Annex A

Wolfson Report No 2702 - Assessment of keel and associated structure of the sailing vessel *Tyger of London*

Report No. 2702

Date : 4th June 2018
Compiled By : [redacted]
Verified By : [redacted]

Marine Accidents Investigation Branch (MAIB)

Assessment of Keel and associated structure of Sailing Vessel 'Tyger of London'

1 INTRODUCTION

The MAIB is conducting an investigation into the loss of the keel and capsize of a Comet 45S sailing yacht, 'Tyger of London' whilst sailing off Tenerife on 7th December 2017. The MAIB would like to establish the following:

- The yacht's keel design assessed to the International standard (ISO 12215-9:2012(E))
- The yacht's keel manufacture versus designers intent
- The possible sequence of failure of the keel structure

The keel design includes a rectangular shaped 'top plate', the edge of which contains 16 bolts to attach to the yacht frame. Within the centre of the top plate are 12 threaded holes following the aerofoil shape of the keel. When in-service the mass of the keel hung from 12 rods threaded into the top plate, and partially welded. When the vessel was recovered it was noted that the top plate had remained attached to the yacht, it was also noted that 8 of the 12 rods had failed within the plate, and 4 threaded holes (centrally located) had been stripped and were empty.

This programme of work has been carried out broadly in accordance with Wolfson Unit proposal no. 4729 and includes contributions from both nC^2 and the Wolfson Unit.

2 KEEL DESIGN ASSESSED TO ISO 12215-9:2012

The drawing, design information and photographs received from MAIB of the vessel have been reviewed using the International Standard ISO 12215-9 static load cases (ref. 1). It must be borne in mind that the standard was not in place at the time when the vessel was constructed but the standard does follow on from previous standards such as the ABS guide (ref. 2).

The design and method of construction of the vessel's keel and associated structure is atypical of keel design options envisaged within the ISO standard, therefore interpretation of the results of this simplified comparison should only be used with caution.

The keel design incorporates significant use of welding in areas of high stress and the standard states that it "presumes a certain relationship between static strength and fatigue strength, which is generally preserved for unwelded metals of modest static strength and low stress concentration effects. However, for welded structures and poor detail design/fabrication, compliance with the "static" load cases cannot guarantee that fatigue failure will not occur. In such cases, an explicit fatigue life assessment or inspection regime shall be considered."

It is also noted that the standard states "The operational life of the craft is assumed to be 8 million stress cycles. This is based on an assumed operational envelope various times on different points of sail, average tacking times for beating, average rolling periods for downwind, typical wave encounter periods, estimated heel angles and is only intended to be representative. This corresponds to about 25–30 years of moderate-to-high usage recreational sailing or about five years of very extensive ocean racing (one, 30 000 NM, competition plus associated training and preparation annually). This is 15 % of the figure of the number of cycles normally used in ship fatigue assessment." The MAIB have reported the yacht's lifetime mileage to be in excess of 30,000 NM which is in-line with these "operational life" values.

This short study does not attempt to assess the keel structures fatigue life, but it is worth noting that:

- The keel rods have welding in high stress areas (i.e. at the junction with the top plate) which will lower the fatigue life.
- Due to the design of the keel, in service inspection of the welded areas was not possible.

The ISO 12215-9 focuses on two keel load cases for the assessment of 'keel bolts':

- Load Case 1: represents a 90° knockdown, the point at which there is typically the highest transverse bending load at the keel root.
- Load Case 4: represents a grounding event.

The program adopted for this assessment to the standard load cases was 'Keel Checker' (ref. 3), developed by a member of the ISO 12215 working group (TC188).

For this vessel, load case 1 has been focussed upon as there was insufficient internal hull structural information available for a valid load case 4 assessment.

The vessel has been assessed in the 'as designed' configuration and the following assumptions have been made:

- Only the rods contribute to load sharing.
- A limiting design stress of 310MPa, which equates to 0.5 times the Ultimate Tensile Strength (UTS) of AISI 316 annealed and cold drawn bar in an un-welded state. This value is the minima of the yield strength and UTS and has been used in the absence of any declared material properties.
- Keel rod locations as per Figure 1

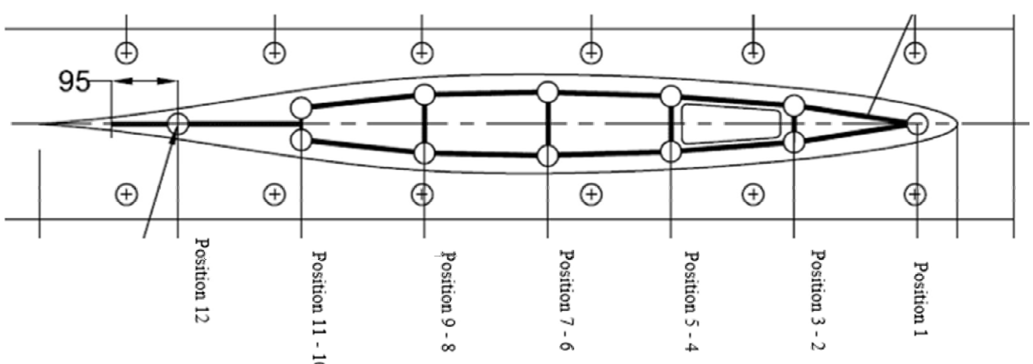

Figure 1 Keel rod locations

For comparison, the same assessment has been conducted on the top plate bolt fixings that attached the keel plate to the vessel itself.

	Limiting Design Stress	Level of Compliance
Conditions	Mpa	Factor
Keel Rods (all intact)	310	**1.12**
Top Plate Bolts	250	**1.67**
Keel Rods (6, 7 removed)	310	**0.93**

Table 1 Load Case 1 assessment

Table 1 presents the results for the assessment of Load Case 1 which shows that the keel rods have a level of compliance of 1.12 where greater than 1.0 means compliance with the standard using this static analysis based on un-welded material properties and in the absence of further information. It must be borne in mind that due to the welding and fabrication nature of the design it would need further assessment of its fatigue characteristics for complete assessment to the standard, hence this result must be used with caution.

The through hull bolting arrangement of the top plate to the vessel was also assessed and this aspect of the design provided an adequate level of compliance.

An assessment was also conducted with rods 6 and 7 removed this showed the ratio of compliance reduced below 1.0, indicating non-compliance with the standard. This does not mean that there would be a failure but indicates that the factors of safety are insufficient.

3 DEVIATION IN MANUFACTURE FROM THE DESIGN INFORMATION

3.1 Information Differences

The following deviations between the 'as manufactured' and the 'as designed' configuration have been noted as follows:

- The design drawings do not indicate welding of the side plates to the keel plate. There is evidence of partial welding of the side plates on the underside of the keel plate.
- A hole in the top plate leading to a well/sump in the top of the keel has not be incorporated.
- There was very limited information in the drawings in relation to the thread(s) detail at the top of the rods and in the keel top plate.
- A conflict exists in the detailing of the rod 1 in different drawings.
- The side plates between rod 12 and rod 10 and 11 are different to those drawn.
- A reasonable level of information has been provided to the specification of the top plate fixing bolts including dimensions and minimum structural properties such as Ultimate tension and yield strength, but this level was not replicated for other elements, as there are no structural properties detailed for the plating and rods over and above 'AISI 316'.

3.2 Observations on Keel Construction

Due to the nature of the design, once the keel structure is cast in lead there is no opportunity for post build quality control.

There are sufficient ambiguities in the drawing information to warrant clarification as to how to manufacture keel internal structure. For example, as the manufactured rods were threaded and screwed into threaded holes, it is not clear if the rod(s) were to be bent prior or post threaded insertion.

The drawings would require a greater level of detail in order to inform a welder or fabricator using standard recognised notation.

The rods were only welded on the outboard side; it is not clear if this could have been the result of difficulties in manufacture and/or inconsistencies in the quality control processes.

4 POTENTIAL SEQUENCE OF EVENTS

A summary of the potential sequence of events prior to final failure is listed Table 2 below, with a more detail discussion included in Appendix 1. The investigation has been based on a visual inspection of the remaining keel top plate. It is estimated that wear in the most heavily loaded rods (6 &7) has been occurring since first usage, but fatigue (of the fractured rods) would not have started until the fatigue limit of the material was reached – i.e. once the loads had increased due to load sheading. Assuming 1 µm striation spacing (not measured) then a 30mm rod would have taken 30,000 cycles to fail. It is likely the fatigue propagation occurred mostly in parallel but assuming they failed in a non-overlapping sequence, then the max cycles to failure would have been approximately 240k cycles.

Stage	Rod locations	Failure mechanism	Comment
Since first usage	6 & 7	Wear due to freedom of movement within un-tensioned threaded joints	6 & 7 would have failed prior to 5 and 9 as they had the largest moment
After significant wear of 6 & 7	5 & 9	Wear due to freedom of movement within un-tensioned threaded joints	
Since loss of load bearing capability of 6 & 7 allowing the fatigue limit to be exceeded	12 and 10 then 11 8 1 and 3 then 2	Fatigue failure. Reverse bending occurred on 1, 2, 12. Unidirectional on 3, 8 and 10. Tension-tension on 11	All displayed macroscopic features consistent with fatigue and post fracture damage such as wear
Final fracture	4	Tension-tension fatigue failure	Fatigue macro features, no post fracture wear

Table 2 Summary of failure

5 CONCLUSIONS

A brief external non-destructive as-received examination has been carried out on the 12 rod sites found on the supplied keel top plate removed by MAIB from the capsized Comet 45S sailing yacht, ‘Tyger of London’.

As far as could be practicably ascertained within the given inspection time the yacht’s keel had not been manufactured to meet the designer’s intent, in that the welding was not completed all the way round each rod. However the design did not take into consideration the access to weld during manufacture and did not highlight the importance of the quality (which would have required multiple passes) nor the size of the welds (no weld notation provided detailing leg length or throat thickness).

It was determined, through examination of the keel structure and fracture surfaces present that the failure most likely started by stripping the male threads on Rods 6 & 7 through a tensile-tensile cyclic load brought on by normal keel loads. The failure occurred because the rods were not securely fixed to the top plate via either:

- a fully welded joint,
- or a tensile pre-load from a bolted joint.

Therefore under local tensile-tensile loading there was relative movement between the rods (6 and 7) and the top plate, which led to thread flank wear which increased the freedom of movement. Once the load was no longer supported by the central rods, load shedding and cyclic deflections failed the remaining rods.

A simplified structural static analysis of the keel rods in isolation predicts compliance with ISO 12215 part 9, but the method of attachment makes the application of such an approach to the evaluation of this design inappropriate.

The design of the keel does not appear to have included any significant allowance for the impact of welding on the fatigue life of the structure, as stated in ISO (ref. 1).

6 REFERENCES

1. ISO Standard. Small craft - Hull construction and scantlings: Sailing craft appendages ISO 12215-9:2012(E)
2. ABS Guide for building and classing offshore racing yachts 1994
3. Keel Checker 12215 Version 3.0.1 Software Manual, Robin Loscombe, 2012

APPENDIX 1

nC^2 report, NCC170 “Assessment of Keel and associated structure of Sailing Vessel ‘Tyger of London’”

ENGINEERING CONSULTANCY

Title of Work: *Assessment of Keel and associated structure of Sailing Vessel 'Tyger of London'*

Reference No: *NCC170*

Work for: *Marine Accidents Investigation Branch (MAIB)*

Client Project Manager: [redacted]

nC² Lead Consultant: [redacted]

Approved for Release: [redacted]

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Date: *4th June 2018*

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1. Introduction

The MAIB is conducting an investigation into the loss of keel and capsize of a Comet 45S sailing yacht, 'Tyger of London'. The MAIB would like to establish the following:

- Item 1: The yacht's keel design vs International standard (ISO 12215-9)
- Item 2: The yacht's keel manufacture vs designers intent
- Item 3: The possible sequence of failure of the keel structure

The keel design includes a rectangular shaped 'top plate', the edge of which contains 16 bolts to attach to the yacht frame. Within the centre of the top plate are 12 threaded holes following the aerofoil shape of the keel. When in-service the mass of the keel hung from 12 rods threaded into the top plate, and partially welded. When the vessel was recovered it was noted that the top plate had remained attached to the yacht, it was also noted that 8 of the 12 rods had fractured within the plate, and 4 threaded holes (centrally located) had been stripped and were empty.

Figure 1: Showing plate still attached to hull as the yacht was removed from the water, image supplied by MAIB.

2. Method

The as-received top plate was arranged on a steel work table; due to its size and weight all camera and examination equipment was brought to the plate; no sectioning took place. The lower face (relative to original orientation in the yacht) of the plate was examined and any features and Regions of Interest (ROIs) noted. Documentation of the condition was recorded using DSLR camera equipment. Macro examinations were performed using a Zeiss Stemi 2000C macroscope with oblique segmented LED lighting. Images were recorded via a digital camera attached to the macroscope.

A dimensional check was performed on the received plate and compared to the dimensions found on the provided documentation.

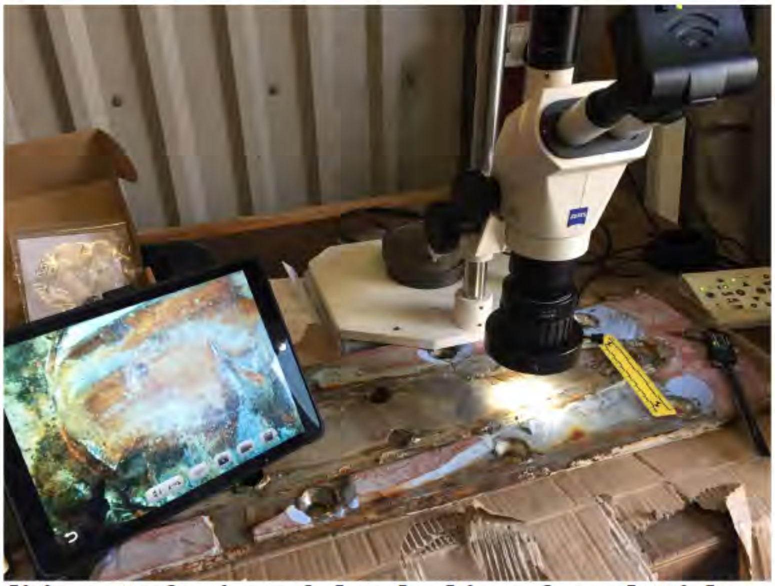

Figure 2: Showing examination conditions. Left: view of plate looking aftward. Right: macroscope set-up. ROIs were examined using a Zeiss macroscope and documented with a digital camera.

3. Results of Examination

3.1. Whole plate condition

The as-received examination of the plate (shown in Figure 2) confirmed what had been previously reported by MAIB: all twelve fixing points had failed. Eight remnants of rod were present at positions 1, 2, 3, 4, 8, 10, 11 and 12. Within the center of the plate four positions were empty of any large rod remnants (5, 6, 7 and 9). Note 1 was at the FWD end and even numbered positions along the port side.

Rod positions 1, 2-3 and 4-5

Rod positions 6-7, 8-9, and 10-11

Rod positions 10-11 and 12

Figure 3: Overview images taken by MAIB.

Key dimensions were measured and checked against the supplied drawings. It was noted that all the dimensions relevant to the construction of the keel were correct – see Figure 4. The expected arrangement of the stiffener plates (shown as thick black lines in Figure 4) was not as shown in the drawing, see Figure 7. Specifically it was noted that position 12 was welded to three stiffener plates not two.

Measurements were also taken of the weld arc angles around each rod position, these are shown in Table 1. It was noted that the welds did not encompass the full circumference of each Rod, see Figure 5, and was not generally present on the inboard side of the welds – contrary to the drawings shown in Appendix 1.1.

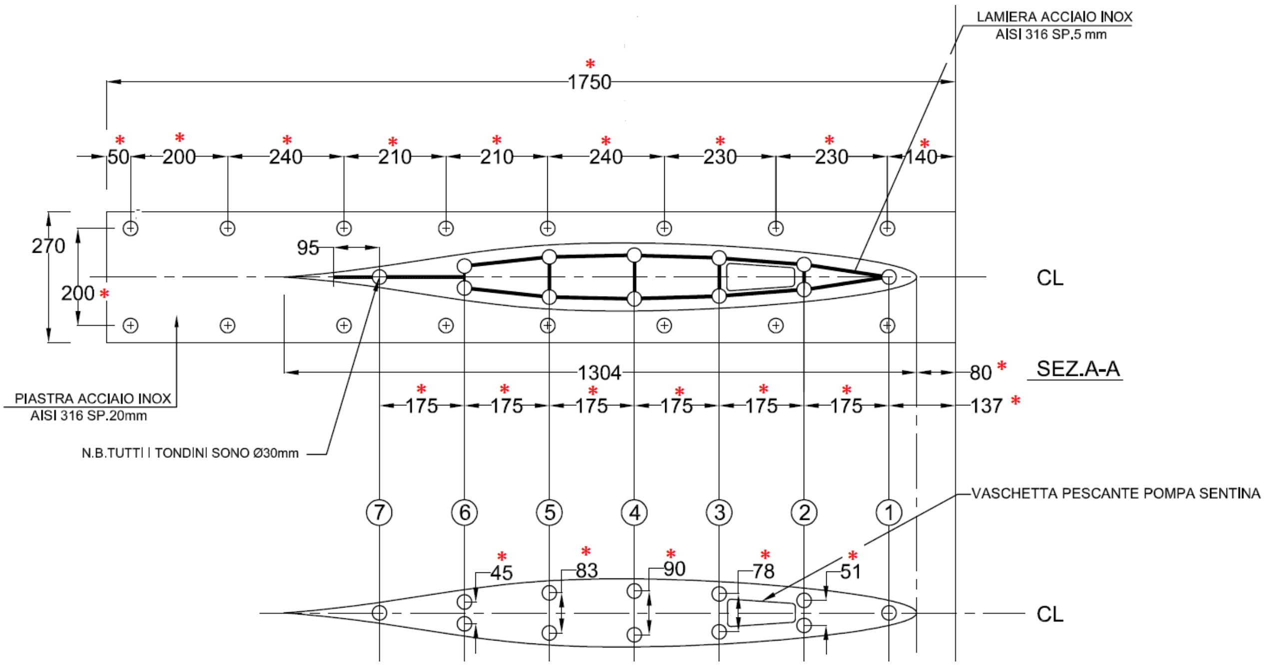

Figure 4: Extract from supplied drawings. The sample has been measured. All the dimensions with a red * are ok. The thickness was measured at 21.22 mm instead of 20 mm. The width of the plate was measured as 257-260 mm instead of 270 mm as in the drawing.

Table 1: Listing the measured arc of weld at each rod position

Location	Welding arc angle (°) around each Rod position
1	280
2	150
3	155
4	180
5	175
6	170
7	170
8	190
9	170
10	180
11	180
12	310

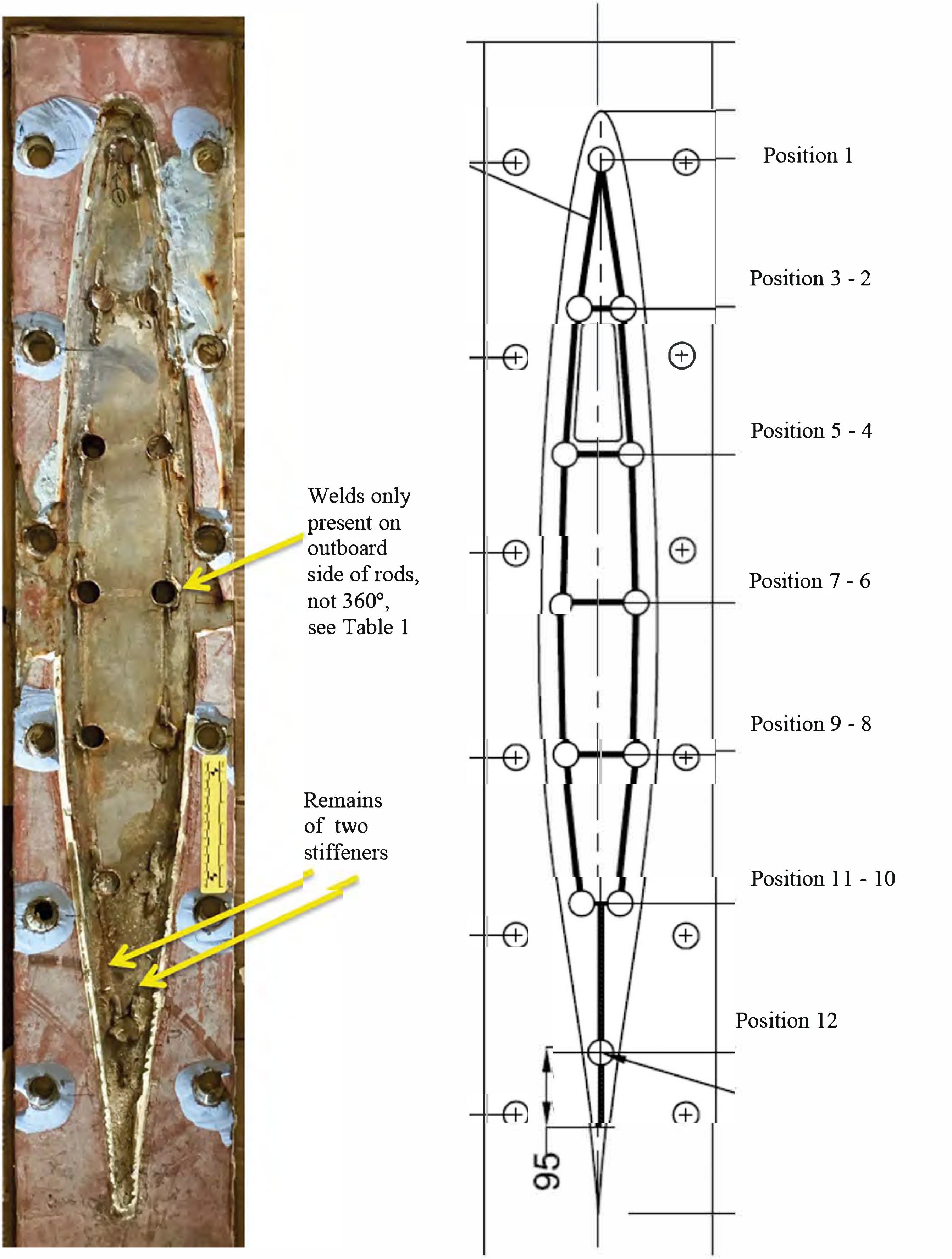

Figure 5: Image and drawing of plate. Note the different stiffener arrangement.

3.2. <u>Rod location 1 (FWD)</u>

Examination of position 1 revealed that Rod 1 had failed by fatigue driven by a reverse bending cyclic load. In addition to the rod fracture, there was remains of a stiffener which had also failed in fatigue, the remains were 38.4 mm long and 5.6 mm above the plate face, see Figure 6.

Rod 1 fracture surface had symmetry about the longitudinal axis, (Figure 7) with raised edges on the port and stbd welded sides (4.4 mm above the plate face). The center of the fracture surface displayed a line feature and was approximately level with the plate face. The shape, profile, roughness and features of the fracture surface indicate that fatigue initiated on the port and stbd sides of the rod at a location coincident to the edge of the weld. The number of ratchet marks indicates that there were multiple crack initiation points and therefore a large stress concentration was present around the circumference. The crack fronts propagated towards the centre of the rod until the loads present were great enough to overload the remaining cross-section of material. This area accounted for less than ten percent of the fracture surface indicating that the overall load at failure was low, suggesting a constant cyclic deflection (not contact stress).

Higher magnification examination of the stiffener fracture surface (Figure 8) revealed evidence of a small overload region on the stbd side and several ratchet marks, confirming that it was subjected to the same loads as the rod and likely occurred at the same time. The lower level of corrosion on the stiffener is expected to be the result of material composition not exposure time.

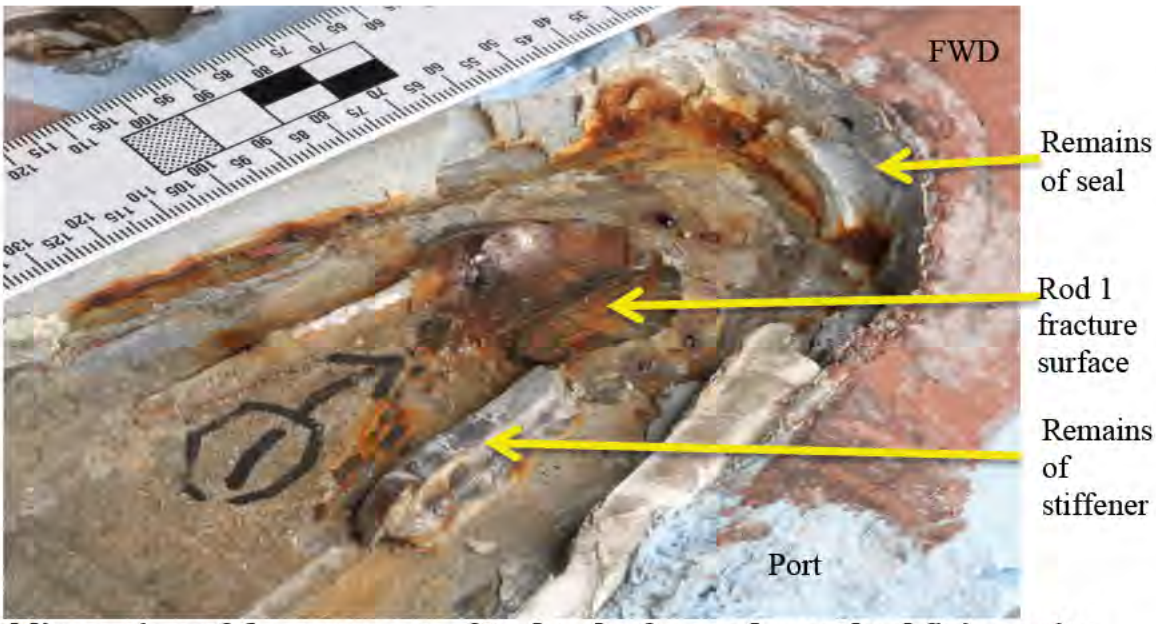

Figure 6: Oblique view of the remnants of Rod 1, the forward most keel fixing point.

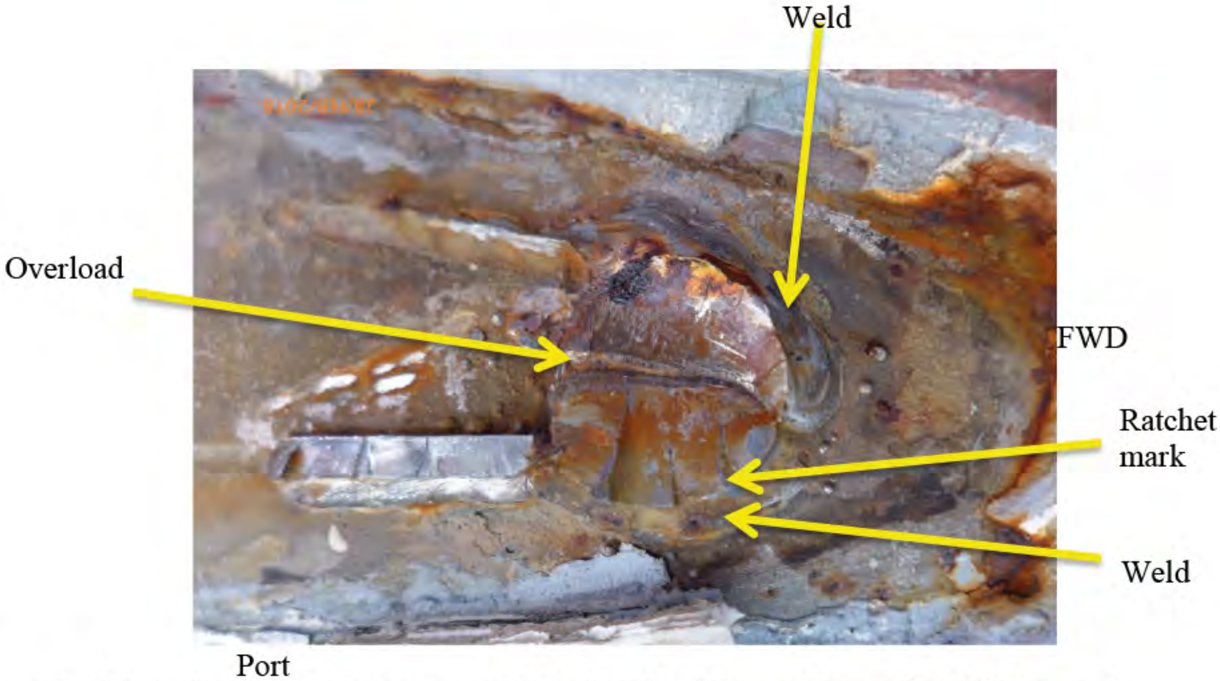

Figure 7: Plan view of the remnants of Rod 1, the forward most keel fixing point.

Figure 8: Macroscope image of the port-side stiffener fracture surface adjacent to Rod 1.

Higher magnification examination of the overload region of Rod 1 revealed that the surface had been worn back and forth in a transverse direction post fracture (Figure 9). Therefore the cyclic movement was still present after fracture. Therefore Rod 1 was not the last rod position to fail.

A schematic of the fracture of Rod 1 and the adjacent stiffener is shown in Figure 10. The figure highlights the key features of the fracture and also explains the weld leg length measurement.

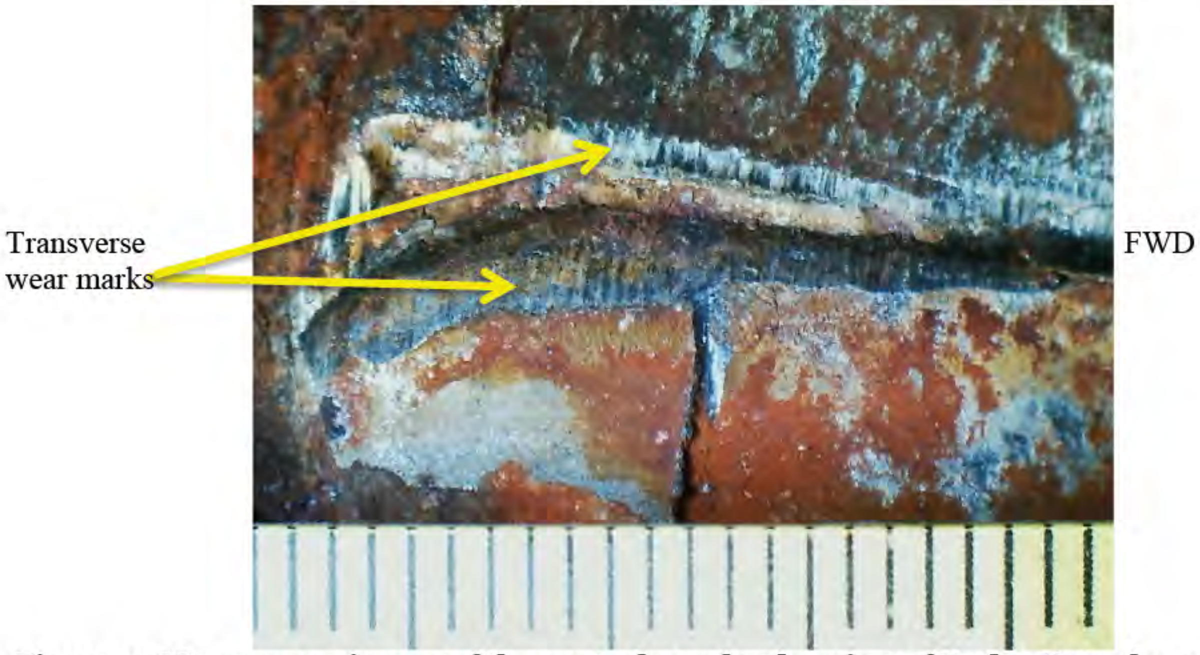

Figure 9: Macroscope image of the central overload region of Rod 1. Note the material has been worn with transverse witness marks present.

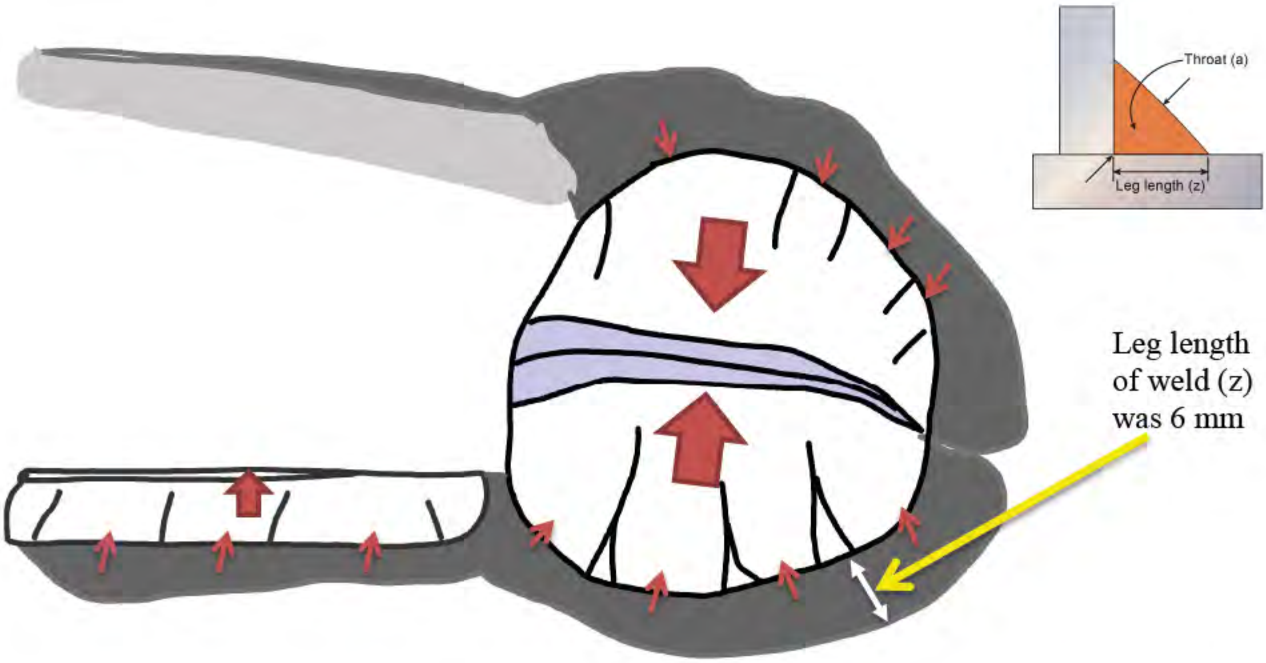

Figure 10: Schematic of Rod 1 fracture. Small red arrows highlight the multiple initiation points at the weld/rod interface. The large red arrow identify the general direction of fatigue crack growth. Note the loading was reverse bending as two fatigue fractures grew towards the centre of the rod. Overload area is shown in blue. The leg length of the weld (insert provides mitre fillet weld schematic) was measured to be 6mm.

3.3. <u>Rod locations 2 and 3</u>

Examination of positions 2 and 3 revealed that both rods failed by fatigue: Rod 3 driven by unidirectional bending; Rod 2 by reverse bending. Co-located with the fracture of Rod 3, there were the remains of a stiffener which had also failed in fatigue; the remains were 37.4 mm long and 6 mm above the plate face, see Figure 11.

Rod 3 fracture surface initiated on the outboard (stbd) side of rod 4.9 mm above the plate face. The shape, profile, roughness and features of the fracture surface indicate that fatigue initiated at a location coincident to the edge of the weld (note the weld leg length was measured to be 6mm). The number of ratchet marks (shown in Figure 12) indicates that there were multiple crack initiation points and therefore a large stress concentration was present around the circumference. The crack propagated through the rod, beach marks (shown in Figure 13) recording the position of the crack front. There was no clear evidence of any overload region, indicating that the overall load at failure was low. The inboard side of the fracture was level with the plate face, the expected position of maximum stress with no weld present.

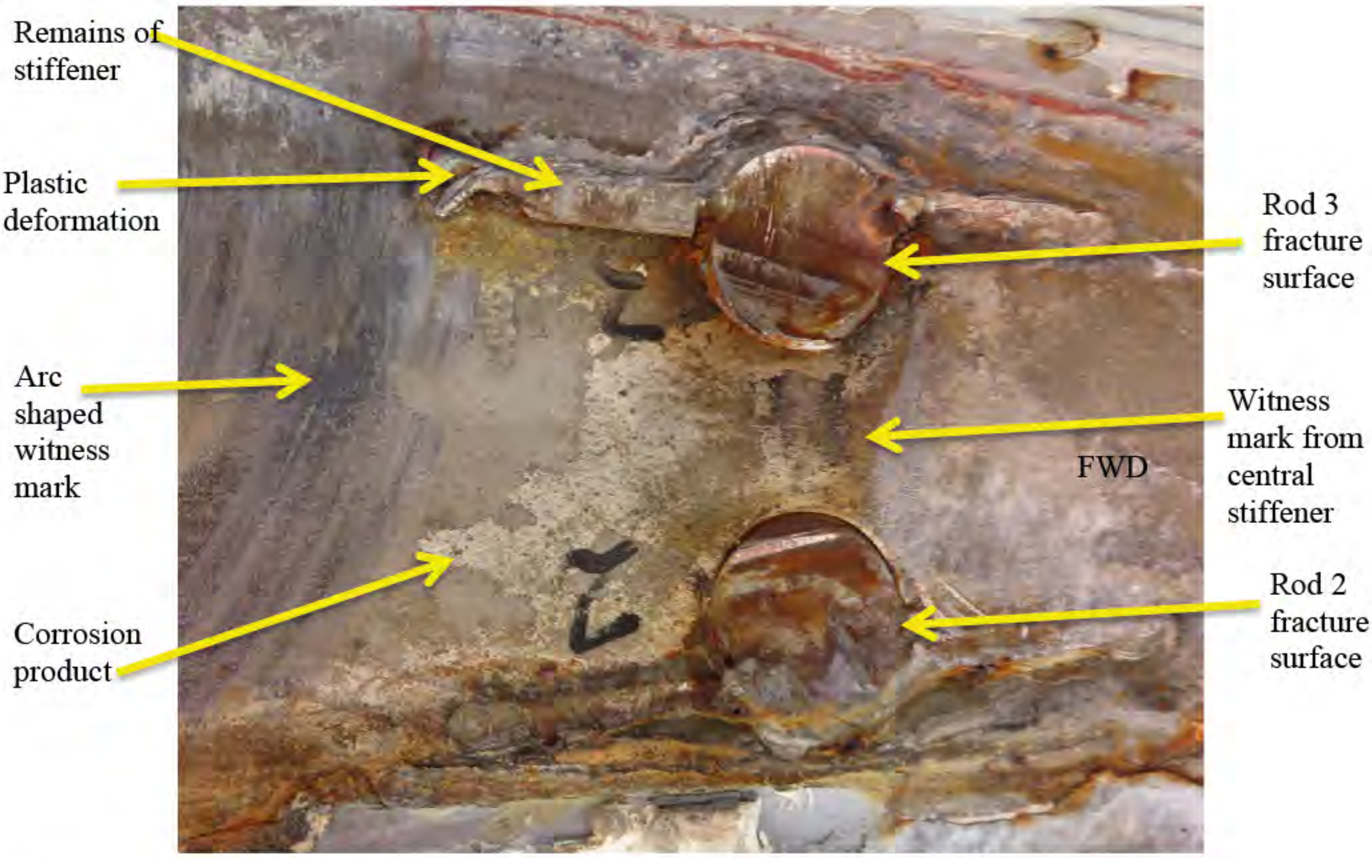

Figure 11: Showing remains of two rods at positions 2 and 3.

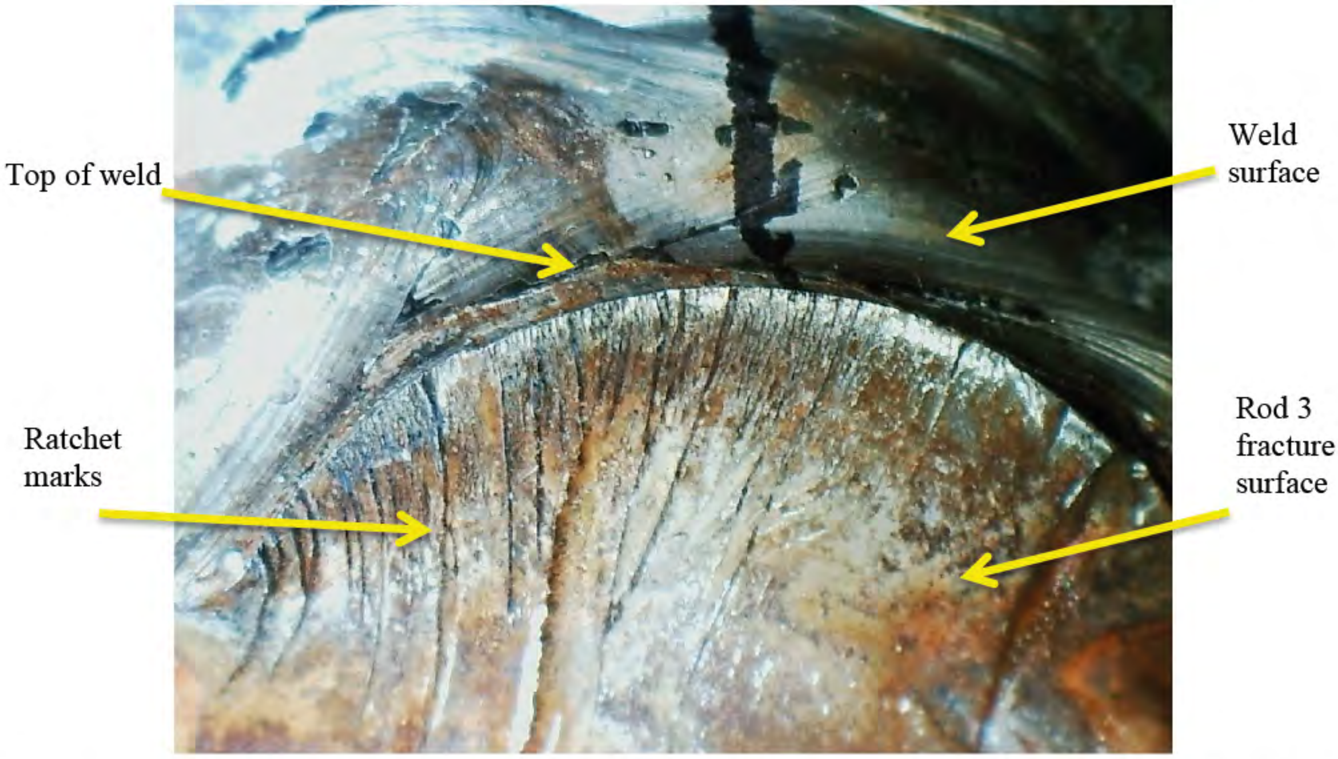

Figure 12: Macroscope image showing multiple fatigue initiation sites (indicated by the ratchet marks) along edge of fracture at the weld/rod interface on the stbd (outboard) side of position 3.

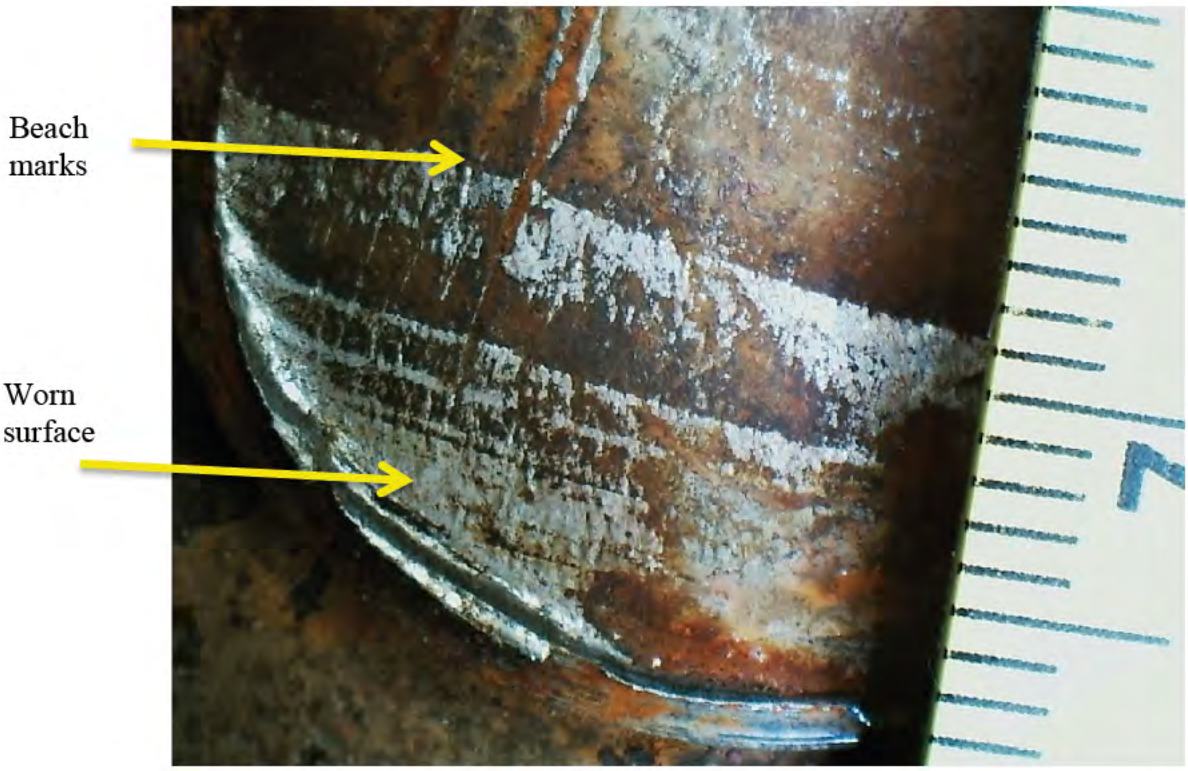

Figure 13: Macroscope image showing beach marks (confirming fatigue) and a worn surface indicating sustained contact after fracture at position 3.

The inboard side of the Rod 3 fracture surface displayed evidence of wear, see Figure 13, suggesting that this was not the last rod to fracture, as the fracture surfaces remained in contact long enough to rub.

Examination of the failed stiffener at position 3, (shown in Figure 14) confirmed the local loading direction of unidirectional bending, forcing the crack to propagate in an inboard direction initiated at multiple points at the weld interface. An arc shaped witness mark and plastic deformation of the stiffener remains (both highlighted in Figure 11) likely occurred as the keel detached.

Rod 2 fracture surface had two opposing crack fatigue crack fronts, indicating reverse bending loads. The largest crack initiated at multiple points along the weld line (5.8 mm above the plate face) on the outboard side of the rod, as shown by the presence of the ratchet marks (see Figure 15). The weld leg length was measured to be 6mm. Beach marks confirmed the direction of crack propagation, which ended at the overload zone as shown in Figure 16. A second smaller fatigue crack was also present, on the inboard side of Rod 2 in the plane of the plate face. The presence of the small fracture suggests that this crack was only initiated after complete fracture of Rod 3. Wear of the outboard side of the Rod 2 fracture surface (Figure 15) and the wear of the overload region (Figure 16) confirmed that Rod 2 was not the last rod to fail. A schematic of the Rod 2 and 3 fractures are shown in Figure 17.

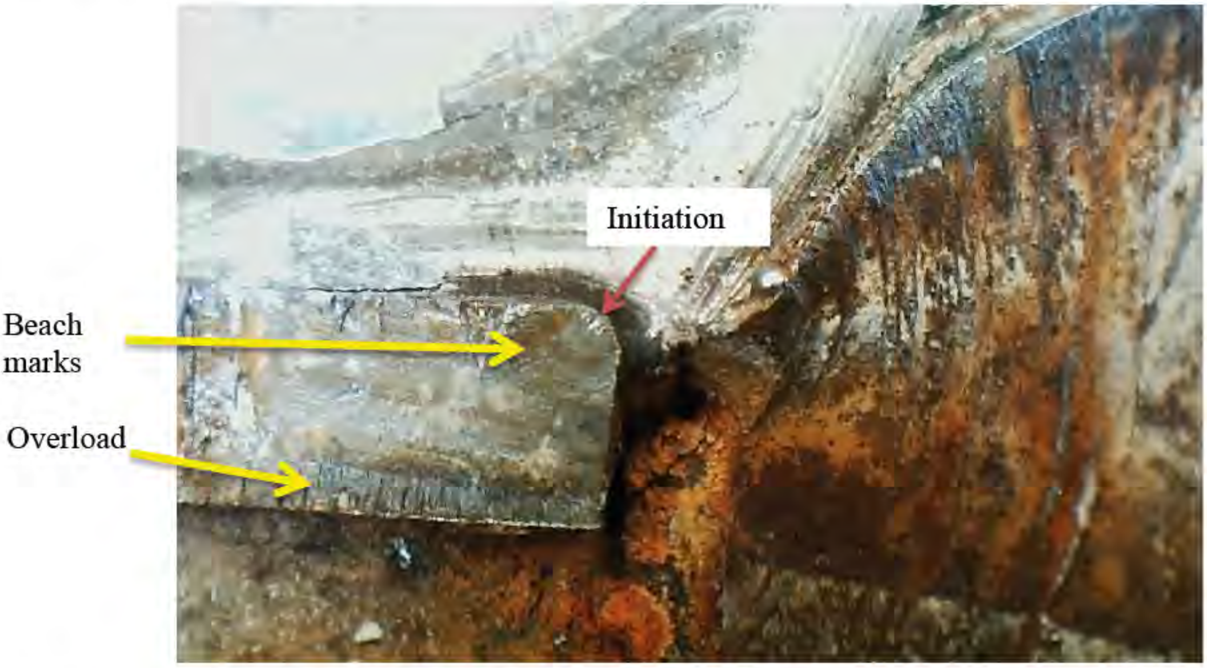

Figure 14: Macroscope image showing beach marks and overload confirming fatigue initiation and direction within the fractured stiffener associated with position 3.

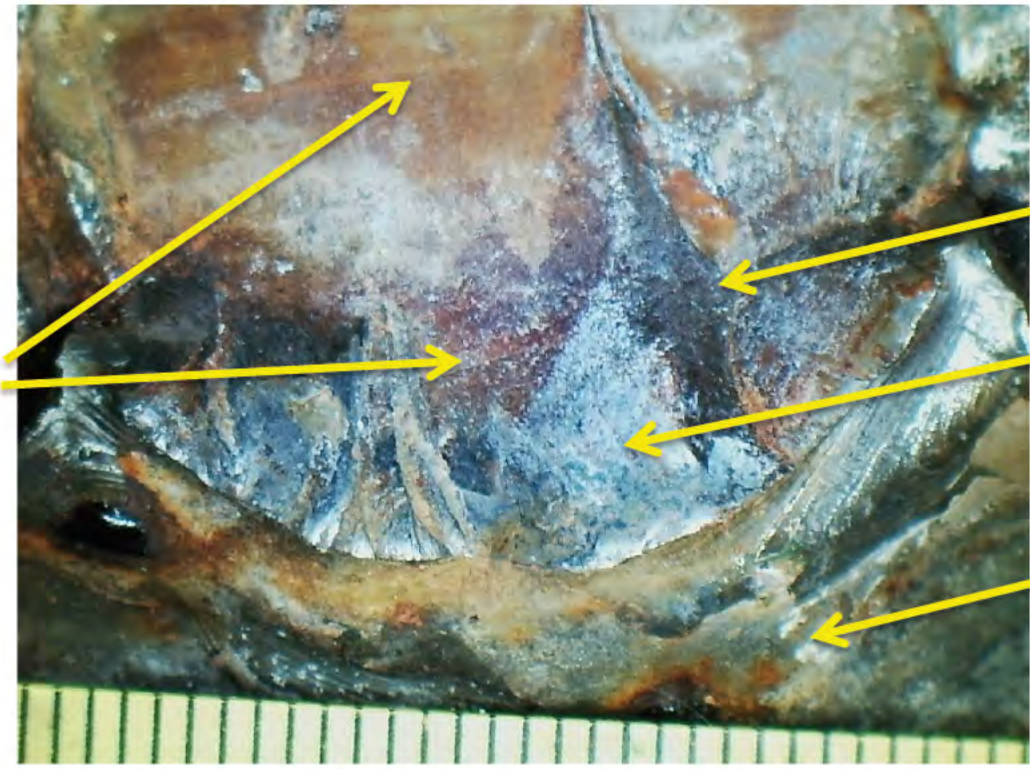

Figure 15: Macroscope image highlighting the presence of beach marks tracking back to multiple origins along the outboard side of Rod 2 at the rod weld interface.

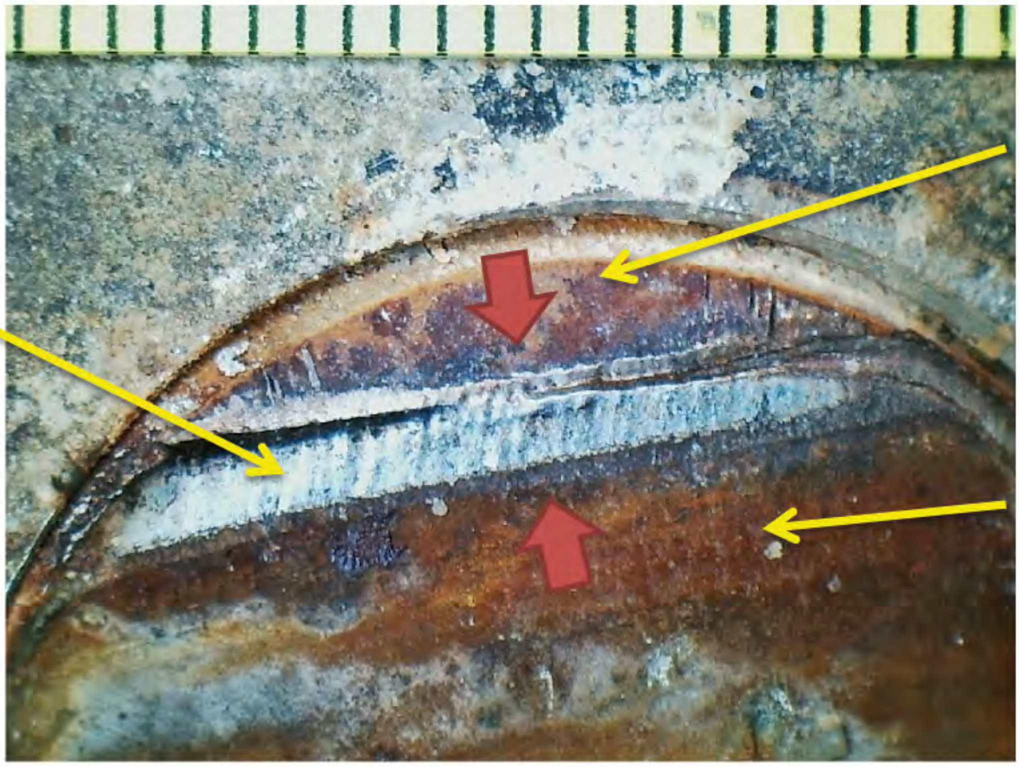

Figure 16: Macroscope image showing the two fatigue fronts meeting in a band of overload . Note the overload area is heavily worn. Rod 2.

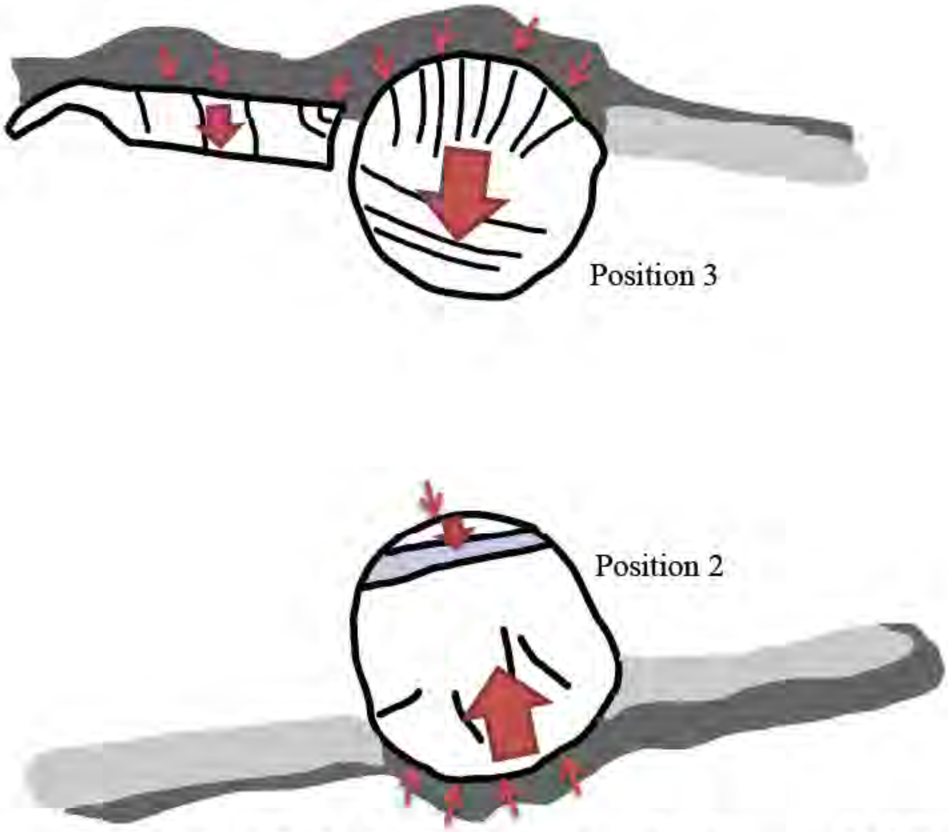

Figure 17: Schematic of Rod 2 & 3 fractures. Small red arrows highlight the multiple initiation points at the weld/rod interface. The large red arrow identify the general direction of fatigue crack growth. Overload area is shown in blue.

3.4. <u>Rod locations 4 and 5</u>

Examination of position 4 and 5 revealed that Rod 5 was missing and Rod 4 failed by fatigue (Figure 18) driven by off-axis (not aligned with the side keel loads) unidirectional bending or tension-tension loading. The weld leg lengths were found to be < 5mm.

The threaded hole at position 5 was examined from the side shown in Figure 18 (upwards relative to its original position on the yacht). Figure 19 shows three views of the FWD side of hole, where it was noted the crests of the threads had been plastically deformed and 'smeared' in a direction consistent with loaded removal of the rod, see Figure 20. No evidence of the rod threads was observed. The remaining circumference of the threaded hole was in serviceable condition, i.e. the threads were still present.

Examination of the weld fracture adjacent to position 5 (highlighted in Figure 18) revealed that the stiffener had not fractured within its bulk but in the weld. It also revealed that the weld had failed in fatigue (beach marks highlighted in Figure 21) which originated on the inboard (port) side of the stiffener (see Figure 21).

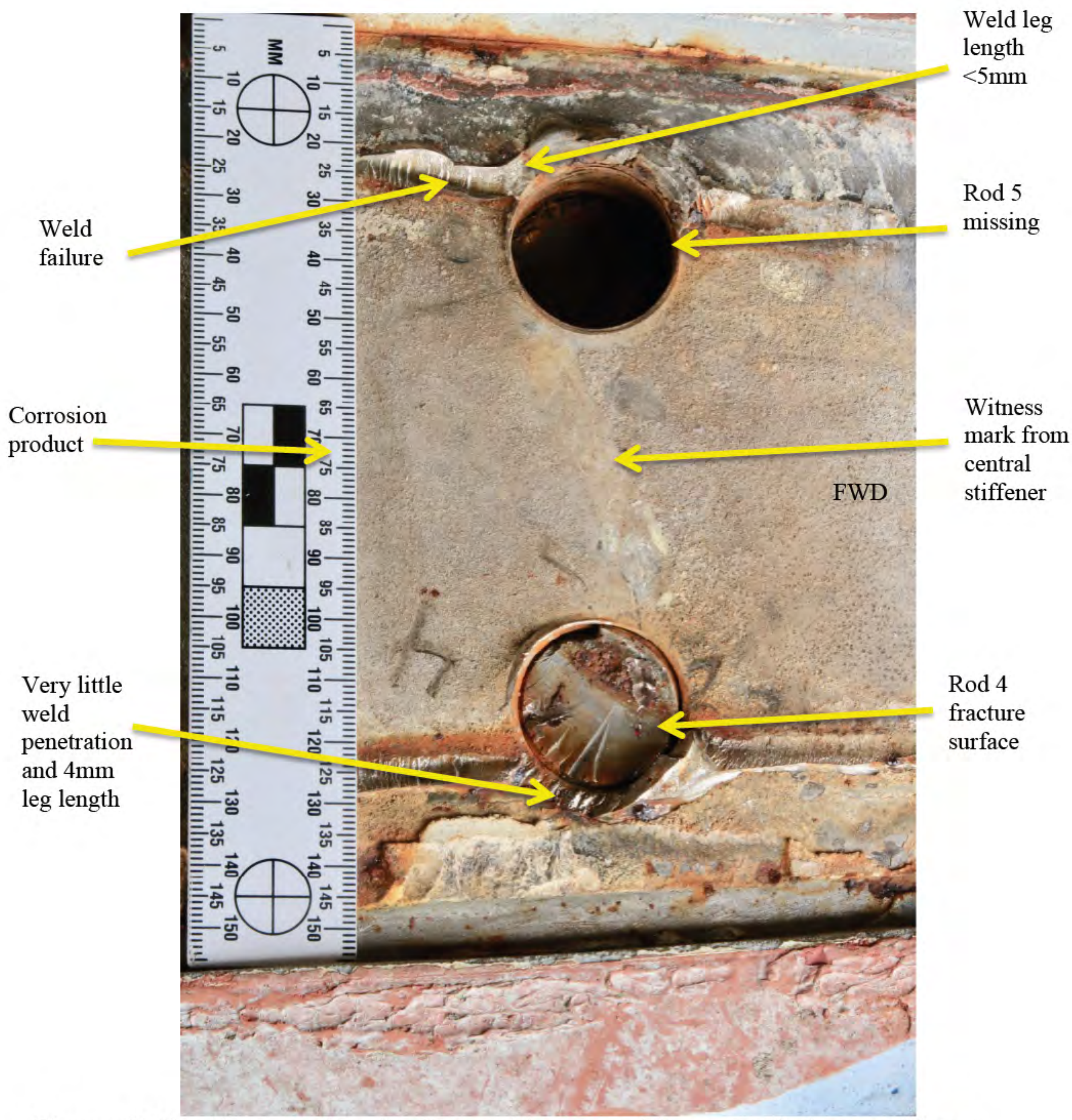

Figure 18: Showing remains of rod at positions 4 and the vacant hole at position 5.

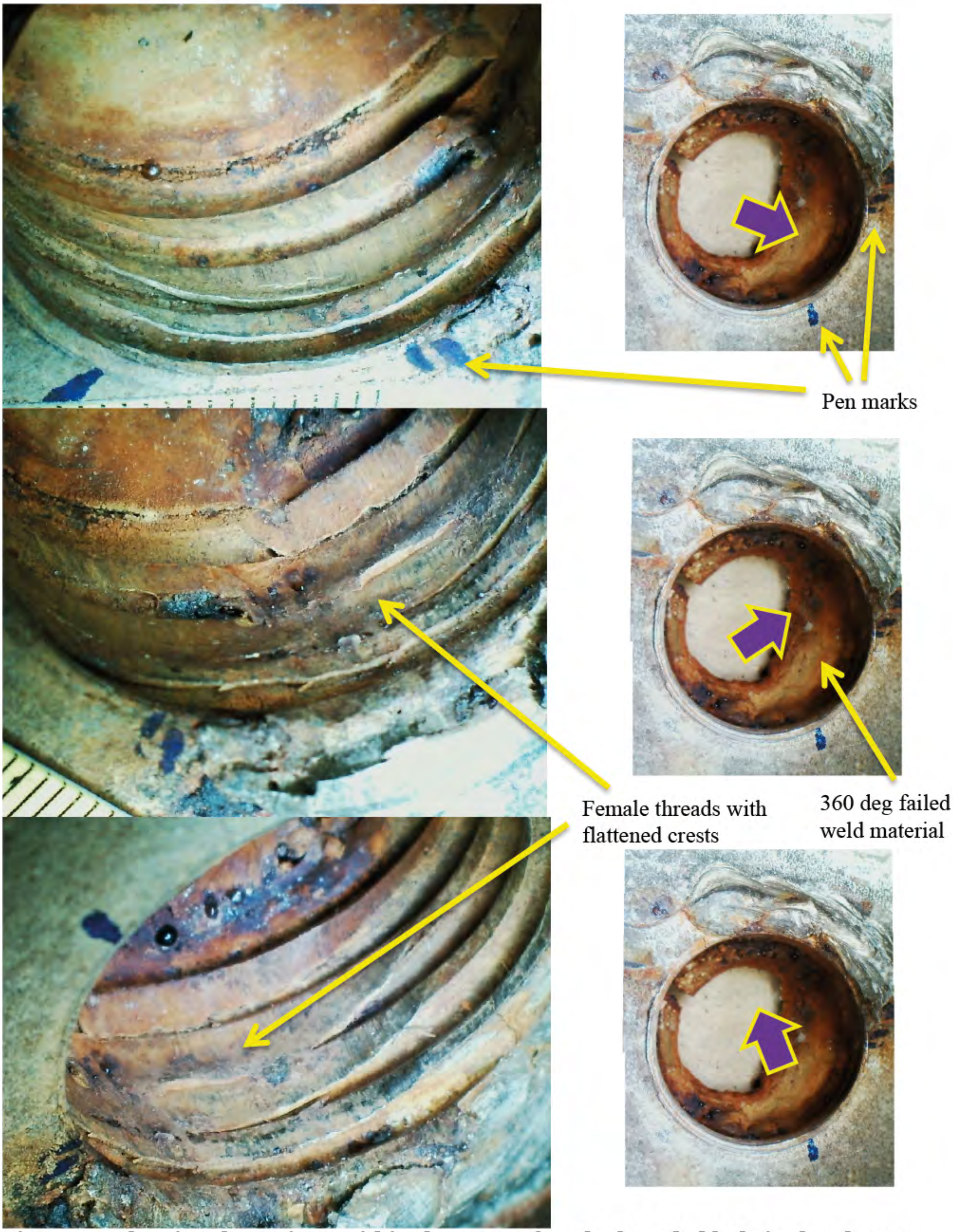

Figure 19: Showing three views within the vacant female threaded hole in the plate at location position 5. Note the forward side of the hole was heavily worn. Evidence of 360 degree weld on 'top' face of plate.

Figure 20: Higher magnification view of the lower image shown in Figure 19.

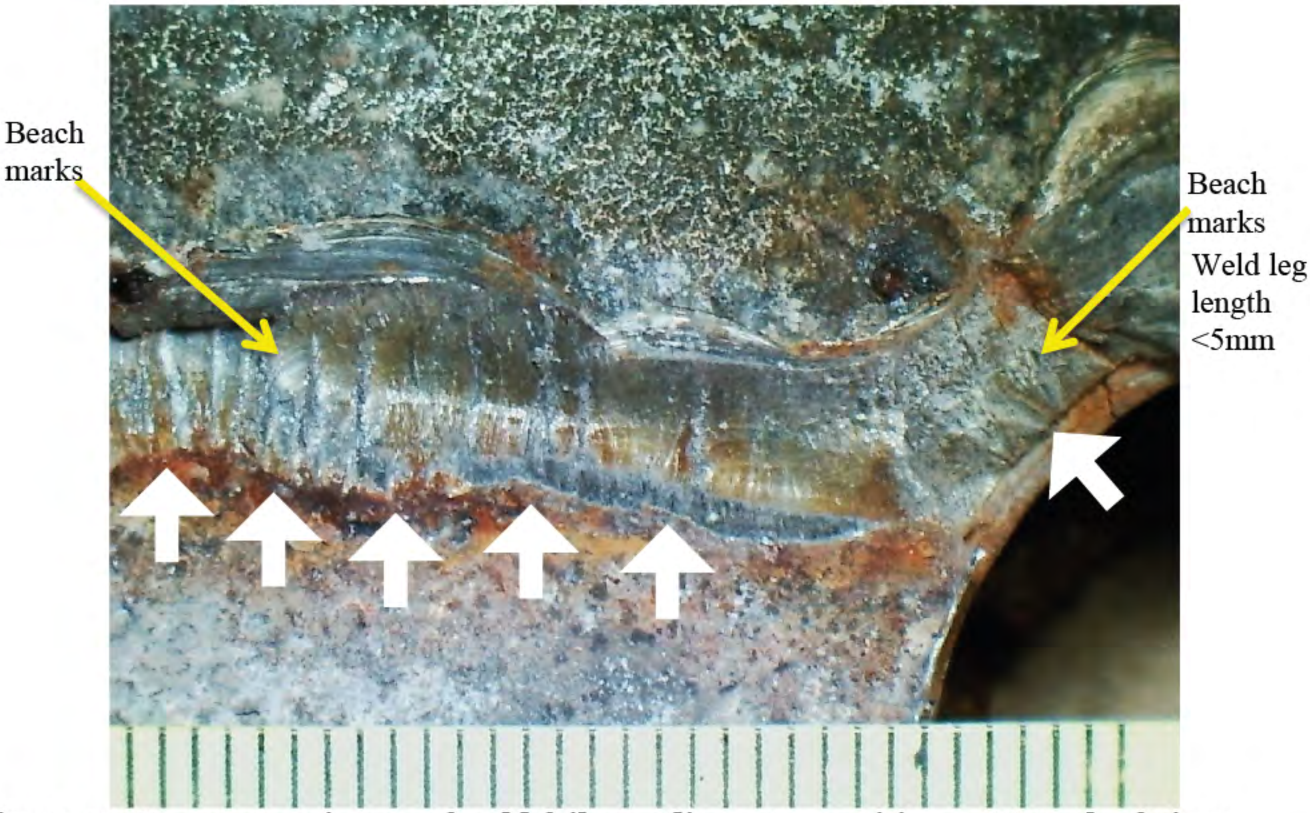

Figure 21: Macroscope image of weld failure adjacent to position 5. Note the fatigue cracks propagated in an outboard (stbd) direction). Origins marked with an arrow.

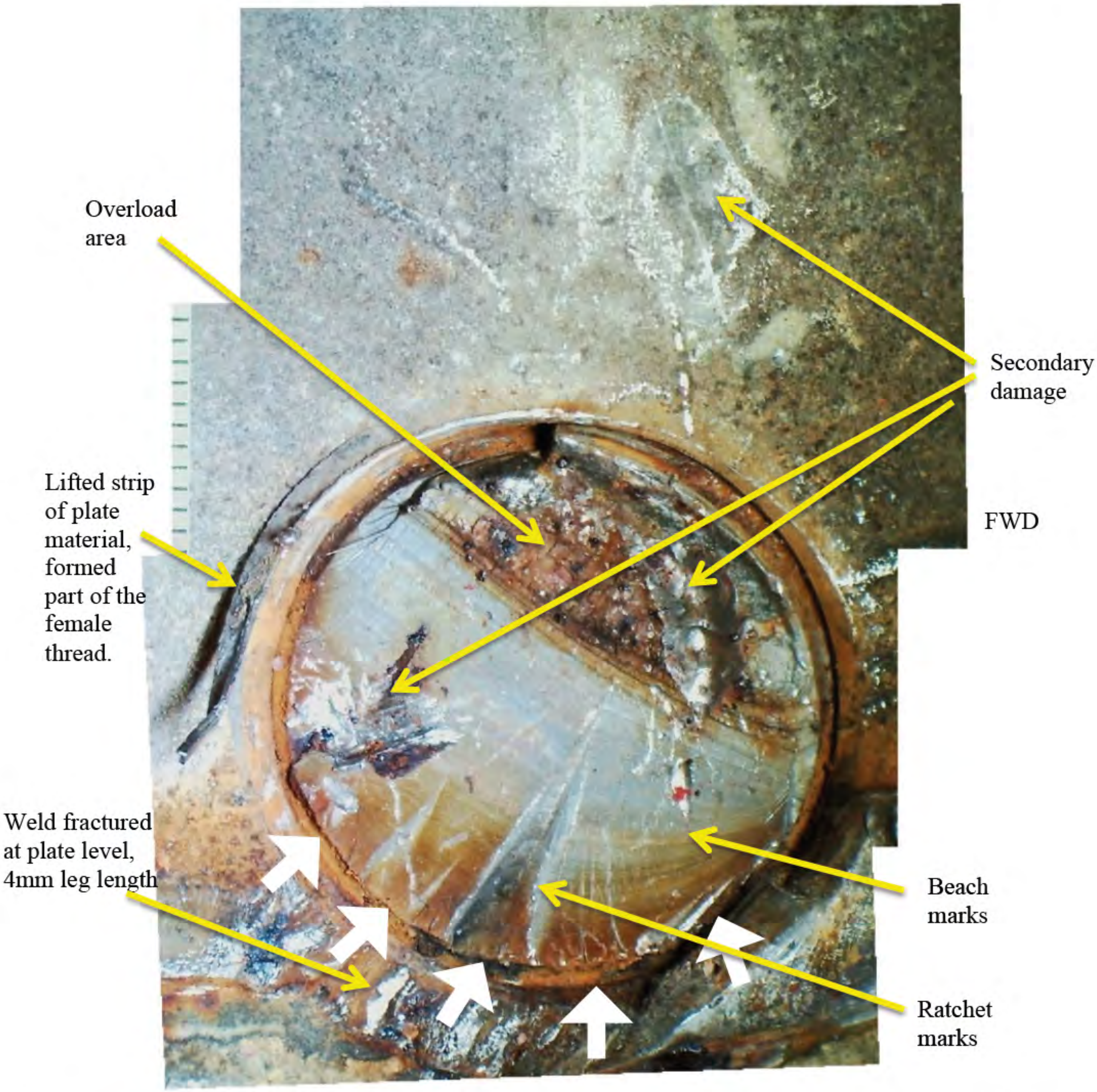

Figure 22: Montage of macroscope images recorded of Rod 4 fracture. Origins marked with an arrow.

Examination of the fracture surface of Rod 4 revealed features not previously witnessed on the previous (Rod 2 & 3), specifically:

- The overload region was approximately 30% of the cross sectional area.
- There was no evidence of rubbing or local reciprocating wear (previously observed).
- The initiation took place level with the plate height (and not 5mm above in the weld join)

- Weld leg lengths (when present) were < 5mm.
- The beach marks ‘turned’ as the fracture progressed.
- The final beach mark was not aligned with a dominant keel bending load direction.
- There was significant presence of secondary damage witness marks

The above points all suggest that this rod underwent a form of tension-tension cyclic fatigue which was at a high stress. It also suggests that this rod was the last rod to fail.

A schematic of Rod 4 and 5 is provided in Figure 23.

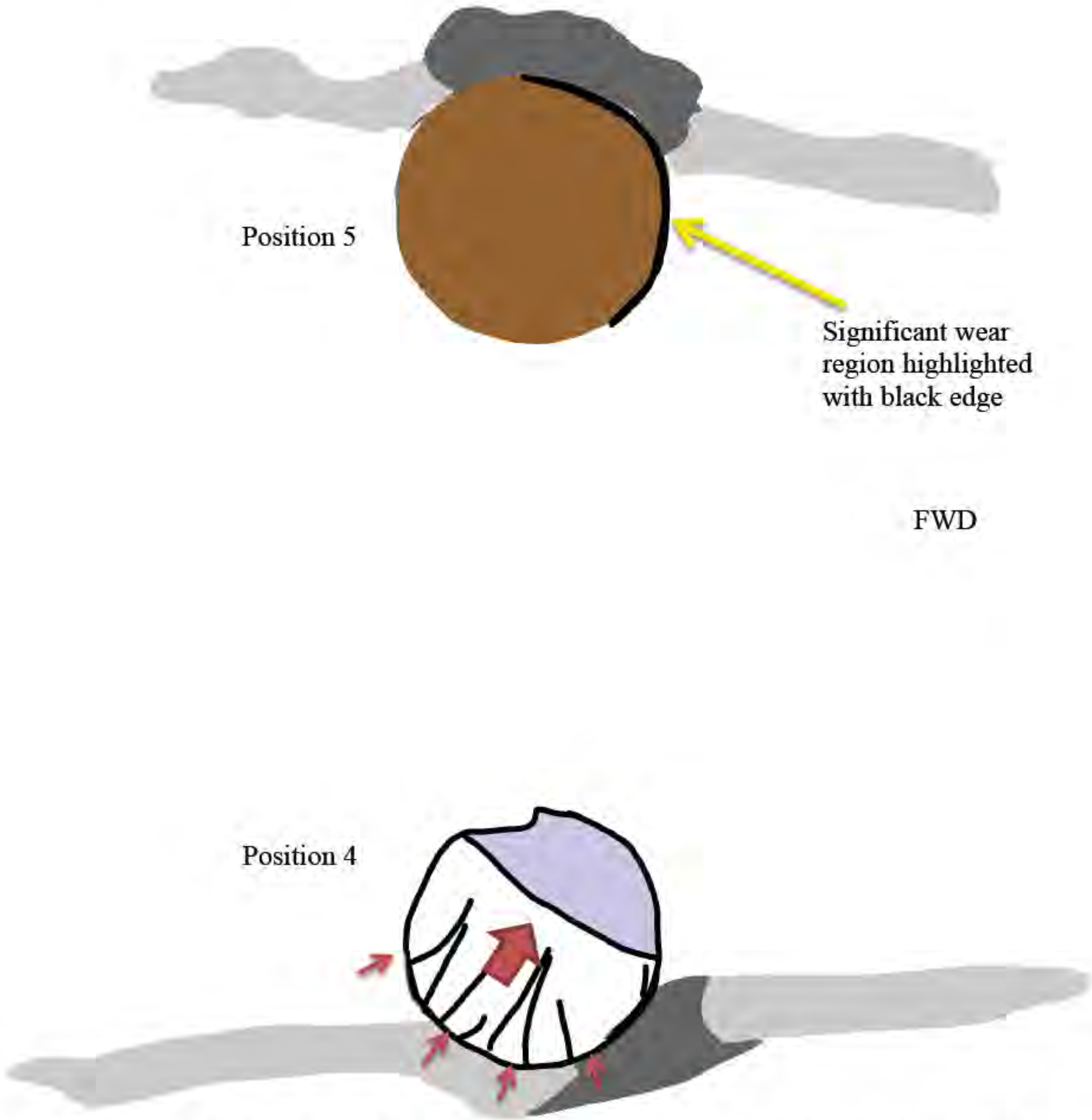

Figure 23: Schematic of Rod 4 & 5 fractures. Small red arrows highlight the multiple initiation points around Rod 4. The large red arrow identifies the general direction of fatigue crack growth. Overload area is shown in blue, the hole left by Rod 5 in brown.

3.5. Rod locations 6 and 7

The rods at positions 6 and 7 had been pulled free of the threaded holes within the plate, see Figure 24. Observations within the hole at position 7 revealed that the threads on the inboard side had been severally damaged, see Figure 25, when compared to the rest of the circumference, see Figure 26. The damage was consistent with a large single direction (out of hole) loaded movement of the rod, however the diameter of the hole left indicated that the rod could not have exited the hole with its threads intact. Examination of the hole at position 6 revealed that the female threads appeared to be in similar condition to Figure 26 with no obvious large scale wear like that seen in Figure 25. There was evidence of a shear loading event which had left a male thread crest from Rod 6 within the hole, see Figure 27. The thread length (1.25 turns long) was removed with pliers and examined, revealing wear damage on the loaded flank in some locations, see Figure 28.

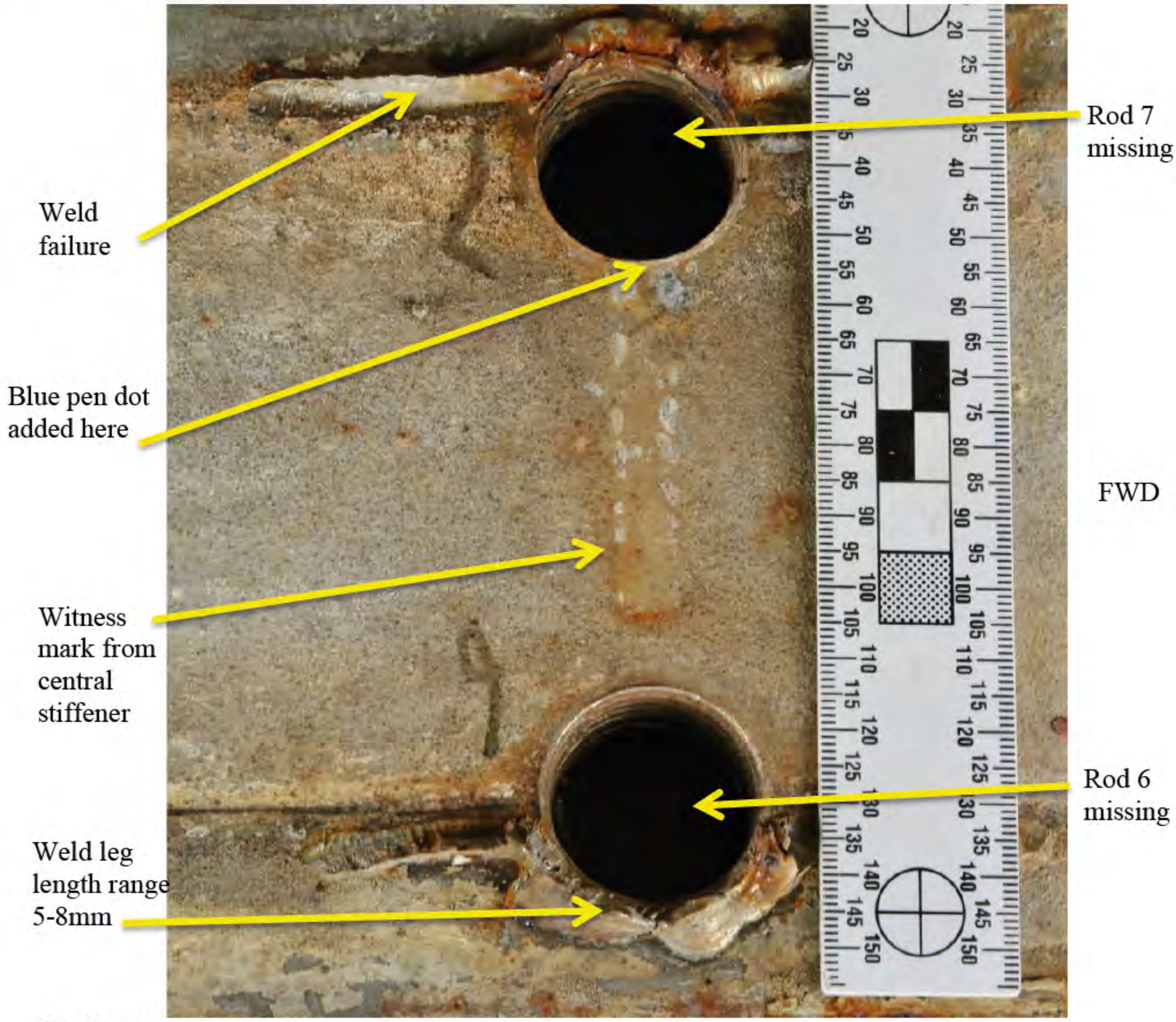

Figure 24: Showing vacant holes at position 6 and 7.

Figure 25: Macroscope image of view looking inboard at damaged threads of position 7. Blue pen dot at base of image provides orientation reference point.

Figure 26: Macroscope image of view looking outboard at less damaged threads of position 7. Blue pen dot at base of image provides orientation reference point.

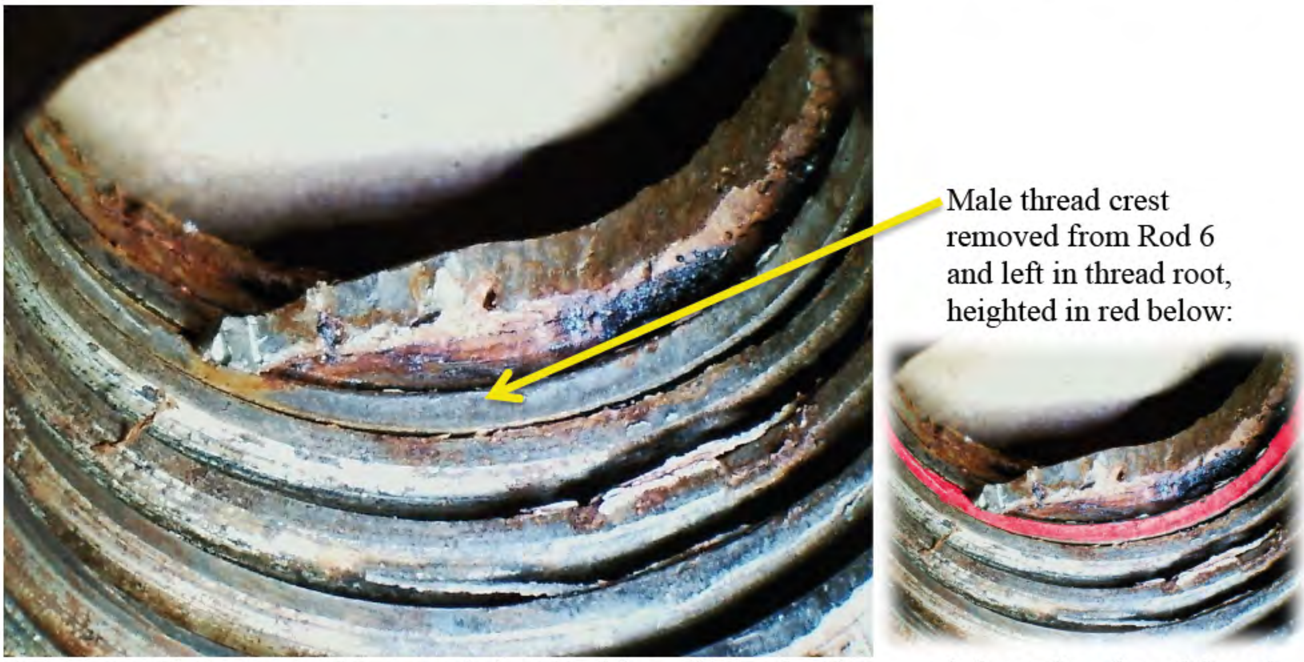

Figure 27: Macroscope image of view looking aftward at internal threads of position 6. Note a thread crest from Rod 6 has remained within the hole.

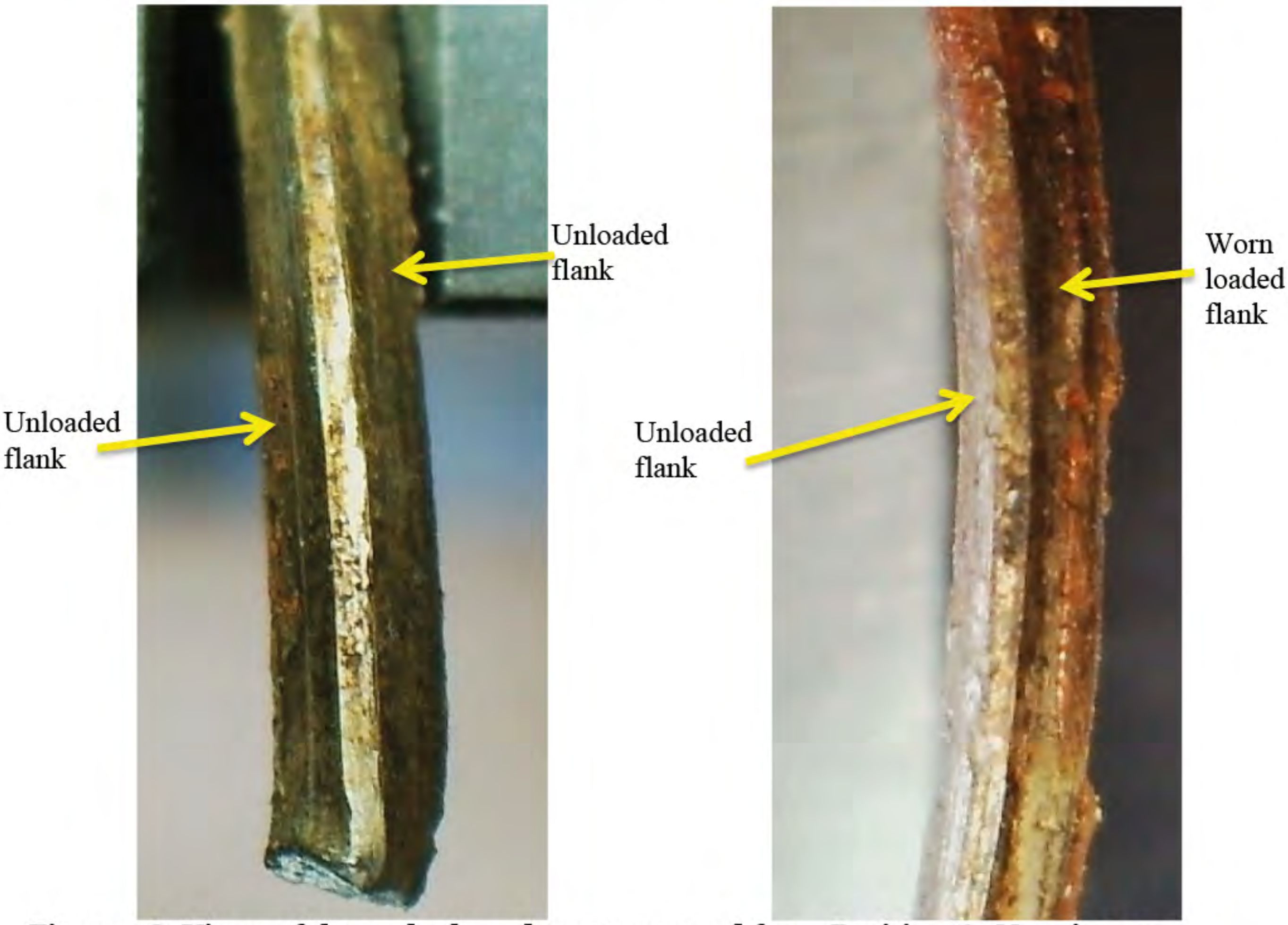

Figure 28: Views of the male thread crest removed from Position 6. Note in some locations the loaded flank has been heavily worn and 'grooved'.

3.6. <u>Rod locations 8 and 9</u>

Examination of positions 8 and 9 revealed that Rod 9 was missing and Rod 8 failed by fatigue (Figure 29) driven by unidirectional bending.

The threaded hole at position 9 was examined. It was noted that the inboard side of the crests of the threads had been plastically deformed and 'smeared' in a direction consistent with loaded removal of the rod, see Figure 30. No evidence of the rod threads were observed. The remaining circumference of the threaded hole was in serviceable condition, i.e. the threads were still present.

Rod 8 fracture surface initiated on the outboard (stbd) side of rod 5 mm above the plate face. The shape, profile, roughness and features of the fracture surface indicate that fatigue initiated at a location coincident to the edge of the weld (Figure 31).

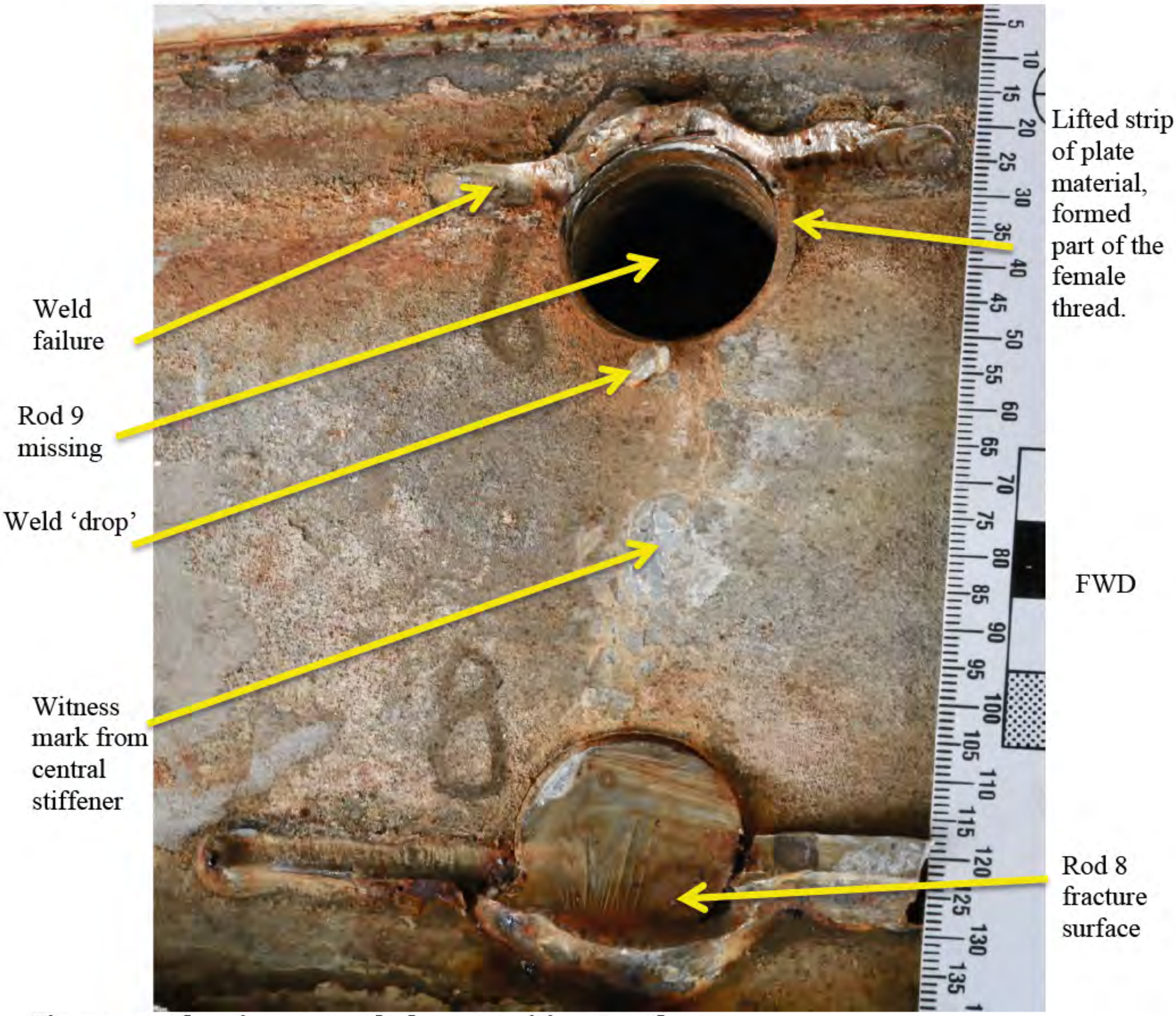

Figure 29: Showing vacant holes at position 8 and 9.

The number of ratchet marks (shown in Figure 32) indicates that there was multiple crack initiation points and therefore a large stress concentration was present around the circumference. The crack propagated through the rod, beach marks (shown in Figure 32) recording the position of the crack front, which appeared to change direction with time, as shown by the bend in the beach marks. There were indications of a small worn overload region. The inboard side of the fracture was level with the plate face, the expected position of maximum stress with no weld present.

Figure 30: View looking inboard at damaged threads of position 9. Weld 'drop' at base of image provides orientation reference point. Image provided by MAIB.

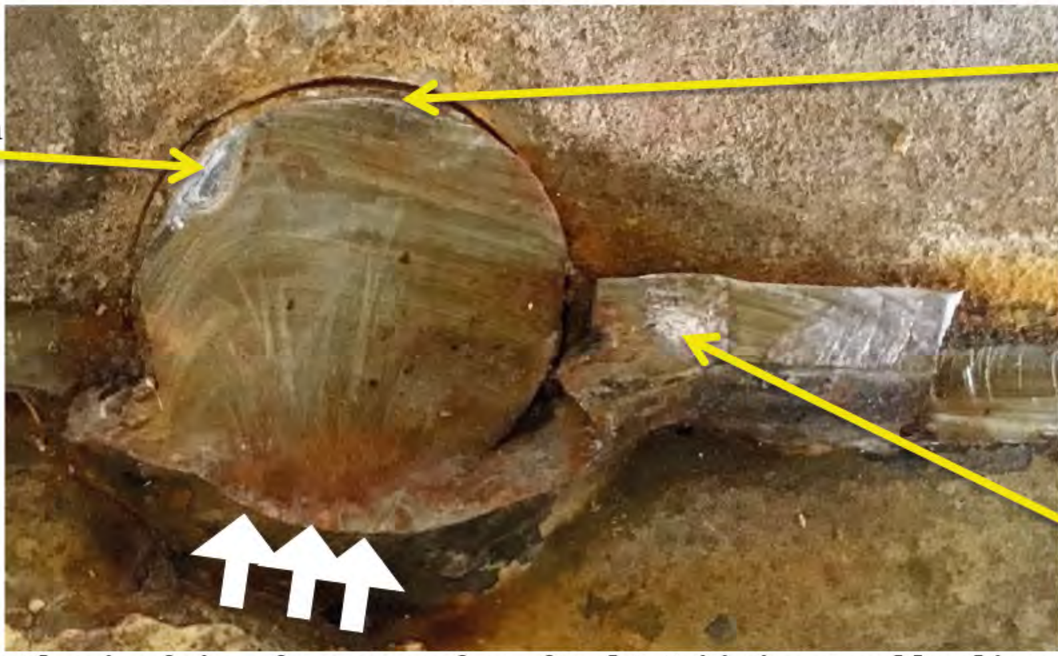

Figure 31: Showing fatigue fracture surface of Rod 8. Initiation at weld rod interface highlighted with white arrows.

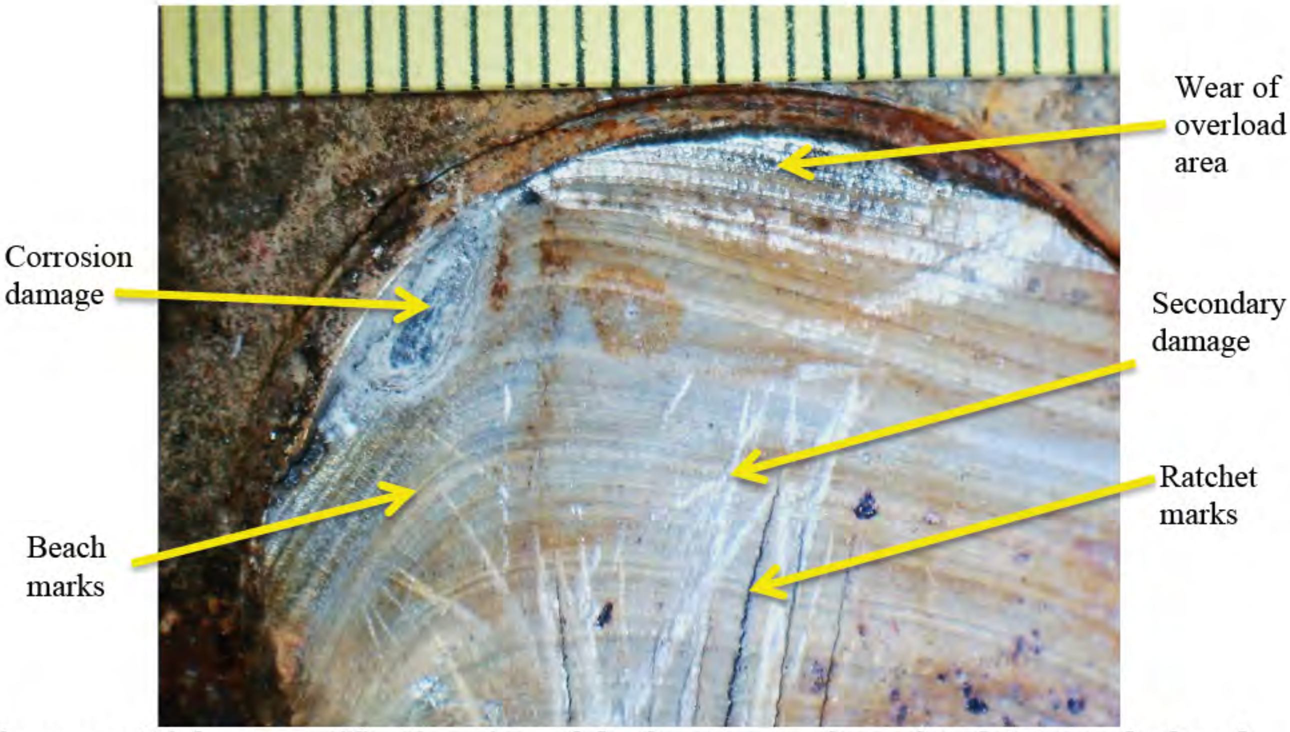

Figure 32: Higher magnification view of the fracture surface of Rod 8. Note the beach marks are 'bending' and also the overload area is very small and worn.

Examination of the remains of the stiffener on the forward side of Rod 8, revealed a 6mm x 6mm square patch of heavily worn material, see Figure 31. High magnification examination, Figure 33, identified that the surface displayed impact fretting damage which had removed significant amounts of material, suggesting that this Rod had not been the last one to fail, as a counter-face had remained in contact post-fracture. This was further supported by the wear noted on the overload region, and local corrosion damage see Figure 32.

A schematic of the Rod 8 and 9 fractures is given in Figure 34.

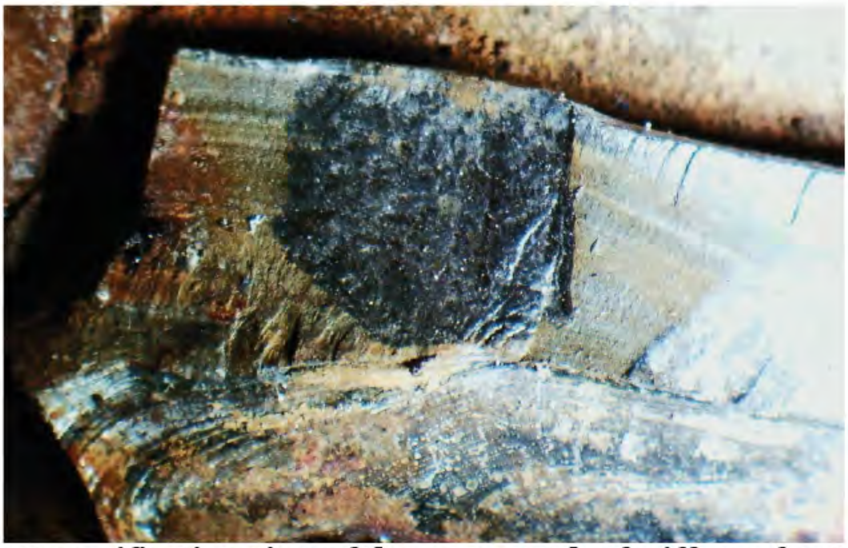

Figure 33: Higher magnification view of the worn patch of stiffener fracture surface at position 8.

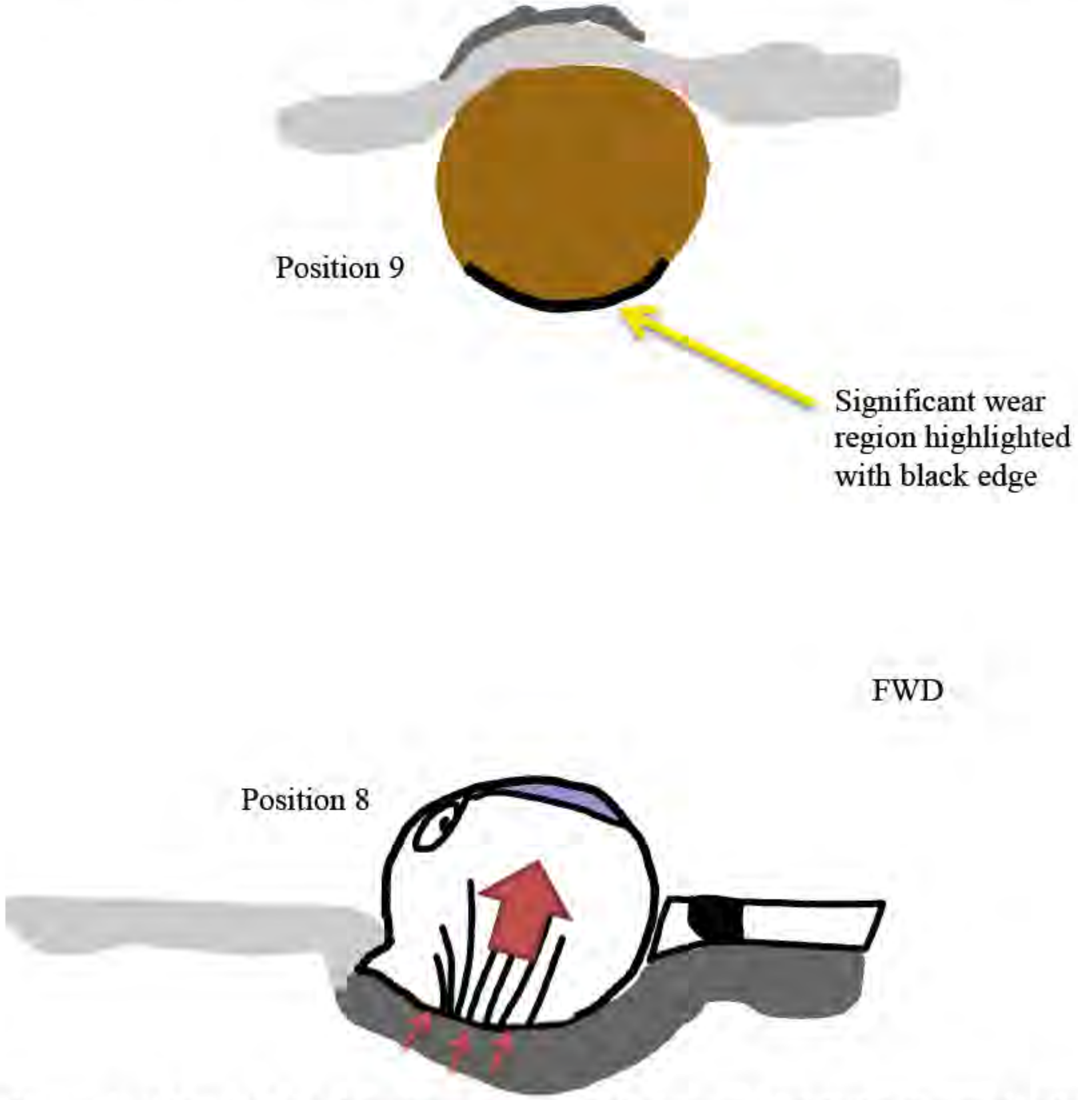

Figure 34: Schematic of Rod 8 & 9 fractures. Small red arrows highlight the multiple initiation points around Rod 8. The large red arrow identifies the general direction of fatigue crack growth. Overload area is shown in blue, the hole left by Rod 9 in brown.

3.7. <u>Rod locations 10 and 11</u>

Examinations of position 10 and 11 were impeded by the level of corrosion present, Figure 35. However indications suggested that both rods failed by fatigue initiating on the outboard sides and propagating through the rods towards the centerline of the plate.

Measuring the heights of the outboard sides of the rod fracture surfaces Figure 36, showed that Rod 10 likely initiated at the weld edge (Figure 37), but Rod 11 appeared to initiate at a position level with the plate. This suggests that the weld at Rod 11 failed under tension-tension cyclic load whereas Rod 10 was driven by a unidirectional bending. The level of cleanliness of Rod 11 compared with Rod 10 suggests that Rod 10 failed prior to 11.

A schematic of the Rod 10 and 11 fractures are given in Figure 38.

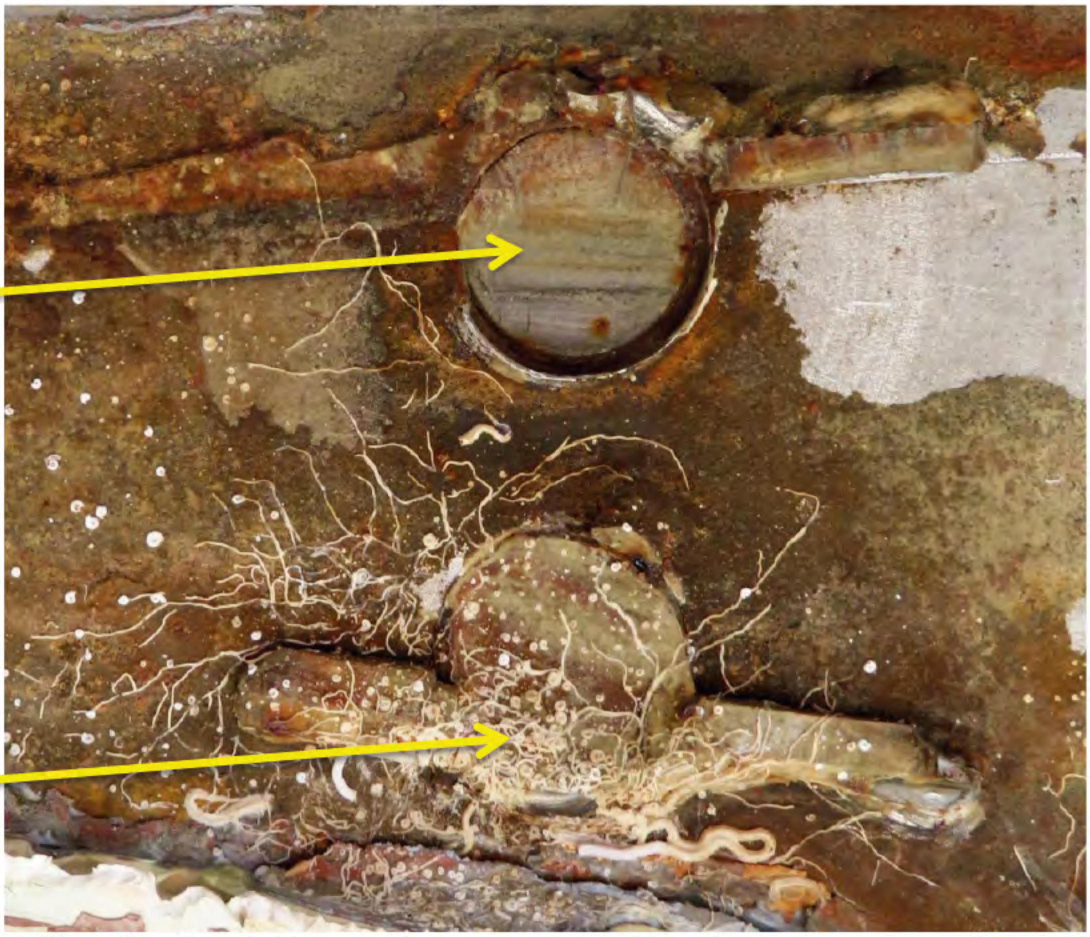

Figure 35: Showing fracture surfaces at positions 10 and 11.

Figure 36: Montage of macroscope images recorded of Rod 11 fracture. Origins marked with an arrow.

Figure 37: Montage of macroscope images recorded of Rod 11 fracture. Origins marked with an arrow. Surface very corroded.

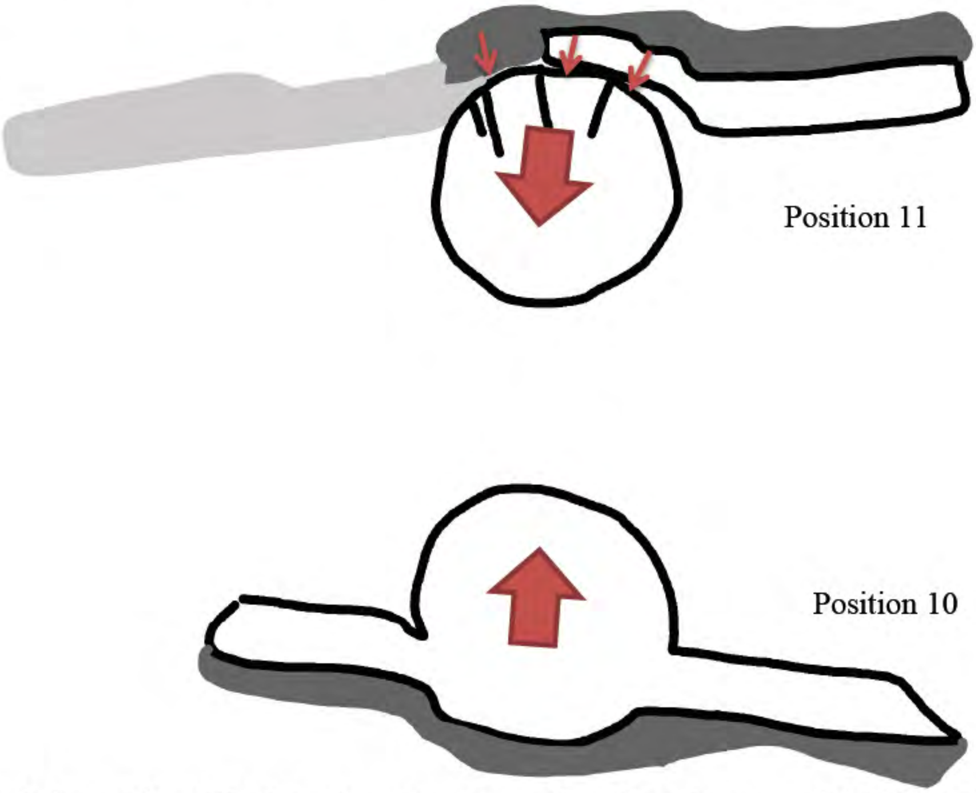

Figure 38: Schematic of Rod 10 & 11 fractures. Small red arrows highlight the multiple initiation points. The large red arrows identify the general direction of fatigue crack growth.

3.8. Rod location 12 (AFT)

Examinations of position 12 and surrounding stiffener remains were impeded by the level of corrosion present, Figure 39. However indications suggested that the rods failed by fatigue initiating on the outboard sides and propagating through the rods towards the centerline of the plate.

Like Rod 1, Rod 12 fracture surface had symmetry about the longitudinal axis with raised edges on the port and stbd welded sides (6.6 mm and 6.7mm above the plate face), Figure 40. The center of the fracture surface displayed a line feature and was approximately level with the plate face. The shape, profile, roughness and features of the fracture surface indicate that fatigue initiated on the port and stbd sides of the rod at a location coincident to the edge of the weld. The crack fronts propagated towards the centre of the rod until the loads present were great enough to overload the remaining cross-section of material.

A schematic of the Rod 12 fracture surface is given in Figure 41.

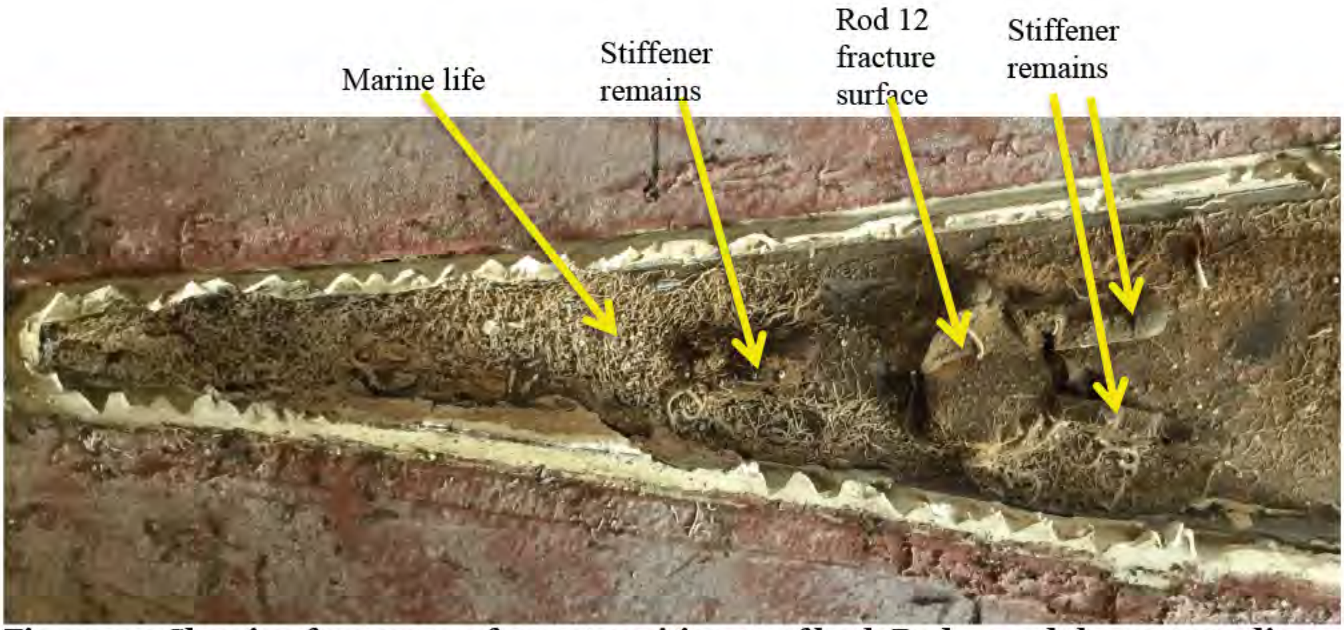

Figure 39: Showing fracture surfaces at position 12 of both Rod 12 and the surrounding three stiffeners.

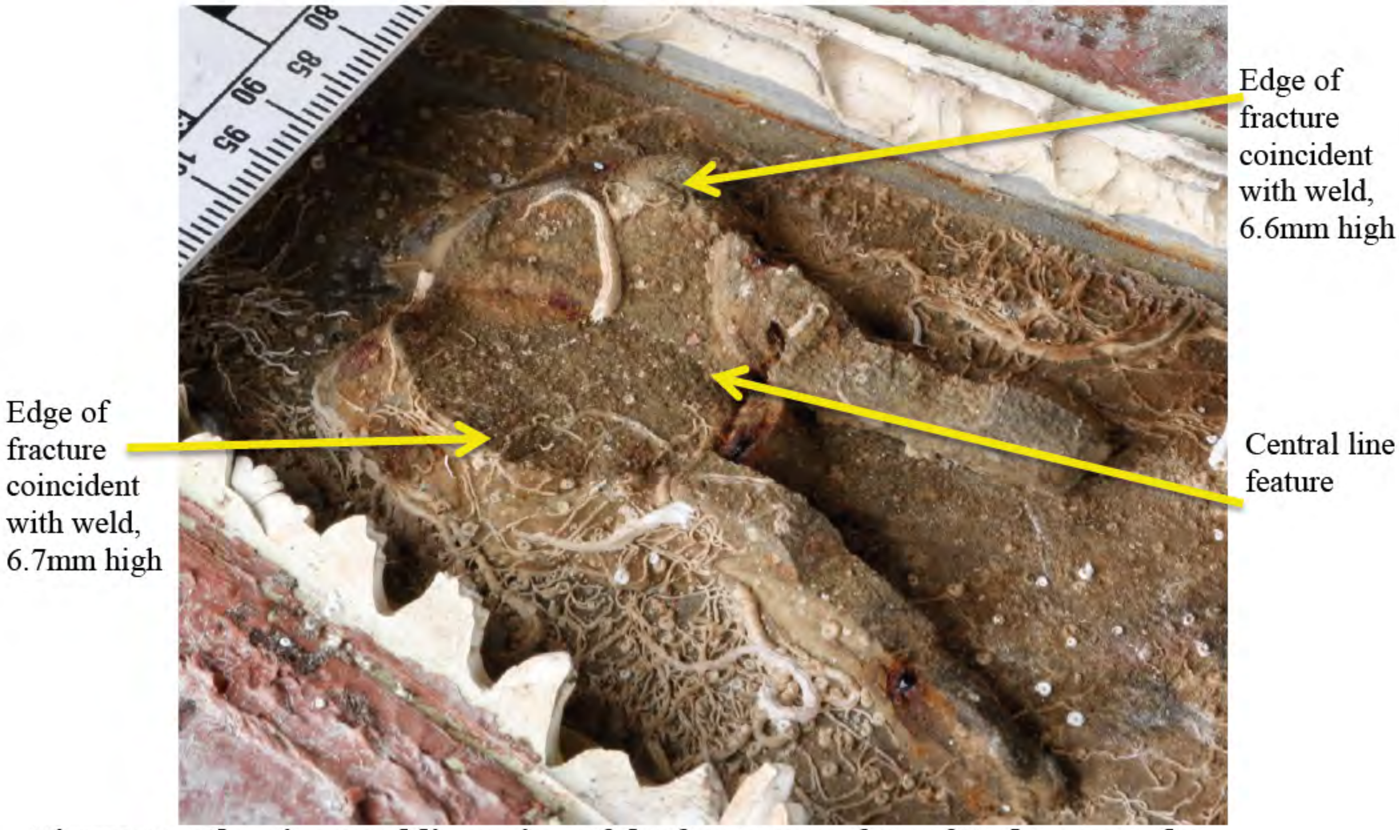

Figure 40: Showing an oblique view of the fracture surface of Rod 12, note the symmetrical features, similar to those of Rod 1.

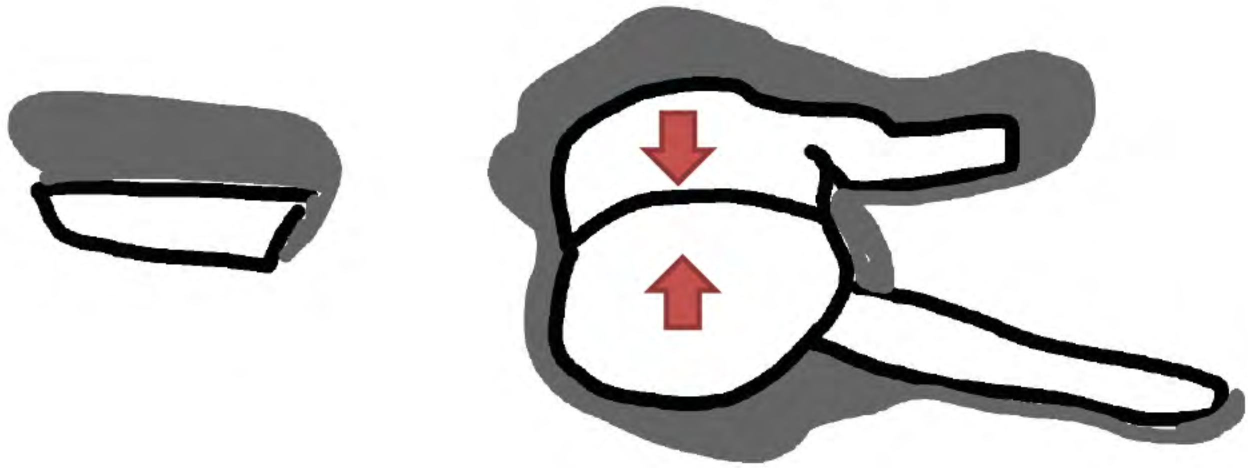

Figure 41: Schematic of Rod 12 fracture. The large red arrows identify the general direction of fatigue crack growth.

4. Discussion

nC² has performed a brief external non-destructive as-received examination of the fracture surfaces found on the supplied failed keel top plate. The plate was removed by MAIB from the capsized Comet 45S sailing yacht, 'Tyger of London'.

The keel design includes a rectangular shaped 'top plate', the edge of which contains 16 bolts to attach to the yacht frame, see drawings in Appendix 1. Within the centre of the top plate are 12 threaded holes following the aerofoil shape of the keel. When in-service the mass of the keel hung from 12 rods threaded into the top plate. It was observed that each rod was partially (Table 1) welded to the plate and also to adjacent stiffeners. There was enough remains of stiffeners found on the top plate to confirm that they were present and on the whole followed the supplied drawings. The only notable difference with regard the stiffeners was found in the aft section as shown in Figure 5.

The drawings (Appendix 1) state "TONDINI ACCIAO INOX AISI 316, ∅30mm FILETTATE NELLA PIASTRA 20mm" which translates to "Rods steel stainless AISI 316, ∅30mm threaded in plate 20mm [thick]". The drawings also provide fillet weld symbols (black filled triangles shown in Figure 42, indicating the requirement for fillet welds to the plate-rod interface on both the upper and lower sides of the plate. Note current examinations only took place on the lower face of the plate, however indications suggest that welds were present on the top face for 360 deg circumference of the rod (see Figure 19). The drawing does not explicitly state any details of the required welds, typically a designer would provide notation (EN 22553, EN ISO 4063) which includes details such as throat size (a) and leg length (z) as shown in the inserts provided in Figure 42. A circle notation is used to show weld all round, however the black filled triangles shown in the drawings (Appendix 1) are present in both transverse and longitudinal views.

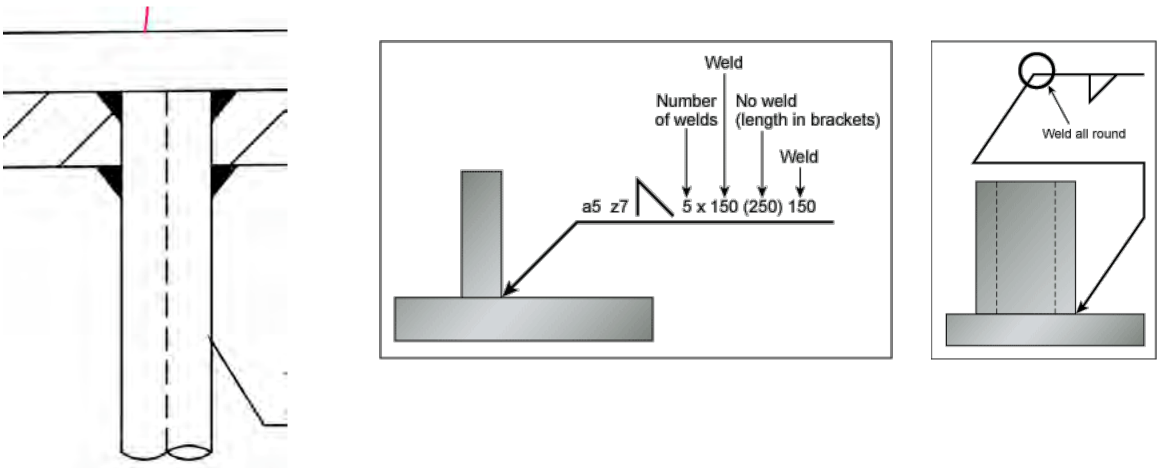

Figure 42: Left: Extract from drawings shown in Appendix 1. Black filled triangles indicate a fillet weld on the upper and lower surface of rod-plate interface. Inserts: show typical expected weld notation.

The welds observed on the lower face of the plate were only welded on the outboard side (possibly due to limited access) not all the way around the rods. Typically for plate where thickness is >20mm, a minimum fillet leg length would be 8mm[1], measurements of 4-7 mm were see on the welds present.

The positions (distance from the centerline) of the rods puts the most in-service loading on Rod 6 and Rod 7. These locations displayed holes where the rods had once been. Evidence in the form of a sheared thread crest (Figure 27 and Figure 28) found within the hole at location 6 strongly suggested that the bolted joint was moving internally and wearing away the male threads on the rods. The evidence suggests that positions 6, 7, 5 and 9 all failed in this manner. Evidently the welds were not sufficient at these locations to prevent movement. The tensile-tensile cyclic loading would have grown in amplitude as the threads wore; the stresses then failed the local welded joint in an outboard direction (evidence of this shown in Figure 21 at position 5).

It is likely that the seal around the keel failed at this point allowing water to enter and fill the keel; it is hypothesized that the waterline of the boat and its motion allowed the water, and hence marine life, to flourish toward the aft end of the keel top plate.

The load intended to be carried by the failing bolted joints would then have passed to the remaining rods, which then subjected to the overall reverse bending loads of the keel motion quickly initiated fatigue at the outboard sides of the bolts at the highly stressed weld/bolt interface. Indications suggest that Rod 4 was likely to have been the last rod to have completely fractured as the remaining fracture surfaces displayed evidence of rubbing contact post fracture.

The root cause of the failure was that the partially welded threaded rods were not the correct fixing to 'hang' the keel from. A threaded joint, especially one expected to be subjected to cyclic loading of any kind, must be held firmly in tension to prevent movement. A nut used on either or both sides of the plate, torqued sufficiently (and regularly checked for lack of torque) would have provided a more fatigue resistant keel fixing. Alternatively if the rods had been left unthreaded and welded sufficiently (and to a high quality), all the way around their circumference, with deep penetration (not evident here, see Figure 18) and on both sides, the joint would have become a solid welded joint not a threaded one – providing a fixing able to withstand (longer) the imposed cyclic loads.

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[1] https://www.twi-global.com/technical-knowledge/faqs/faq-how-do-you-determine-the-minimum-size-of-a-fillet-weld/

5. Conclusions

nC^2 has performed a brief external non-destructive as-received examination of the 12 rod sites found on the supplied failed keel top plate removed by MAIB from the capsized Comet 45S sailing yacht, 'Tyger of London'.

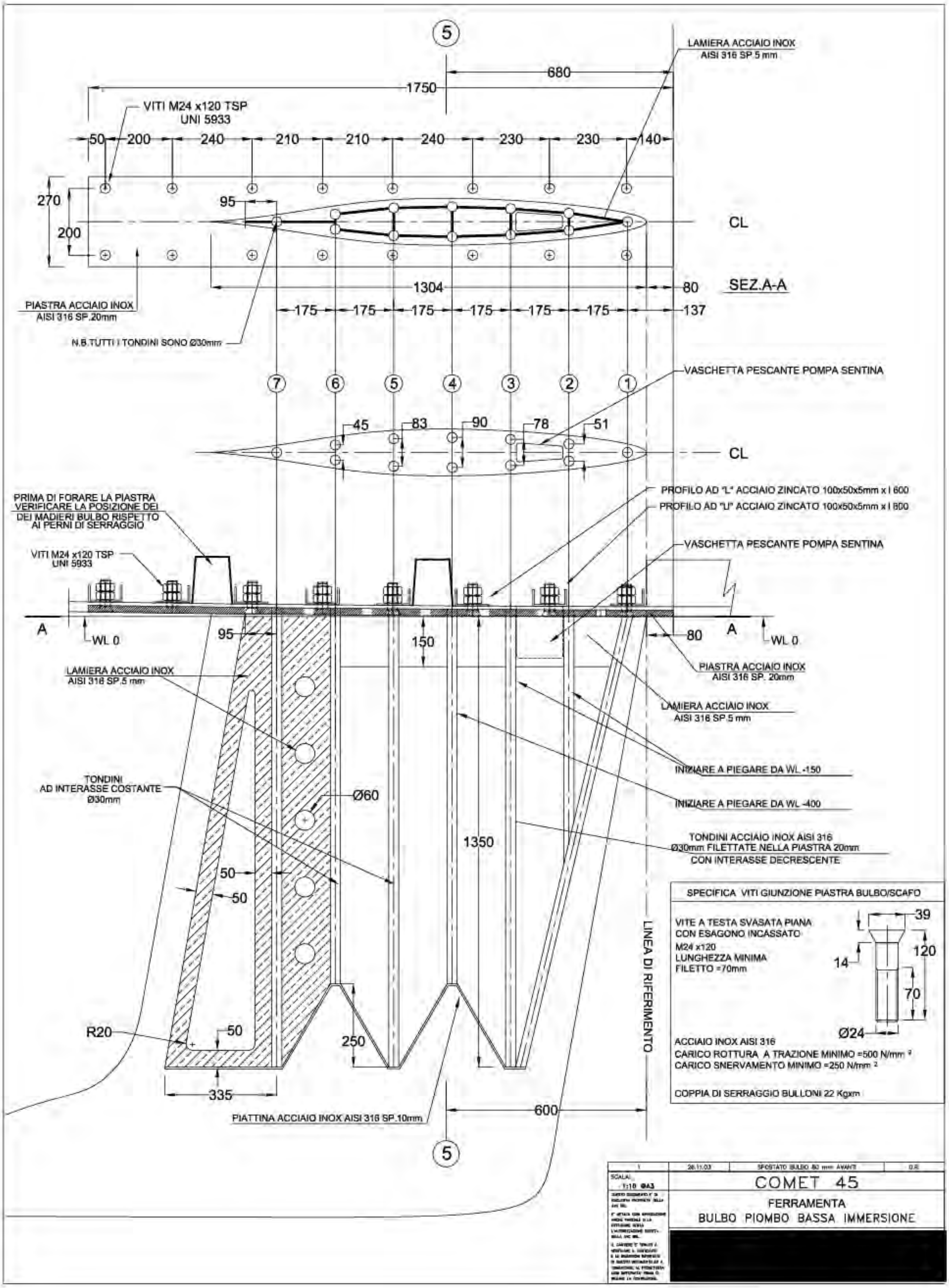
As far as could be practicably abstained within the given inspection time the yacht's keel had not been manufactured to meet the designers intent, in that the welding was not completed all the way round each rod. However the design did not take into consideration the access to weld during manufacture and did not highlight the importance of the quality (which would have required multiple passes) nor the size of the welds (no weld notation provided detailing leg length or throat thickness).

It was determined, through examination of the keel structure and fracture surfaces present that the failure most likely started by stripping the male threads on Rods 6 & 7 through a tensile-tensile cyclic load brought on by normal keel loads. The failure occurred because the rods were not securely fixed to the top plate via either:

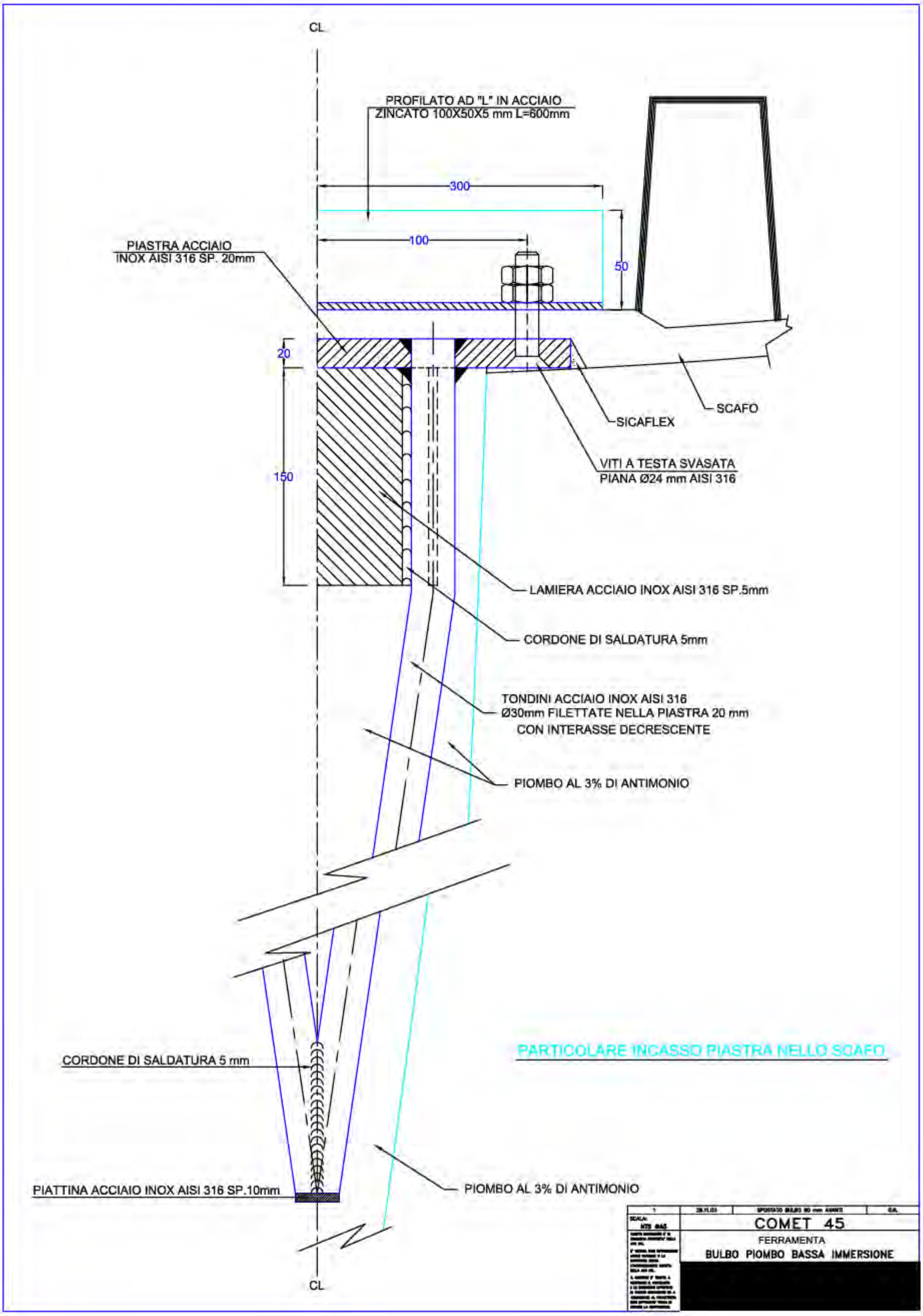
- a fully welded joint,
- or a tensile pre-load from a bolted joint.

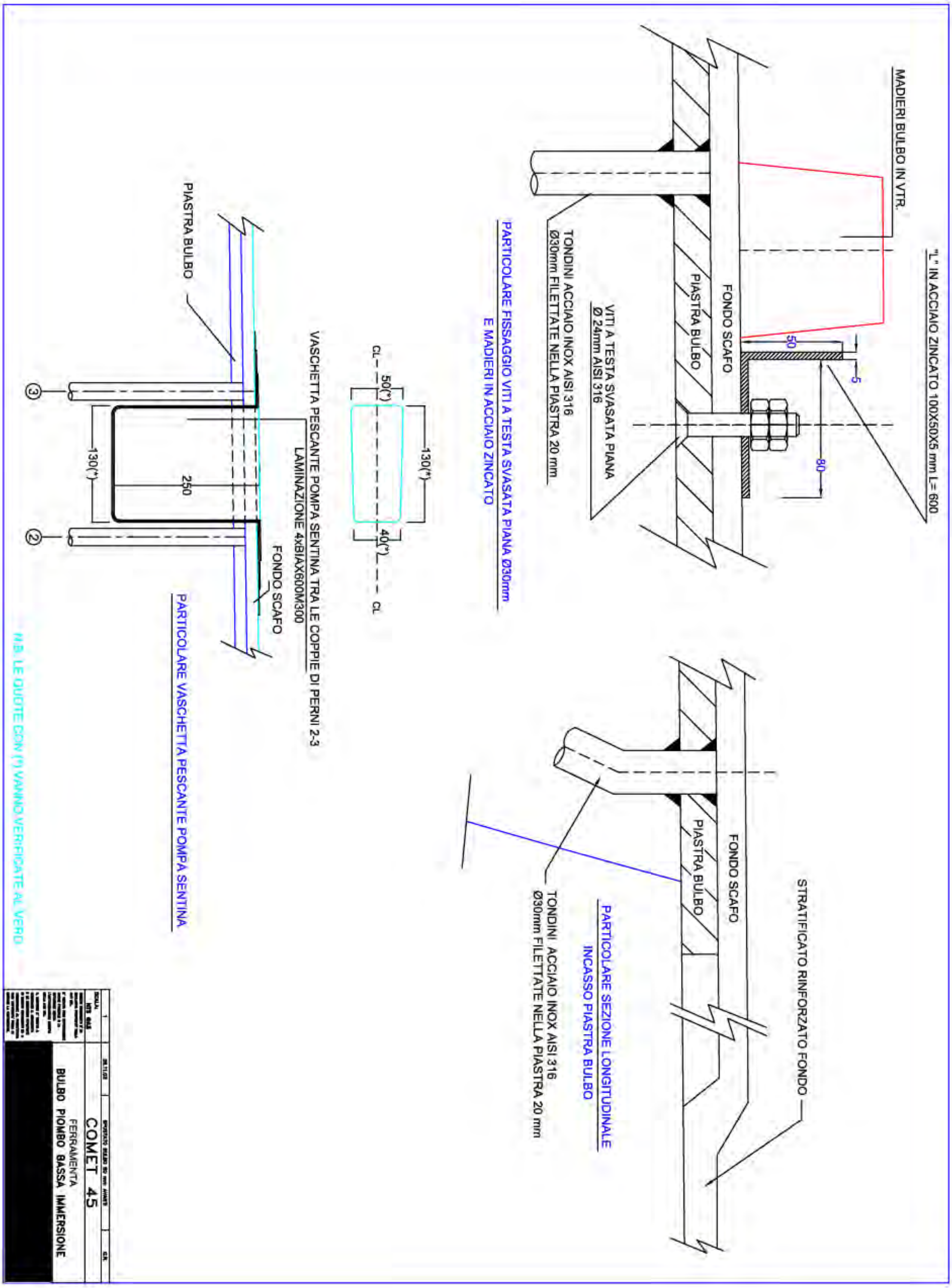
Therefore under local tensile-tensile loading there was relative movement between the rods (6 and 7) and the top plate, which led to thread flank wear which increased the freedom of movement. Once the load was no longer supported by the central rods, load shedding and cyclic deflections failed the remaining rods.

Appendix 1.1: Supplied Drawings



LAMIERA ACCIAIO INOX AISI 316 SP.5 mm
VITI M24 x120 TSP UNI 5933
1750
680
50 200 240 210 210 240 230 230 140
270
200
95
CL
1304
80
SEZ.A-A
175 175 175 175 175 175 137
PIASTRA ACCIAIO INOX AISI 316 SP.20mm
N.B.TUTTI I TONDINI SONO Ø30mm
VASCHETTA PESCANTE POMPA SENTINA
45 83 90 78 51
PRIMA DI FORARE LA PIASTRA VERIFICARE LA POSIZIONE DEI DEI MADIERI BULBO RISPETTO AI PERNI DI SERRAGGIO
PROFILO AD "L" ACCIAIO ZINCATO 100x50x5mm x l 600
PROFILO AD "U" ACCIAIO ZINCATO 100x50x5mm x l 600
WL 0
150
PIASTRA ACCIAIO INOX AISI 316 SP. 20mm
LAMIERA ACCIAIO INOX AISI 316 SP.5 mm
INIZIARE A PIEGARE DA WL -150
INIZIARE A PIEGARE DA WL -400
TONDINI AD INTERASSE COSTANTE Ø30mm
Ø60
1350
TONDINI ACCIAIO INOX AISI 316 Ø30mm FILETTATE NELLA PIASTRA 20mm CON INTERASSE DECRESCENTE
LINEA DI RIFERIMENTO
R20
250
335
600
PIATTINA ACCIAIO INOX AISI 316 SP.10mm
SPECIFICA VITI GIUNZIONE PIASTRA BULBO/SCAFO
VITE A TESTA SVASATA PIANA CON ESAGONO INCASSATO M24 x120 LUNGHEZZA MINIMA FILETTO =70mm
39 120 14 70 Ø24
ACCIAIO INOX AISI 316
CARICO ROTTURA A TRAZIONE MINIMO =500 N/mm²
CARICO SNERVAMENTO MINIMO =250 N/mm²
COPPIA DI SERRAGGIO BULLONI 22 Kgm
SPOSTATO BULBO 80 mm AVANTI
SCALA: 1:10 @A3
COMET 45
FERRAMENTA
BULBO PIOMBO BASSA IMMERSIONE
[redacted]


CL
PROFILATO AD "L" IN ACCIAIO
ZINCATO 100X50X5 mm L=600mm
300
100
50
PIASTRA ACCIAIO
INOX AISI 316 SP. 20mm
20
150
SCAFO
SICAFLEX
VITI A TESTA SVASATA
PIANA Ø24 mm AISI 316
LAMIERA ACCIAIO INOX AISI 316 SP.5mm
CORDONE DI SALDATURA 5mm
TONDINI ACCIAIO INOX AISI 316
Ø30mm FILETTATE NELLA PIASTRA 20 mm
CON INTERASSE DECRESCENTE
PIOMBO AL 3% DI ANTIMONIO
PARTICOLARE INCASSO PIASTRA NELLO SCAFO
CORDONE DI SALDATURA 5 mm
PIATTINA ACCIAIO INOX AISI 316 SP.10mm
PIOMBO AL 3% DI ANTIMONIO
COMET 45
FERRAMENTA
BULBO PIOMBO BASSA IMMERSIONE
[redacted]
CL


MADIERI BULBO IN VTR.
"L" IN ACCIAIO ZINCATO 100X50X5 mm L= 600
50
5
80
FONDO SCAFO
PIASTRA BULBO
VITI A TESTA SVASATA PIANA
Ø 24mm AISI 316
TONDINI ACCIAIO INOX AISI 316
Ø30mm FILETTATE NELLA PIASTRA 20 mm
PARTICOLARE FISSAGGIO VITI A TESTA SVASATA PIANA Ø30mm
E MADIERI IN ACCIAIO ZINCATO
CL
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VASCHETTA PESCANTE POMPA SENTINA TRA LE COPPIE DI PERNI 2-3
LAMINAZIONE 4xBIAX600M300
FONDO SCAFO
PIASTRA BULBO
250
130(*)
3
2
PARTICOLARE VASCHETTA PESCANTE POMPA SENTINA
N.B. LE QUOTE CON (*) VANNO VERIFICATE AL VERO
STRATIFICATO RINFORZATO FONDO
FONDO SCAFO
PIASTRA BULBO
PARTICOLARE SEZIONE LONGITUDINALE
INCASSO PIASTRA BULBO
TONDINI ACCIAIO INOX AISI 316
Ø30mm FILETTATE NELLA PIASTRA 20 mm
COMET 45
FERRAMENTA
BULBO PIOMBO BASSA IMMERSIONE

MAIB Safety Bulletin SB3/2018

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

SAFETY BULLETIN

SB3/2018

August 2018

Extracts from The United Kingdom Merchant Shipping (Accident Reporting and Investigation) Regulations 2012

Regulation 5:
"The sole objective of a safety investigation into an accident under these Regulations shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of such an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

Regulation 16(1):
"The Chief Inspector may at any time make recommendations as to how future accidents may be prevented."

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01932 440015

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NOTE

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall be inadmissible in any judicial proceedings whose purpose, or one of whose purposes is to attribute or apportion liability or blame.

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Keel failure and capsize of the commercial yacht *Tyger of London* 1 nautical mile south of Punta Rasca, Tenerife on 7 December 2017

MAIB SAFETY BULLETIN 3/2018

This document, containing safety lessons, has been produced for marine safety purposes only, based on information available to date.

The Merchant Shipping (Accident Reporting and Investigation) Regulations 2012 provide for the Chief Inspector of Marine Accidents to make recommendations at any time during the course of an investigation if, in his opinion, it is necessary or desirable to do so.

The Marine Accident Investigation Branch (MAIB) is carrying out an investigation into the keel failure and capsize of the commercial yacht *Tyger of London,* while on passage from La Gomera to Tenerife on 7 December 2017.

The MAIB will publish a full report on completion of the investigation.

Andrew Moll
Chief Inspector of Marine Accidents

NOTE

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall not be admissible in any judicial proceedings whose purpose, or one of whose purposes, is to apportion liability or blame.

This bulletin is also available on our website: www.gov.uk/maib

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Public Enquiries: 0300 330 3000

BACKGROUND

The MAIB is investigating the keel failure and capsize of the UK registered commercial yacht *Tyger of London* (Figure 1) while on passage from La Gomera to Tenerife, on 7 December 2017. The five persons on board were rescued from the water by the crew of a nearby yacht.

Figure 1: *Tyger of London* post-capsize

INITIAL FINDINGS

Tyger of London was a Comar Comet 45S designed by Vallicelli & C and built in 2007 by Comar Yachts s.r.l, at Fiumicino, Italy. In common with other vessels built by the shipbuilder, the Comet 45S could be fitted with a choice of two keels:

- A 3200kg, 'deep draught bulb keel', consisting of a cast iron fin with a lead bulb fixed to its base **(Figure 2a)**; or,
- A 3700kg 'shallow draught, lead keel', consisting of a fabricated rectangular stainless steel top plate and frame, onto which lead was cast to form the keel **(Figure 2b)**.

Tyger of London was fitted with the 'shallow draught, lead keel', which is the subject of this safety bulletin.

Figure 2a: Deep draught bulb keel not affected by this safety bulletin

Figure 2b: Shallow draught, lead keel, fitted to *Tyger of London*, subject of this safety bulletin

The post-salvage inspection of the yacht identified that the keel's stainless steel top plate was still attached to the hull **(Figure 3a** and **b)**. The MAIB recovered the top plate to the UK for technical assessment. The lead section of the keel sank in deep water and could not be recovered.

The technical assessment of the top plate revealed that the keel had not been manufactured in accordance with the designer's drawing or intent. Specifically, the stainless steel rods forming the frame and their interconnecting plates had been only partially welded to the underside of the top plate. As a result, the joins progressively failed over time **(Figure 3c)**. The final joins failed while the yacht was underway, causing the lead keel to separate from the keel plate, following which the yacht quickly capsized and inverted.

Tyger of London had been employed as a charter vessel since 2013. It is estimated that the yacht had sailed approximately 29,000nm since build. The MAIB has been informed that prior to the accident the yacht had grounded on a number of occasions, all reportedly at slow speed and onto sand or mud.

The yacht's manager had removed the yacht from the water 22 months before the accident, for maintenance, during which paint and filler were removed to allow the keel plate and lead keel to be inspected. The securing arrangements between the keel and the hull matrix were found to be in good condition, however the lead casting prevented the inspection of the welded joins between the keel's fabricated frame and top plate.

YACHTS FITTED WITH SIMILAR KEELS

The MAIB understands that there are likely to be between 50 and 100 yachts fitted with keels fabricated in a similar manner to the 'shallow draught lead keel' fitted to *Tyger of London*. The majority of these yachts were built between 2003 and 2011 and include the Comar:

- Comet 41, 45, 50, 51, 52rs, 54, 62ed; and,
- Genesi.

SAFETY LESSON

The MAIB is not aware of any similar keel failures in yachts of a comparable design. However, owners should be aware that the 'shallow draught, lead keels' fitted to the yachts listed above might not have been fabricated in accordance with the designer's drawings. Where this is the case, the connection between the stainless steel keel plate and rods will not be as strong as intended. Furthermore, the condition of the connection cannot be inspected or assessed using traditional survey methods.

To prevent a similar accident, owners are recommended:

- To note that the securing bolts within the bilge of their boats, for this type of shallow draught lead keel, connect the top plate to the hull. The condition and tightness of these keel securing bolts do not indicate the true condition of the keel's internal frame structure.
- To arrange for an out of water inspection of their vessel by a suitably qualified yacht surveyor at the earliest opportunity if the yacht has grounded, been heavily used, or if they have any concern whatsoever as to the condition of the keel, noting the difficulty of inspection of the junction between lead keel and top plate.

Figure 3a: Comar Comet 45S keel bolt arrangement

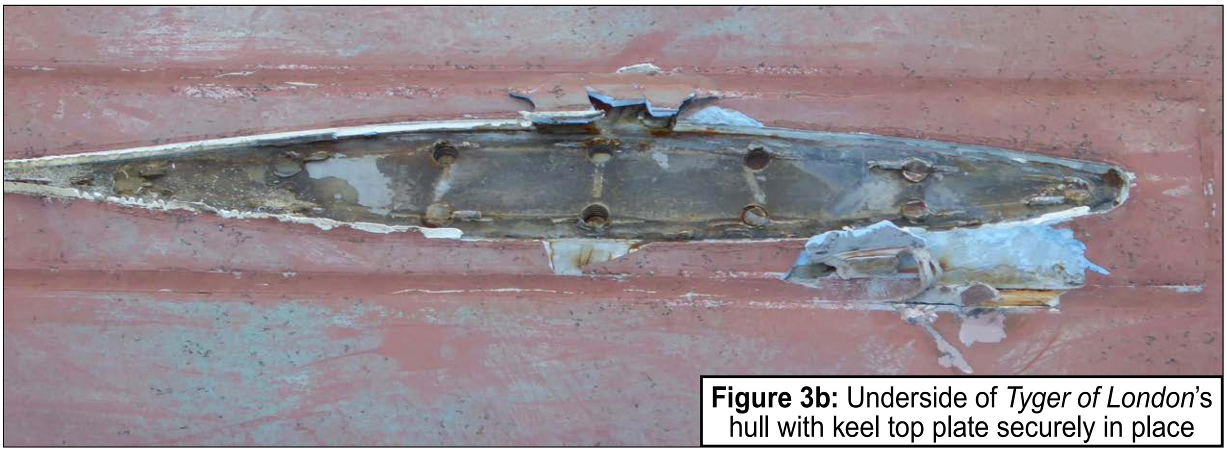

Figure 3b: Underside of *Tyger of London*'s hull with keel top plate securely in place

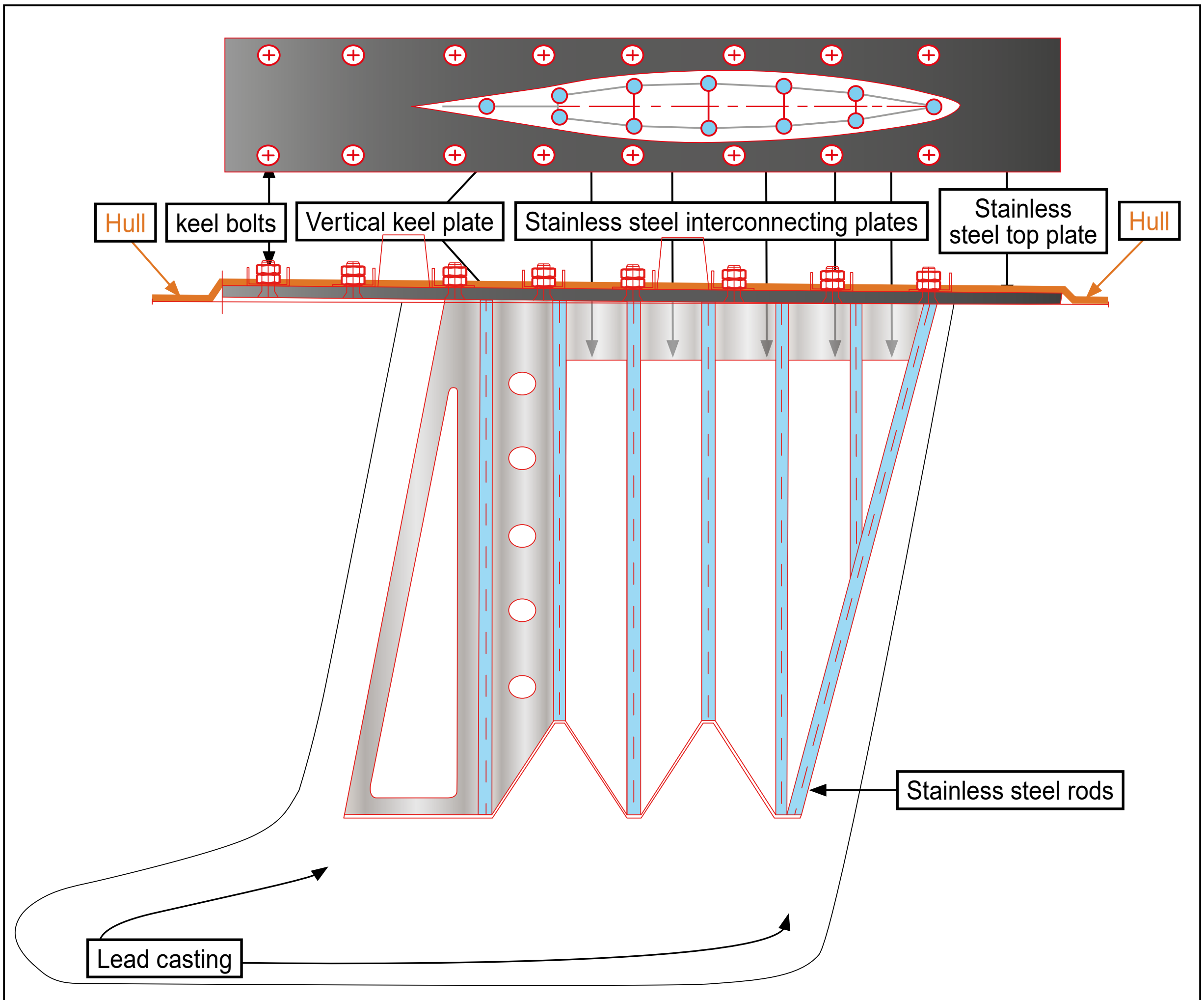

Figure 3c: Plan of the shallow draught keel

- To note that although the manufacturer, Comar Yachts s.r.l, has ceased trading, technical advice may be sought from **Gesti Nautica s.r.l**, a ship repair yard that has experience of these vessels. Their contact details are:

  Gesti Nautica s.r.l
  Via Fulco Ruffo dia Calabria snc
  00054 Fiumicino (RM)
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The MAIB's investigation is ongoing and it is intended that a full report will be published later in the year.

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