPA, the cast epoxy restored the pintle bearing clearances to normal, but if the epoxy disappeared, the free play of the pintle bearing would increase sharply and rapidly. The use of screws caused drawbacks in the structure: bronze and steel were in direct contact with each other, the screws were weak because of the hex sockets and the majority of the screws had been screwed so deep that water could enter as lubricator between the bush and epoxy after a screw had broken off. Because of the reduced friction the screws created local stress peaks in the epoxy. *The installation screws accelerated the breaking of the epoxy. It would have been crucial to prevent the rotation of the bush in some other way.* Without the screws the bronze bush would have rotated anyway, the epoxy would have worn off gradually and would probably have started to crack at the lower edge at some point.

A special control plan should have been drawn for the epoxy as well as a schedule for the replacing of the epoxy with a permanent solution, for instance repairing the housing by surface welding and replacing the bronze bush with one like the original, as was finally done after the accident.

The use of cast epoxy as a part of the structure of the pintle bearing of the rudder in touch with seawater on a vessel as large as the SILJA EUROPA was a rare event and unique in this repair yard. Cast epoxy is commonly used in the inside premises of the vessel, e.g. in the engine room when mounting the machinery on its bases. In the case of the SILJA EUROPA, epoxy was affected by divergent forces and stresses instead of compression which is common in its typical use. According to the investigators' opinion, when used as in this case, cast epoxy cannot be regarded as a permanent solution when repairing pintle bearing corrosion. The breaking of the cast epoxy in both bearings and disappearing in the SB-bearing is an indication of this.

Using this repair option would have required that the forces[38] directed from the bearing bush to the epoxy would have been taken into consideration and that the condition of the casting would have been controlled more often than normally. Preparations should have been done concerning the coming off of the epoxy for instance with a structure which would have prevented it from falling off.

The significance of the cast epoxy repair in the developing of the fatigue breakage. The repair made the evolution of the fatigue breakage stop, even though nobody was aware of that. On the other hand, the bearing housings were grinded a couple of millimetres in order to remove the corrosion waste and to smooth the walls. At the same time the generation of a larger free play was made possible, in case the cast epoxy disappeared. Without anybody being aware of it, the third stage of the fatigue process was accelerated by this.

The analysis of the planning and realisation of the cast epoxy repair done in connection with the 2004 docking and the consequences of the repair have been presented in Figure 31. The red text boxes and arrows have been used to show the quick repair process which took approx. three days. The process included the planning of the repair between the shipping company, the repair shipyard, the cast epoxy supplier and the founder, consultation with the class and the casting itself.

[38] A repair done by using cast epoxy should be planned in such a way that the shearing forces directed from the bearing bush to the epoxy and their control are also taken into consideration. The classification society should make or require strength calculations. Adequate adhesion between the epoxy and bearing bush and housing should be ascertained. Strength requirements may then require the use of alternative materials, e.g. Belzona or similar.

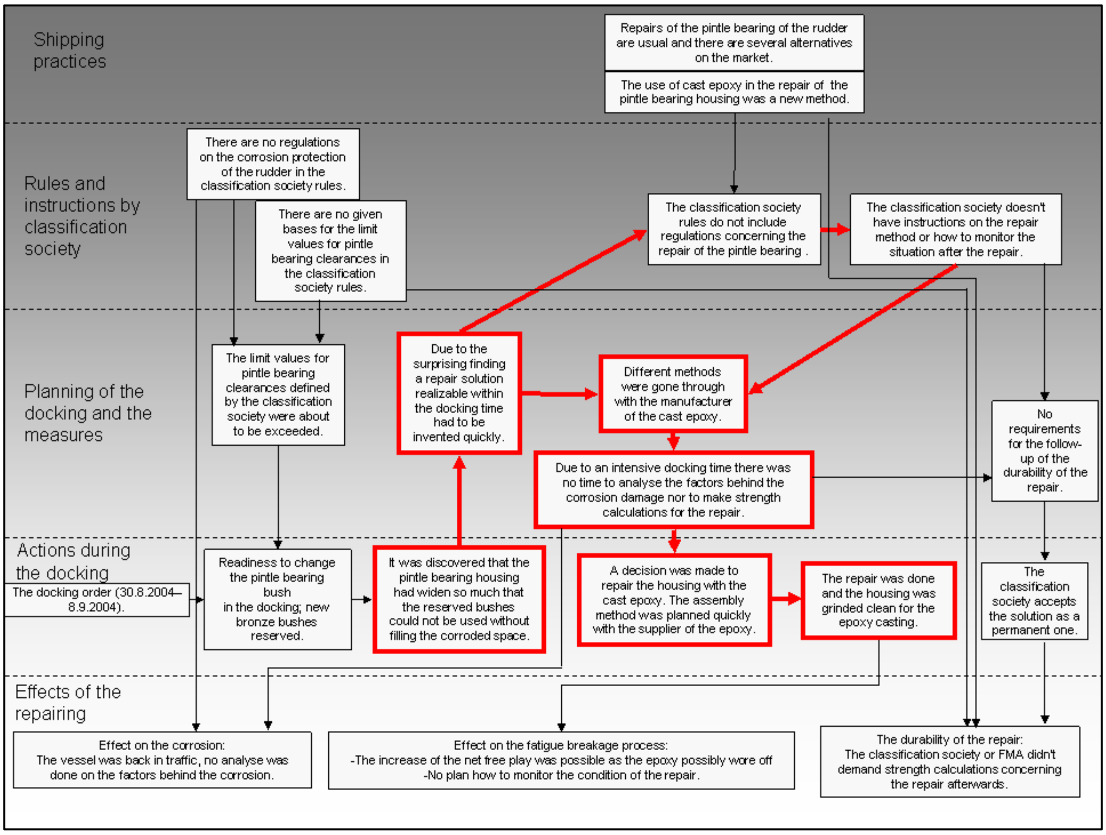


Figure 31. Analysis of the planning and realisation of the cast epoxy repair completed in connection with the 2004 docking and the consequences of the repair. The red text boxes and arrows have been used to show the quick repair process which took approx. three days. The process included the planning of the repair, consultation with the class and the casting itself.

2.3 Summary of the breaking process

The evolution of the breaking process and its causes are examined below from different perspectives. Table 4 assesses the significance of different factors and their simultaneousness in the breaking process of the rudder shafts of the SILJA EUROPA. It has been presumed, as explained earlier, that the Wöhler curve of the BB shaft was better than the curve of the SB shaft.

Table 4. The concurrence of different factors in the breaking of the SB shaft. The grey line indicates the situation which led to the breaking of the shaft, whereas the other lines are possible alternatives; the uppermost line corresponds to good shipbuilding practice.

Corrosion	Resonance	Notch in the BB shaft	BB shaft	Notch in the SB shaft	SB shaft
no	yes	rounded	Does not break	rounded	Does not break
no	yes	sharp	Does not break	sharp	Does not break
yes	yes	rounded	Does not break	rounded	Does not break
yes	yes	rounded	Does not break	sharp	**BREAKS**
yes	no	rounded	Does not break	sharp	**LATER**

The chronological progress of the fatigue failure process with reference to the SB rudder shaft of the SILJA EUROPA has been illustrated in Figure 32. It is worth noticing the accelerating speed of the growth of the breakage once it started, which is characteristic of a fatigue phenomenon. When considering similar cases, this leads to a need to consider carefully the time span between the dockings.

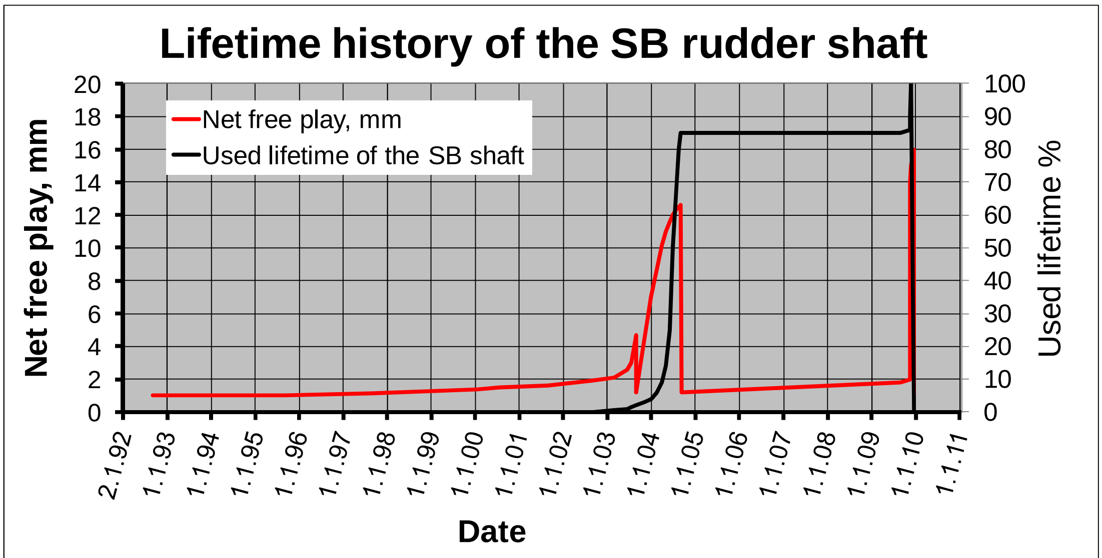


Figure 32. The development of the free play of the SB shaft and the shortening of the service life. The moment the service life starts to become shorter and the level, on which it stops after the epoxy casting, are estimates. The figure illustrates the fundamentals of the events.

The typical development trends of the net free play and shortening of the service life presented in Figure 32 are correct in the investigators' opinion. Instead, the numerical values indicating moments of time and especially the shortening of service life are uncertain.

The factors contributing to the breaking of the SB shaft have been presented in a compiled form in Figure 33 by using a picture of the rudder.

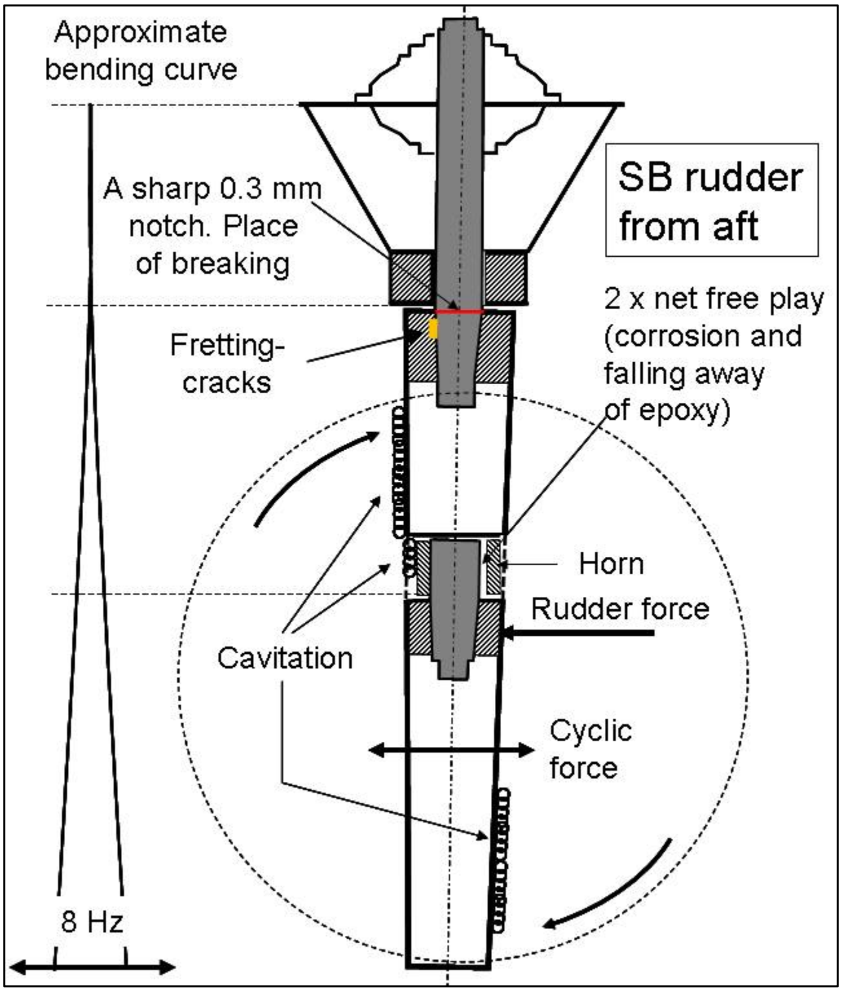


Figure 33. The SB rudder seen from behind. The transverse movement of the rudder and the factors leading to the breaking of the SB shaft are shown in the picture. In the picture the shaft and the rudder have bent towards the centre line of the vessel. The pintle bearing touches the wall of the rudder horn housing. This means that there is empty space on the other side, 2 x net free play.

2.4 Control of the vessel on the accident voyage

2.4.1 Point of time of the breaking of the shaft

The investigators have estimated the time of the breaking of the rudder shaft on the basis of a comparison of rudder angle curves from seven different days. The curves have been constructed so that the rudder angles are shown on each day at the same place (Figure 34). In addition to this, a statistical analysis of the rudder angles in Figure 34 (the mean value ± two times the mean deviation was drawn) and the information on the heading for those days were used. On the basis of these pictures, the rudder angles of the accident day started to differ from the angles of other days after 15:10.

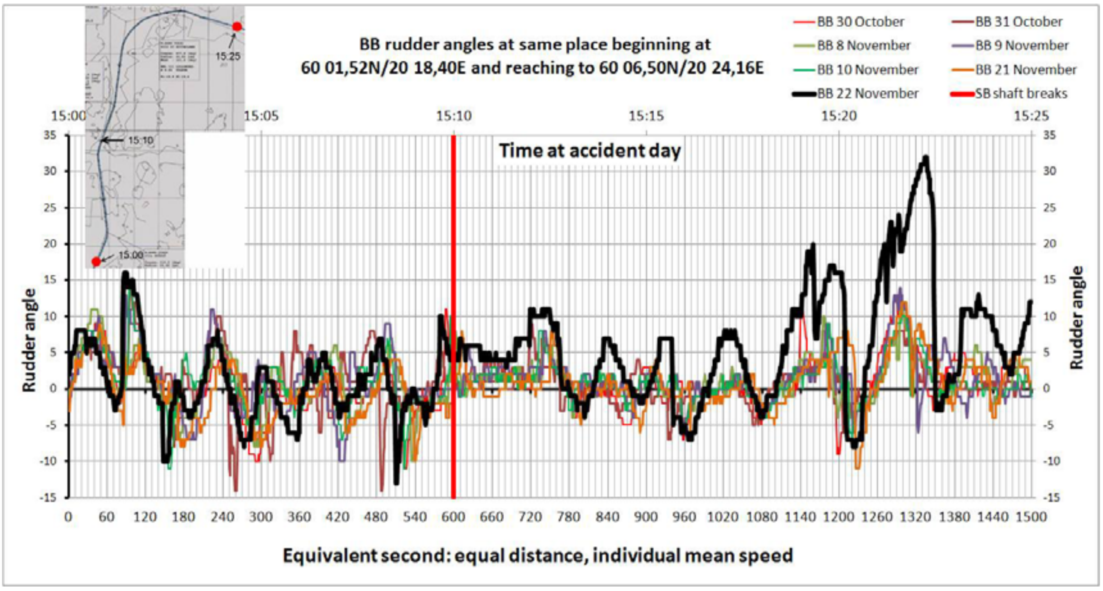


Figure 34. Curves of BB rudder angles on different days transferred to start and end at same place. The curve of the accident day has been marked with black. The start and end points have been indicated in the ship's route by using red circles.

On the basis of the study of the fracture surface of the rudder shaft, it can be concluded that the shaft has broken while it bended outwards (in other words when the rudders were turned to port). This was possible during the turn, at approx. 15:10 (then the turn to starboard was stopped by using counter rudder to port).

On these grounds it has been estimated that the rudder shaft broke at approx. 15:10.

2.4.2 Awareness and control of the situation

The breaking of a rudder shaft is so rare that it is difficult to be considered as the cause of manoeuvring difficulties. Even when it is not possible to settle the root cause of the problems at once, it is important to understand the risks related to the manoeuvring difficulties of a vessel proceeding along a narrow archipelago fairway with many bends. A vessel having reduced steerability is at risk to drift off the course at any moment. Decisions concerning the proceeding of the vessel must take this into consideration.

One may divide the control of a situation like this into three stages:

1. Noticing that there is something unusual in the manoeuvring of the vessel
2. Taking appropriate measures
3. Determining the root cause of the failure

The first stage is the most important one, because only after it will the next stages follow. In this case the first stage lasted quite long, because the steerability of the vessel having two rudders was maintained even though it was weakened. There was no direct indication of any kind of damage like this on the bridge, which means that the conclusions had to be drawn only on the basis of the changed manoeuvring behaviour of the vessel and by monitoring the displays.

The analysis tries to answer to the following essential questions concerning the control of the situation: how was the failure noticed and could it have been discovered faster and why did the steering of the vessel succeed quite well in spite of the weakened manoeuvring characteristics?

In the centre of an operative bridge management are the route pilot and the Officer of the Watch (hereafter referred to as “the OOW”) who together as a bridge team steer the vessel. They are the first who observe the irregular behaviour of the vessel and they have the best prerequisites to analyse the possible failure situation. Their actions were based on the routines of mutual communication (BRM-culture) and also on the interaction with the technical system. The operation of the technical system was affected by the known and sporadic characteristics of the vessel and her equipment, the steering methods in use, which were possibly of routine character, and the prevailing environmental conditions and other traffic.

The measures taken in order to determine the cause of the irregularities observed in the steering of the vessel and to manage the situation have been analysed from the point of view of the persons manoeuvring the vessel with the help of an applied SHELL model[39] presented in Figure 35. It describes the human and technical interactions of bridge management considered significant in connection with the manoeuvring of the vessel.

In the course of the situation now under analysis, the route pilot, who was manoeuvring, changed. Therefore also the central object of the analysis, the bridge team changed. This has been taken into consideration in the analysis.

[39] With the help of a SHELL model one can examine the actions of a person in his/her environment and try to determine the effects of various factors on the person’s performance. The name is derived from the initials of the components: S(oftware) includes schooling, manuals, procedures and rules. H(ardware) means for example equipment or the vessel itself, which are controlled by a person. E(nvironment) is the external environment as a whole. L(iveware) in the centre is the person whose actions are observed and the outer L includes other persons who work with the person using the equipment in question. The purpose of the model is not to concentrate on a single component but to investigate the entirety and the mutual interactions between the various components. The IMO recommends that the SHELL model be used as one of the methods applied in accident investigations because of its systematic nature.

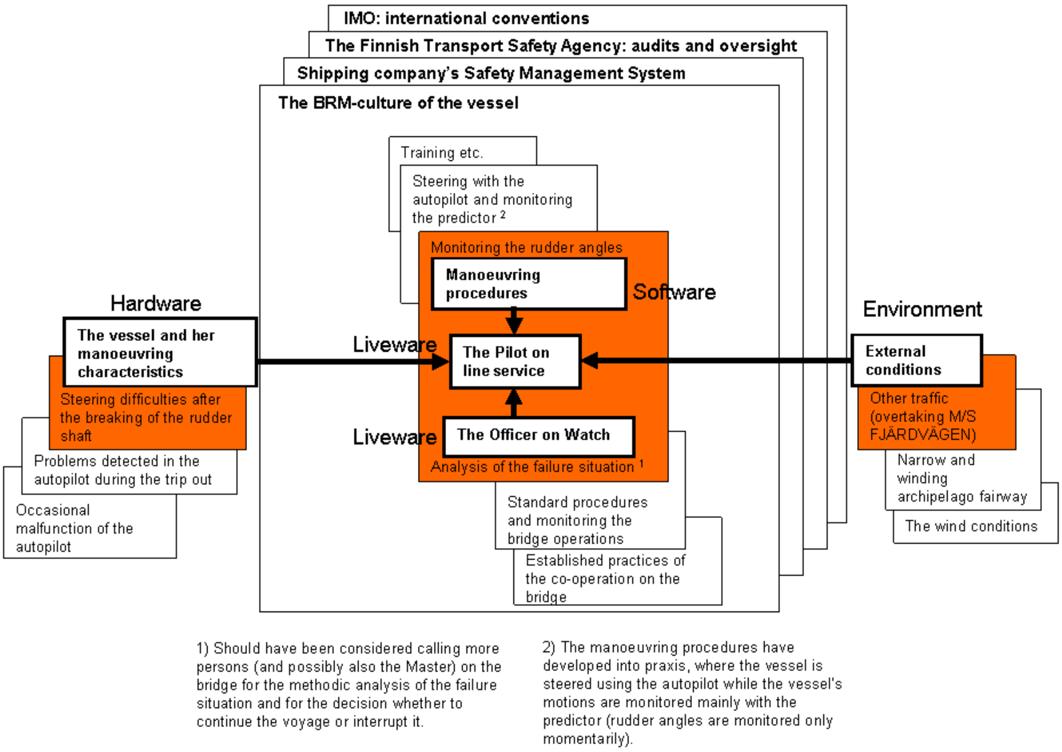


Figure 35. The factors affecting the control of the vessel and decision-making on the bridge after the rudder shaft had broken described with the help of an applied SHELL model.

Figure 35 shows the components under examination: the route pilot (Liveware), the Officer of the Watch (Liveware), manoeuvring procedures (Software), the vessel and her manoeuvring characteristics (Hardware) and external conditions (Environment). In addition, some background factors affecting the components have been taken into consideration, too.

Mutual cooperation on the bridge (BRM, Bridge Resource Management) acts as the frame of reference for the operative actions on the bridge. Established cooperation practices on the bridge may be called the BRM-culture. This is based on the shipping company's Safety Management System (SMS), which is audited, approved and controlled by the Finnish Transport Safety Agency. The international conventions of the IMO form the basis of the SMS. The BRM culture is a central background factor as shown in the figure.

How was the failure noticed and could it have been realised faster?

Reactions of the bridge team to the behaviour of the vessel and environmental conditions[40].

The route pilot is the main actor in the manoeuvring of the vessel. However, he works as a member of the bridge team closely together with the OOW. External conditions, e.g. bends in the fairway and wind, affect the behaviour of the vessel and consequently the use of the manoeuvring equipment by the bridge team.

When the rudder shaft broke causing steering difficulties, no one could imagine that the reason for the irregular steering behaviour was as serious as the breaking of a rudder shaft. The rudder could get stuck at an angle or at times turn in the propeller wake. This may have caused the manoeuvring behaviour of the vessel to seem illogical thus making it more difficult to make reliable observations on the situation. The wind was believed to have caused the irregular manoeuvring behaviour. Especially the starboard turns were difficult to carry out. After the breaking of the rudder shaft there were only two such turns, and after the latter one, the vessel was stopped. Between these turns the vessel overtook M/S FJÄRDVÄGEN and the overtaking also interrupted making observations and analysing the possible failure.

In the course of the entire incident, not a single piece of equipment on the bridge gave an alarm. This fact partly made it difficult to believe that a failure in the steering machinery could be the cause of the manoeuvring difficulties. There is no direct indication of the breaking of the rudder shaft on the bridge. The possible failure could be noticed only indirectly by examining the vessel's motion state, changed steering behaviour and manoeuvring variables. However, the breaking of one rudder shaft was not clearly visible in the manoeuvring behaviour of the vessel having two rudders, because the damaged rudder did not get stuck in an extreme position. The vessel with two rudders remained steerable, albeit weakened – a vessel having only one rudder would have lost her manoeuvrability in a similar situation.

Exceptionally large rudder angles and their long duration were the most notable indication of the possible rudder failure seen in the measuring devises. Extra large rudder angles (approx. 30 degrees) were for the first time possible noticed at the end of the Stockgrund turn, which was the first major turn after the breaking of the rudder shaft. These exceptionally large rudder angles were possible to be noticed at the end of a starboard turn or at the beginning of a turn to port. After one turn had been completed, the bridge crew had to wait for the next one before observations could again be made.

In addition, the rudder angles needed for steering were one-sided. These rudder angles were also at times quite large (approx. 20 degrees). This unusual behaviour was more difficult to observe than the extra large rudder angles. Because the failure was not noticed immediately on the basis of the extra large rudder angles, additional time was

[40] Examination of Liveware – Hardware + Environment interactions.

needed before more observations were gathered (several rudder angles over 20 degrees and some rudder angles over 30 degrees).

The bridge team changed at the watch change of the route pilots and grew by one person. Before the actual start of the new watch, the incoming second route pilot was briefed on the problems which had been noticed. He steered the vessel in one large and one small yaw. During these yaws he observed that it was not possible to stop the turning by counter rudder in a proper way and the seriousness of the failure began to become apparent.

A decision was made to stop the vessel in a channel extension suitably nearby. After the detection of the problems there were only few free water extensions large enough along this narrow and bendy archipelago fairway to offer a real possibility to stop a large passenger ferry without disturbing other traffic.

Cooperation on the bridge and manoeuvring procedures[41]

At the first turn after the breaking of the rudder shaft the route pilot and the OOW observed irregularities in the manoeuvring behaviour of the vessel. The functioning of the autopilot and large rudder angles were wondered at and the course was adjusted a little as a reaction to the unusual rudder angles. However, no discussions were carried out concerning the largest rudder angles (30 degrees), in spite of the fact that they were clearly bigger than those normally in use. The autopilot generally uses short rudder angles of 10-15 degrees which at the maximum prevail approx. 10 seconds[42]. Now the autopilot used rudder angles of 25-30 degrees (Figures 8, 9 and 34, at 15.21-15.22) continuously for approx. one minute. The rudder angles were twice as large and lasted even four times longer than on a normal fairway passage at a speed of 18 knots. Normally the vessel would have developed a heavy turn and heeled considerably with these rudder angles.

The manoeuvring procedure had developed into a praxis, in which the radar was monitored and the landscape was followed through the window in a normal fairway passage. On the radar screen especially the predictor is monitored. The predictor gives the actual and future position of the vessel in relation to the space allowed by the fairway and other traffic. Rudder angles are monitored momentarily, not continuously. If one does not take a look at the rudder angles at the right moment, information of a long lasting, large rudder angle will remain unnoticed. The displays for the rudder angles are situated in the Conning-display, in the displays above the front window and on the ceiling of the bridge.

The bridge team consisted of two persons when the first indications of the steering problems were observed. After the incoming second route pilot arrived on the bridge, the bridge team grew by one person already shortly before the watch change. At the watch change the central person of the cooperative bridge team changed. The route pilot leav-

41 Examination of Liveware – Liveware + Software interactions.

42 For example when M/S ISABELLA grounded, the autopilot of the same brand had used a mean rudder angle of 10 degrees to compensate for a turning force generated by a side wind, the speed of which was 34 m/s.

ing the watch stayed on the bridge also after the watch change. This shows that the detected steering problems were considered serious.

After the changes in the bridge team, its working manner and analysis of the situation developed in spite of the fact that there was no division of labour concerning the tasks related to the monitoring of the various parameters. When the second route pilot began to get acquainted with the situation by asking questions, the communication intensified: the previous bridge team reported their observations on the irregular behaviour of the vessel and a common understanding of the situation began to get clearer.

Because the seond route pilot had been briefed on the steering problems of the vessel, he had better preparedness to notice the seriousness of the problem. In addition, he got a touch to the steering of the damaged vessel as if “on the clean table”. The second route pilot reported continuously to the others about his observations concerning the behaviour of the vessel.

At the turns after the watch change the second route pilot observed difficulties to stop the turns. This made it clear for him that the cause of the irregularities was in the vessel herself, not in the environmental conditions. After this the vessel was stopped.

More persons and particularly the Master could have been called to the bridge earlier, already after the first clear irregularities were observed. In this way the bridge resources would have increased and intensified the analysis of the failure situation and the decision to interrupt the voyage had been made earlier.

Why did the steering of the vessel succeeded quite well in spite of the weakened manoeuvring characteristics?

The effect of the manoeuvring method and training on the management of the vessel

Even if it took time to understand the seriousness of the failure and the voyage was continued with reduced manoeuvring properties, the skilled crew having a sound experience of the route in question managed to hold the vessel on the fairway and to stop her safely. In order to find the most effective steering method and the reason for the irregular behaviour, the vessel was manoeuvred by changing autopilot modes and by using manual steering at times. These actions were carried out carefully and deliberately.

The bridge personnel had got preparedness to steer a vessel with irregular behaviour in simulator training. The situation with a stuck rudder had also been trained. Both route pilots run the damaged vessel through a hard turn by manual steering. This was a demanding manoeuvre.

Apparently the manoeuvring method which had been practised in simulator training and which was used as a normal procedure in manual steering helped in keeping the vessel with damaged steering gear under control and in the fairway. This manoeuvring method utilised the predictor in the observation of the quick changes in the vessel’s motion state.

On the other hand this manoeuvring method did not support the observation of rudder angles to an extent which would have been necessary in this case.

2.4.3 Assessment of the management of the situation

The course of events shows that the technical failure was very difficult or even impossible to detect and understand in a correct way. The rudder damage was not apparent for the bridge team, but instead it required *a comprehensive analysis (contrary to failure analysis)* of the situation, which is a demanding task. The vessel behaved in an illogical way but not a single piece of equipment gave an indication of the true nature of the failure, i.e. the breaking of one rudder shaft. A failure exactly like this had not been simulated in connection with the training.

When a vessel's behaviour in turns differs clearly from its normal behaviour without any apparent external reason or known technical failure in the vessel, *a methodical search to find the cause* must be started. The objective is to determine if it is safe to continue the voyage or whether it should be interrupted immediately.

In this decision-making situation it would have been useful to start *immediately reinforcing human resources* in accordance with a good BRM practice. Skilled navigators and at least the Master could have been called to the bridge. In any case, an effective BRM includes a methodical registration of the vessel's course, especially the observation and documenting of actual rudder angles required in turns.

The nucleus of BRM is *effective communication*. In this case it means that it would have been useful to discuss the observations and to analyse the situation, measures to be taken and e.g. the risks of overtaking another vessel when the steering behaviour was not normal. After the watch change had been completed, the presence of a new person in the bridge team started up an active analysis of the situation, which led to a relatively quick decision.

The situation which had developed was so unclear that the bridge crew needed time to gather observations in order to make the decision to interrupt the voyage. The decision could have been made faster by a more effective BRM practice, i.e. active communication for the methodical monitoring of the situation and the decision to use all available navigator resources onboard in the analysis of the situation.

Alerting and rescue activities

No alert was given. When the vessel was stopped, the Archipelago VTS was notified of the situation in accordance with the Vessel Traffic Service Act. A passenger had informed the MRCC about the situation; the MRCC contacted the vessel. Consequently, the Master did not need to make an MAS report to the MRCC. According to the Master's assessment, the situation did not require any other rescue activities in addition to tug assistance because the vessel was manoeuvrable and entirely seaworthy. The Investigation Commission agrees with this view.

The Master of the vessel quickly made arrangements on tug assistance in order to ascertain the arrival of the vessel in Turku. The possibilities to manoeuvre the vessel were assessed by testing her, and she was moved away from the narrow channel to an open sea area. There the wind prevented anchoring and the vessel started to navigate along an ellipse-shape route.

To determine the reason for the steering problems, a diver was brought to the scene and he then found out the nature of the failure.

In the investigators' opinion the quick ordering of the tug assistance, exploring the manoeuvring possibilities in wider waters by navigating in a circle, bringing the vessel to its destination and learning the nature of the failure were carried out in proper form and without jeopardizing the safety of the vessel.

3 CONCLUSIONS

The breaking of the rudder shaft is a highly unusual incident. It was caused by the fatigue breakage due to the excessive bending of the rudder shaft. The excessive bending was possible because of the exceptional corrosion of the pintle bearing housing, which caused a large free play in the pintle bearing twice, before and after the cast epoxy repair in 2004.

3.1 Findings

1. The breaking of the SB rudder shaft on a channel in the archipelago caused a serious emergency situation.
2. The rudder shaft broke as the result of a fatigue failure.

Development of the fatigue failure

3. Three factors contributed to the development of the fatigue failure:

   The corrosion prone construction of the pintle bearing (which made the galvanic corrosion of the pintle bearing possible and caused a large net free play in the pintle bearing).

   The 0.3-mm notch which had remained in the rudder shaft during the machining phase (the fatigue life of the SB rudder shaft decreased considerably), and

   The rudder forces and resonance vibrations of the rudder, which generated cyclic stresses (because of the large net free play the cyclic stresses exceeded clearly the rated values of the shaft; the shaft was weaker than planned because of the notch).
4. The corroding of the pintle bearing started slowly. The net free play of the pintle shaft increased to 12–13 millimetres by 2004. The fatigue failure started to develop. The majority of the fatigue life of the rudder shaft was spent by the year 2004.
5. An unexpected corrosion in the pintle bearing housing was discovered in the 2004 docking. The pintle bearing bush had dropped against the rudder.
6. The corrosion was repaired with cast epoxy without studying the factors which had led to the development of the failure. Classification society accepted the repair as permanent.
7. The progress of the fatigue failure stopped along with the cast epoxy repair and the development of corrosion became effectively slower.
8. The clearance was within the set limits in the 2007 docking. The measuring of the clearance was not, however, comparable with the previous measuring. The condition of the cast epoxy was checked only superficially.
9. The cast epoxy used in the repair started to break slowly. Further corrosion in the bearing housing contributed in this, and the breaking of the epoxy became faster and it broke off entirely. The epoxy disappeared completely and the free play of the

pintle bearing increased to 16–18 millimetres. The fatigue breakage process continued.

10. The rudder shaft broke on 22 November 2009.

Control of the vessel

11. The breaking of the rudder shaft caused steering problems to the vessel. The weather did not affect the course of events.
12. No direct indication on the breaking of the rudder shaft is available on the bridge; it must be observed from the vessel's motion state and manoeuvring variables. The bridge crew therefore gradually accumulated evidence about the possibility that there might be a failure in the vessel's steering gear. The bridge personnel did not take immediate measures to interrupt the voyage of the vessel.
13. The voyage was interrupted approx. 30 minutes after the manoeuvring difficulties started. A tug was called to the scene and the vessel slowly continued its voyage to Turku.

3.2 Causes of the incident

The breaking of the SB rudder shaft was caused by two hidden construction defects which had been left on the vessel already in the construction stage. There was *a sharp notch* on the rudder shaft, and the material selections and the structure of the pintle bearing made *galvanic corrosion* possible. The free play of the pintle shaft increased as the result of the corrosion of the pintle bearing, which allowed the rudder shaft to bend more than planned. Because of this, the stresses of the rudder shaft grew considerably over the rated values. In addition, because of the notch the increased stresses were directed to the rudder shaft which was weaker than planned. The stresses were fluctuating, which led to the fatigue of the metal.

The breaking process of the SB rudder shaft took altogether 17 years. The process progressed in *three* stages. *The first stage* was a slow corroding of the pintle bearing housing in the course of 11 years, which resulted in hidden fatigue failures in the rudder shaft. The repair by cast epoxy eliminated the free play in the pintle bearing caused by corrosion. *In the second stage* the process evolved slowly as the cast epoxy broke and the corrective action disappeared entirely and the free play became somewhat larger than in the first stage. *In the third stage* the service life still remaining after the fatigue process in stage one came to its end.

The SILJA EUROPA has resonance vibrations in rudder which is typical of this type of vessels. The natural frequency of the rudder falls on the used blade frequencies of the propeller. This accelerated the fatigue process of the shaft. It would be possible to find out the vibration characteristics of a horn rudder in order to reduce the risk of resonance in the design stage of the vessels, which is recommended by some classification societies.

Contributing factors

The corrosion was detected in both pintle bearings in connection with the 2004 docking and its extent was a surprise. The short docking time had an effect on the choosing of cast epoxy as a repair measure, because this assured that the repairing could be performed quickly. Furthermore, the use of epoxy was familiar from other situations. The hidden risks related to the structure could not be seen, especially as the classification society accepted the solution as a permanent one.

3.3 Other safety observations

The planning and inspection of the structures. It would have been possible to detect the construction defects which remained hidden during the construction stage of the vessel before the commissioning of the vessel. The risk that the pintle bearing might corrode could have been identified from the construction drawings in the light of conventional knowledge of corrosion, because the choices of material were known and the metals which were in contact with each other had not been corrosion protected. It was possible to make this observation both at the design stage and anytime when the vessel was operational. It would also have been possible to notice the notch in the SB rudder shaft before the delivery of the vessel, in connection with the delivery inspection by the classification society and the shipping company.

The factors leading to corrosion and its possible consequences on the rudder shaft were not dealt with in connection with the 2004 and 2009 repairs, only the damages were repaired. Rudder shafts are not removed at specified intervals for inspection during dockings.

The usability of cast epoxy in the repair of the pintle bearing. When used as it was, cast epoxy cannot be considered to be a permanent solution when repairing the corrosion in a pintle bearing, which is proved by the breaking of the cast epoxy in both pintle bearings and disappearing in the SB-bearing. Cast epoxy was used to attach a bearing bush without taking into consideration all the loads and load directions directed to the epoxy material and its boundary surfaces. Permanent repairs with cast epoxy are possible only if there is long-time experience from using it. If the intention is that the repair solution stands for the duration of a docking interval in accordance with inspection requirements, this requires planning of the cast epoxy repair, planning of the follow-up of the condition and proper control often enough. Furthermore, it must be made certain that there is adequate adhesion between the epoxy, bearing bush and housing, or the rotation of the bearing bush is prevented in some other way.

Dockings. The docking dates are arranged in such a way that a docking causes as little inconvenience as possible to the operating of the vessel. Therefore the docking time is as short as possible, usually 7–10 days, which means that repairing of unexpected damages might have to be done with inadequate planning.

Some docking intervals had been so long that the corrosion and fatigue processes which evolved with increasing speed had enough time to generate damages.

The measuring method of bearing clearances by using feeler gauges or jacking is a routine, and an unusual free play – caused for instance by the corrosion of the bearing housing - is not searched for.

Control of the vessel. The bridge personnel did not take immediate action to interrupt the voyage of the vessel. This can be explained by the fact that the situation was difficult to interpret. A more effective BRM practice might have speeded up the decision-making. Because of the manoeuvring exercises performed e.g. in a simulator, the bridge personnel was, however, able to react to this exceptional situation in a safe manner.

Notifying the maritime surveillance and rescue organisations of the situation took place in accordance with the regulations.

Controlling the motion state of the vessel by using manual steering can be practised in simulator training in order to find out how the behaviour of the vessel (change in the motion state variables) depends on the steering parameters (mainly rudder angle). This may produce grounds for the consideration of the stopping decision of the vessel when the steering does not function as usually.

4 IMPLEMENTED MEASURES

Concerned parties and parties from the industry have been kept up to date with reference to the most important findings of the investigation. In connection with presenting the results of the investigation, the shipping company has been warned about the corrosion problem still hidden in the pintle bearings.

The occurrence of possible corrosion damages is nowadays under closer control. The shipping company has marked the pintle bearing housing and bush in such a way that even a diver can find out whether the bush has rotated. At the same time a feeler gauge is used to check the clearance. At the measurement by the feeler gauge the diver uses also a specially designed jack, and then one gets reliable results. There are at least four such inspections performed by a diver or a shipyard per year. The jack measurement is not carried out at every diving; however the bush is always inspected.

5 SAFETY RECOMMENDATIONS

When the SILJA EUROPA was built, using quality systems was still rare in companies. Nowadays large companies have certified and audited quality systems such as for example ISO 9001. The detected deficiencies in the design, production and inspections were of the kind that they should not appear if the operations follow a quality system. A successful completion of a vessel's building process in order to achieve correct constructional solutions including details (as in this case making the structure of the pintle bearing such that the corroding of the housing would have been prevented) in the final product requires especially an input in the coordination of activities of the shipping company, the classification society, the shipyard and subcontractors. It has, however, not been deemed necessary to give safety recommendations on quality control as the existing instructions are adequate in this respect.

Instead, **the control procedures concerning steering gear** should be specified. Clearance measurings in connection with dockings by using conventional methods do not detect exceptionally large corrosions on the pintle bearing of the rudder. The too large free play of the pintle bearing causes dangerously high stresses on the rudder shaft. If they persist, these stresses may damage the shaft. Clearance measurings completed at different points of time had not been comparable, which has hampered with the appropriate use of the results.

Fatigue phenomenon may develop surprisingly quickly to the stage of breakage once it has started. Shipping companies have a tendency to lengthen docking intervals, which may in some cases become too long considering the hidden fatigue failure process.

Nowadays rudder shafts are not removed at specified intervals at the dockings for inspections as for instance propeller shafts do.

The SIA recommends to Bureau Veritas and other classification societies that their instructions for the surveyors should include in the future among other things:

1. *The measuring method used on clearances be registered in the inspection report of the classification society. The measuring method must be such that it gives comparable results and it must be based on the structure of the pintle bearing in such a way that it is possible to detect all changes in the boundary surfaces of different materials (possible corrosion).*
2. *If 3–4 mm clearances have been detected repeatedly, the rudder shaft and its counterparts be checked for cracks and corrosion. When agreeing with the shipping company upon docking times, the classification society must consider whether there are any indications in the vessel's repair history on possible fatigue failure process in the steering or other gear.*

The SIA recommends to Bureau Veritas and other classification societies that:

3. *The classification society should consider adding in the rules the inspection of rudder shaft by removing them at specified intervals.*

The use of cast epoxy as a part of the structure of the pintle bearing of the rudder and thus in touch with seawater on a vessel as large as the SILJA EUROPA was a rare event and unique in the repair shipyard.

The SIA recommends to Bureau Veritas and other classification societies that

4. *Repairing the pintle bearings with cast epoxy be a provisional solution. The provisional nature of the repair has to be taken into consideration when deciding upon the control methods and inspections intervals concerning the state of the repair. When planning the repair, all stresses directed from the bearing bush to epoxy must be taken into consideration.*
5. *Prior to the provisional or permanent repair of the pintle bearings, the factors which have led to the need for repair should be found out. They must be taken into consideration when planning the repair.*

Assessing the vessel's behaviour in diverging situations is possible with the help of effective BRM, which includes the distribution of duties into control of the vessel and analysis of the situation. If the steering systems of the vessel function in an irregular manner, it has to be determined whether the vessel can continue her voyage.

The target-oriented analysis of the situation is based on a thorough understanding of the vessel's basic behaviour and requires registration of the manoeuvring variables, for example a methodical observation and registration of the rudder angles needed in turns. In addition, an assessment on the severity of the situation and a decision on further measures, including calling the Master and/or extra personnel to the bridge, must be made on the basis of them.

The SIA recommends to the shipping company that:

6. *Simulator training should be developed further in such a way that the preparedness of the trainees to work out and analyze in a systematic way a situation in which the maneuvering systems of the vessel do not function in a normal way will improve. The objective must be to develop data gathering to support the decision-making on whether to interrupt or continue the voyage.*

Helsinki, on 9 November 2012

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SUMMARY OF THE RECEIVED STATEMENTS

Statement of the Finnish Transport Safety Agency

The Finnish Transport Safety Agency had nothing to comment on the final draft of the investigation report.

Statement of the Bureau Veritas

Bureau Veritas in its statement noticed that there is no evidence of the existence of a possible hairline crack in the rudder shaft at the docking in 2004.

Moreover, Bureau Veritas emphasizes, referring to their own rules (Rules for the Classification of Steel Ships, PtA, NR467, Ch3, Sec4, 2.5 (Bottom Survey), that the visible parts of the rudder shaft are examined regularly. If considered necessary by the surveyor, the rudder is to be lifted and/or its inspection plates are to be removed for the examination of pintles.

The statement notes that corrosion protection is not a Class item and that the Classification Rules are not designed, intended or required to include neither repair methods of the pintle nor measuring methods of pintle bearing clearances. These methods should be as per manufacturers' or ship owner's instructions.

In addition, the statement comments on the use of cast epoxy as a permanent repair.

The statement of Tallink Silja

Tallink Silja wanted in its statement to specify some details in the investigation report. Those were among other things the steering of the vessel and the equipment on the bridge, training of abnormal situations in the ship simulator, the influence of the ship speed on the evaluation of the steering forces and the use of cast epoxy in the repair of the pintle bearings. Moreover, an addition to the measures carried out by the shipping company after the accident was received.