Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org
ISSN: 2379-3252

Vol. 38 No. 1 June 2021

Forensic Issues from the Investigation of a Marine Shaft Failure

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Abstract

The starboard propeller shaft of a twin-screw diesel electric rail ferry in New Zealand failed just after the ferry left port. Weather was not a factor. The ship was on a regular schedule of three sailings a day. The starboard propeller was found in 120 meters of water approximately two nautical miles from the channel — some distance from the point where power was observed to reduce to zero on the shaft. The fracture surface of the shaft showed a classic fatigue failure pattern. However, there were questions to be answered, including what initiated the failure, and why a tension failure occurred in a shaft that was primarily under compression from the reaction forces of the propeller. This paper will look at some interesting factors in the investigation, the techniques used to limit the investigation (and its cost) to relevant areas, a few of the false trails that were followed, and the processes eventually used that were the most convincing.

Keywords

Marine shaft failure, fatigue, fretting, precision scanning, digital shape comparison, digital modeling

Introduction

On November 5, 2013 on a trip from Picton to Wellington the starboard shaft of a ferry failed shortly after the ship left the Tory Channel. Once on-board tests had established that the propeller had been lost, the ship proceeded on one shaft to Wellington harbor — where it berthed successfully, unloaded, and was then shifted alongside for investigations to commence.

An underwater survey revealed no hull damage and provided good high-resolution photographs of the fracture face, which was protected from corrosion by the cathodic protection systems on the ship. The fracture face was subsequently protected by a grease-filled cap, which was removed once the vessel was docked for repair to allow metallurgical examination.

The starboard propeller was found in 120 meters of water approximately two nautical miles from Tory Channel, standing upright, with one of the four blades embedded in the ocean floor. It was recovered on December 10, 2013 and returned to Wellington.

The propeller and the stub of the shaft, which was still retained in the propeller hub, were examined by the investigating team. It was noted at this time on the recovered starboard propeller that there was a small bend at the tip of the C blade — and that the suction faces of all blades showed varying degrees of surface cavitation damage (with the C blade showing the most severe damage). A review of recent underwater surveys showed that the bent tip was not present in the 2012 survey, but was noted as present (but not requiring any remedial action) in the 2013 survey by the Marine Class Surveyors and the owner's technical staff.

Background Information

The outline specification of the ship is as follows:

Ship type:	Passenger/ RORO cargo ferry
Built	1988
Service speed:	19.5 knots
Gross tons:	17,816
Deadweight:	5,464 tons
Number of propellers:	Two, 3.95 m diameter, four blade, fixed pitch inward rotating (currently fitted)
Total kW:	2 x 5,200 kW (6973 hp) at 160 rpm normal operating speed.
Drive system	Variable-frequency electric propulsion from LFO Generators through ABB SAMI Megastar system
Length B.P. (m):	183.5 (as modified by a midships extension in 2011)

The ship was lengthened by insertion of a 30-meter mid-section and fitted with new high-efficiency propellers in 2011. The extension did not affect any of the propulsion

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DOI: 10.51501/jotnafe.v38i1.168

Figure 1
Arrangement of shaft, propeller, and rudder. The exposed shaft end is where the starboard propeller was mounted before it was lost.

Figure 2
The port side arrangement is similar. In this photo, the new high-efficiency propeller is in place and rudder is inclined toward the camera.

equipment except for the fitting of the new propellers. There was no evidence of cracking or shaft damage when the old propellers were removed.

The general arrangement (**Figures 1** and **2**) of the stern equipment was symmetrical with each propeller followed by an in-line rudder. This close up (**Figure 3**) shows the area between the aft end of the stern tube and the hub of the propeller. **Figure 3** is the port side, which was undamaged; the starboard side was similar.

Initial Observations

The high-resolution underwater photographs (**Figure 4**) showed a distinctive pattern on the fracture face, which clearly indicated that the failure was a uni axial fatigue failure[1,2]. This type of failure is caused by a fluctuating force that increases and decreases stress on one side of the shaft and generates a fatigue fracture with a single origination point that progresses across the shaft from the side where the force is being applied and results in the final overload failure occurring on the opposite side from the fluctuating force.

Because fatigue failure is a cyclic process — and requires a tensile stress to drive crack growth — an early check was made to determine if the failure originated in the use of the astern mode (propeller reversal to reverse thrust) during docking that would generate tensile stresses in the main propulsion shaft. As the rotational speed of the propellers is fixed at 160 rpm and the operating schedule is regular, annual cycle calculations showed 4.6 million revolutions on full ahead versus 80,000 on full astern. The ship is also equipped with a 2 MW bow thruster that minimizes the use of asymmetric shaft rotation. The influence of astern operation was not significant in terms of fatigue life over the two years that the new propellers had been installed and was discounted.

Figure 3
The fracture in the starboard shaft occurred just inside the propeller hub.

It was noted that the fracture face was approximately 20 millimeters inside the propeller hub, and that a certain amount of damage to the propeller hub could clearly be attributed to relative movement between the two halves of the shaft as the failure progressed.

When the shaft stub was removed from the propeller hub, there were marks on both the shaft and the bore of the propeller that indicated there may have been fretting occurring at the shaft to propeller hub interface

(**Figures 5** and **6**). Fretting is a form of surface damage that occurs when there are very small relative movements between two surfaces in very close contact. Fretting is known to reduce the ability of steel shafts to resist fatigue loading. While it can facilitate the initiation of a fatigue crack, the full development of the crack into a fracture still requires a significant fluctuating force capable of driving the fracture through the body of the shaft[3].

Detailed measurements were undertaken of both components to eliminate the possibility that the propeller was off center. Within the tolerances of the measuring equipment, it was confirmed that the hub and shaft were both constructed in accordance with the original drawings.

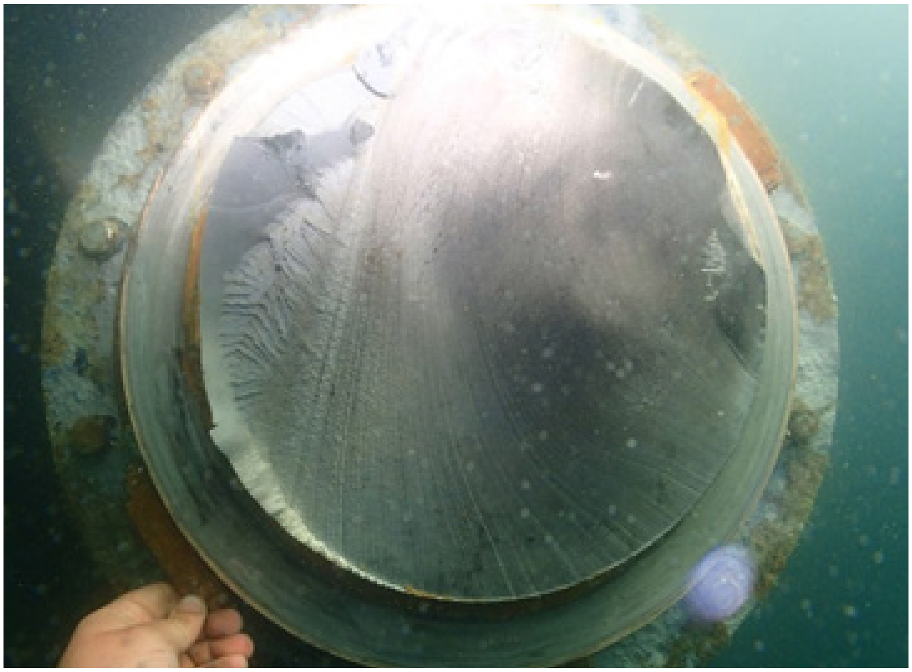

Figure 4
This fracture is distinctive and cannot be generated by any other loading pattern.

Figure 5
Fretting marks on the shaft stub.

Specialist examination by international ship repairers and marine surveyors established that the damage and the bent tip were repairable but noted there was evidence that cavitation had been originating at small defects on the leading edge and depressions on the propeller surface (**Figure 7**). Measurements also showed that there were some significant unexpected depressions on the propeller blades. The specialist expressed the opinion that the bent tip was typical of normal operational damage and was unlikely to have any significant effect on propeller performance — and did not represent a threat to the integrity of the propulsion system. Examination showed that the cavitation damage on the starboard propeller was most

Figure 6
Fretting marks and failure damage on the propeller hub.

Figure 7
Cavitation erosion caused by small indentations and poor edge form to the leading edge.

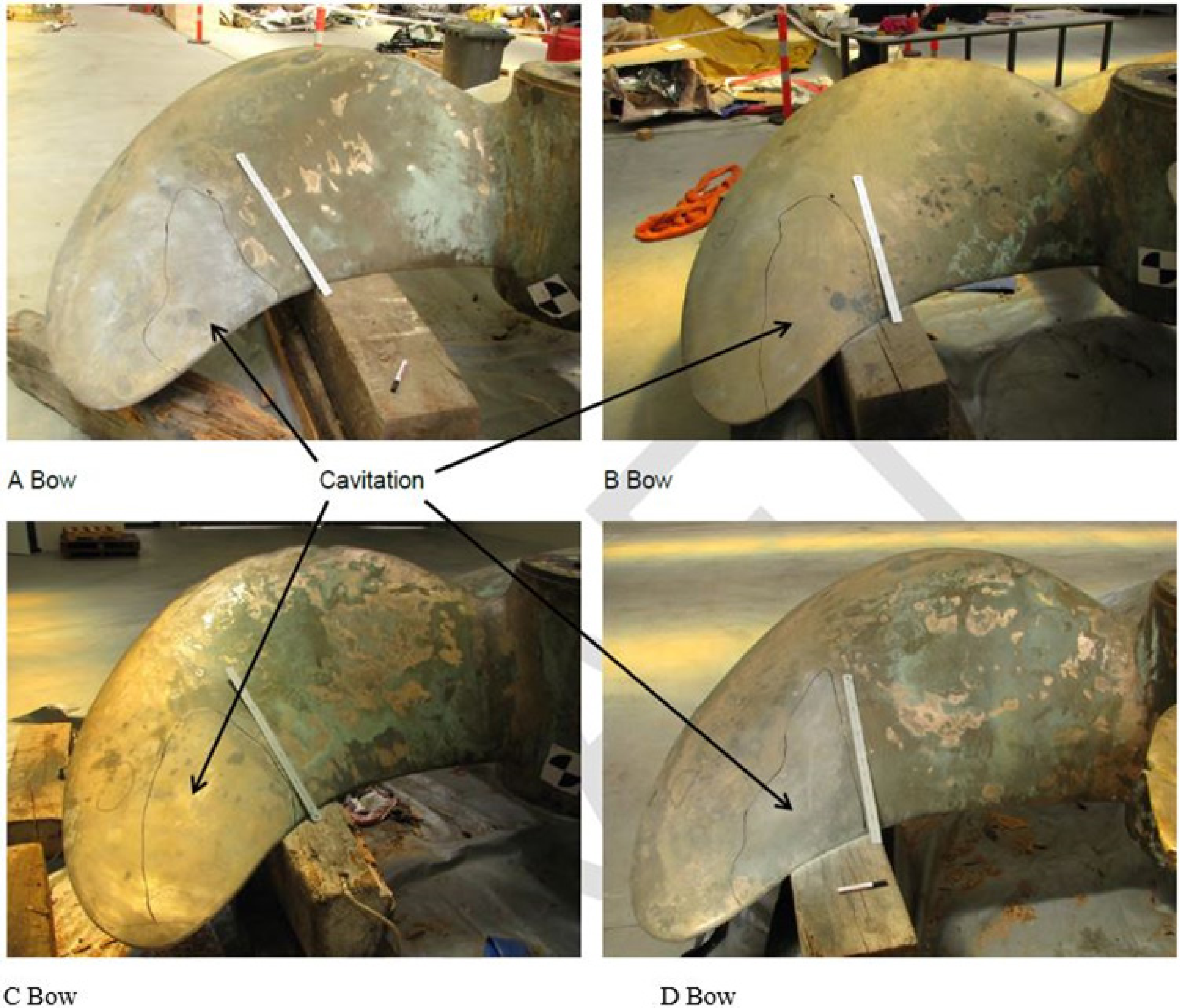

Figure 8
Cavitation patterns were observed on the suction (bow) side of the starboard propeller varying in depth and area. The C blade was the worst.

severe on the C blade (**Figure 8**).

To record the propeller shape for future analysis, the propeller was scanned using laser digital technology. Analysis of these scans showed possibly significant differences in shape between blades — particularly, the C blade (the blade with the most severe cavitation damage) appeared to be the most significantly different in terms of propeller form.

The bent tip of the C blade was measured, and an elastic/plastic analysis of the bend was done to determine the load that the creation of this bend would place on the shaft. The estimate of the instantaneous stress at 80 MPA was not sufficient to fracture the shaft or deform the propeller and was considered unlikely to have played a part in the initiation of the fatigue failure.

Some rough order finite element calculations were carried out to establish stress levels in the shaft at the plane where the fracture occurred but were inconclusive because of the many assumptions required to allow the model to be resolved, which the investigation team considered rendered the results of indicative value only. However, they did show that combined stresses, taking into account gravity loading, stresses from the interference fit, and torsion, could resolve into tensile principal stresses in the shaft in the area of the failure.

Figure 9
The fracture face on the tail shaft after removal of the protective cap.

Figure 10
Starboard rudder outboard side leading edge to right.
Arrow is at center line of propeller shaft.

Investigation in Singapore

Because of limitations of local dry docks in Australasia, the vessel sailed to Singapore on one shaft after modifications to allow all generators and drive systems to be applied to that shaft — and analysis and testing to ensure the remaining shaft was sound. Singapore was chosen because the dock was available, and there was extensive large marine repair experience there.

In the dry dock in Singapore, the fracture face on the starboard shaft was uncovered (**Figure 9**) and examined metallurgically in place. It was also noted that there was an unusual pattern of paint removal on the starboard rudder that was consistent with cavitation damage (**Figures 10** and **11**). This paint damage was not present on the port rudder.

Figure 11
Starboard rudder inboard side leading edge to left.
Arrow is at center line of propeller shaft.

It was noted that the paint damage on the inboard side of the rudder was significantly more than on the outboard side. It is known that there is a wide boundary layer called a wake field along the vessel hull and that hydrodynamic conditions in this boundary layer are different from the free field flows over most of the propeller operating volume. These facts were both relevant when evaluating the effects of the cavitation damage observed on the starboard propeller later.

The port propeller was examined in place and then removed. The end of the port tail shaft was also subjected to magnetic particle inspection and detailed metallurgical inspection in place to see if there was any sign of distress or incipient failure — and to examine in detail the fretting damage that was also found under the port propeller hub. The surface of the propeller was closely examined for any evidence of cavitation damage. None was found.

Following in place examination, the tail shaft was removed, and a small section of shaft (which included the fracture face) was cut off and taken to a local independent metallurgical laboratory with marine equipment experience for detailed examination. The independent metallurgical laboratory in Singapore also examined the propeller seating area on the port shaft and reached the following conclusions:

1. There was no metallurgical defect at the origin of the fatigue failure on the starboard shaft.

2. There was no surface damage from fretting at the origin of the fatigue failure on the starboard shaft.

3. Fretting damage on the port shaft was more severe than on the starboard shaft.

4. There was no sign of cracking or incipient failure on the port tail shaft.

5. In their opinion, the fracture was caused by a significant uniaxial fluctuating bending forces.

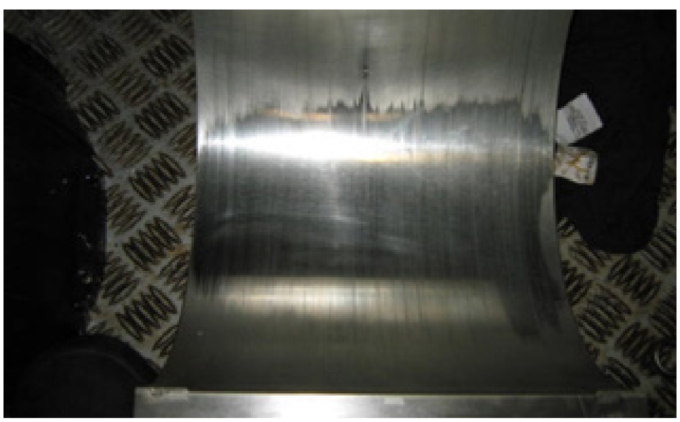

Figure 12
Starboard aft bearing.

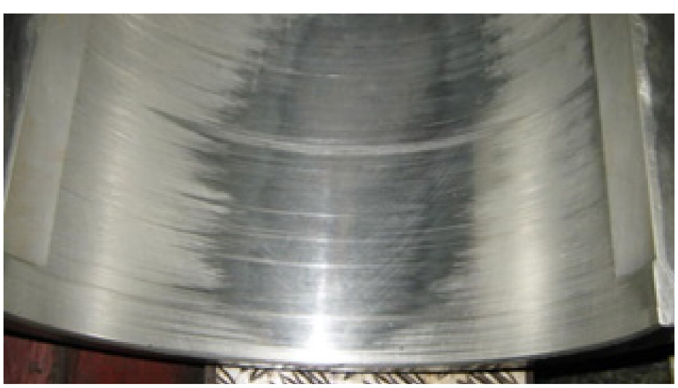

Figure 13
Port aft bearing.

While in Singapore, the alignment of the shafts was thoroughly checked and the bearings examined for signs of vibration damage. While the alignment was found to be less than satisfactory, there was no damage to the bearings that could be attributed to vibration. There was a small area of fatigue failure on both aft stern tube bearings, which was consistent with normal loading (**Figures 12** and **13**). There was no wiping of the bearing material, and no unusual wear patterns when assessed against ISO 7146-1:2008 *Plain Bearings Appearance and Characterisation of Damage to Metallic Hydrodynamic Bearings Part One General*.

Given that bearing position and condition is a significant element in the onset of vibration, it was considered unlikely that vibration had been a problem with the original drive configuration.

Late in the repair process, it was discovered that the rudder stocks were cracked and that the starboard rudder stock had growing fatigue fractures on the port and starboard sides, indicating that some force had been bending the rudder stock from side to side. This is consistent with the expected loading that fractured the shaft and with the variation in paint damage on opposite sides of the rudder. Both rudder stocks were replaced.

Investigation Plan

Given the wide range of potential causes — and the somewhat random pattern of acquisition of information during a long investigation — a key strategy was the comparison of the port and starboard propulsion systems, since they were identical when constructed, yet the port system showed no signs of distress or incipient failure even under detailed metallurgical examination during the dry docking in Singapore.

From this, the investigation team was able to include or eliminate factors by comparison between the two systems. If something was the same on both systems — and it had not initiated a failure on the port shaft — it was assessed as being unlikely to be a root cause of the failure. If a significant difference existed between the two systems, this difference was assessed as requiring further

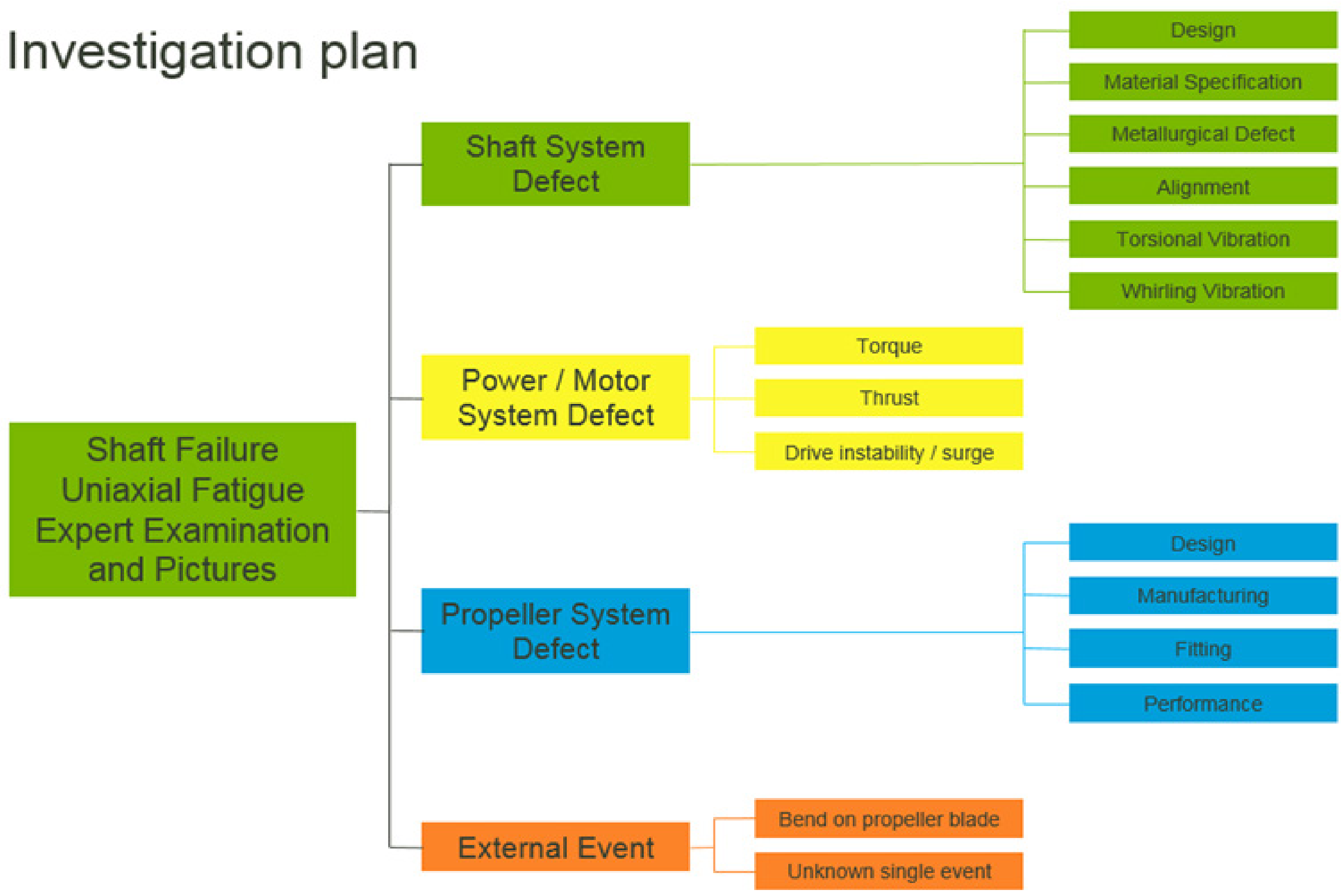

Figure 14
Detailed investigation plan.

detailed examination as a possible root cause.

To provide some structure, the system was analyzed and divided into four primary systems based on operational elements of the propulsion system. These were the propeller, shaft, power and motor system, and an external event (**Figure 14**). Observations were accumulated under each heading and potential causes evaluated with a view to confirming or eliminating their possible contribution.

External Event

There was always a possibility that the fracture had been initiated by some external event, such as an impact with a floating object. However, the nature of a fatigue fracture is that it occurs over time, so the single event does not remove the need for a uniaxial fluctuating force.

There were no reports in the ship's log of any significant impact incidents.

Power and Motor System Defect

The nature of forces in the drive system allow the defects to be considered in three areas: the torque or twisting forces in the shaft that turn the propeller; the thrust in the shaft that pushes the ship through the water; and some instability in the electrically controlled drive motor system.

Torque

The first important fact is that the motor and drive system of the ship had not changed specification since the original build so the possibility of an overload in the shaft from the system was remote.

In addition, a torque failure produces a characteristic fracture that runs at 45° to the main axis of the shaft (**Figure 15**), and is completely different from the uniaxial

Figure 15
A typical torque failure.

fatigue failure observed on the starboard shaft. On this basis, a failure related to torque can be positively ruled out.

Thrust

The new high-efficiency propellers produced 7% more thrust than the original propellers fitted to the ship. This is well within the design safety factors. If it had been a problem, we would expect to see evidence of this on both systems as they are identical. In addition, a uniaxial fatigue failure requires tensile stresses while the thrust of the propellers should only generate symmetrical compressive stresses in the shaft. Compression stress from thrust increase can therefore be ruled out.

Drive instability or a power surge

There was no record of any drive instability during the entire service life of the ship. Should this have been the cause of the failure, the nature of the fracture would have been significantly different — either being a characteristic torque failure or a fatigue failure with multiple points of origin. The team concluded that the failure did not have a root cause in the power or motor system.

Shaft System Defect

Shaft design

The port shaft, which showed no signs of distress or failure, was identical to the starboard shaft. On that basis, a design fault of the shaft can be eliminated as a root cause.

Shaft material specification

The shaft material from both shafts was tested and met the required specification in the design document and class design rules for shafting HS LC 2011-01 DET Norske Veritas Rules for Classification of High-Speed Light Craft and Naval Surface Craft January 2011.

Metallurgical defect

It is often the case that a small metallurgical defect is found at the origin of a fatigue failure. The origin area of the fracture face was examined by three independent metallurgists, all of whom could not find any defect under microscopic examination. Therefore, it is reasonable to conclude that there was no metallurgical defect present.

Alignment

Although the alignment of the shaft was less than ideal at the time of the failure, both shafts were in a similar condition, and the port shaft did not fail. Consideration of the effects of misalignment — and the constraints imposed by the bearings in the stern tube where the shaft is held in by forward and aft bearings and two intermediate bearings — makes it extremely unlikely that misalignment could have created a uniaxial force at the location of the fatigue fracture.

Torsional vibration

As discussed previously, torsional failures have a distinctive characteristic and are aligned at 45° to the axis of the shaft. The uniaxial nature of the fatigue failure rules out torsional vibration as a root cause.

Whirling vibration

Whirling vibration can usually be detected by examining the wear pattern of the bearing lining materials. There was no evidence of whirling seen in the bearings of either shaft. Machine condition vibration monitoring was inconclusive at expected whirling frequencies, but showed no evidence of any shaft vibration — although it did record blade pass frequencies.

Whirling vibration would create symmetric forces on the shaft that would result in at least two fracture origination points, which is not consistent with the evidence of the fracture surface.

Propeller System Defect

Considering the previous analysis — and the fact that clearly a significant force was required to fracture a 352 millimeter (13.8-inch) diameter shaft — the propeller system was likely to have some influence in the failure process. Not only were many of the other potential causes ruled out, but the propeller is a large mechanical element generating forces capable of pushing the ship through the water. And if there was any problem in the propeller system, it has the potential to generate effects that could have significant consequences.

To assist in the analysis of the propeller system, this was divided into four sub areas: the design of the propeller, the manufacturing process of the propeller, the fitting of the propeller, and the performance of the propeller in service.

Propeller design

The new propellers were designed to improve fuel performance and provide some increased thrust that would assist in keeping timetables in a difficult passage

The new propellers were significantly lighter than the original propellers, and analysis by the designers showed there was a possibility that the new shaft/propeller combination may vibrate in service. To overcome this, the rear bonnet of the propeller was extended — adding weight behind the main propeller to recreate the original propeller system characteristics that had operated successfully for 23 years. This change was assessed by calculation as having a minimal effect on the stresses in the shaft.

The new propellers had a slightly higher power density in kilowatts per square meter of blade area than ships of similar design and service. The propeller improvement report noted that the new high-efficiency propellers would be slightly closer to cavitating in service. A diagram included in that report showed that, as designed, the propellers were within accepted service parameters (**Figure 16**), although the sensitivity to cavitation had increased. Therefore, damage or surface defects became more likely to initiate cavitation.

We understand that the propellers were designed using digital techniques, which calculated the geometry of the propeller to a high level of accuracy — much less than 1 millimeter. They were specified to be built to the ISO 484/1, the International Standard for Propellers of Diameter Greater Than 2.5 m, which has a base construction tolerance band of plus 2 millimeters minus 1.5 millimeters.

Manufacture

It was noted by several marine equipment experts that the thickness of the propeller blades varied quite significantly, although such physical measurements as could be taken indicated that these fell just inside the tolerance band as allowed by ISO 484-1 2015-Shipbuilding-Ship Screw Propellers Manufacturing Tolerances – Part 1: Propellers of Diameter Greater Than 2.5 m. The propellers were cast and not machined and had non-critical casting surface artefacts. The form of the blades was typical of cast components and of a shape and evenness that could not be generated by overload damage.

These observations led to the decision to digitally scan both propellers and carry out a shape comparison.

Once the two propellers were returned to New Zealand, they were digitally scanned at the same time using the same equipment in the same environment with digital and survey control measures to allow the accuracy of the scan to be assessed as plus or minus 2 millimeters for the surfaces. (This was at the limit of the technology at the time. Current equipment with proper survey control can now exceed this accuracy.) Because both propellers are inward rotating, one propeller was then digitally reflected so that the two digital images could be placed together and any differences in shape highlighted by subtraction.

The propellers were aligned using the machined

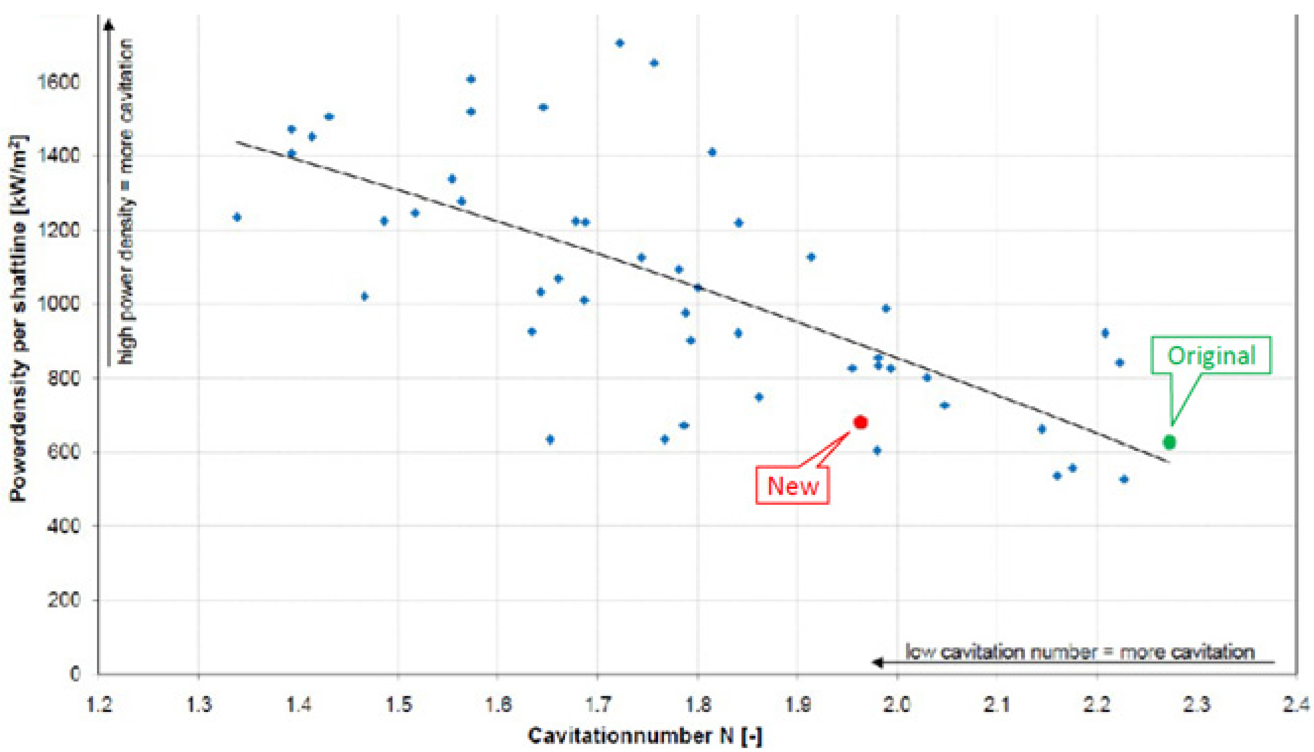

Figure 16
Power density and cavitation number for the design and the ferry reference set.

front face of the hub, and rotated until the A, B, C, and D blades were in matching positions (there is a standard naming convention for blade position). Then the difference between the two blade surfaces could be assessed. The differences were mapped, and any differences greater than plus or minus 2 millimeters (a zone that contained the acceptable manufacturing tolerances) were color-coded. **Figure 17** shows the suction face, which is where cavitation occurs. (The black spots are noise from the scan, and analysis can be ignored.)

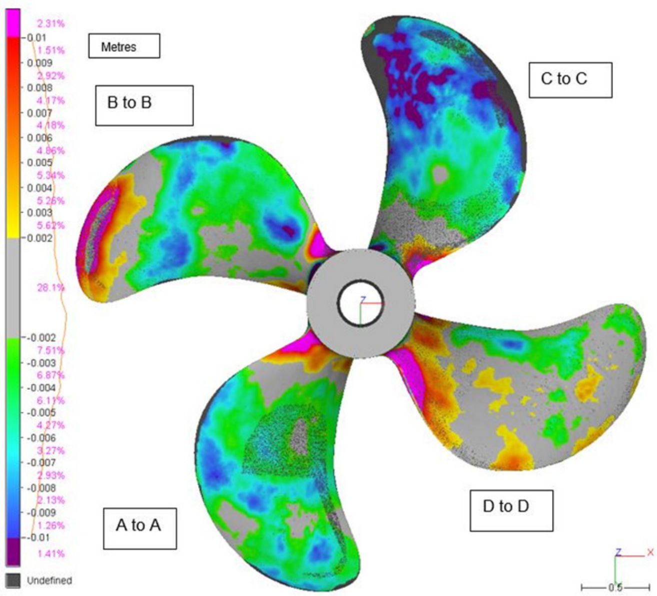

Figure 17
Digitally calculated differences between the suction faces of the two propellers.

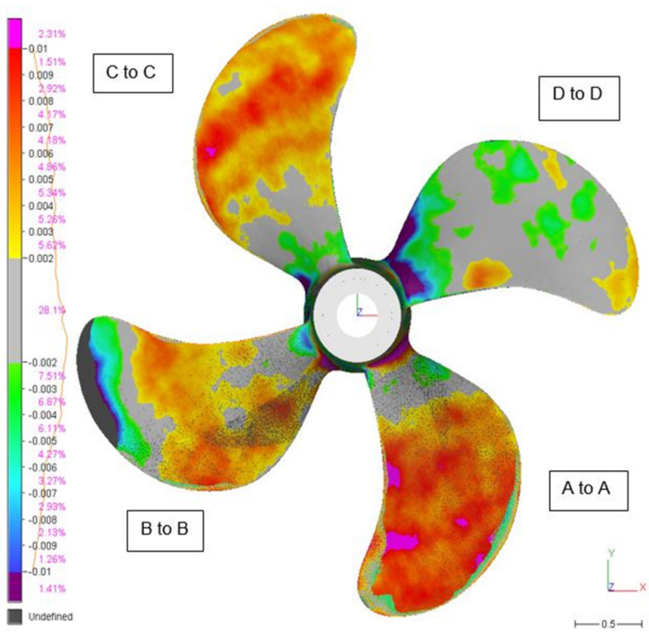

Figure 18
Digitally calculated differences between the pressure faces of the two propellers

It was clear from this comparison that there were significant differences between the A, B, and C blades of the port and starboard propellers, while the D blades fell largely within the base tolerance zone. **Figure 18** compares the pressure faces of the two propellers. The C blades were significantly different, and the C blade of the starboard propeller was also displaced rotationally around its main axis (**Figure 19**). Comparison between the mapped differences in shape (colors), and the observed cavitation (inside line) showed a close correlation in location when the two images were overlaid (**Figure 20**).

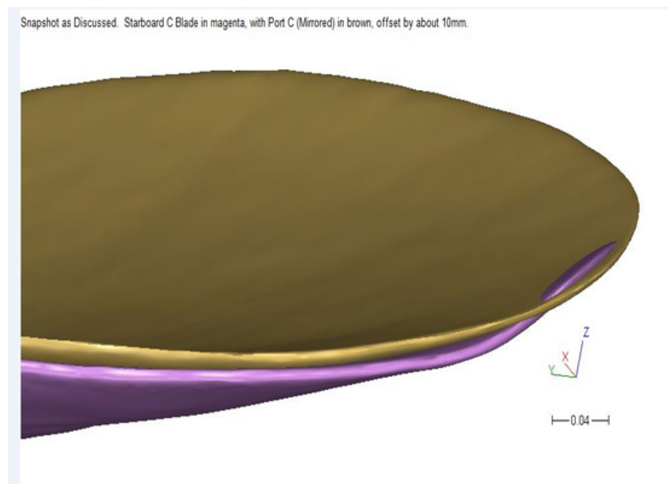

Figure 19
View of the digital model showing that the C blade of the starboard propeller is displaced rotationally around its main axis.

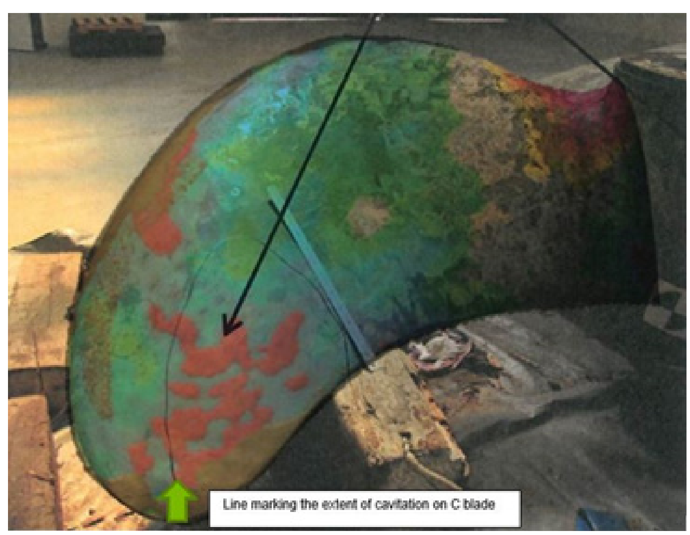

Figure 20
By overlaying the photograph of blade C in Figure 8 and blade C in Figure 17, it can be seen there is good correlation between the largest shape deviations and the observed areas of cavitation.

Propeller fitting

Because of the historical regularity of shaft failures (where propellers were secured to the tail shaft by a keyway), recent shipbuilding practice is to secure the propeller and transfer the driving torque by means of an interference fit between the tapered end of the tail shaft and the tapered bore of the propeller hub.

This interference fit is defined by the distance that the propeller is forced up the tapered end of the tail shaft. This is a controlled procedure generally monitored by the class surveyor and documented in the shipyard records. The design of the interference is intended to hold the propeller firmly on the shaft without movement. There is significant pressure at the interface between the shaft and the propeller hub and the contact area required before final push up as defined was reported, although not recorded, as complying.

If the interference fit is inadequate fretting can occur. However, fretting can only promote the initiation of a crack, and no fretting was found at the origin of the fracture face and the starboard shaft. Fretting by itself cannot drive the crack through the shaft. An external fluctuating stress must exist that is great enough to do this.

The metallurgical evidence referred to above confirmed that there had been fretting between the shaft and the propeller hub on both the port and starboard shafts. It also confirmed that there was no fretting damage at the site of the origin of the uniaxial fatigue failure. On this basis, fretting arising from any possibility that the interference was inadequate was ruled out as a root cause, leaving a fluctuating force as the remaining cause.

Propeller performance

A key factor in the performance of a propeller is a phenomenon known as cavitation. A propeller generates the thrust that pushes the ship through the water in two ways: by the back face of the propeller that pushes on the water as the propeller turns and by the suction on the front face of the propeller created as it drags the water in front of the propeller toward it. While the pushing force is generally stable, the suction force depends on the water sticking to the propeller face. If the suction becomes too strong, the water in front of the propeller cavitates, and the force generated by the blade, which is cavitating, is significantly reduced. This is a situation that propeller designers can control by design and is to be avoided. Sensitivity to cavitation is measured by the cavitation number. Cavitation occurs when the number is less than -2.

The design performance of propellers is often checked in free flow fields prior to manufacture by using hydrodynamic modeling techniques and to check and assess any improvement in performance if propellers are being changed. A hydrodynamic modeling company was commissioned to carry out this check on the scanned propeller forms. Hydrodynamic modelers were also commissioned to determine, if possible, the effect of the bent tip on the C blade to see whether this was affecting the performance of the starboard propeller in some way. These analyses were limited to free field flow for financial reasons.

The comparison between the propellers by modeling proved to be somewhat inconclusive, as the scanned forms had to be smoothed to allow the computations to run. The modelers concluded that any difference between the two propellers in terms of forces generated (with or without the bend on the tip of the C blade of the starboard propeller) fell within the uncertainty band of plus or minus 5% associated with their calculations. More accurate calculations were not possible.

While it was disappointing that the modeling did not generate results that matched the cavitation patterns on the propeller surfaces, this was explained by the limits of the software and in computational capacity. (Note: This was in 2015, and both have developed significantly since then.) They were, however, able to provide maps of the propensity of the propellers to cavitate through the calculation of a standard measure called the cavitation number. This showed that, according to their calculations, the scanned shape of the propellers operated at a cavitation number much closer to the critical level than the number proposed in the original investigation reports to determine the benefits of the new propellers. White areas in **Figure 21** are cavitating.

These results supported cavitation as a significant factor for consideration, but the uncertainty in the results meant that the physical evidence became the most reliable indicator of any performance problems with the propellers.

The investigation team was able to show from underwater dive surveys that the paint damage to the starboard rudder (**Figure 22**) was present after one year of service and prior to the appearance of the bent tip on the starboard propeller C blade. The presence of cavitation damage to the paint before the bend appeared on the propellers was accepted as evidence that the bend was not significant as suggested by other experts early in the investigation.

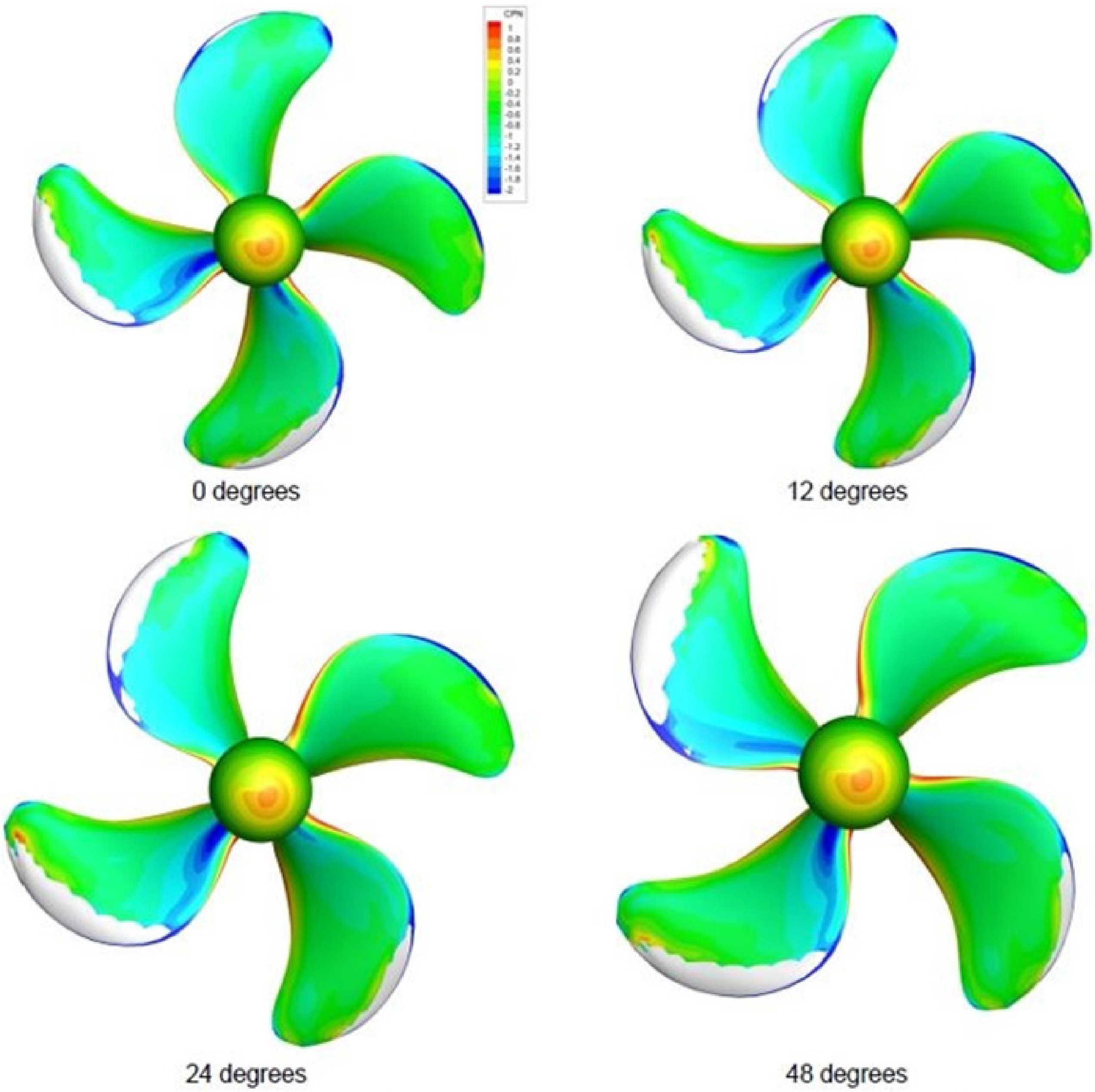

Figure 21
Pressure distribution (CPN) and sheet cavitation pattern for starboard propeller (shown mirrored, overloaded condition, 150 RPM, PD = 5,148 kW). Edge effects only, surface deformities could not be modeled.

The investigation team considered that the paint damage on the inboard side of the rudder was due to cavitation bubbles being shed as the propeller passed through the boundary layer along the hull. Physical observation of the starboard propeller showed one blade with significantly more surface damage from cavitation than the other three blades. It was considered likely by the investigation team that the blade showing the surface damage cavitated as it passed through the boundary layer.

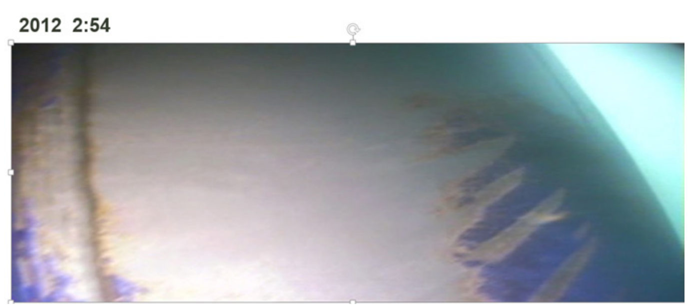

Figure 22
2012 dive inspection shows paint loss on starboard rudder.

The other better formed blades with less surface damage were not cavitating significantly when passing through the boundary layer. When the poorly formed blade was passing through the boundary layer and cavitating three of the four blades would be operating at 100% thrust, while the inboard blade would be generating significantly less thrust. This asymmetry in the forces would generate a repeating uniaxial bending couple that could initiate tensile principal stresses in the shaft surface, and once a crack had initiated could drive the fatigue failure through the shaft. This opinion was drawn from observations and experience as modeling, and calculations failed to provide conclusive numerical proof — although the generalized results supported the reasoning.

Conclusion

The investigation team set out a plan that would allow analysis of all possible credible failure paths, and commissioned independent testing where this could contribute value to the investigation process. Some of the failure paths led rapidly to technical conclusions, which ruled them out as credible causes, and no further investigation in those areas was carried out.

The availability of a similar drive system on the port side of the vessel provided a valuable benchmark to assess the significance of observed differences and similarities, allowing more weight to be given to the differences as potential contributors to the failure.

In some areas, particularly in the hydrodynamic modeling and theoretical stress analysis areas, the number of assumptions that had to be made to allow numerical processes to be used led the team to give less weight to the outcome of those analyses and to limit these as the associated cost of more extensive calculation was assessed as contributing little value to the investigation.

Historical evidence allowed a timeline to be established where the team could see the sequence in which some of the physical evidence appeared in the record. This provided valuable information as to circumstances when that evidence appeared and allowed certain issues (such as the bend on the tip of the C blade of the starboard propeller) to be discounted as causative of the cavitation evidence as the cavitation damage preceded the appearance of the bent tip.

The team also concluded that the shape differences measured on the starboard propeller, when compared to the port propeller, were significant and consistent with the physical evidence of the fatigue fracture and the cavitation damage. Considering the physical evidence available — and by comparison between the port and starboard propeller and shaft systems — the author generated the following summary of observations and investigation:

Observations:

1. Fretting on the port shaft was worse than fretting on the starboard shaft, indicating that fretting was unlikely to be a root cause.

2. The naturally fluctuating forces of the port propeller were not able to initiate or drive a fatigue failure on the port shaft despite the higher level of fretting present.

3. There was no fretting damage present on the surface of the starboard shaft where the fracture originated suggesting that an additional force above the natural fluctuations of a rotating propeller initiated and drove the fatigue crack.

4. There was clear evidence of abnormal performance of the starboard propeller by way of cavitation damage to the suction surfaces of the propeller and paint erosion on the rudder caused by the shedding of cavitation bubbles.

5. The failure was a uniaxial fatigue failure that originated close to the C blade.

Investigations:

1. Finite element analysis, while uncertain as to the actual stresses, showed the principle stresses from torsion, interference fit, weight and bending summed to tension in one direction at the surface.

2. By comparison, between the scanned shapes of the port and starboard propellers, the C blade of the starboard propeller was most significantly different from other blades on the starboard propeller and from matching blades on the port propeller.

3. The surface damage from cavitation was most pronounced on the suction face of the C blade of the starboard propeller.

4. It is known that cavitation affects the capability of a propeller blade to generate thrust.

5. One non-performing blade on a propeller would generate a uniaxial force that fluctuated once per rotation in a consistent transverse direction across the shaft as it passed through the boundary layer.

6. That fluctuating force would generate a couple on the propeller that would act to maximum effect at the plane where the fracture occurred on the starboard shaft.

7. The intermittent couple generated by the starboard propeller initiated and drove a fatigue failure.

8. The bent tip on the C blade appeared after the evidence of cavitation on the rudder; therefore, it was not a contributing cause to the cavitation.

Based on the physical evidence, it is reasonable to conclude that a malformed C blade on the starboard propeller was the primary cause of the failure. If this blade had been well formed — and the propeller had performed symmetrically — the uniaxial driving force required to initiate and drive the fracture would not have been present.

References

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