Department of Transport

Investigation Report

Capsize of the yacht 'Finistere' on 24 February 2018.

Prepared for Department of Transport

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Date 12/11/2018

Objective number TBA

Contents

Safety Summary

What happened

- On 23 February 2018 Finistere was competing in the Bunbury Ocean Yacht Race.
- On-board were: [redacted]
- Sometime around 23:45 the crew heard a loud bang and the vessel capsized.
- [redacted]

What DOT found

- Finistere capsized rapidly to starboard after the catastrophic failure of its keel.
- The part of the keel contained within the keel case, above the shaped foil, was found to have considerable damage, which is believed to have occurred over a long period of time.
- Much of the damage is associated with modifications undertaken by the owner in 2012.

Safety Message

Modifications and repairs should be undertaken in accordance with best industry practice. The owners of vessels should consider a thorough inspection of their keel, particularly if the vessel is grounded, and as part of their annual maintenance schedule. In the case of vessels with a lifting keel this should include inspection of the part of the keel contained within the keel case.

Overview

The Vessel

Finistere is a 15.7metre yacht built in xxxx ([redacted] Do you know when the vsl was built?) by boat builder [redacted] The vessel was designed by Naval Architect [redacted] and plans drawn up as the Davidson 50 Sailing Yacht.

It is a composite constructed vessel with a lightweight wooden core encased in fibreglass and resin. The yacht was designed for ocean racing and in this role, had competed in numerous races including the Sydney to Hobart. The vessel had a proven track record on rough ocean passages.

When it was originally designed it had a solid keel however, in the configuration at the time of its loss the keel was a lift type designed by Bakewell – White, Yacht Design Limited in New Zealand[1].

This keel was fitted to the vessel in 2009 after a lift keel, installed by a previous owner, delaminated near Albany. At the time, Finistere was returning to Perth after participating in the Sydney to Hobart yacht race. The new keel was constructed by Shipwright, [redacted]

The new keel was of composite design with an Oregon core encased in carbon fibre and resin. According to the manufacturer, the keel design exceeded the requirements of the American Bureau of Shipping Guide for Building and Classing Offshore Racing Yachts[2].

Image 1 Finistare (image source: https://thewest.com.au/news/wa/wa-yacht-race-tragedy-two-men-dead-after-the-fimistere-capsizes-ng-b88755993z)

[1] See appendix 1 Keel Plans

[2] See appendix 2 letter from Bakewell-White; Appendix 3 American Bureau of Shipping Guide for Building and Classing Offshore Racing Yachts (1994)

There were some initial problems with the tolerances between the new keel and the keel case. The new keel had a different shaped lead bulb to that of the keel it replaced, and this caused it to move in a forward and aft direction when underway. To fix the problem, spacers were added to the trailing edge of the keel block.[3]

Another problem was that the locking pins were located at the vessels waterline. *Locking pins are metal pins that pass through the keel case and keel to lock it in place when it is in the downward position.* The location of the locking pins was such that water was able to enter the vessel through the holes in the keel case, when the keel was in an upright position, or the pins were not in place. While the ingress of water through the holes was not excessive, [redacted] made the decision to rectify the issue in 2012.

[redacted] consulted with Bakewell-White, Yacht Design and sent them a proposed modification to the keel [redacted]

Bakewell – White Naval Architect, [redacted] proposed another solution in which a steel plate was fitted into the keel. In this version the locking pins are pushed through sleeved holes in the top area of the steel plate, which extends above the original keel. Therefore, the holes through the keel case could now be located above the waterline (see image 2).

Post incident analysis has confirmed that the latter is the plan to which the modifications were made.

[redacted]

There was no legislative requirement for Finistere to meet a standard in relation to design, build and stability. It had only to comply with the safety equipment regulations governing recreational vessels.[6] But as a yacht competing in ocean races it had to meet the requirements set out by Australian Sailing.

On 12 September 2017, Finistere was audited by Australian Sailing as part of the auditing process required to compete in category 3 yacht races.[7] The vessel passed this audit, which was valid at the time of its loss.[8]

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3 [redacted]

4 Appendix 4, [redacted] email original proposal.

5 [redacted]

6 Western Australian Marine Act 1982, Navigable Waters Regulations 1958.

7 See Appendix 5, Australian Sailing (AS) 2017-2021 Special Regulations Equipment Audit Form. Offshore Blue Book, Section 2- Application and General Requirements for an outline of yacht racing categories.

8 Appendix 6, Audit form

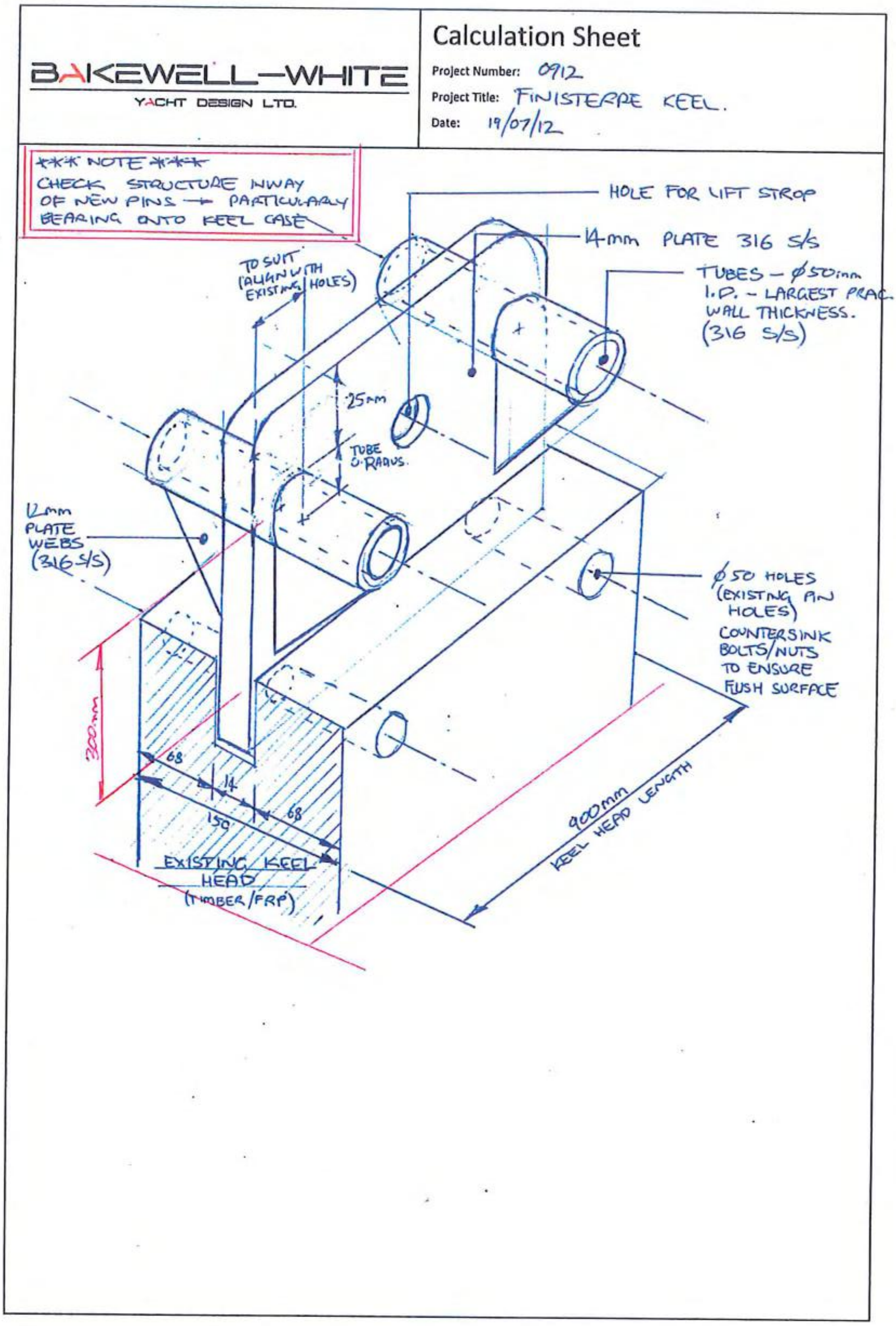


Image 2, Keel modification plans.

The Incident

Race

On Friday 23 February 2018 Finistere was one of 16 vessels competing in the Fremantle to Bunbury Ocean Yacht Race. The event was organised by the Royal Freshwater Bay Yacht Club and vessels departed from Fremantle Harbour at 1730.

The race was classified as a category 3 offshore race and participants were required to follow a stringent set of rules set out by the governing body, Australian Sailing.[9]

In addition to the category 3 rules, organisers required participants to carry individual Personal Locator Beacons that were registered with the Australian Maritime Safety Authority (AMSA).

All competing vessels were required to have a tracking device installed and their process was monitored by a United Kingdom based company 'Yellow Brick Tracker'.

Prior to the race, Finistere was lifted from the water on 21 February and the hull was cleaned and inspected [redacted]

Weather

The Bureau of Meteorology issued the following marine forecasts valid for the 23 February 2018;

Coastal Waters Forecast for Western Australia

Issued at 4:00 am WST on Friday 23 February 2018
for the period until midnight WST Sunday 25 February 2018.

Perth Coast: Two Rocks to Dawesville

Forecast for Friday 23 February until midnight
Strong Wind Warning for Friday for Perth Coast
Winds: Southerly 20 to 25 knots, reaching up to 30 knots during the afternoon and evening. Winds tending south easterly in the late evening. Seas: 2 to 3 metres. Swell: South westerly 1.5 to 2.5 metres. Weather: Partly cloudy.

Forecast for Saturday 24 February
Strong Wind

Bunbury Geographe Coast: Dawesville to Cape Naturaliste
Forecast for Friday 23 February until midnight
Strong Wind Warning for Friday for Bunbury Geographe Coast
Winds: Southerly 20 to 25 knots, reaching up to 30 knots during the afternoon and evening. Winds tending south easterly in the evening. Seas: 2 to 3 metres. Swell: South westerly 1.5 to 2.5 metres. Weather: Partly cloudy.

[9] Appendix 7, Australian Blue Book, Special Regulations, Part 1 for racing boats. Application and General Requirements, pp13. Appendix 8, Supplementary Sailing Instructions.

Coastal Waters Forecast for Western Australia

Issued at 4:03 pm WST on Friday 23 February 2018
for the period until midnight WST Monday 26 February 2018.

Forecast for Friday 23 February until midnight

Strong Wind Warning for Friday for Perth Coast

Winds: Southerly 25 to 30 knots tending south easterly in the late evening. Seas: 2.5 to 3 metres, increasing to 2.5 to 4 metres offshore. Swell: South westerly 1 to 1.5 metres inshore, increasing to 2 metres offshore. Weather: Clear.

Mandurah Wave Buoy

The Department of Transport wave buoy, located offshore from Mandurah recorded the following significant wave heights (Hs) on 23 and 24 February 2018.The graphed information (Image 3) represents the recorded average for the highest 1/3 of waves that were measured at the location of the buoy over a 30-minute interval. They are not the maximum seas and swells that were encountered, which could be up to twice the height of those recorded. Of note is that uncalibrated data taken from the buoy over a 15-minute period recorded maximum wave heights (H Max) of 2.50 to 3.23 metres. The uncalibrated data provides a more accurate reflection of the conditions at the time of the incident. ([redacted] I am going to attempt to get this data calibrated. It's not inaccurate however, the buoy was not calibrated to record Hmax every 15 mins at the time as they were recording Hs every 30 mins).

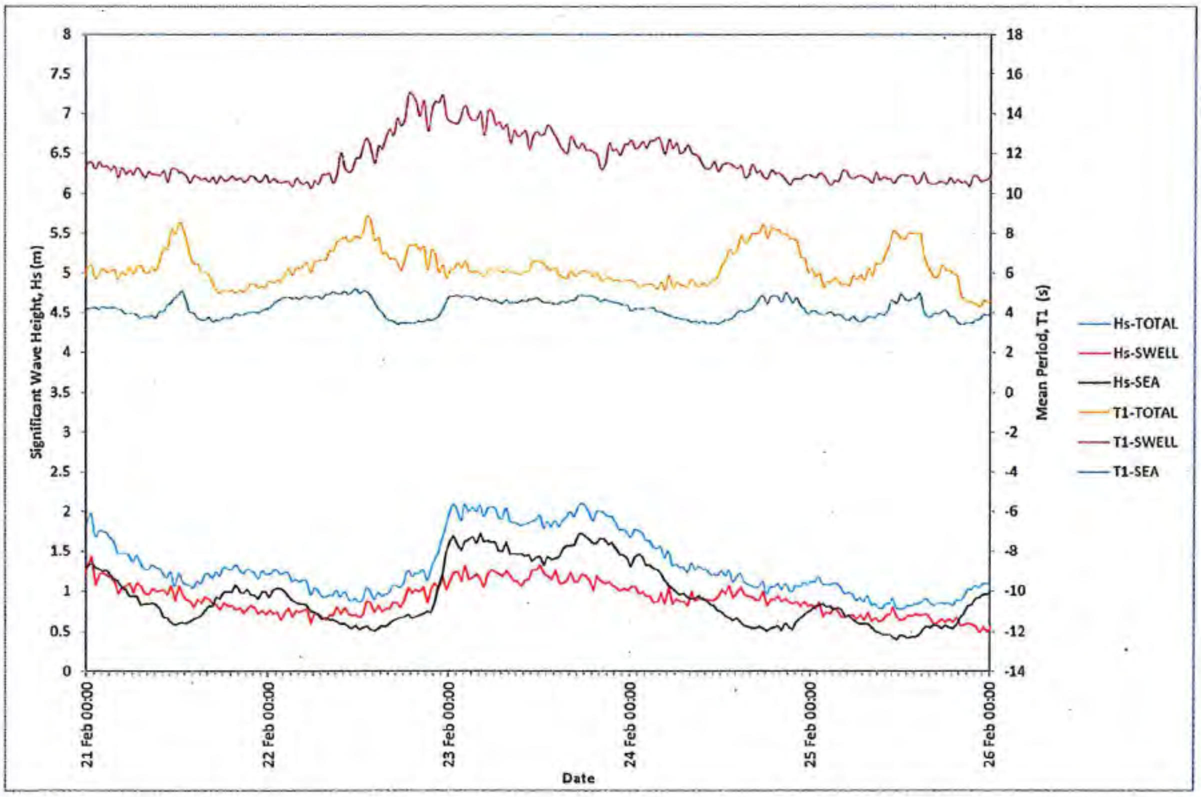


Image 3 Graphed data from the Mandurah wave buoy showing seas swell and wave period

Yachts such as Finistere are capable of being navigated in these conditions, so long as they are structurally sound and under the control of a competent master and crew. However, the weather and sea state are important factors because with an increase in the wind and seas, there is a corresponding increase in the pressures placed on a vessel, its equipment and the fatigue levels of the master and crew. The likelihood that a vessel will be damaged, or equipment will fail increases in inclement weather, as does crew fatigue.

Capsize

After starting the race in Fremantle Harbour, Finistere was navigated in a westerly direction, towards Rottnest Island, before turning onto a southerly course near the south passage markers which are locally known as the 'windmills'. The mapped routes (Images 4 to 8) were constructed from tracking information supplied by Yellow Brick Tracker. Finistere's track is red and the last known position of the vessel is the position where its track ends. The coordinates on the chart, near the end of the route are the location of a Personal Locator Beacon (PLB) activation. The other tracks are those of yachts that responded to the emergency.

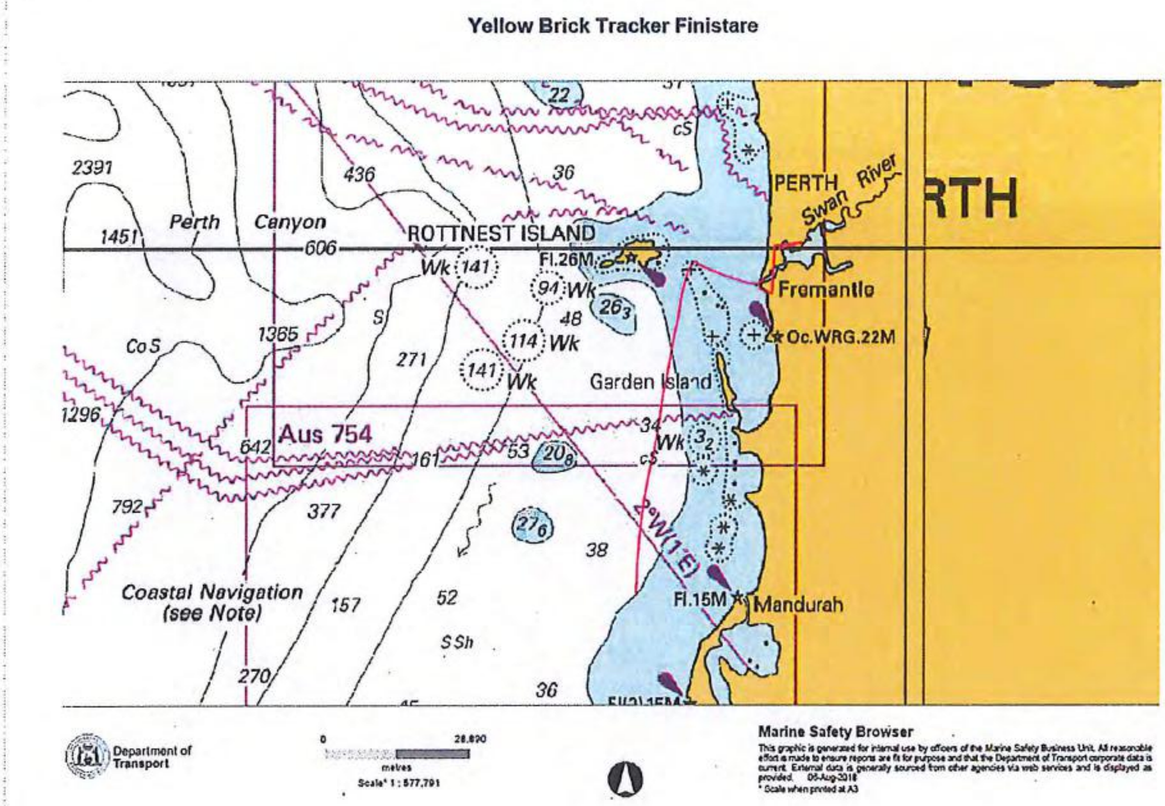
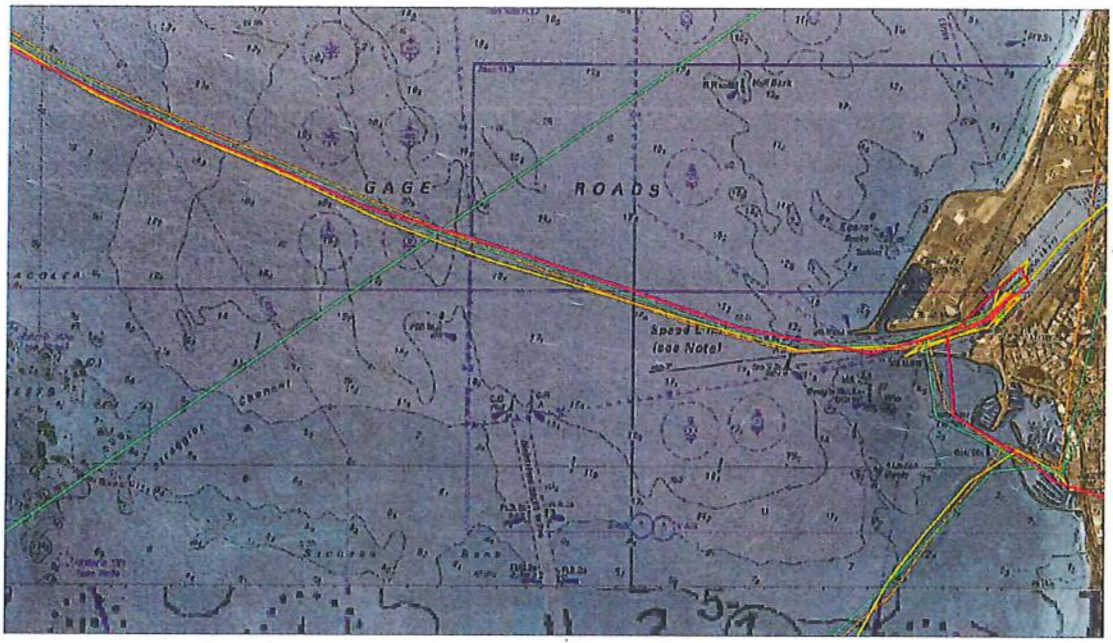


Image 4 Finistere's course (Yellow Bick Tracker) is denoted by the red line exiting Fremantle Harbour and terminating west of Mandurah.

Fremantle to Bunbury Ocean Race,Start.



Department of Transport

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metres
Scale* 1 : 36,112

Marine Safety Browser

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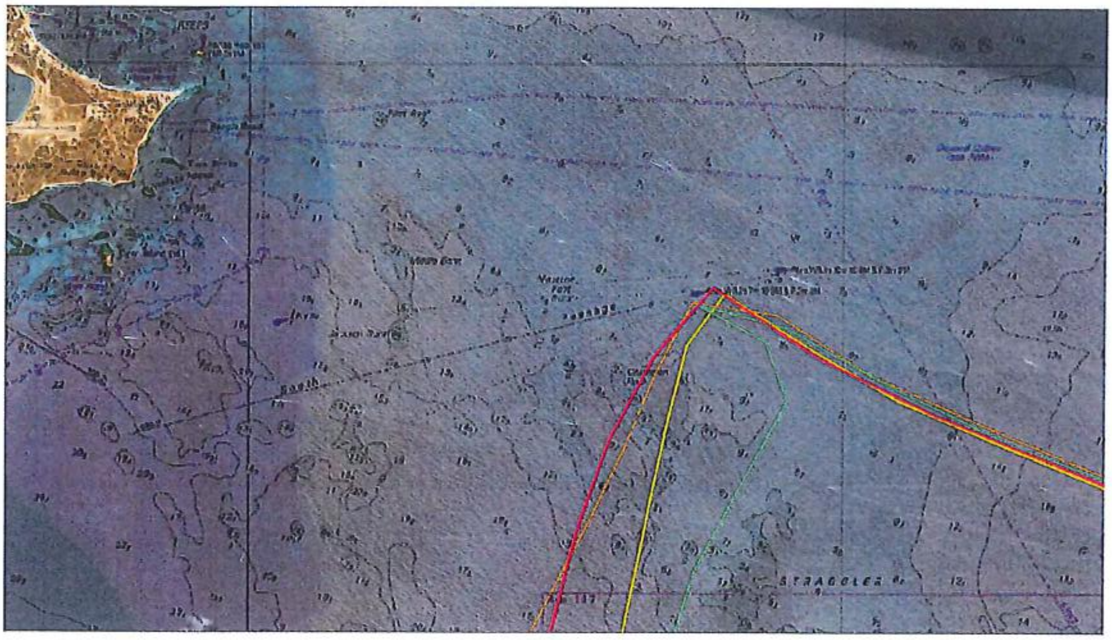
* Scale when printed at A3

Image 5

Fremantle to Bunbury Ocean Race,Turning Point.



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* Scale when printed at A3

Image 6

Fremantle to Bunbury Ocean Race.

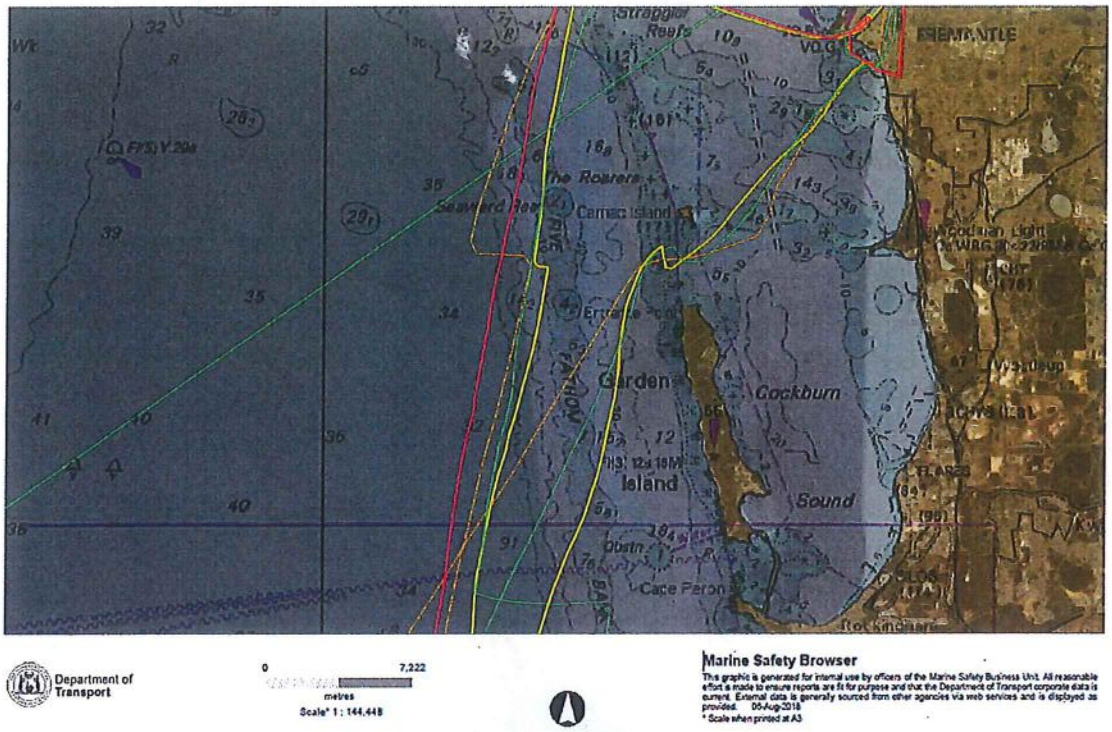

Image 7

Capsize

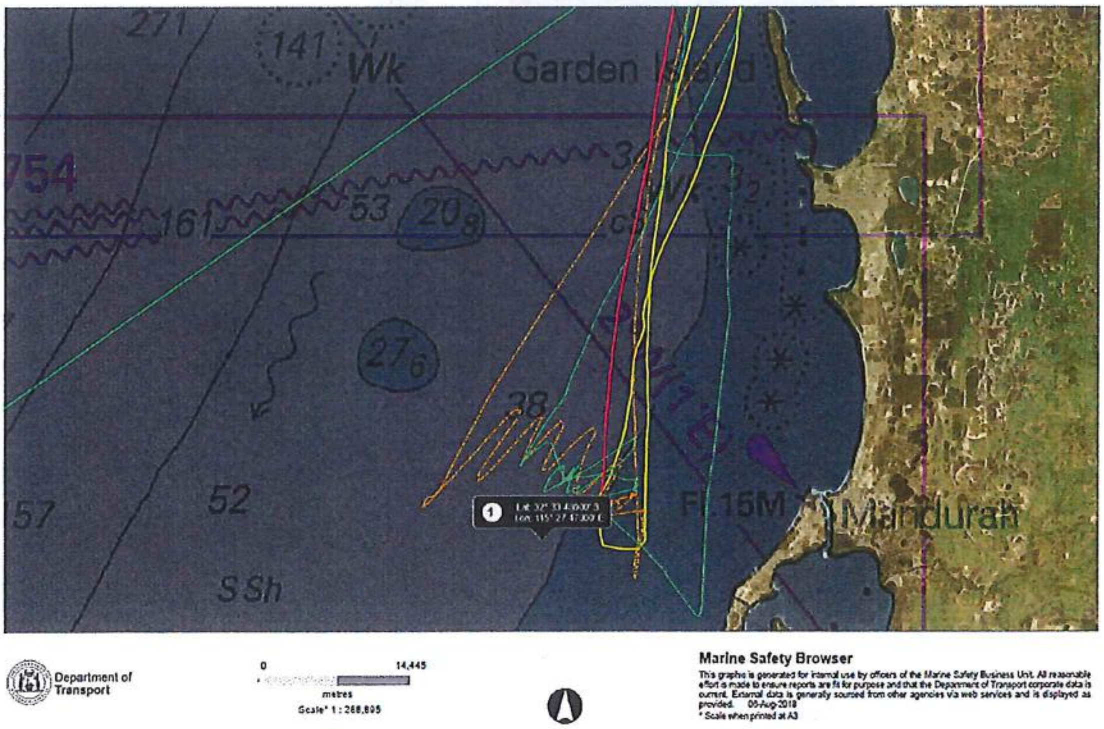

Image 8

At about 2315 [redacted] radioed the vessels position to race control. [redacted] the vessel listed onto its starboard side, then continued to roll and capsize.[10] [redacted] at the time of capsize the vessel was running with one reef in the mainsail, and a partly furled headsail.[11]

[redacted]

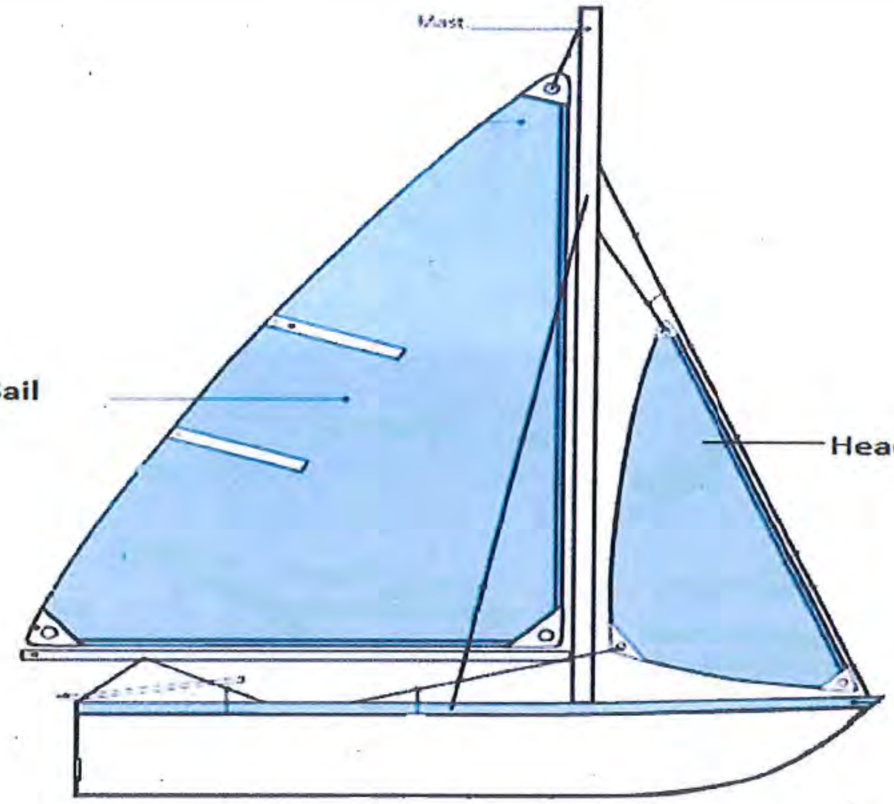

Image 9, Yacht sail configuration. Note: Head sail is any sail forward of the mast and does not denote a type.

10 [redacted]

11 See image 9 for sail configuration. Reefing and furling are ways of reducing a yachts sail area. This is generally done in response to the wind speed, to prevent damage to the vessel, improve performance and mitigate the risk of capsize, excessive heel (lean) and broaching.

12 [redacted]

13 [redacted]

14 [redacted]

Of note is that race rules dictated that all competitors were required to wear lifejackets after sunset, when working on the deck.[15] [redacted]

Rescue

At 2330, Finistere missed its scheduled radio transmission to race control and at about the same time, [redacted] on board the yacht Fourth Dimension, received an Automatic Information System (AIS) activated man overboard alarm.[18]

At 2348 a PLB activation was received at the Joint Rescue Coordination Centre(JRCC) in Canberra. A second activation was received at 2357. In response a search was initiated involving multiple government agencies, volunteer marine search and rescue, and yachts involved in the Bunbury Ocean Yacht Race.

At 1225 a rescue helicopter located the capsized Finistere, and yachts Fourth Dimension, Huckleberry and Circa converged on the location. Huckleberry was the first vessel to arrive [redacted] ([redacted] I have included a very brief overview of the rescue as it will be covered in detail by police)

[15] Blue book Section 5-Personal Equipment, 5.01, Lifejackets, pp70-71.
16 [redacted]
17
18

Findings

Keel

The upturned hull of Finistere was towed to Mandurah Ocean Marina where it was removed from the water. On inspection it was found that the keel had broken off level with the hull. A search was conducted for the broken off portion based on the last known position of the vessel. The search parameters were established from race tracking data and the Global Positioning Systems (GPS) locations of PLB activations. However, based on the available information the scope of the search was not narrow enough to result in a successful outcome. The Australian Transport Safety Bureau (ATSB) supplied technical assistance and attempted to extract a more precise location from coordinates from Finistere's GPS plotter, which had been damaged by immersion in salt water; however, no meaningful data was able to be recovered.

The purpose of the keel on sail craft is to provide ballast and counteract the leeward (downwind) force caused by the wind in the sails. Sailboats without a keel, would not be efficient in maintaining a straight course, instead being pushed sideways by the wind (The keel provides hydrodynamic lift due to the way that the water flows around it. This flow allows the vessel to maintain forward momentum).

Without ballast sail craft are susceptible to capsize because there is no counteracting force to resist the heel (lean) caused by wind in the sails, and the high metacentric height (centre of balance) caused by the weight of the mast and rigging.

Therefore, when Finistere lost its keel, it was subject to a sudden catastrophic rise in its vertical centre of gravity. This was combined with the immediate loss of the keel's counter balancing effect to its wind heel moment (lean caused by the wind). With the wind on the port side, the vessel immediately listed to starboard and capsized.

Computer modelling of Finistere's stability was conducted in 2012 by Bakewell–White to validate the vessels compliance with racing regulations after being fitted with the new keel. The modelling was based on estimates taken from a number of sources, and the manufacturers drawings.[19] No physical examinations, such as an inclining experiment, were carried out; however, the modelling indicates that Finistere exceeded the requirements set out by Yachting Australia. The vessels angle of vanishing stability (the angle to which the vessel could lean over before capsizing) was calculated as being 139.7° (required 113.7). The STIX (stability index) value was 58.5 (required value was 35, ISO 12217-2). Taking the vessels stability characteristics into consideration, and the known facts pertaining to the incident, there is no evidence to suggest that it capsized for any reason other than the loss of its keel

[19] Bakewell–White correspondence, dated 16 November 2012

Post-accident inspection of keel

The portion of the keel, still present in the keel case, was removed from the vessel. An initial visual inspection found areas of friction between the keel and the keel case. The accompanying wear had exposed the inner wooden core. The worn areas were hidden from view inside the keel case and were not apparent until it [the keel] was removed from the vessel. The pattern of wear is suggestive of it happening over time and is not consistent with damage that occurred due to an incident.

The original holes through which the keel locking pins passed were present and consisted of a metal sleeve that went through the wooden core and metal plate. It was also noted that the position of the anti-gravity pin had been raised and the original hole filled.

Inspection of the core around the metal sleeves, and the modified location of the anti-gravity pin, indicated extensive water damage to the wooden core. This was suggestive of water ingress over a prolonged period and not consistent with ingress caused at the time of the incident.[20]

The keel skin on the port side appeared to have delaminated and slumped.[21]

The anti-gravity pin (the pin that runs in a channel on the inside of the keel box) no longer passed through both sides of the keel. It exited on the port side and faced in a downward direction. This supports the slumping of the keels starboard side.

Keel Deconstruction

On 11 June 2018 the upper portion of the keel was deconstructed. The purpose of the de-construction was to ascertain how the keel had been built, and to identify any factors that may have contributed to its failure.

The following observations were made:

- The adhesive bond between the steel plate (used to raise the keel pins above the waterline) and the epoxy adhering it to the wooden core had failed.
- Extensive water ingress and associated damage including rot and de-lamination was identified in the wooden core. The waterlogged areas were associated with the positions through which the original locking pins passed, the modified location of the anti-gravity pin and the area below the steel plate.
- The skin on the port side of the keel was separated from the rest of the structure and had slipped below the level of the skin on the starboard side.[22]
- There is oxidisation staining (rust) at the junction between the steel plate and the top of the skin but no oxidation below this level, between the epoxy and the steel. This lack of staining may indicate that the adhesive failure was incident related or recent.

[20] See image 11 for a visual explanation of the parts of the keel.

[21] Keel skin refers to the outer laminates and carbon fibre layers.

[22] See Images 10 - 14.

Image 10, shows externally visible damage to the port side of the keel. The wooden core has dropped, and the anti-gravity pin has been pulled through to the port side. Deconstruction would later confirm that extensive de-lamination (of the wooden core, steel/epoxy interface, through keel fittings and external keel skin) had occurred causing the port side skin to slip.

Image 11, Remaining portion of keel prior to deconstruction (port side view).

Red arrow – Steel plate keel modification and new location for keel pins.
Yellow arrow – Original sleeved holes for keel pins, pre-modification.
Green arrow - Area of abrasion showing worn carbon fibre and exposed wooden core.
Note: The steel pin exiting the keel is the anti-gravity pin. The hole below it was its original position.

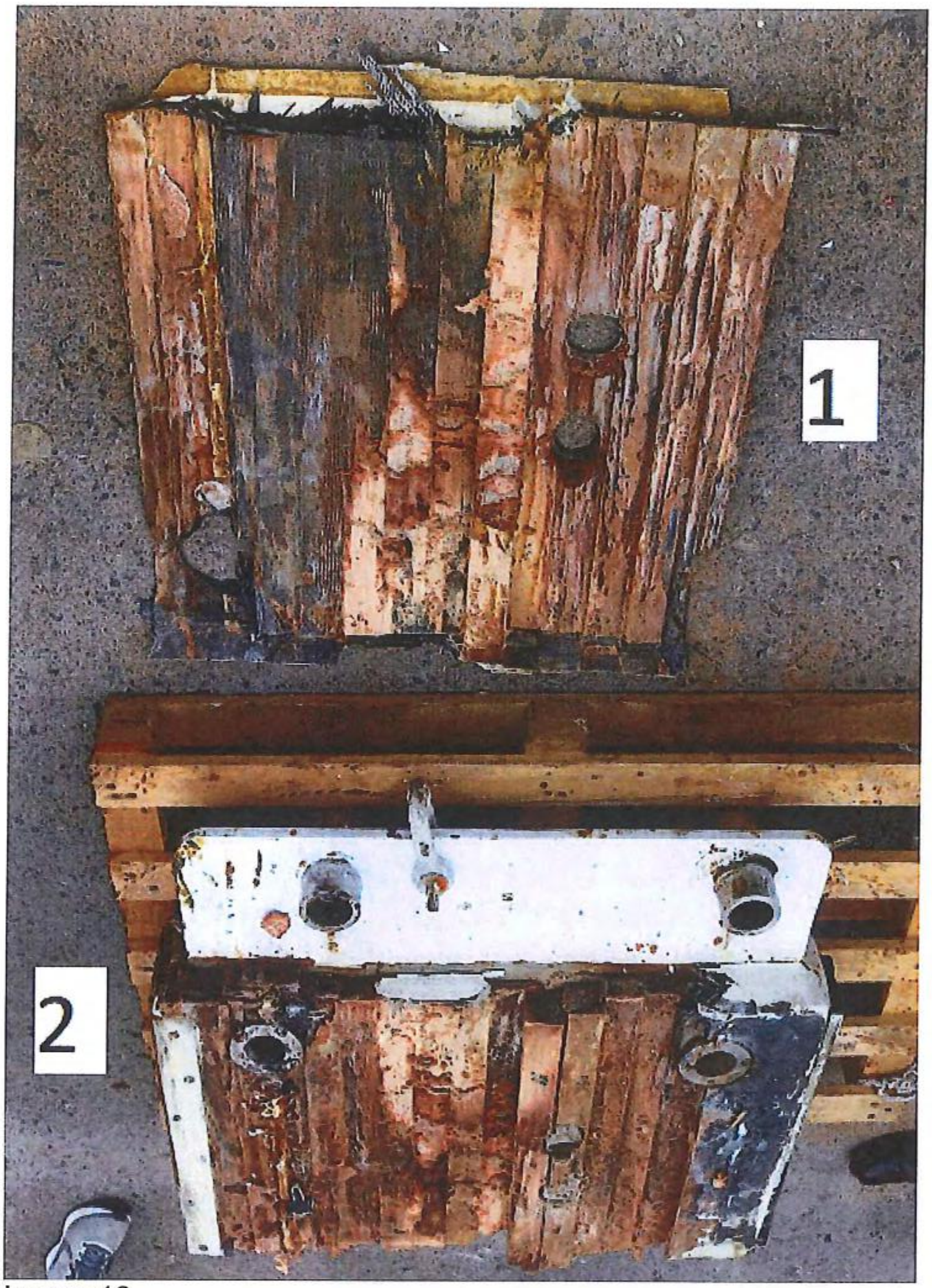

Image 12.
1 – Skin, carbon laminate and part of the wood core as lifted from the port side of the keel.
2- Port side of keel with section one removed.

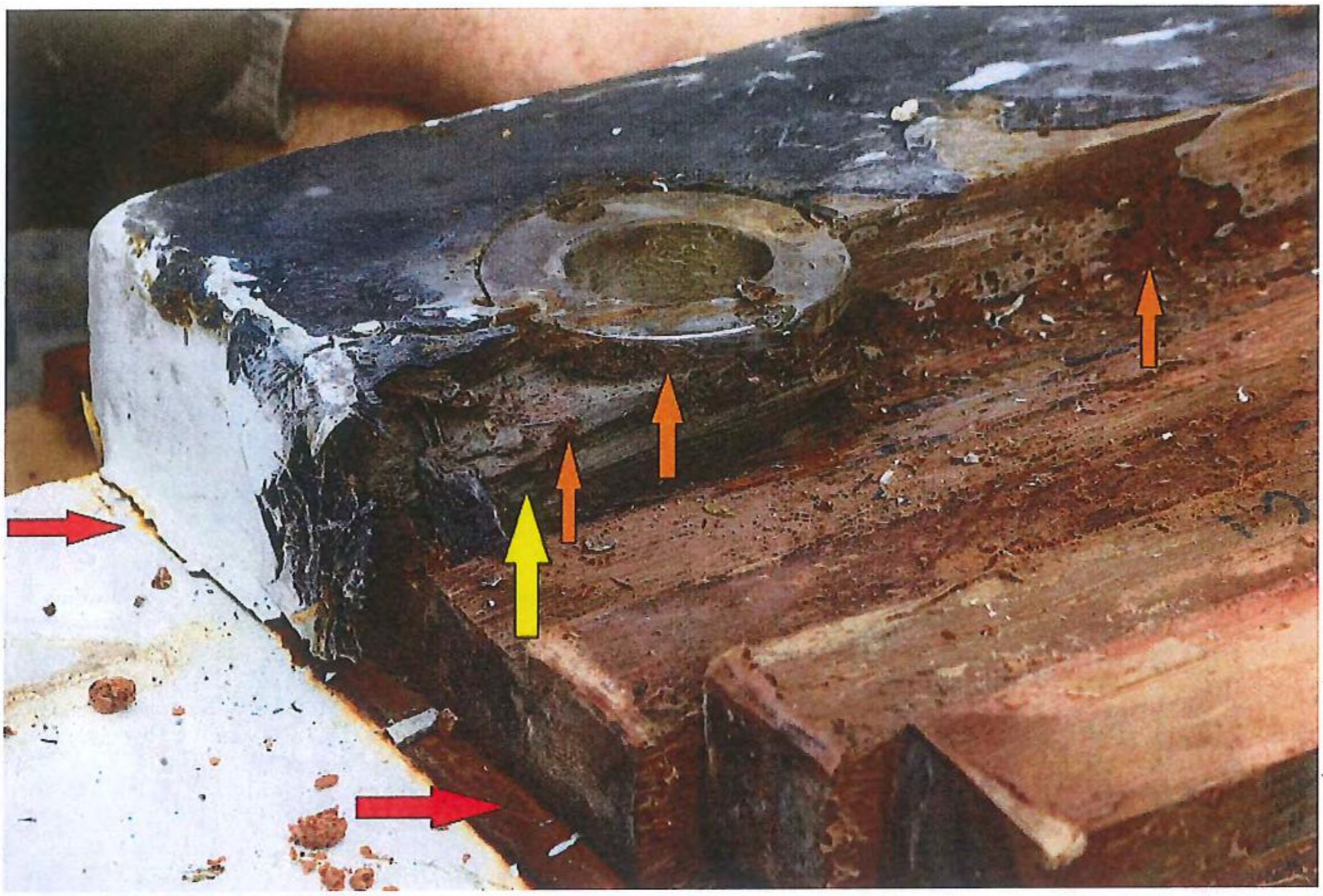

Image 12, Keel deconstruction.

Red arrow – delamination between steel plate modification, epoxy sheath and outer casing.
Yellow arrow – waterlogged wooden core.
Orange arrow – areas of rotten timber.

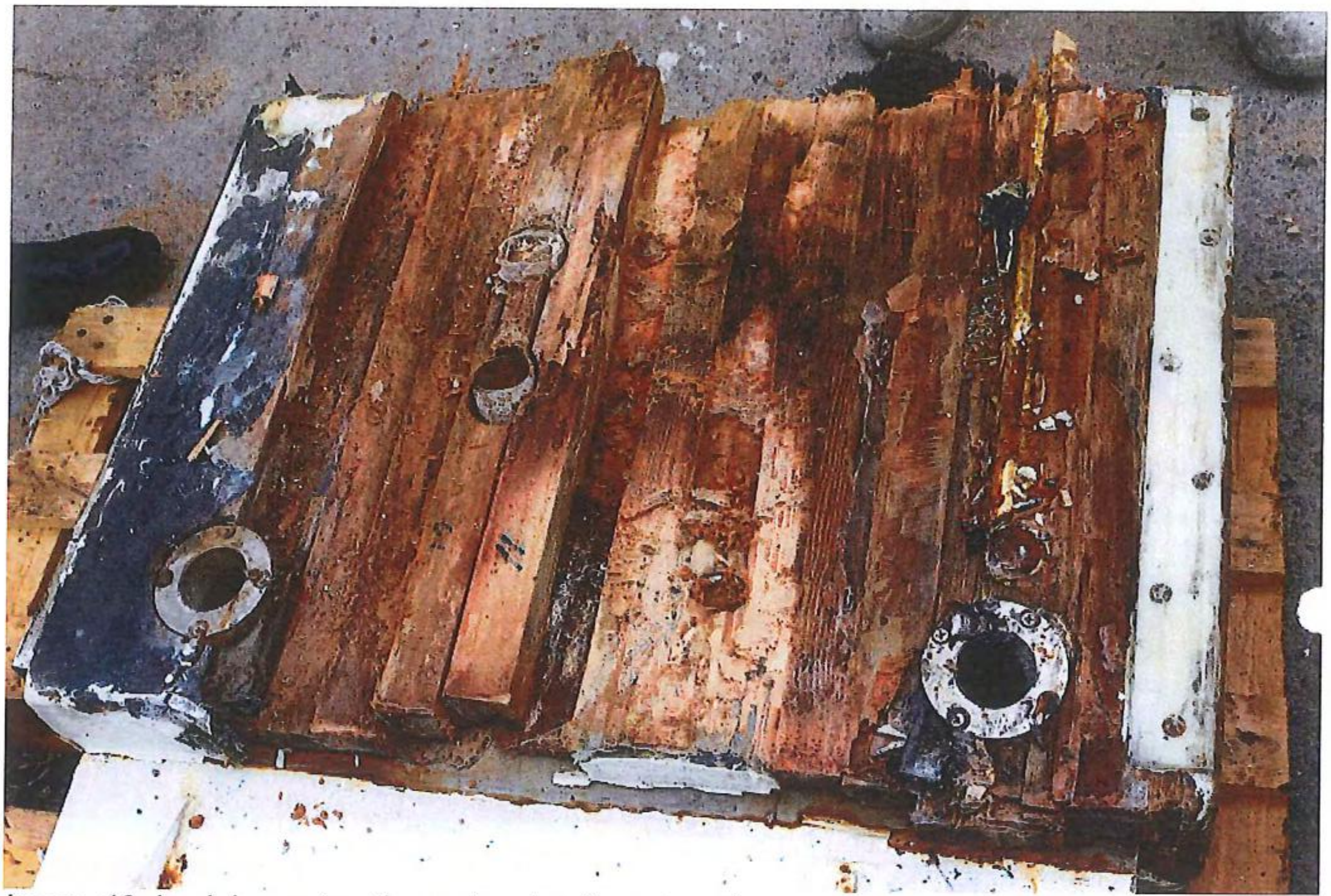

Image 13, keel deconstruction outer sheath removed.

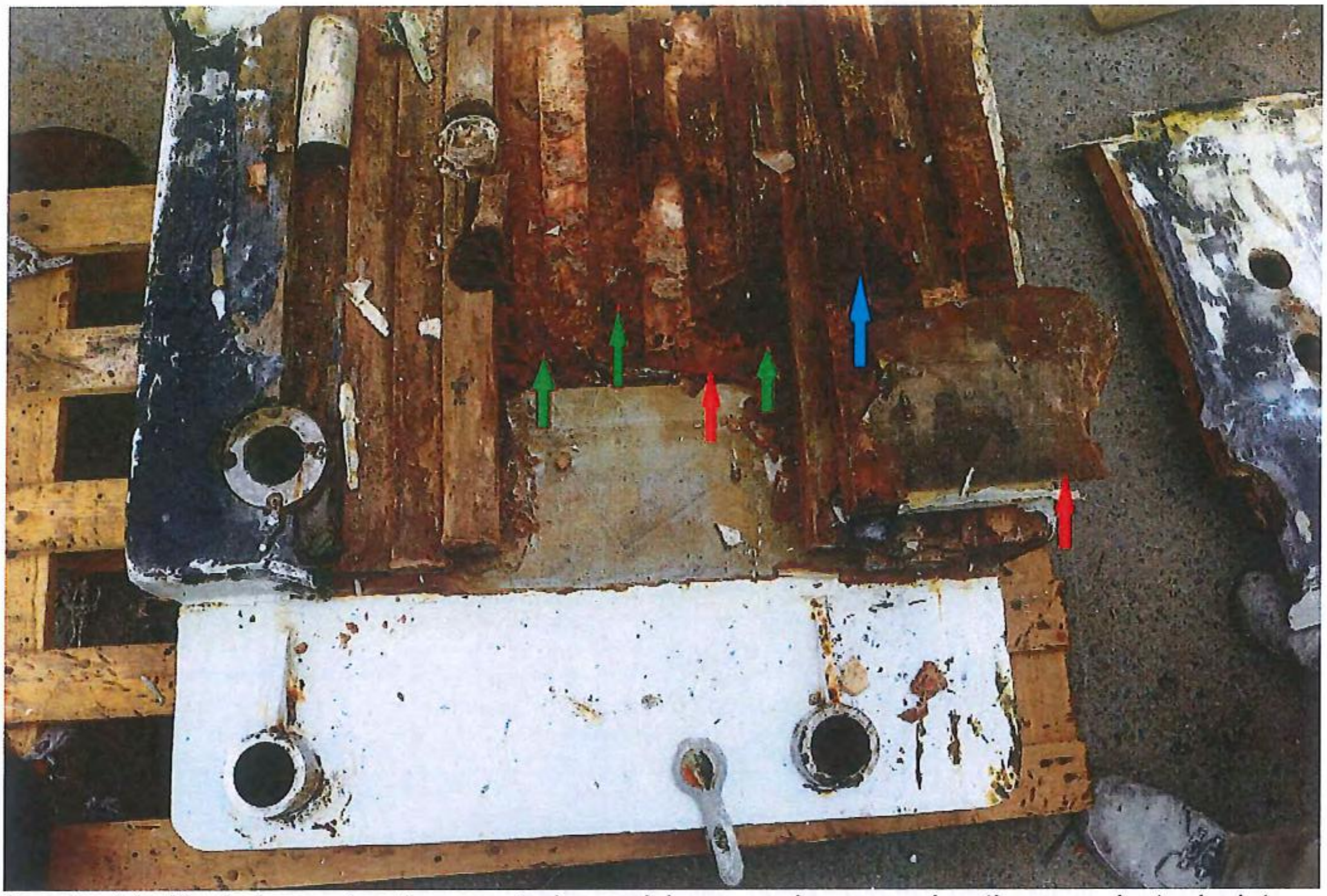

Image 14, Keel deconstruction central wood layer and epoxy sheath around steel plate lifted.
Green – waterlogged and rotting timber.
Red – epoxy resin sheath around steel plate.
Blue – Section of epoxy sheath and timber removed to expose central area of keel core, and steel plate.

The epoxy resin has not adhered to the steel plate (Image 14), instead lifting away with the wooden core (to which it was securely bonded). This is indicative of an adhesive failure at the epoxy/metal interface due to the shearing forces to which it was subjected.

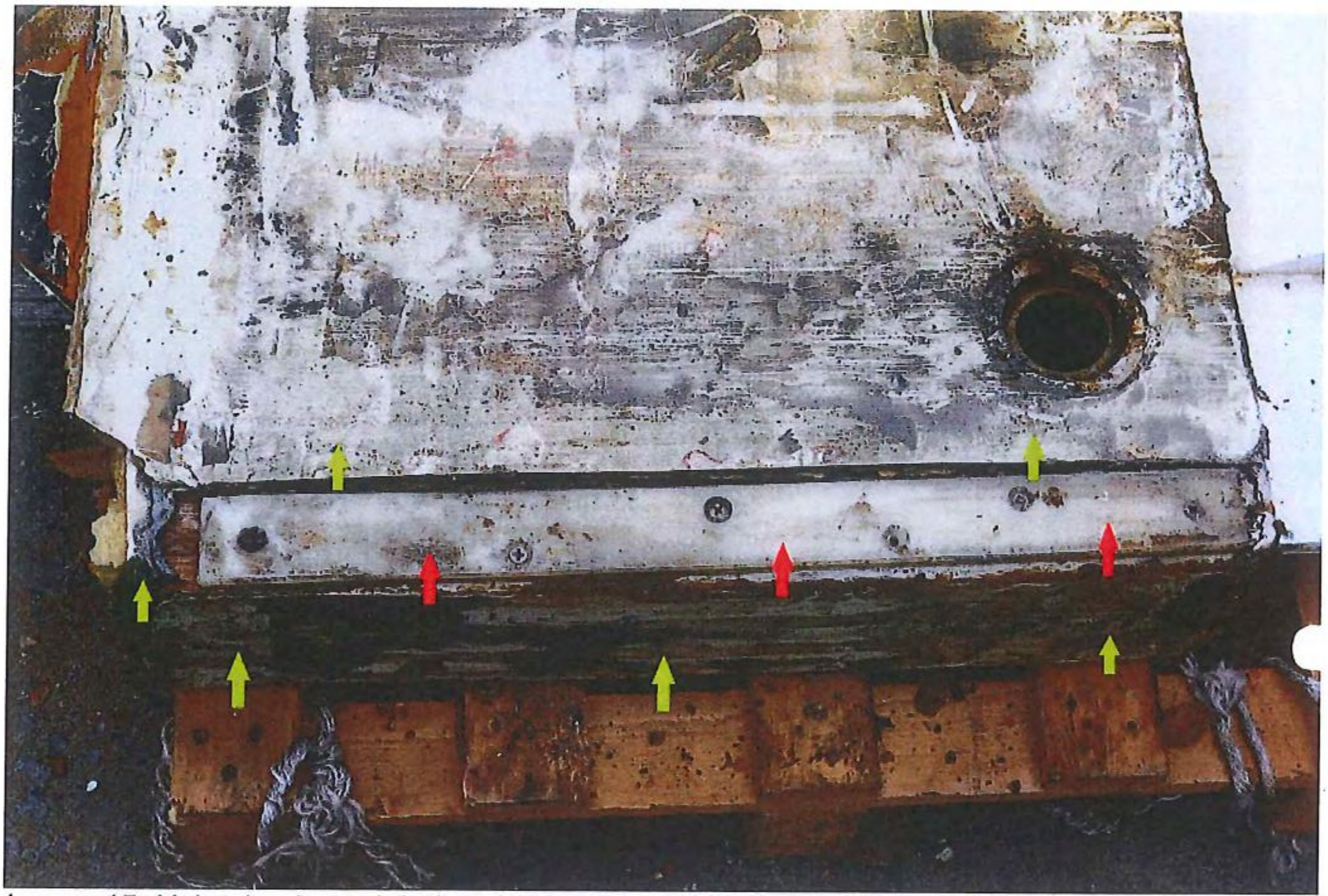

Image 15, Nylon bush on right hand side of the leading edge of the keel.
Nylon bush – red
Outer carbon fibre sheath – green.

Noticeably in Image 15 the carbon fibre sheath was absent underneath the nylon bush. Therefore, the carbon fibre sheath did not extend around the entire core on the portion of the keel contained within the keel case. An outer skin cover laminate consisting of carbon fibre and epoxy, encasing the entire keel, is noted on the plans.[23]

[23] See Bakewell – White, Keel Laminate – Keel, Skin Cover Laminate.

Why did the keel fail?

The keel on a sailing vessel is subject to a number of opposing forces that must be taken into account when they are designed and built. A miscalculation or omission in either design or construction can have catastrophic consequences, as can damage that has not been, or has been, poorly repaired.

In addition to the forces to which it is subject during normal operations, a keel can be damaged by incidents such as groundings, and this damage may not be visibly apparent.

Image 16-17, Keel inside the keel box viewed from the top. note: damage is evident on the port side of the keel.

The effect of modifications

Evidence suggests that the factors identified as causing the failure of the keel are associated with the modifications undertaken to raise the locking pins.

An assessment of the suitability of the modification was carried out by Naval Architect, [redacted] found that the design parameters for the modified keel structure were of an appropriate standard and not the cause of its failure. Therefore, consideration has been given to whether errors in the manufacturing process, ineffective inspection and maintenance, material wear or external factors contributed to its failure.

[redacted] noted that the keel modification drawings contained no details relating to the bonding and sealing arrangements between the steel plate and original keel.[25]

Manufacturing Process

The surface preparation of steel is critical to ensuring that a strong bond is formed with epoxy Ozes and Neser (2015) and Wang et al (2016). The degree of preparation undertaken [redacted] modified the keel is not known; however, what appears to be paint overspray on the bonded surface would suggest that it may not have been sufficient. It is also noted that a steel screw was embedded in the epoxy, and the mottled appearance of the bonded surfaces may be indicative of the presence of voids and areas of weakened bonding between the epoxy and the steel.

Image 16.
Red arrow – appears to be paint overspray and may indicate that the steel plate was not adequately prepared prior to being embedded in epoxy.
Green arrow – Light coloured areas may represent voids in the epoxy/steel interface.

[24] See Finistere Keel Failure Assessment Report.
[25] Finistere Keel Failure Assessment Report. pp15

Additionally, ensuring that any intrusions through the keel's skin are watertight is critical to maintaining its structural integrity. The absence of a waterproof skin under the nylon bush on the leading edge of the keel could be considered an error in the manufacturing process. [26] The presence of water ingress around through skin intrusions such as the antigravity pin and locking pin holes could be due to manufacturing errors, or the consequence of material failure caused by other factors such as groundings.

Inspection and Maintenance

One of the functions of the keels external skin is to protect the vulnerable internal core from the effects of water immersion. When it was removed from the vessel it was found that the skin had worn through to expose the wooden core in several places. This wear appears to have taken place over a prolonged period. It is not known when the portion of the keel contained within the keel case was last inspected.

External Factors

It is known that Finistere grounded several times. [redacted] the vessel grounded during the race prior to the race in which it capsized.[27] Groundings and collisions carry a high risk of causing structural damage to a vessel. In the case of a keel they can cause severe damage and instantly incapacitate the vessel, or cause more subtle damage that may not be immediately apparent. As an example, micro fractures around the keel's skin caused by a grounding, may get progressively worse over time and provide access points for water to enter the structure. Another example pertinent to Finistere would be fractures forming in the epoxy surrounding the steel plate.

Summary of keel failure

Progressive cracking and/or delamination over a prolonged period of time between the steel plate and epoxy interface and/or around through skin intrusions caused a situation where water was able to enter the core. Accumulation of damage continued until the keel was no longer capable of resisting the forces acting against it.[28]

Of relevance in making a determination of where water entered the keel, is the absence of oxidation and water related staining on the steel plate, at the epoxy/steel interface. While stainless steel is resistant to oxidation it would be expected that staining would occur if this was the source of water ingress. Therefore, the association between waterlogged areas of the core and through skin intrusions tends to favour these as the source. This is the likely scenario proposed by Naval Architect, [redacted] in the Finistere 'Keel Failure Assessment Report'.

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[26] Image 15

[27] See [redacted] email 12/03/2018

[28] Refer to report prepared by MMD Naval Architects for a comprehensive assessment of the keel failure.

Influencing factors on 24 February.

Investigation has established that damage to the keel was well advanced prior to it breaking on 23 February 2018.Therefore its failure could have occurred in a broad set of circumstances.

The following information is relevant in determining what forces were acting on the vessel leading up to its capsize on the night of 23 February.

- The vessels last known course was 186.16 degrees at 5.1knots (23 Feb 2018 ,2330 AWST).
- The wind was S/SE at 25 to 30 knots.
- Seas were S/SE at 2.5 to 3 metres.
- The swell was from the SW at 1 to 1.5 metres.

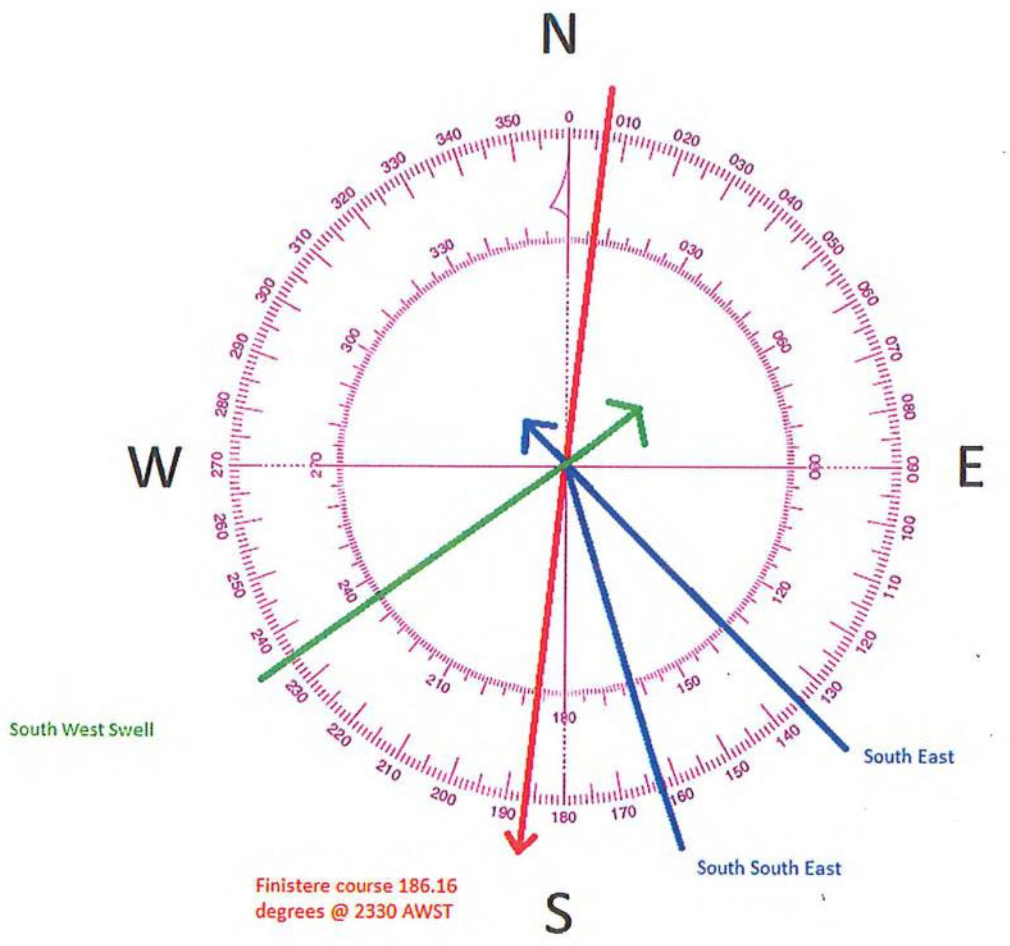


Image 17 Finistere's course and wind direction.

This meant that with the wind approaching from the port side to forward of the port beam (forward of the centre of the hull) Finistere was heeling to the starboard side. The tendency of the ballasted keel is to resist a heeling moment and return the vessel to an upright position. With the wind on the port side tension increases on the port side and compression on the starboard side. The weakened structure above the shaped foil (within the keel case), under increased tension slipped on the port side and the resulting movement caused the keel to break off at the shaped foil (where the keel enters the hull when it is in the downward position).

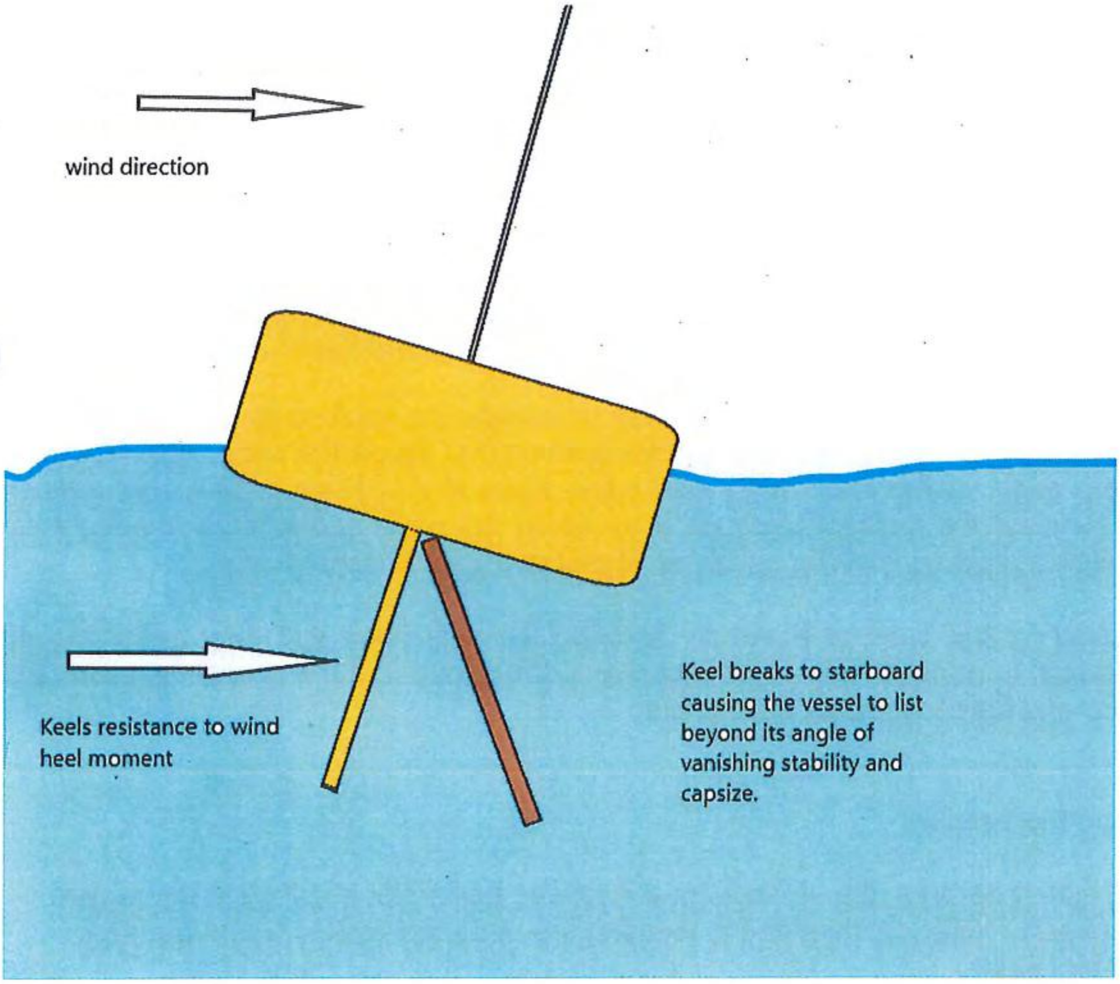


Image 18, Shows the keels resistance to wind heel. The ballasted keel resists the heel as it tries to return the vessel to an upright position. In the case of Finistere the keel has broken away (brown) and with no resistance to wind heel the vessel capsized.

Safety Equipment

Finistere was carrying safety equipment well in excess of its legislated requirements. Race rules dictated the mandatory wearing of PFD's when on deck at night, and the carriage of a PLB by all crew members.

With the main Electronic Position Indicating Radio Beacon (EPIRB) inaccessible after the vessel capsized, the PLBs played a critical role in the subsequent search and rescue operation.

The wearing of a PFD while on the deck of a vessel that is subject to a sudden catastrophic incident enhances the wearers chances of surviving in the water. However, the opposite could occur if the PFD traps the person below the upturned vessel. Both factors have been demonstrated during this incident.

[redacted]

[redacted]

[redacted] In addition, it is noted that due to the speed that the vessel capsized the vessels main epirb and flares were not accessible.

Difficulties during the rescue

During the post incident de-brief, the air crew on the rescue helicopter involved in the search voiced concerns over the difficulty they had in locating the upturned vessel due to the dark colour of the anti-foul paint.

Conclusion

Post incident examination, and historical information, suggests that a combination of mistakes during the modification process, age wear, and damage from minor groundings either separately or in combination are the likely causes of the slow deterioration of the upper portion of the keel. When combined with the external forces applied by the prevailing wind and the sea state on the night of February 24, the keel finally gave way, causing the vessel to roll.

No conclusion has been drawn in relation to its condition prior to being modified in 2012, nor is it known how long after modification the deterioration began; however, it is likely that it took place over a prolonged period. A review of the keel and modifications by an independent source indicates that its design was appropriate and not a causal factor.[29]

The weather at the time was within the safe operational limits of the yacht provided that it was structurally sound and competently crewed. However, a strong wind warning was in force and the yacht was experiencing rough conditions. With poor conditions there is a greater risk that an incident will occur, and greater stress is placed on vessels and their crews. The survivability for a person in the water also decreases in inclement weather.

[redacted] much of the damage was hidden from view, as it was located within the keel case or contained within the keels core. When it was inspected post incident Finistere presented as a well-maintained vessel. [redacted]

Organised yachting events in Australia are held under comprehensive rules (see Offshore Blue Book) which include standards to which vessels must be built, maintained, and the carriage and use of safety equipment. [redacted]

While it is peripheral to the DOT investigation, it has been identified that the aerial search team had difficulties locating the upturned hull because it was painted with black anti foul paint. Lighter colours are easier to locate when set against a darkened ocean and this investigation was unable to find any literature suggesting performance issues when using lighter colours.[30]

[29] See report by MMD Naval Architects.

[30] The purpose of anti-foul paint is to inhibit marine growth on the underside of vessels.

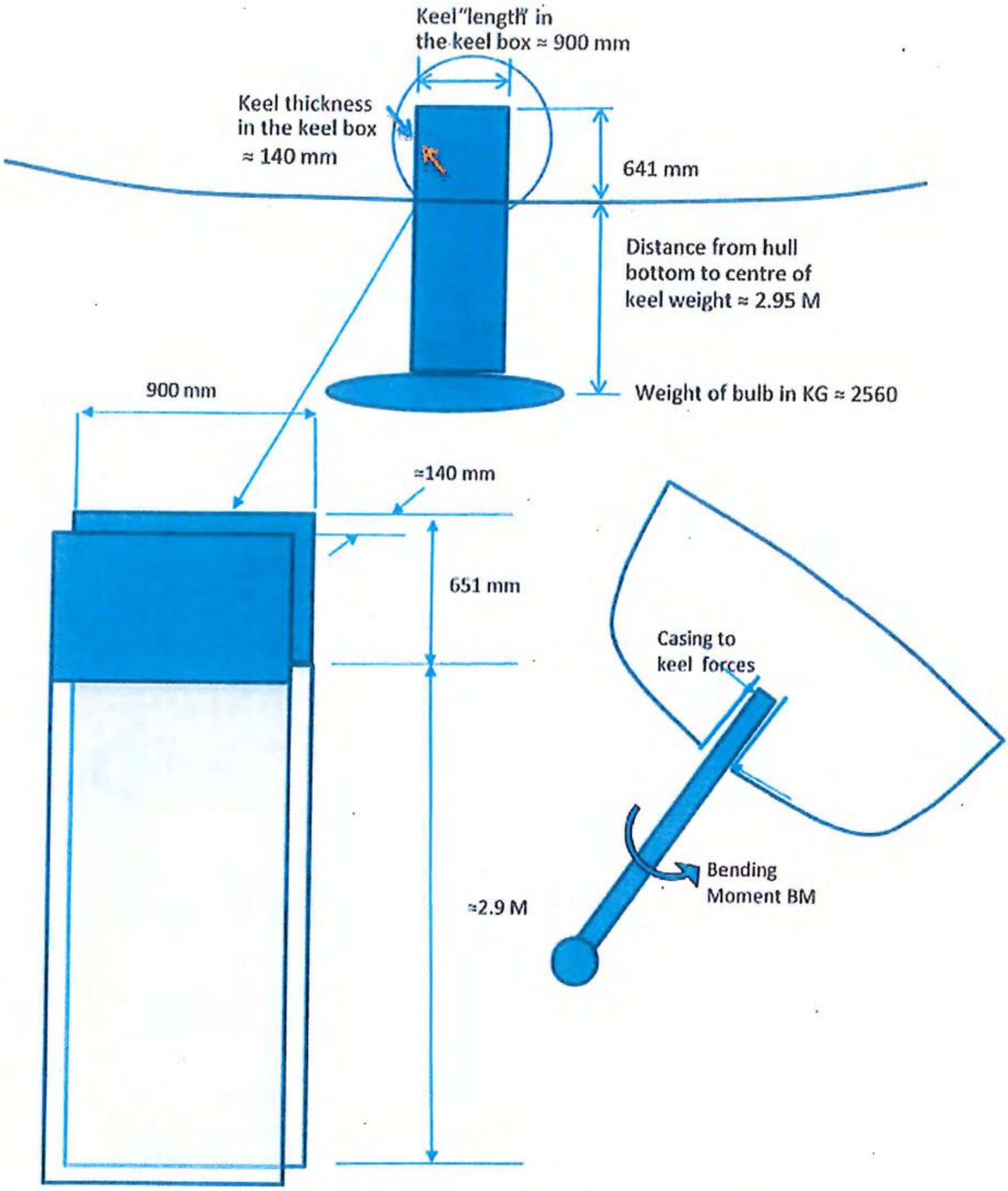
Recommendations

The following recommendations are made in relation to the capsize of Finistare:

1. Modifications and repairs should be undertaken in accordance with best industry practice.
2. The owners of vessels should consider a thorough inspection of their keel (and other components), if the vessel is grounded, and as part of their annual maintenance schedule. In the case of vessels with a lifting keel this should include inspection of the part of the keel contained within the keel case.
3. Where a vessel competes in an organised event the relevant governing body should be informed of any modifications, replacements or repairs that have been undertaken so as to determine whether they meet the required standard.
4. Consideration should be given to the suitability of rescue pods such as life cell as a survival aid for carriage on yachts and whether their use could be mandated through the rules surrounding organised racing events. These pods provide an efficient floatation aid to persons in the water and additionally they can be stocked with an EPIRB, flares and other aids to survival and recovery. Pods can be fitted to a vessel so that they float free in the advent of a capsize and be attached to the craft with a shock absorbing line. Persons in the water can attach themselves to the pod rather than attempting to hang onto the upturned hull. The use of a pod also mitigates the risk that safety equipment such as epirbs will be inaccessible should a vessel capsize or sink. Alternatively, consideration could be given to the carriage of a life raft on vessels competing in category 3 races.
5. Due to concerns raised by the aerial search crew, consideration should be given to the colour of anti-foul paint on the underside of vessels competing in ocean races. Consideration could be given through race rules to a certain percentage of a hull being a high visibility colour.
6. The question of the mandatory wearing of PFDs is a complex issue, as demonstrated by this incident. While there is no doubt that they enhance the survivability of a person in the water they can also hinder escape from a capsized vessel. Therefore, a sensible approach needs to be taken when considering recommendations about when it is appropriate for them to be worn.

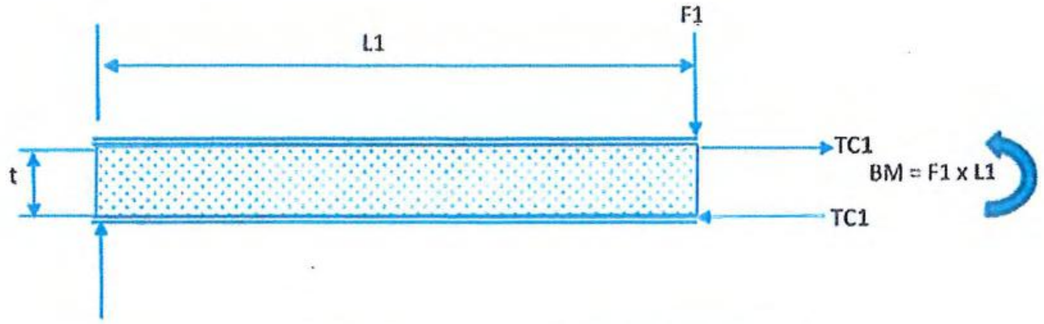
[redacted] Stand by for more info RE: Lifejackets. There are some changes occurring and I should have mere details shortly.

Appendix



The bending moment at the intersection of the keel and hull bottom = BM (Don't know the worst case; BM could be a maximum when the sails hit by a sudden gust while upright, at maximum speed with a steady wind, or immediately after a knock-down. Just call the maximum bending moment "BM".

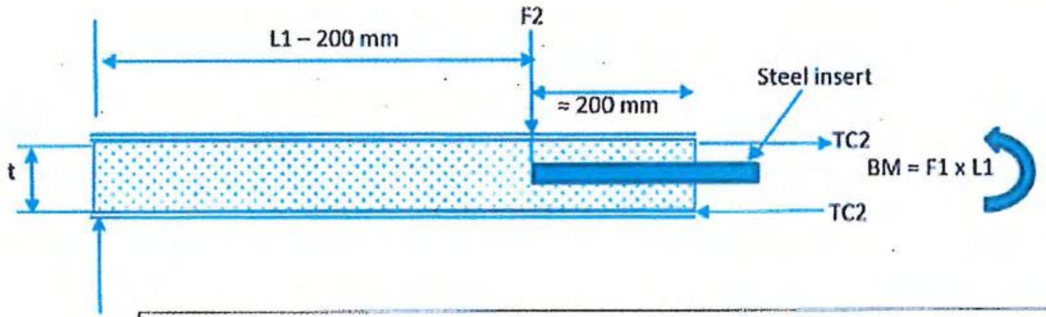
The casing has to apply forces to the keel to counteract that bending moment. Assume the keel within the casing is supported only by reaction forces at the ends (simple, but not pessimistic). Drawing the keel within the case in a horizontal orientation – next page:



BM before modification = BM = F1 x L1
and
BM = TC1 x t
Therefore TC1 = F1 x L1 / t

Shear in wood core = τ_1 = TC1 / (L1 x 0.9M)
Shear stress — Core cross-sectional area

After core is cut to insert steel plate, assuming no shear connection between the steel plate and wood core:



BM after modification = same as before core is cut = F1 x L1
= F2 (L1 – 0.2M) after core is cut, and
therefore F2 = F1 x L1 / (L1 – 0.2) …. F2 is larger than F1

BM = TC2 x t and so TC2 = BM / t and bending moment has not changed.
Therefore TC2 = BM / t = F2 x (L1 – 0.2) / t and TC2 = TC1.

Shear in wood core must increase because there is less shear area:
τ_2 = TC2 / [(L1 – 0.2) x 0.9M] =

So τ_2 = [TC1] / [(L1 – 0.2) x 0.9M]

So shear has increased: τ_2 / τ_1 = [TC1] / [(L1 – 0.2) x 0.9M] / [TC1 / (L1 x 0.9M)]
= (L1) / [(L1 – 0.2)]

L1 was 0.651M, so shear has increased to 0.651 / 0.451 = 1.44 times the original shear.

Survey Report.

As requested by Club Marine this Report is for the Sailing Vessel Finistere,berthed at the Fremantle Sailing Club
[redacted]

Hull Structure .

Finistere is a Racing Yacht of length 15.40 metres
[redacted] she was built in 1990,to ABS Standard [redacted]

It's construction is Composite West System, vacuum bagged and sheathed with Kevlar.

Bulkheads and Ring Frames are well bonded showing no movement.
Chainplates for supporting the Swept Back Spreaders are mechanically attached to the bulkheads, photo attached.
Finistere does have a Lifting Keel taking the draft from 3.40 m to 2.50m using a hydraulic ram.
Both the ram and the Lifting Webb were replaced in 2012.
The attached photo shows the Center case and the 2 Locking Pins of 50 ml diameter .

Propulsion

In 2012 a new Volvo Motor and Saildrive was installed.
The motor is a D 2 55 hp 4 cylinder, non turbo diesel, driving through a 3 bladed, Stainless Steel Folding Propellor .

Steerage.

The current Rudder is 5 years old and has an 85 ml Stainless Shaft.
Steering is by a quadrant to the central wheel by stainless wire.
Spare wires , a spare a Tiller and a spare Emergency Rudder is carried on board.

Pumps

There are 2 manual pumps of 40ml diameter, one downstairs and one in the cockpit.
Also carried is an electric diaphragm pump of 16 litres per minute.

Navigation Lights

The vessel complies for both sailing with masthead lights and deck lights when under power.

Anchors

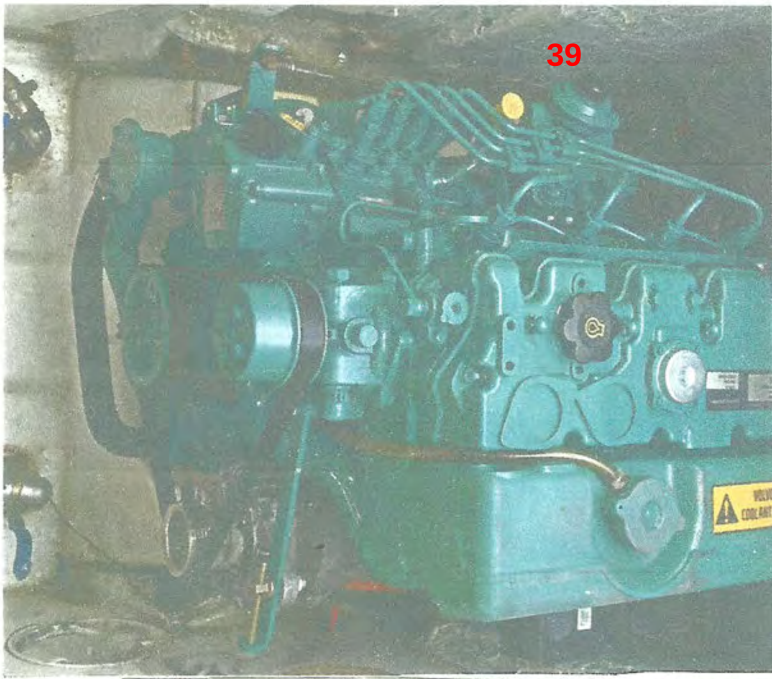
On board are 2 Danforth Anchors of suitable size with sufficient chain and wharps.

In Summary

Finistere is a well founded yacht in very good condition. Having competed in the 2012 Rolex Sydney to Hobart Yacht Race she carries
all the necessary Safety Gear including HF and VHF radios.
On the way to Sydney off Cape Leeuwin,winds of 68 knots were experienced.
This gives testament that the vessel is well founded, well rigged and well mountained.

This Report is issued without prejudice to Club Marine and the Undersigned shall not be held liable whatsoever for any act,error,
omission or default in connection therewith.

[redacted]




KEEL OPERATION
TO LOWER
1: Release tension bolt (front)
2: Press up button - remove bolts
3: Press ▼ button - insert bolts
4: Tighten tension bolt
KEEL DEPTH
UP 2.50
DOWN 3.40

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE
MANDURAH 6210

Report printed on 25/05/2018 14:01

Incident Report

Incident Type: Water Search
Stop Time: 24/02/2018 12:36
Response Area: External
Territory: 4
ESL Area: ESL Category 1
Map Reference: -32.52241, 115.71167

How Call Detected: Other agency/persons raising alarm not classified
How Call Reported: Exchange telephone call direct to authority, includes call to BGU
Type of Occupant: Commonwealth Government
Type of Owner: Commonwealth Government
Occupants Name or Desc:
General Property Use: Waterfront complex/on water. Included Marina's, Piers and Main Water Ways
Fixed Property Use: In open sea, tidal waters
Action Taken: Search
Problems Encountered:

Notifications:

Electricity:	Not notified	Gas:	Not notified
Water:	Not notified	Police:	Not notified
Ambulance:	Not notified	SES:	Not notified
Govt. Welfare:	Not notified	EPA:	Not notified
Charity Agencies:	Not notified	Local Shire:	Not notified
Other Agencies:	Not notified	Other Fire Service:	Not notified

First Agency on Scene:
DFES Fire Investigation: N
DFES Incident Significance:

Incident Controller:
Report Approved By:
Report Entered By:
Report Validated:
Comments:

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

[redacted]

Rescue Authority:	Police rescue		
Rescue Type:	Transportation/vehicle accident (incl boating, aircraft & rail)		
Evacuations		People Evacuated:	0
Start:		End:	
Evacuation Authority:			
Evacuation Problems:			
Notes:			

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

CAD Commentary

24/02/2018 07:46	AIR DESK - AIR ATTACK 7 TURNING OUT TO ASSIST WAPOL AND AMSA WITH AN AIR SEARCH
24/02/2018 07:46	FOR A CAPSIZED YACHT 11 NAUTICAL MILES OFF THE COAST OF MANDURAH.
24/02/2018 08:01	SIMON MILLER [redacted] (MARINE RESCUE) IS ATTENDING DUE TO LIAISON
24/02/2018 08:46	SAO: DO P SAINT REQUESTED 2 SES AIR OBSERVERS TO ATTEND 25B MUSTANG RD JANDAKOT
24/02/2018 08:46	BY 10.00 HRS THIS MORNING. DAC GIFFORD APPROVED AND MDC HARES CURRENTLY SOURCIN
24/02/2018 08:46	G
24/02/2018 09:22	DO MATT REIMER - SOURCED 2 SES AIR OBSERVERS TO ATTEND JANDAKOT BY 1000. [redacted]
24/02/2018 09:22	[redacted] FROM MELVILLE SES AND [redacted] FROM BASSENDEAN SES.
24/02/2018 13:41	SES UPDATE - SES AIR OBSERVERS HAVE RETURNED TO JANDAKOT AFTER ASSISTING [redacted]
24/02/2018 13:41	[redacted] DEBRIEF CONDUCTED WITH WAPOL, DEPARTING FOR HOME SHOR
24/02/2018 13:41	TLY
24/02/2018 14:57	SAO: DFES LIASION SIMON MILLER ADVISES THAT THE SEARCH WAS CALLED OFF BY WATER P
24/02/2018 14:57	OLICE COORDINATION CENTRE AT APPROXIMATELY 1236HRS [redacted]
24/02/2018 14:57	[redacted]
24/02/2018 14:57	[redacted]
24/02/2018 14:57	[redacted] HOT DEBRIEF WI
24/02/2018 14:57	TH VOLUNTERS AND POLICE HELD AT VMR BUIDLING MANDURAH. WELLNESS HAVE BEEN ADVISE
24/02/2018 14:57	D AND PROVIDED WITH CONTACT DETAILS.
02/03/2018 08:32	CHIEF : Special Service
22/05/2018 14:01	Support Report (4947) converted to Primary Report by dbo
22/05/2018 14:01	Primary Report (5910) converted to Support Report by dbo

The information above are notes made by CAD Operators while in communication with personnel or members of the public in relation to the Incident, and are used primarily as reminder information for subsequent communications. They should not be considered a true or complete record of events.

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE
MANDURAH 6210

Report printed on 25/05/2018 14:01

Attendance Reports

Respondant: MELVILLE SES (4947)
Respondant First Advised: 24/02/2018 09:22
Action Taken Search

Report Approved By:
Report Validated:
Comments:

Resources & Personnel

Vehicle or Response Type: INCIDENT ATTENDED OTHER MEANS

Mobile: 4WD Used: 4wd - Not used
On Scene: 24/02/2018 10:00 Km to Site:
Returning: 24/02/2018 12:36
Available: 24/02/2018 12:36
Travel Code: 003 - Normal Road Traffic Regs
Delay Factor: No delay experienced/not applicable

Name	BA Used	Injured	Driver
[redacted]	N	N	N

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

Attendance Reports

Respondant: HELITAKS PERTH (5911)

Respondant First Advised: 24/02/2018 07:44

Action Taken

Report Approved By:

Report Validated: N

Comments:

Resources & Personnel

Vehicle or Response Type: AIR ATTACK 7 - FIREBIRD 630

Mobile: 24/02/2018 07:44

4WD Used: 4wd - Not used

On Scene:

Km to Site:

Returning: 24/02/2018 12:36

Available: 24/02/2018 12:36

Travel Code:

Delay Factor: No delay experienced/not applicable

Name	BA Used	Injured	Driver

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

Attendance Reports

Respondant: AVIATION SERVICES UNIT (5910)

Respondant First Advised: 24/02/2018 07:46

Action Taken

Report Approved By:

Report Validated: N

Comments:

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

Attendance Reports

Respondant: BASSENDEAN SES (4905)
Respondant First Advised: 24/02/2018 09:22
Action Taken Search

Report Approved By:
Report Validated: N
Comments:

Resources & Personnel

Vehicle or Response Type: INCIDENT ATTENDED OTHER MEANS
Mobile:
4WD Used: 4wd - Not used
On Scene: 24/02/2018 10:00
Km to Site:
Returning: 24/02/2018 12:36
Available: 24/02/2018 12:36
Travel Code: 003 - Normal Road Traffic Regs
Delay Factor: No delay experienced/not applicable

Name	BA Used	Injured	Driver
[redacted]	N	N	N

DFES Department of Fire & Emergency Services

DFES Incident Report No. **383803**

Incident Date/Time: 24/02/2018 07:43

Incident Address: BREAKWATER PDE MANDURAH 6210

Report printed on 25/05/2018 14:01

Attendance Reports

Respondant: VMR COORDINATION UNIT (427)

Respondant First Advised: 24/02/2018 00:00

Action Taken

Report Approved By:

Report Validated: N

Comments:

Resources & Personnel

Vehicle or Response Type: IN PRIVATE VEHICLE

Name	BA Used	Injured	Driver	On Site before App.	On Site before Control	On Site after Control
MILLER, SIMON	N	N	N	N	N	N

MMD Naval Architects

Department of Transport Western Australia

Finistere Keel Failure

Assessment Report

Document no:	18243-900
Revision:	A
Document status:	Final
[redacted]	[redacted]
[redacted]	[redacted]
Date	29/10/18
Pages	24

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I. DOCUMENT CHANGE CONTROL

Revisions made to this document.

Revision	Date of Issue	Author	Brief Description of change
A	29/10/18	[redacted]	Original Issue

II. MODEL CONTROL

Ref.	Model No.	Rev	Brief Description	Analysis Software

III. RULES, CODES, STANDARDS AND REGULATIONS

Ref.	Publisher	Year	Title
B1	Australian Sailing	2017	Special Regulations
B2	ISO	2012	ISO 12215-5-2008 Small craft - Hull construction and scantlings - Part 5- Design pressures for monohulls design stresses, scantlings determination
B3	ISO	2008	ISO 12215-9-2012 Small craft - Hull construction and scantlings - Part 9- Sailing craft appendages

CONTENTS

1 SCOPE AND PURPOSE

This report was prepared for the purpose of offering an opinion to the Western Australian Department of Transport on the failure of the keel of the yacht *Finistere*.

The focus of the investigation was to determine the factors contributing to the failure of the keel including those related to the vessel operation and design.

2 SUMMARY

It appears as though water has ingressed into the timber core of that part of the keel contained within the keel case.

It is possible that water ingress has led to a degradation of the structural properties of the timber core.

The core of the keel spar within the keel case appears to have failed in shear resulting in the loss of structural integrity and total detachment of the remainder of the keel spar.

The original design of the keel spar appears to meet the requirements of the applicable standards. There is not enough information available to determine if modification of the keel has invalidated the original keel spar calculations.

The weather at the time of the incident was not abnormal and is not considered to have led to, or be, the cause of failure.

3 INCIDENT NARRATIVE

On Friday, 23 February 2018, the 50ft yacht *Finistere* capsized off Mandurah [redacted] whilst competing in the 2018 Bunbury return race. At the last known position, *Finistere* was heading into a 20-25 kn wind at a speed of 5.1 kn.

When the yacht was salvaged it was identified that the keel had failed where it exited the hull.

Picture 1 - Remainder of keel flush with underside of salvaged hull.

4 BACKGROUND INFORMATION

4.1 Keel

The yacht was fitted with a lifting keel. This permitted the keel to be raised when yacht entered shallow harbours or anchorages. The keel is able to slide vertically within a case through the bottom of the yacht and secured in place by pins through the case.

The keel consisted of a laminated timber spar with substantial carbon fibre laminations either side. There was a 2.56 tonne lead bulb attached to the bottom of the keel spar.

The constructions and dimensions of the keel are as described in Keel Fin Structure drawing 0900, dated June 2011 (Appendix C).

4.2 Keel modification

In approximately 2012 the keel was modified with the addition of a stainless-steel extension at the top of the keel. This modification had the effect of raising the keel retaining pins 300mm higher than the original configuration (Appendix D).

4.3 Keel as found

The first observation of the keel as found is that the pin arrangement at the top of the keel is not in accordance with the Keel Fin Structure drawing 0900, dated June 2011. That drawing describes a 22mm lifting pin, a 32mm retaining pin and a 50mm ‘Anti-gravity’ pin. It is not clear what an ‘Anti-gravity’ pin is as the description indicates it runs in channels either side of the case. If the 50mm pin was a securing pin it would be more usual for it to be secured through holes in the case, rather than running in channels.

The photograph of the extracted keel (Picture 2) shows what appears to be two securing pin positions in the original keel spar. One pin located towards the leading edge and the other located towards the trailing edge. Both pins are located towards the top edge of the of the keel spar.

There is a third, smaller diameter pin located between the two securing pins that appears to be a guide pin. This guide pin possibly aligned with slots in the keel case.

Beneath the guide pin there appears to be evidence of a second hole through the keel spar that had been filled.

The second observation was that the outside skin on the port side of the keel appears to have moved down relative to the remainder of the keel by between 25-50mm. This movement is evident both in the resultant angle of the guide pin, and the misalignment of the locating pin holes (Picture 3).

When one outer skin of the remaining keel part was removed there was evidence of a failure of the bond between the steel insert plate and the timber core. The timber core showed evidence of water ingress and degradation. The timber core appeared to have sheared through between the securing pins, roughly at the level of the steel insert plate.

Picture 2 - Remains of keel as extracted from hull.

Picture 3 - Port skin moved down relative to remainder of keel.

Picture 4 – Core failed in shear, outside skin moved relative to remainder of keel.

Picture 5 – Outside skin of keel removed, evidence of water ingress and degradation of core.

5 KEEL SPAR CONSTRUCTION ASSESSMENT

In order to compete in Category 1 and Category 2 yacht races, Australian Sailing Special Regulations require certain structural standards to be met. The Bunbury return race is not a Category 1 or 2 race, but the yacht *Finistere* had qualified for, and competed in category 1 and 2 races in the past.

In relation to hull construction standards (Scantlings), the 2017-2020 Special regulations require;

3.03.2 A monohull with Primary Launch between 1987 and 1 July 2010 shall have been designed, built, maintained, modified or repaired in accordance with the requirements of:

(a) 3.03.1,

(b) the ABS Guide for Building and Classing Offshore Yachts and have on board either an ABS certificate of plan approval, or written statements signed by the designer and builder confirming that they have respectively designed and built the boat in accordance with the ABS Guide,

(c) the EC Recreational Craft Directive for Category A having obtained the CE mark, or

(d) ISO 12215 Category A, with written statements signed by the designer and builder confirming that they have respectively designed and built the boat in accordance with the ISO standard, and

(e) have written statements or approvals in accordance with (a), or (b) or (c) and (d) above for all significant repairs or modifications to the hull, deck, coach roof, keel or appendages, on board, except

(f) that a race organizer or class rules may accept, when that described in (a), (b), (c), (d) or (e) above is not available, the signed statement by a naval architect or other person familiar with the standards listed above that the boat fulfils these requirements

For the purpose of this report, the structure of the keel spar as described in Keel Fin Structure drawing 0900 dated June 2011 has been reviewed against the requirements of ISO 12215.

5.1 Keel Load Cases

ISO 12215-9 requires 6 load cases to be considered when assessing keel structures.

- Load case 1 – Fixed keel at 90^0 knockdown
- Load case 2 – Canted keel steady load at 30^0 heel with dynamic overload factor
- Load case 3 – Keelboat vertical pounding
- Load case 4 – Keelboat longitudinal impact
- Load case 5 – Centreboard on capsize recoverable dinghies
- Load case 6 – Centreboard or dagger board upwind.

Not all load cases are applicable to all vessels. In the case of *Finistere*, Load cases 1, 2 and 4 are applicable. Given the nature of the keel failure, only Load case 1 has been assessed for the purpose of this report.

Based on the keel bulb weight stipulated in Keel Fin Structure drawing 0900 and an estimate of the keel fin weight, the design force and bending moment to be applied to the keel in accordance with ISO 12215-9 Load case 1 are as follows:

Design force	$P =$	27337	N
Shear forces	$V_1 =$	143046	N
Keel heeling design moment at the keel junction	$M_{1.1} =$	75242	N.m

It has been assumed that the movement of the pins has not resulted in any change to the position of the bulb relative to the hull or the spar within the case.

The supporting calculations are included as Appendix A.

5.2 Keel Structure

The keel spar has been assessed in accordance with ISO 12215-5 Annex H.

For the purpose of the assessment the keel spar has been approximated as a rectangular timber core 400mm wide by 106mm deep with 30 layers of 450g Carbon fibre unidirectional and 4 layers of 400g Carbon fibre double bias cloth each side. These laminates are as detailed in Keel Fin Structure drawing 0900 at the point where the keel spar exits the hull.

With the loads applied in accordance with Load case 1 the compliance factors in bending and shear are as follows.

1	20	21	25
Ply No.	Compliance Factor Bending	Location of shear	Compliance Factor Shear
2 x CU450	1.88	Shear in 2 x CU450 at interface w ith 1 x CDB400	59.2
1 x CDB400	1.50	Shear in 1 x CDB400 at interface w ith 7 x CU450	410.7
7 x CU450	1.92	Shear in 7 x CU450 at interface w ith 1 x CDB400	13.3
1 x CDB400	1.58	Shear in 1 x CDB400 at interface w ith 7 x CU450	97.8
7 x CU450	2.03	Shear in 7 x CU450 at interface w ith 1 x CDB400	7.7
1 x CDB400	1.68	Shear in 1 x CDB400 at interface w ith 7 x CU450	56.9
7 x CU450	2.15	Shear in 7 x CU450 at interface w ith 1 x CDB400	5.5
1 x CDB400	1.79	Shear in 1 x CDB400 at interface w ith 7 x CU450	40.8
7 x CU450	2.29	Shear in 7 x CU450 at interface w ith Timber Core	4.3
Timber Core	1.77	Shear in Timber Core at interface w ith Timber Core	1.3
Timber Core	1.77	Shear in Timber Core at interface w ith 7 x CU450	1.9
7 x CU450	2.29	Shear in 7 x CU450 at interface w ith 1 x CDB400	5.5
1 x CDB400	1.79	Shear in 1 x CDB400 at interface w ith 7 x CU450	41.1
7 x CU450	2.15	Shear in 7 x CU450 at interface w ith 1 x CDB400	7.6
1 x CDB400	1.68	Shear in 1 x CDB400 at interface w ith 7 x CU450	57.4
7 x CU450	2.03	Shear in 7 x CU450 at interface w ith 1 x CDB400	13.1
1 x CDB400	1.58	Shear in 1 x CDB400 at interface w ith 7 x CU450	99.4
7 x CU450	1.92	Shear in 7 x CU450 at interface w ith 1 x CDB400	55.1
1 x CDB400	1.50	Shear in 1 x CDB400 at interface w ith 2 x CU450	442.0
2 x CU450	1.88	Shear in 2 x CU450 at interface w ith	0.0

Compliance factor is the ratio of actual stress divided by allowable stress. As such a minimum required value for compliance factor is 1.

From the assessment it can be seen that the minimum compliance factor for the keel in bending is 1.50, and the minimum compliance factor for the keel in shear is 1.3.

The compliance factor includes an inherent factor of safety of 2. As such a compliance factor of 1.3 equates to a factor of safety on failure of 2.6.

The supporting calculations are included as Appendix B.

5.3 Keel Modification

The keel spar was modified to include the addition of a stainless-steel extension at the top. This extension is detailed in Calculation Sheet, Project number 0912 dated 19/07/12.

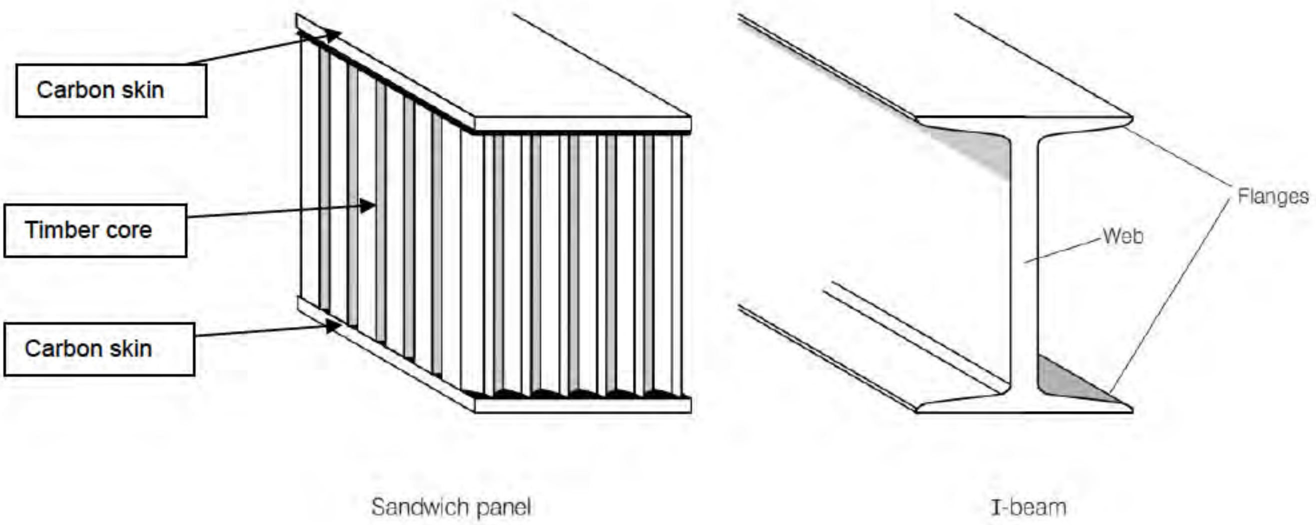
The extension is shown as being inserted into a 14mm wide recess at the top of the keel fin. No detail is given on the calculation sheet in relation to the treatment of the exposed core when this recess is made. Nor is any detail given on the bonding or sealing arrangements between the keel and the extension piece.

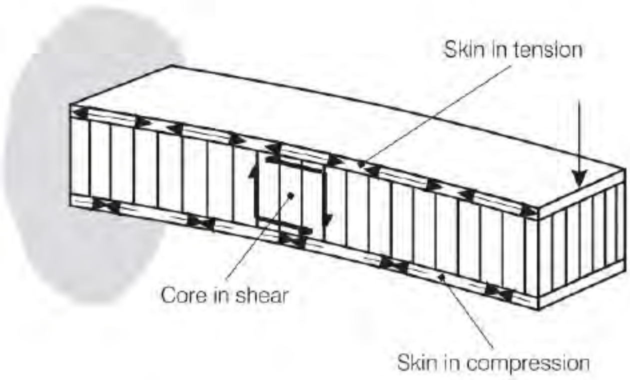
The addition of the extension piece would not impact on the compliance with ISO 12215 provided the structural properties of the keel spar were maintained. In this instance that would require the shear strength of the bond between the timber core and the steel plate to be equivalent to the shear strength of the unmodified timber core.

6 SANDWICH CONSTRUCTION

The keel can be considered to be a sandwich construction. There are two carbon fibre skins separated by a timber core. The skins can be compared to the flanges of an I-beam. When the keel is subjected to bending one carbon fibre skin is in compression whilst the other is in tension. This tension and compression are forces that act in opposite directions.

Similarly, the timber core can be compared to the web of the I-beam. The core resists the shear loads and increases the stiffness of the structure by holding the two skins apart. Since one carbon skin acts in tension, and the other in the opposite direction in compression, without a core there would be nothing to stop the two skins moving relative to each other. The shear strength of the core resists the two skins from sliding relative to each other.





7 CONCLUSION

The calculations show that the keel spar as designed complied with the applicable standard for the intended purpose. If the modifications are also considered, the keel spar is still in compliance. Structurally, the design and further modification of the keel are not considered to be the cause of failure.

The weather conditions during the race were not abnormal and are not considered to be the cause of failure.

With the keel inserted into the case, the maximum shear force within the keel would be expected to have been uniform between the top of the keel spar and the point the keel exited the hull.

The shear distribution within the keel spar will have been a maximum through the centre of the timber core. Based on the drawings available, the edge of the steel plate insert is positioned within 7mm of the centre of the timber core.

Based on the drawings available, there is no detail of the adhesive bond or sealing arrangements between the steel insert and the original keel spar.

It is probable that the keel core failed in shear within the keel case. Once that failure occurred the individual keel skins would have been unable to support the keel loads and the keel detached at the exit from the keel casing.

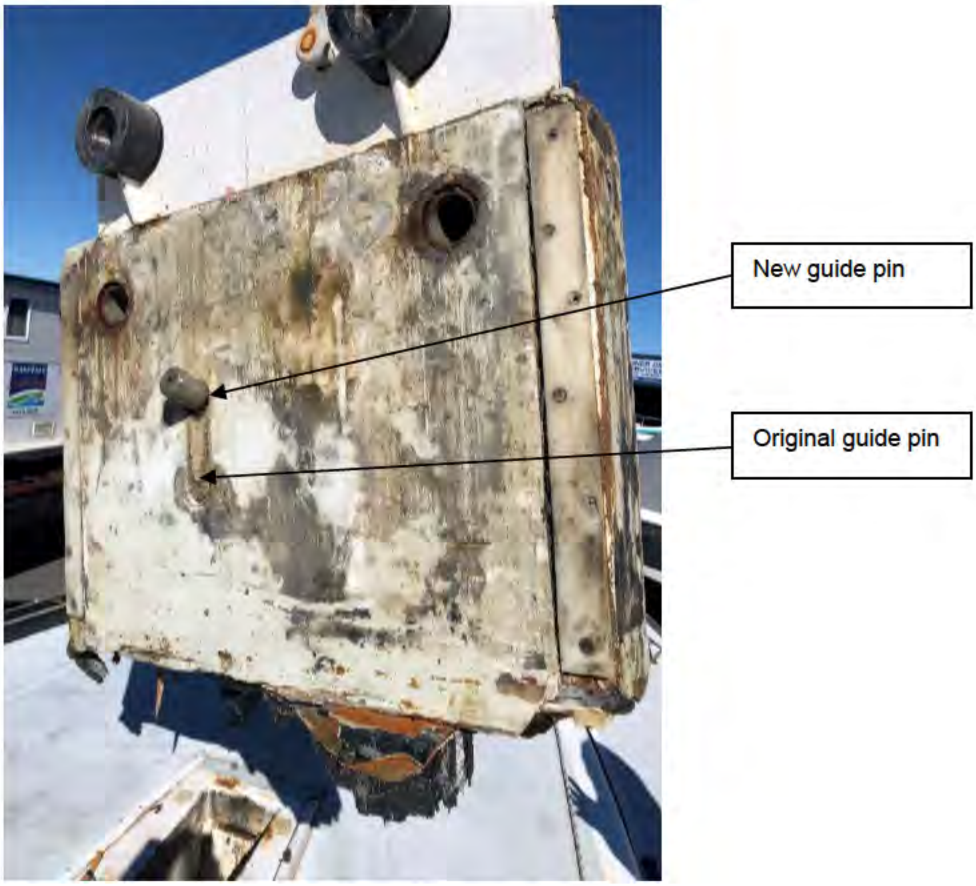
The onset of the core shear failure could be attributable to a number of factors or a combination thereof. These include;

- Water ingress into the keel at the modification or through the connecting pins degrading the shear capacity of the core timber. As evidenced by the appearance of the timber near the core in the photos, noted below.
- The shear strength of the bond between the timber core and the steel insert plate being less than the shear force through the core at that point. As evidenced by the bare steel of the insert with no adhered glue, noted below.
- Accumulation over time of cracks or delaminations in the bond between the timber core and steel insert reducing the shear capacity of the bond. As evidenced by the bare steel of the insert with no adhered glue, noted below.

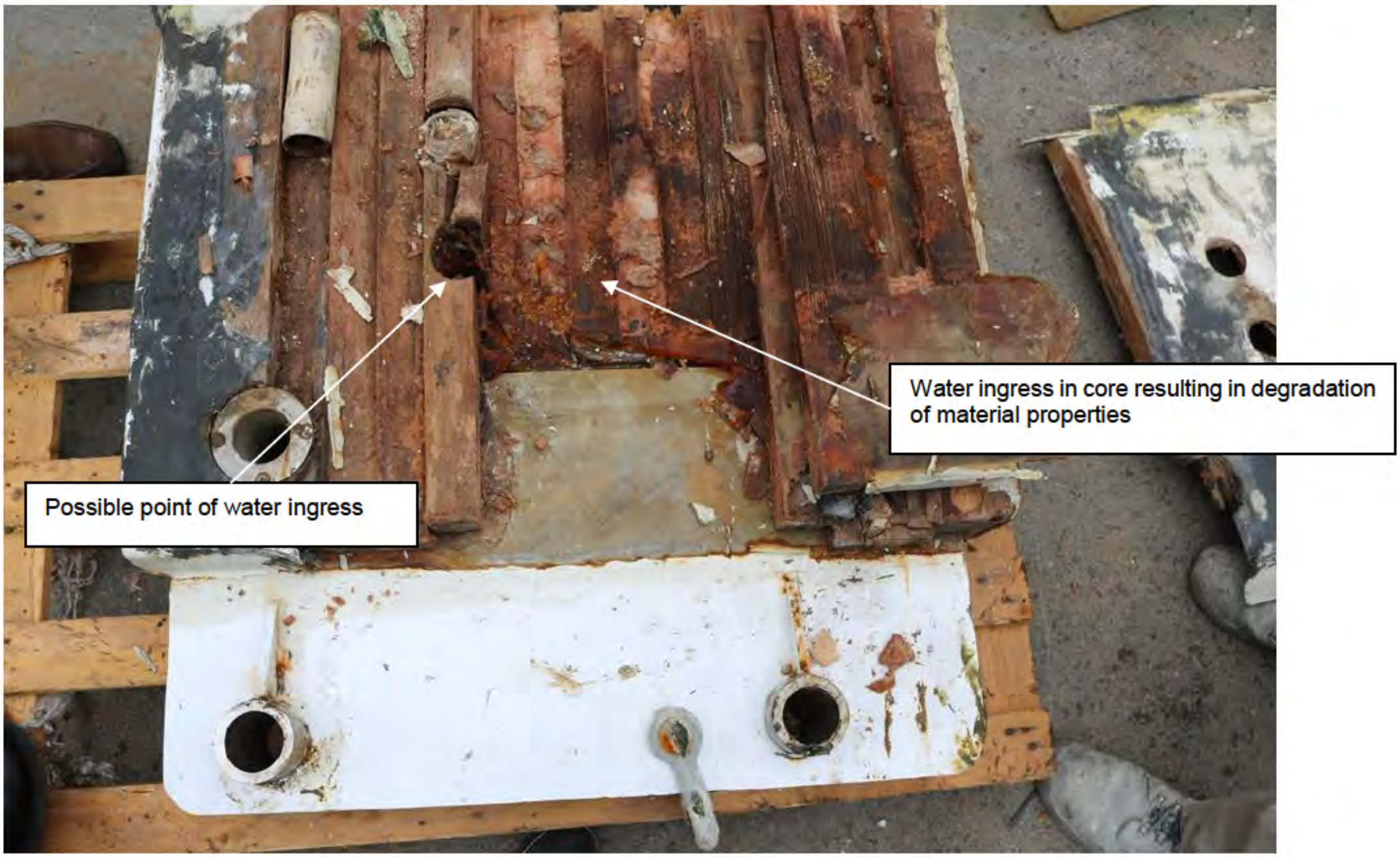
The compliance factor assumes the material properties are intact. Degradation of material properties will reduce the factor of safety on structural failure.

It is possible the failure occurred as follows;

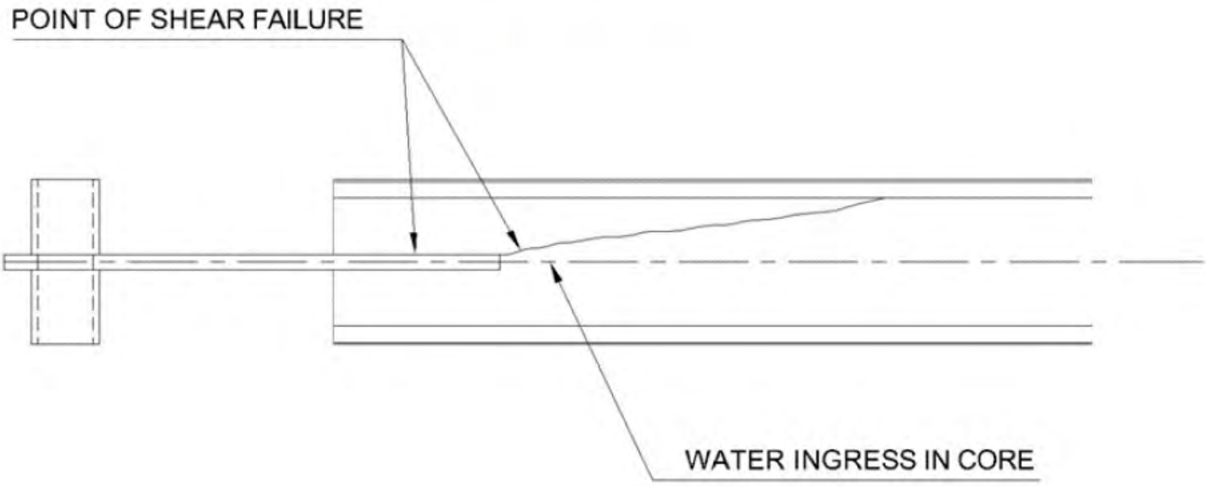
1. The location of the guide pin has been raised.



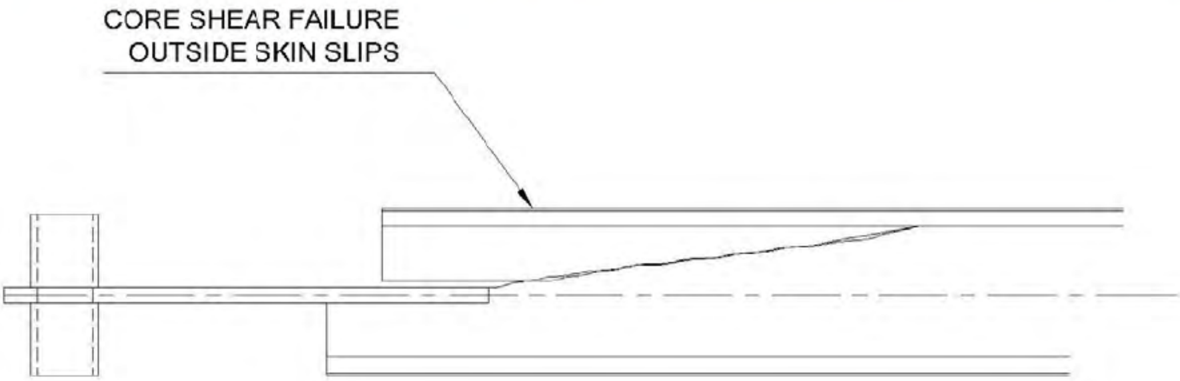
2. Water has ingressed into the keel core and degraded the material properties. It appears that the water ingress may have occurred through the hole for the relocated guide pin.



3. At the point of highest shear distribution, the timber core has begun to fail.



4. The glue joint between the timber core and the steel insert has failed in shear. The timber core has failed in shear below the steel insert.



5. Once the initial failure occurred the material failures have cascaded throughout the keel core within the case. The carbon skins either side of the core are no longer working as part of a sandwich structure and the individual skins fail in bending and / or shear at the hull / keel interface.
6. The keel below the hull has detached.

APPENDIX A – ISO 12215-9 CALCULATIONS

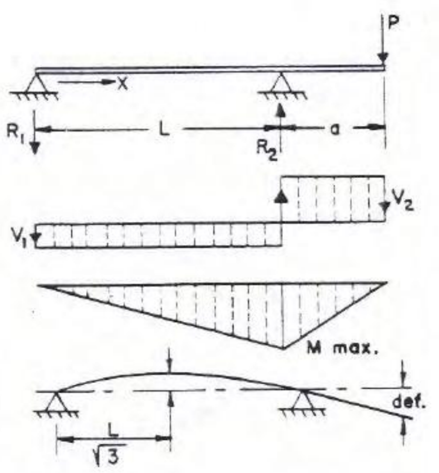
ISO 12215-9

7.2 **Load case 1 — Fixed keel at 90° knockdown**

	Weight kg	Lever m	Moment kg.m
Fin timber core	141	1.146	161.405
7 x CU450 - 300mm each side	17	1.153	19.640
1 x CDB400 - 400mm each side	2	1.153	2.112
7 x CU450 - 300mm each side	11	1.153	12.470
1 x CDB400 - 400mm each side	2	1.153	2.112
7 x CU450 - 300mm each side	9	0.923	8.709
1 x CDB400 - 400mm each side	1	0.75	1.067
7 x CU450 - 300mm each side	7	0.549	3.936
1 x CDB400 - 400mm each side	1	0.348	0.353
2 x CU450 - 300mm each side	2	0.291	0.469
Outer skin	24	1.137	26.846
Inserts and reinforcements	10	-0.34	-3.400
Bulb	2560	2.904	7434.240
Combined	2787	2.752	7670.0

3.4 m_{keel} = 2787 kg

The acceleration of gravity, taken as 9,81 g = 9.81 m/s^2



Concentrated load, P, at end of overhang

Reactions: $R_1 = -\frac{Pa}{L}$

$$R_2 = \frac{P}{L}(L + a)$$

Shear forces: $V_1 = -\frac{Pa}{L}$

$$V_2 = P$$

Maximum bending moment:
$M_{max} = -Pa$, at right support

Deflections:
Maximum downward def. $= \frac{Pa^2}{3\,EI}(L + a)$, at load

Maximum upward deflection; at $x = \frac{L}{\sqrt{3}}$

$$= \frac{PaL^2}{9\,EI\sqrt{3}} = 0.06415\,\frac{PaL^2}{EI}$$

(2)	Design force	$P =$	27337	N
	Distance betw een points of contact	$L =$	0.526	m
	The distance, in metres (m), along the keel centreline, from the keel CG to the keel's junction with the hull or tuck;	$a =$	2.75	m
	Reaction	$R_1 =$	-143046	N
		$R_2 =$	170383	N
	Shear forces	$V_1 =$	-143046	N
		$V_2 =$	27337	N
(3)	Keel heeling design moment at the keel junction	$M_{1.1} =$	-75242	N.m

APPENDIX B – ISO 12215-5 ASSESSMENT

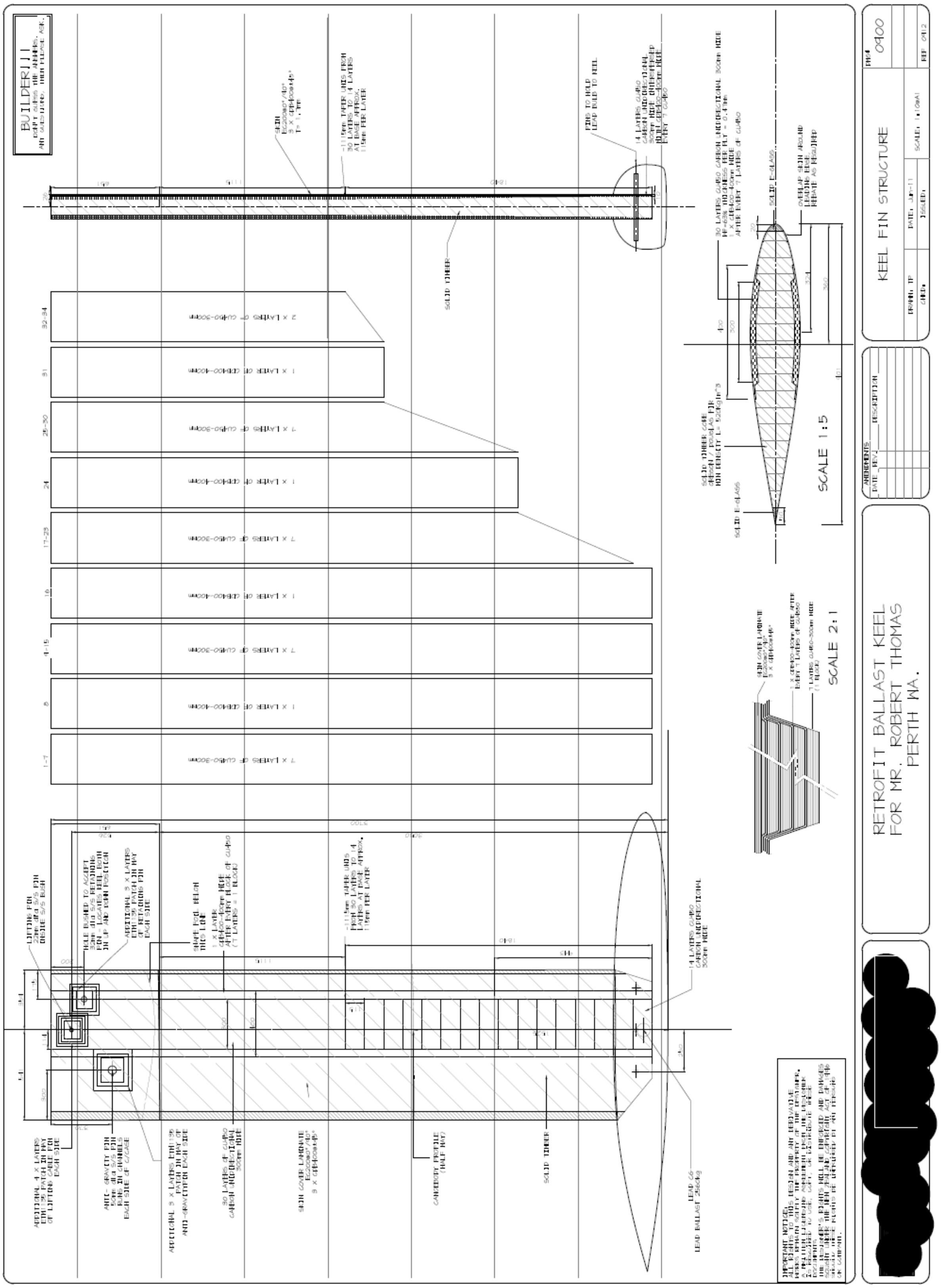
Design force	Keel Span			Design shear force	Design bending	
P	Lu			Fd	Md	
N	mm			N	Nm	Nmm
27337	2752			143046	75242	75242276

1	2	3	4	5	6	7	8	9
Element No.	Depth h mm	Width b mm	Modulus E_{ti} N/mm^2	σ_t/c_u N/mm^2 Annex C	Interlaminar $\tau_{u\ interlam}$ N/mm^2	$\sigma_{tcd}/\sigma_{tcu}$ τ_d/τ_u * Table 7	σ_{tcd} N/mm^2 (5).(7)	τ_d N/mm^2 (6).(7)
2 x CU450	0.94	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
Timber Core	53	400	10140	74	9	0.5	37.0	4.5
Timber Core	53	400	10140	74	9	0.5	37.0	4.5
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
7 x CU450	3.29	300	47840	480	27	0.5	240.0	13.4
1 x CDB400	0.418	400	6200	48.96	150	0.5	24.5	75.2
2 x CU450	0.94	300	47840	480	27	0.5	240.0	13.4
Total	137.544	**7000**	**27414**					

1	10	11	12	13	14	15	16	17
Element No.	Area mm (2).(3)	E_i x A N/mm (4).(10)	Dist *zgi* from outside mm Calc	E_i x A x zg_i N (11).(12)	E_i x A x zg_i^2 Nmm (12).(13)	E_i x b x h^3/12 (3).(4).(2)^3/12	$(EI)_i$ From base Nmm^2 (14)+(15)	z_{crit} from z_{NA} mm Calc
2 x CU450	282.000	13490880	137.07	1849248885	253483941679	993378	253484935057	68.77
1 x CDB400	167.200	1036640	136.40	141392513	19285231783	15094	19285246877	67.83
7 x CU450	987.000	47218080	134.54	6352767701	854707719298	42591102	854750310400	67.41
1 x CDB400	167.200	1036640	132.69	137548652	18250917945	15094	18250933039	64.12
7 x CU450	987.000	47218080	130.83	6177683061	808244807873	42591102	808287398974	63.71
1 x CDB400	167.200	1036640	128.98	133704791	17245110182	15094	17245125275	60.42
7 x CU450	987.000	47218080	127.13	6002598420	763080324143	42591102	763122915244	60.00
1 x CDB400	167.200	1036640	125.27	129860929	16267808492	15094	16267823586	56.71
7 x CU450	987.000	47218080	123.42	5827513779	719214268107	42591102	719256859209	56.29
Timber Core	21200.000	214968000	95.27	20480431296	1951211650433	50320426000	2001532076433	53.00
Timber Core	21200.000	214968000	42.27	9087127296	384131045057	50320426000	434451471057	-53.00
7 x CU450	987.000	47218080	14.13	667049816	9423412753	42591102	9466003855	-56.29
1 x CDB400	167.200	1036640	12.27	12722683	156145485	15094	156160579	-56.71
7 x CU450	987.000	47218080	10.42	491965176	5125785164	42591102	5168376265	-60.00
1 x CDB400	167.200	1036640	8.57	8878822	76047107	15094	76062201	-60.42
7 x CU450	987.000	47218080	6.71	316880535	2126585270	42591102	2169176371	-63.71
1 x CDB400	167.200	1036640	4.86	5034960	24454803	15094	24469897	-64.12
7 x CU450	987.000	47218080	3.00	141795894	425813070	42591102	468404172	-67.41
1 x CDB400	167.200	1036640	1.15	1191099	1368573	15094	1383667	-67.83
2 x CU450	282.000	13490880	0.47	6340714	2980135	993378	3973514	-68.77
Total	**52197.600**	**842955520**	Z_{NA} **68.77**	**57971737021**	**5822485417351**		EI_{Base} **5923469105672**	EI_{NA} **1936636807233**

1	18	19	20	21	22	23	24	25
Ply No.	SM_i cm³ Calc	σ_i N/mm² Calc	Compliance Factor	Shear Stress Analysis: Loca ion of τ	First mt Q $\sum E_i.A\ (z_i-z_{NA})$ Nmm	Shear flow q N/mm	τ_i average N/mm²	Compliance Factor *
2 x CU450	588.63	127.8	1.88	2 x CU450-1 x CDB400	921454086	68.1	0.2269	59.2
1 x CDB400	4604.92	16.3	1.50	1 x CDB400-7 x CU450	991554792	73.2	0.1831	410.7
7 x CU450	600.49	125.3	1.92	7 x CU450-1 x CDB400	4097040696	302.6	1.0087	13.3
1 x CDB400	4871.20	15.4	1.58	1 x CDB400-7 x CU450	4163297542	307.5	0.7688	97.8
7 x CU450	635.44	118.4	2.03	7 x CU450-1 x CDB400	7093698804	524.0	1.7465	7.7
1 x CDB400	5170.17	14.6	1.68	1 x CDB400-7 x CU450	7156111789	528.6	1.3214	56.9
7 x CU450	674.71	111.5	2.15	7 x CU450-1 x CDB400 interface	9911428411	732.1	2.4403	5.5
1 x CDB400	5508.23	13.7	1.79	1 x CDB400-7 x CU450 interface	9969997535	736.4	1.8410	40.8
7 x CU450	719.16	104.6	2.29	7 x CU450-Timber Core interface	12550229516	927.0	3.0900	4.3
Timber Core	3603.58	20.9	1.77	Timber Core-Timber Core interface	18246881516	1347.8	3.3694	1.3
Timber Core	-3603.58	-20.9	1.77	Timber Core-7 x CU450 interface	12550229516	927.0	2.3175	1.9
7 x CU450	-719.16	-104.6	2.29	7 x CU450-1 x CDB400 interface	9969997535	736.4	2.4547	5.5
1 x CDB400	-5508.23	-13.7	1.79	1 x CDB400-7 x CU450 interface	9911428411	732.1	1.8302	41.1
7 x CU450	-674.71	-111.5	2.15	7 x CU450-1 x CDB400 interface	7156111789	528.6	1.7619	7.6
1 x CDB400	-5170.17	-14.6	1.68	1 x CDB400-7 x CU450 interface	7093698804	524.0	1.3099	57.4
7 x CU450	-635.44	-118.4	2.03	7 x CU450-1 x CDB400 interface	4163297542	307.5	1.0250	13.1
1 x CDB400	-4871.20	-15.4	1.58	1 x CDB400-7 x CU450 interface	4097040696	302.6	0.7566	99.4
7 x CU450	-600.49	-125.3	1.92	7 x CU450-1 x CDB400 interface	991554792	73.2	0.2441	55.1
1 x CDB400	-4604.92	-16.3	1.50	1 x CDB400-2 x CU450 interface	921454086	68.1	0.1702	442.0
2 x CU450	-588.63	-127.8	1.88	2 x CU450-interface	0	0 0	0.0000	

APPENDIX C – KEEL FIN STRUCTURE



APPENDIX D – MODIFICATION

Calculation Sheet

Project Number: 0912

Project Title: FINISTERRE KEEL.

Date: 19/07/12