Annex I

Steel fabricator’s design calculations

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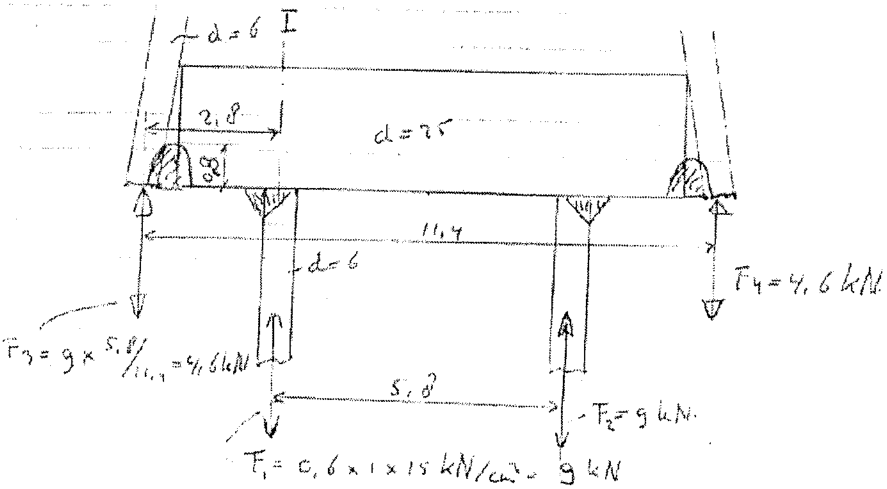
1

Concerns keel of Maxfun 35 by order of Breehorn.
Strength calculation of the fin profile at the insert in the hull of the boat.



Considered is a length of 1 cm. Where the fin profile is at its widest.

It was assumed that the maximum stress in the fin is 15kN/cm² in connection with varying stress.
The maximum push/pull force (F2 and F1) in a 1 cm piece is 0,6x1x15=9kN.

The maximum push/pull force from the side plate (F3 and F4) 9kN x 5.8/11.4=4,6kN.

2

Moment in cross-section I:
4.6 kN x 2,8 cm – 12,9 kN cm.

W = 1/6 x 1 x 2,5² = 1,04 cm³.

Bending stress G1 = 12,9/1,04 = 12,4 kN/cm².

This is less than the assumed permissible stress in the fin plates of 15 kN/cm².

Shearing stress in the outer weld (a=8)

$4{,}6\ \mathrm{kN} / 0{,}8 = 5{,}75\ \mathrm{kN/cm^2} < 8{,}7\ (15/\sqrt{3})$

Assessment where the fin becomes thinner:

The occurring bending stress (pull/push) becomes less in proportion to the thickness of the fin.

Where the thickness is 1 cm less:

$$F_1 = F_2 = 9\ kN \times 4{,}8/5{,}8 = 7{,}45\ kN$$

$$F_3 = F_4 = 7{,}45 \times 4{,}8/11{,}4 = 3{,}13\ kN$$

$$M_I = 3{,}13 \times 3{,}3 = 10{,}3\ kN\,cm < 12{,}9 ,$$ therefore not indicative.

3

Assessment insert:

Cross-section of the fin:

$$I \approx 280\ cm^4$$

$$W = 280/3{,}2 = 87{,}5\ cm^3$$

At a bending stress of 15 kN/cm² the moment that the fin exercises on the insert is: $87{,}5 \times 15 = 1313\ kN\,cm.$

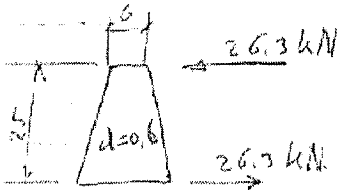
At a height of the insert of 25 cm the horizontal force underneath and above the insert is:

$$1313/25 = 52{,}5\ kN$$

The transversal force in the insert is taken in by the front and the rear plate.

Per plate the transversal force is

$$52{,}5/2 = 26{,}3\ kN$$



Occurring shearing stress:

$$\tau = 26{,}3/6 \times 0{,}6 = 7{,}3\ kN/cm^2$$

$$< 8{,}7\ (15/\sqrt{3})$$

Oudega 19-3-2007

J. de Jong

Annex J

Explanation of yacht racing optimisation

OPTIMISATION FOR RACING

Boats applying for a rating under IRC rules complete an application form detailing the physical data of the boat. This includes length overall, waterplane length, weight, rig configuration, sail dimensions, keel and rudder configuration. This data is used to calculate a Time Correction Coefficient (TCC).

The TCC is then used to calculate the boat's 'corrected time' in a race by multiplying her elapsed time (i.e. the time that she takes to complete a race) by her TCC. For example, a boat with TCC of 1.050 takes 1 hour to complete a race. Her corrected time is then 1:00:00 x 1.050 = 1:03:00. A boat with TCC of 1.100 also takes 1 hour, but then has corrected time of 1:00:00 x 1.100 = 1:06:00. At the end of a race, the race committee calculates the corrected time for all boats in the race. The boat with the lowest corrected time is the winner.

In simplistic terms, each 0.001 difference in TCC equates to 3.6 seconds of corrected time. So:

1 hour = 3600 seconds. 1.000 x 3600 = 3600. 1.001 x 3600 = 3603.6

There is therefore an incentive for a boat to be rated with the lowest TCC possible and so owners modify their boats to reduce their TCC. Noting that TCCs are calculated figures, a change in TCC is generally only achieved by a physical change to the boat's rated data. Typical modifications include reduction in sail area, number and type of sails carried, or changes to the weight and/or ballasting of the boat.

Such changes also have an effect on the actual speed of the boat. A reduction in sail area will produce a lower TCC, but will also slow the boat down. Owners and their advisers are therefore seeking to slow the boat down less than the reduction in TCC. Conversely, in particular cases, the best result may be achieved by speeding the boat up in a way that doesn't increase the TCC by a commensurate amount. As simplistic examples, a boat with an initial TCC of 1.000 is modified in a way that reduces speed by 0.5%. The amended TCC is 0.990, i.e. a reduction of 1% and so the boat is better off. Or the modifications achieve a speed gain of 0.5%, but TCC increases to 1.010, i.e. an increase of 1%, in this case the boat is worse off. Inevitably, in practice, the process is much more complex and less certain as changes are made to the rules without owners or their agents necessarily being aware of these.

Rating optimisation is therefore the process of balancing the speed of a boat against rating to achieve the highest possible ratio of speed to TCC.

Annex K

Extract of The Test House (Cambridge) Report T70266 dated 16 April 2007

EXTRACTS FROM THE TEST HOUSE (CAMBRIDGE) REPORT

6. SUMMARY

6.1 The Martin Hick photographic images of the keel blade taken immediately prior to the out-of-water repairs (completed between November 2006 and January 2007) showed extensive evidence of both corrosion of the keel blade and distress to the paintwork along the keels interface with the yacht hull. The evidence collectively suggested that the keel blade to hull interfacial region had been exposed to very high service stresses and that breakdown of the protective resin and paint finish had resulted from their exposure to such high stresses. One of the images of the port side of the blade also showed evidence of a possible crack, which was located over a significant length of the blade to taper box fillet weld toe.

6.2 The keel support bolts exhibited no evidence to suggest that they had been either recently re-tightened or verified in respect of their tightening torque. Had the tightening torque been verified, it would have been readily apparent that the aft and middle bolts had suffered reversed bending fatigue fractures some significant time preceding both the re-fitting and casualty.

6.3 The keel securing bolts were found to be of relatively high strength thread rolled property class 8.8 quenched and tempered carbon steel, two having been produced by one maker and the third (aft bolt) by a different maker.

6.4 The design for the yacht had specified class 70 type 316 austenitic stainless steel keel bolts. The substitution of quenched and tempered galvanised ferritic steel bolts was not considered to be significant, as comparatively such bolts could have been expected to exhibit a higher fatigue strength than the class 70 type 316 stainless steel bolts that had been specified.

6.5 The fabricated keel blade had been resin or adhesively bonded directly to the GRP pocket, and the pocket had in turn been supported by a cruciform support structure. The hull in way of the keel, the cruciform support structure and the keel box pocket all appeared free from cracking and disbonding. The presence of earlier longstanding rusting damage along the longitudinal underside edges of the keel box did, however, suggest that local stresses were resulting in some flexing or movement of the steel keel relative to its support, and that such relative movement had locally damaged and breached the resin and paint protective system.

6.6 The keel had apparently been suffering ingress of sea water, and the presence of a pronounced water mark inside the upper tapered steel box suggested that the in-leaking was of some age and long standing. The presence of sea water flooding of the keel would increase its effective weight, which would in turn add magnitude to both the static and dynamic sailing stresses.

6.7 The keel blade had been fabricated to a modified design that involved fillet welding of the blade to the underside of a fabricated tapered steel box. The modified design placed a fillet weld in a location of the keel that was subjected to high cyclic fatigue stresses during sailing.

6.8 The keel blade had fractured by a mechanism of reversed bending fatigue cracking. Fatigue cracks had initiated at stress concentration sites in the toes of the fillet welds joining the keel blade to the underside face of the tapered steel box. The keel also contained secondary fatigue cracks propagating outwards from the inner blade face and from the root of the fillet welds.

6.9 The plate material that had been used to fabricate the upper tapered keel box and the keel blade were either directly or indirectly verified as meeting the S235 grade requirements specified in the design data provided to the laboratory by MAIB.

6.10 Thickness of the upper keel box and blade plate were both confirmed to be in accordance with the design specified requirements. The sizes (leg lengths and throat thickness) of the fillet welds joining the keel blade to the upper tapered box were also compliant with those specified in the original design. The keel had, however, been built to an alternative design, and MAIB had confirmed that no fillet weld sizes were specified for the alternative design.

6.11 Though a number of welding defects were identified in the tapered box underside longitudinal welds, the defects had not grown in service and the shortcomings in the two box seam butt welds was not judged to be significant in the casualty.

7. CONCLUSIONS, DISCUSSION AND OPINION

The keel fracture had resulted from a failure mechanism of reversed bending fatigue cracking, and two of the keel securing bolts had also failed by an identical reversed bending fatigue cracking mechanism. The keel bolt fractures were thought to be of some considerable age and certainly pre-dated the out-of-water re-fit that had been completed immediately prior to the casualty. Failure of the keel securing bolts was not thought to have materially increased the fatigue loading on the keel blade fillet welded joint, rather the fatigue fractures in the two bolts was symptomatic of a much wider cyclic (fatigue) design stress issue.

Fatigue failures of the type identified in this case arise from the repeated component cyclic stressing ranging from tens of thousands to millions of cycles at stress levels typically below yield strength proportions. The failure mechanism exhibits three clearly separate phases including crack initiation, sub-critical crack growth and terminal fracture. In the case of most components that are subject to moderate or relatively low cyclic stress amplitudes, a large part of the available component life is found to be in the crack initiation phase. In the case of fatigue cracks originating in welds, the crack initiation phase is either not present or it accounts for a very short proportion of the total overall fatigue life; a fact that emphasises the need to consider palliative fatigue life extension techniques for welded joints. In steel structures and welded steel structures it is technically possible to design for an infinite fatigue life, which is usually achieved by designing to maximum dynamic stress levels which are within a materials fatigue strength limits.

The keel appeared on our examination and tests to have been both fabricated from and fitted with materials that either met or exceeded the specified requirements in respect of both critical mechanical properties and dimensions. The keel failure is not, therefore, attributed to any deficiencies or defects in the materials of construction.

Two design modifications appear to be potentially material in the failure, these include,

a) Modification of the keel design in respect of how it was fabricated

b) Addition of additional lead to the bulb weight

The first modification placed a fillet weld in a critical stress location. Weld toes, and those of fillet weld in particular, are widely acknowledged as exhibiting relatively poor performance in fatigue environments. The designer and builder had taken no measures to negate or reduce the local fatigue sensitivity; as could have been achieved by weld dressing, hammer peening, toe grinding or the use of other such like well established improvement techniques.

The placing of additional lead on the keel bulb weight could be expected to have increased the service stress amplitude of the cyclic reversed bending stress on the keel, and potentially to a point of criticality. The apparent evidence of in-leakage of sea water could also be expected to have increased the magnitude of the fatigue stress via its potential to add additional weight to the keel.

The source of the damaging cyclic fatigue stress is most likely to have arisen from the loads imposed on the keel during normal sailing of the yacht. It is, however, also technically feasible that the damage could have occurred as a consequence of resonance fatigue conditions generated by the high winds during the time that the yacht hull was out of the water. This latter source of the fatigue stress would not, however, account for the much older fractures in the two keel securing bolts. The weight of the hull acting downwards onto the keel would also offer a very significant anti-resonance damping potential, rendering the potential for wind resonance remote. The yards report of the yacht hull oscillating in its cradle, also implies a relatively slow rate of movement, which would be unlike the high frequency, vibration like motion, excited by wind resonance.

The client is advised to engage the services of a naval architect or yacht designer to check the design calculations for the keel. The design checks should be commissioned in such a manner that a number of different scenarios are checked, these should include the original design, its modifications in respect of construction detail, the added bulb weight, and internal sea water flooding of the keel.

Report prepared and authorised by

D Ellin
Director and Head of Laboratory

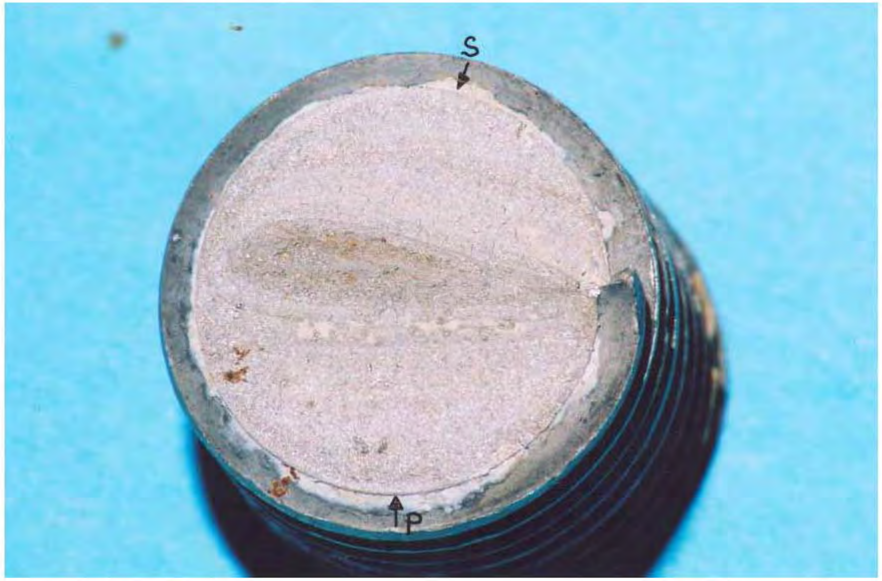


Figure 24: Middle keel bolt fracture surface, showing origins of the reverse bending fatigue cracks (arrow S = starboard side crack origin, arrow P = port side crack origin).

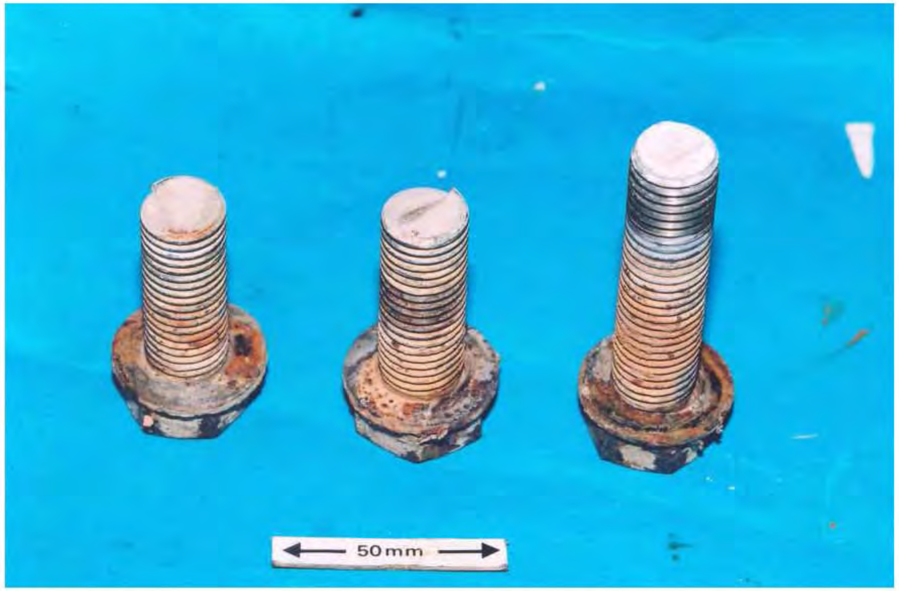


Figure 15: Keel securing bolts, showing fractures in the aft bolt (left of field) and the mid location bolt (centre field).

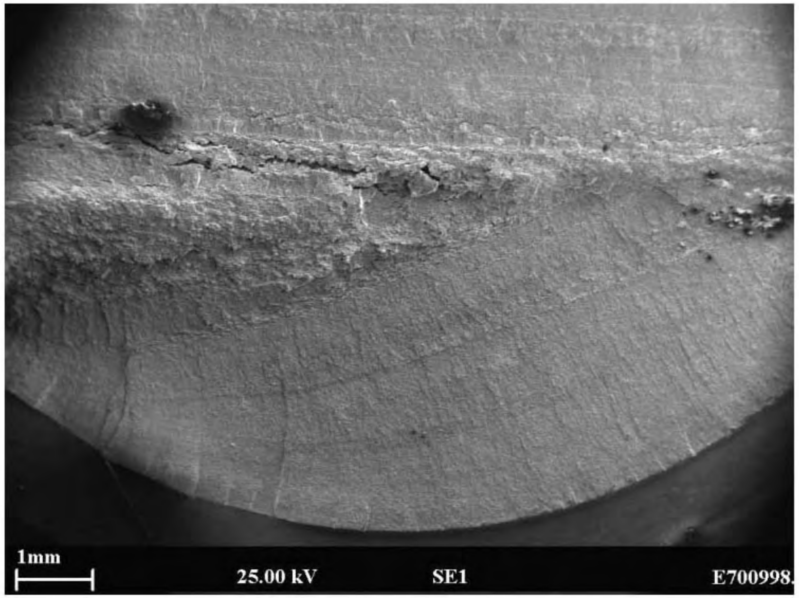


Figure 27: SEM fractograph, showing fatigue crack origin ratchet marks and fatigue crack arrest beach markings in the second (starboard side) fatigue crack in the aft bolt.

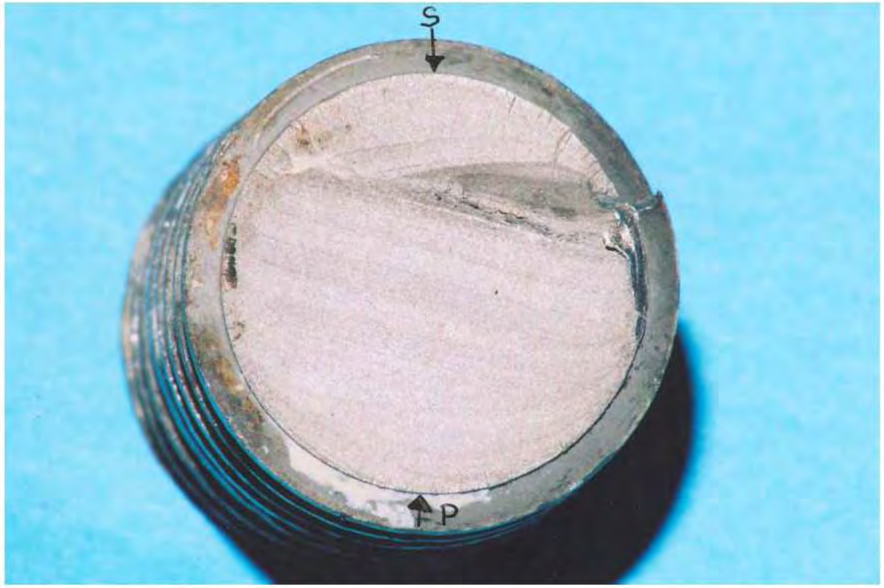


Figure 23: Aft keel bolt fracture surface, showing origins of the reverse bending fatigue cracks (arrow S = starboard side crack origin, arrow P = port side crack origin).

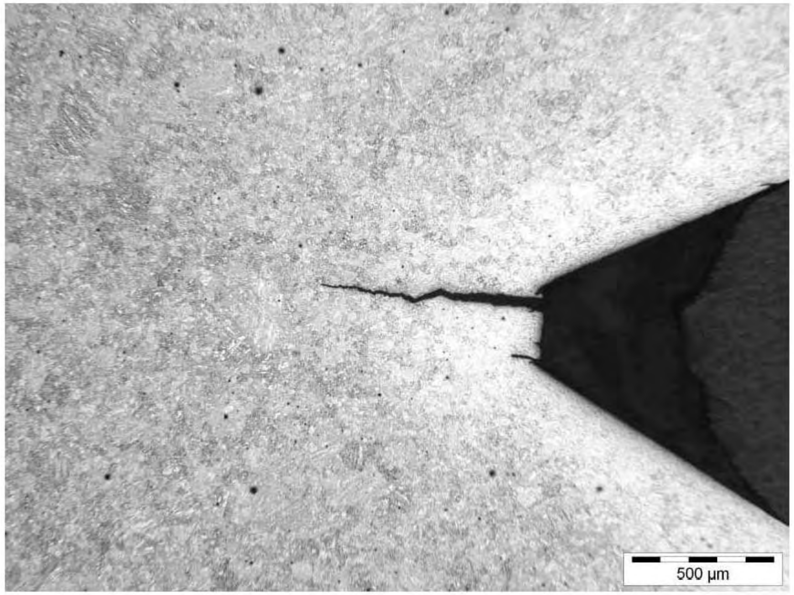


Figure 39: Micrograph (original image captured at X50), specimen etched in Nital. Longitudinal section from the middle bolt, showing detail of a secondary fatigue crack with intergranular cracking in its tip region.

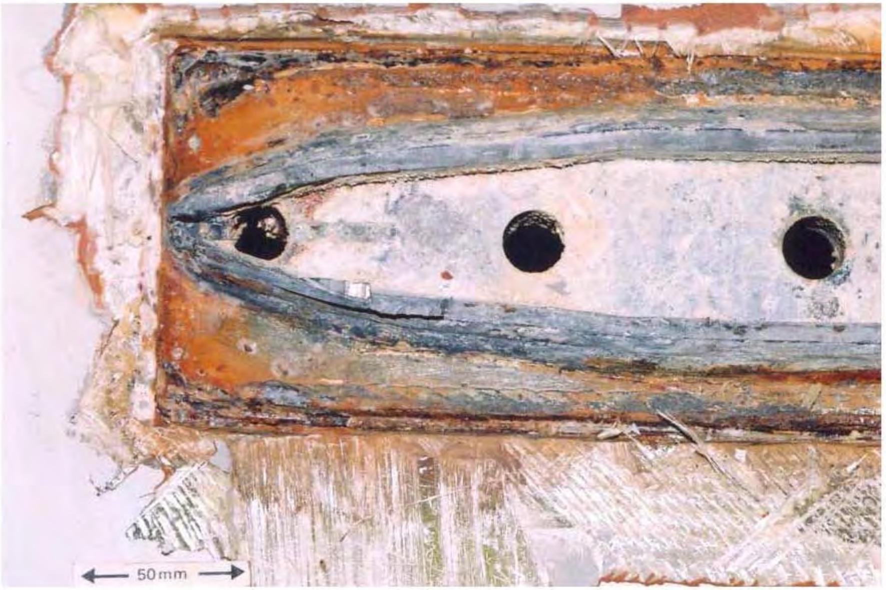


Figure 50: Forward end of the upper keel box fabrication, exposed by chiselling away the resin and paint finish to the hull underside.

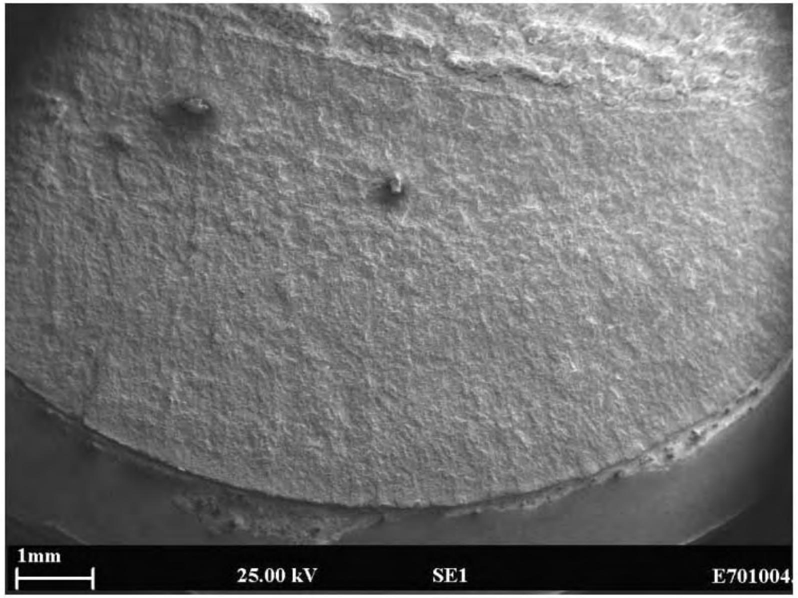


Figure 30: SEM fractograph, showing starboard side fatigue crack in the middle bolt.

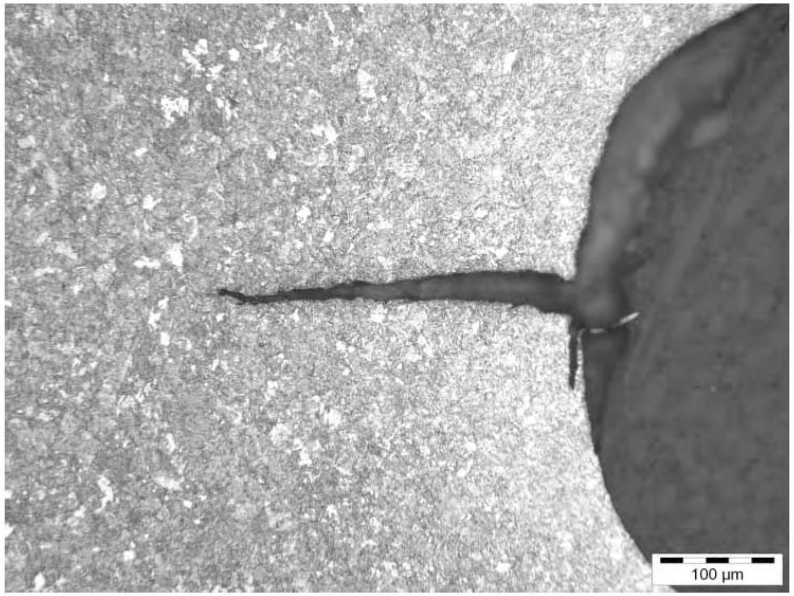


Figure 37: Micrograph (original image captured at X200), specimen etched in Nital. Longitudinal section from the aft bolt, showing detail of a secondary fatigue crack.

Figure 51: Aft end of the upper keel box fabrication, exposed by chiselling away the resin and paint finish to the hull underside.

Figure 56: Detail of the internal water mark and long standing corrosion which had exposed areas of the steel substrate.

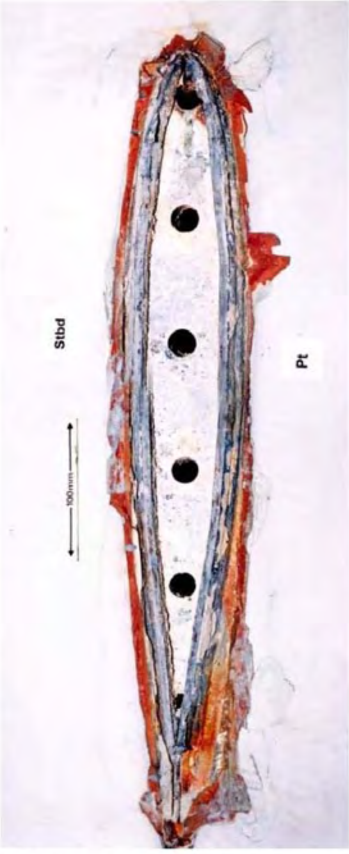


Figure 57: Keel blade fracture site, which was coincident with the toes of the fillet welds joining the keel blade to the face of the fabricated upper tapered box.

Figure 59: A region of the port side keel blade fracture, showing association of fatigue crack initiation sites with stress concentrations arising from aspects of weld toe profile.

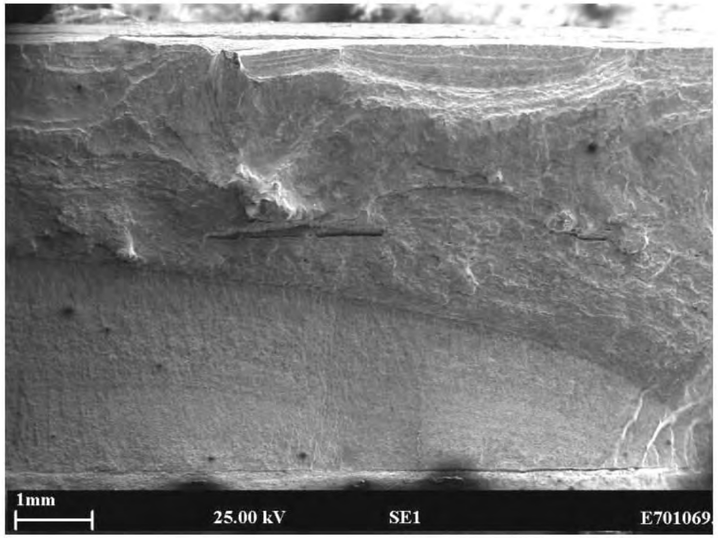


Figure 63: SEM fractograph, showing deep principal fatigue crack (lower field), shallow secondary fatigue cracks (upper field) and ductile terminal fracture between the two crack fronts - starboard side keel blade fracture.

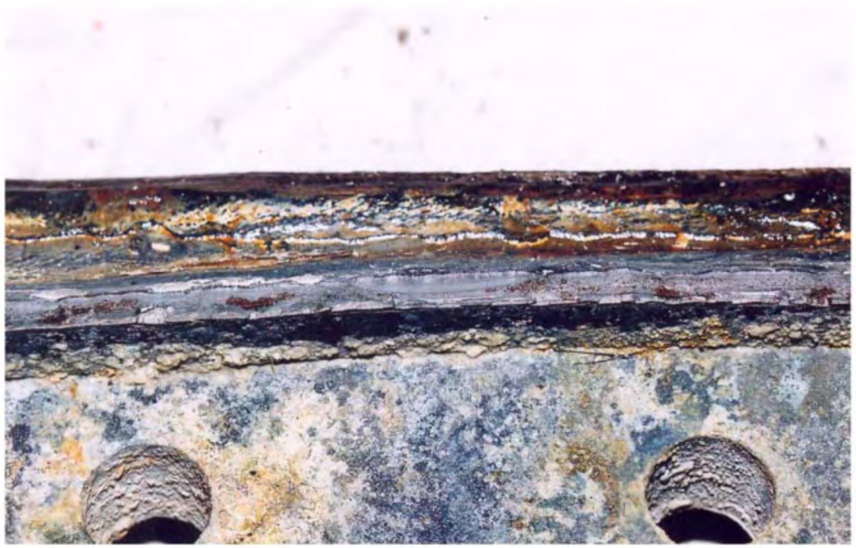


Figure 60: A region of the starboard side keel blade fracture, showing association of fatigue crack initiation sites with stress concentrations arising from aspects of weld toe profile.

Figure 65: Macrograph (original image captured at X4), specimen etched in Nital. Cross section from fracture in port side of keel blade, showing fatigue fracture top of field, and secondary fatigue crack originating from the blade to box weld root. The figure also shows lack of root fusion and penetration in the taper box construction weld (lower right field).

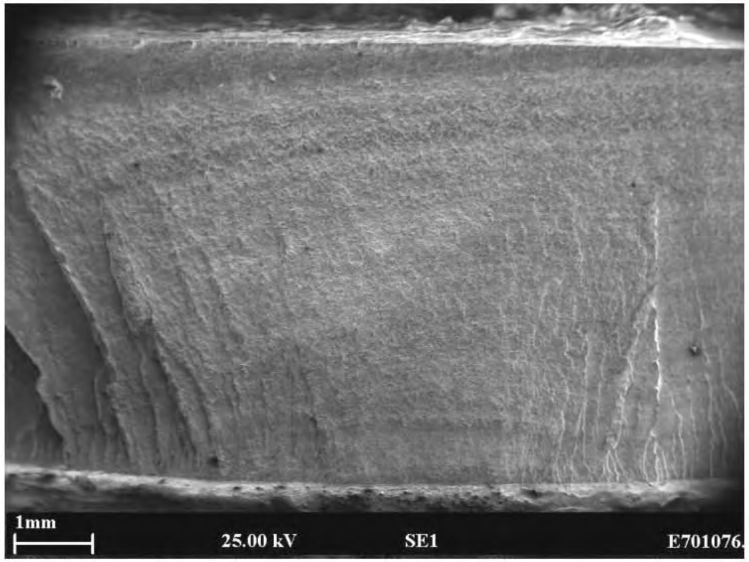


Figure 61: SEM fractograph, showing through plate fatigue crack in the port side of the keel blade. The figure also shows ratchet marks at the crack origin side and a number of relatively indistinct beach markings.

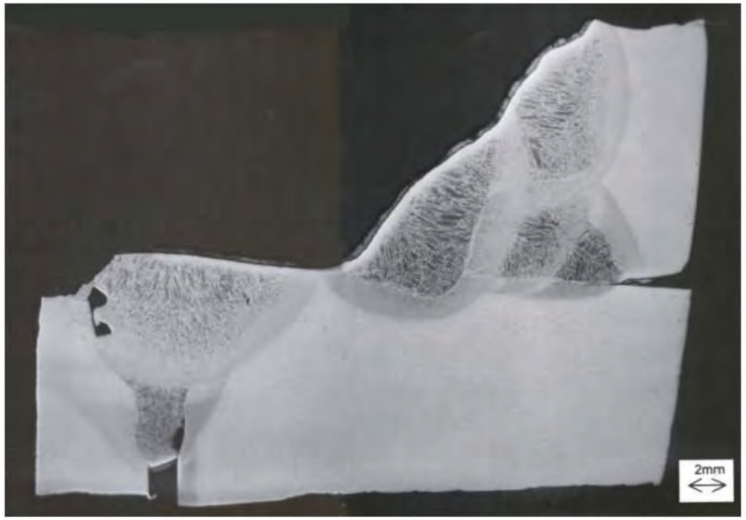


Figure 68: Macrograph (original image captured at X4), specimen etched in Nital. Cross section from fracture in starboard side of keel blade, showing fatigue fracture top of field and a hot crack in the weld root. The figure also shows lack of fusion, porosity and lack of root fusion and penetration in the taper box construction weld (lower left field).

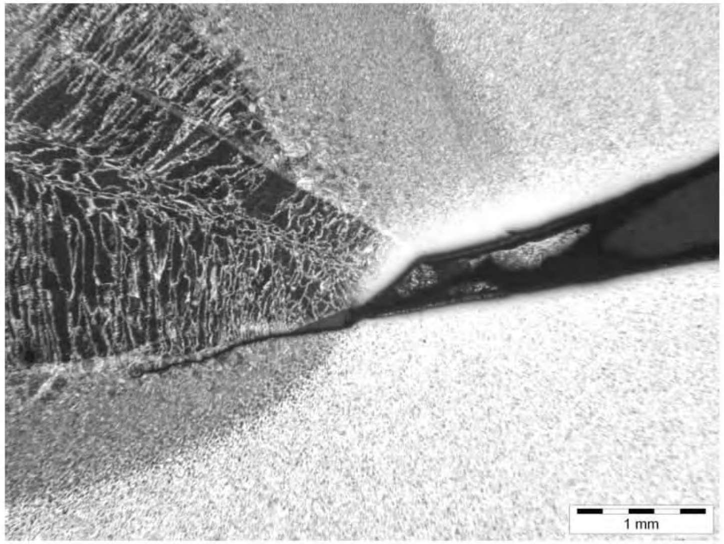


Figure 70: Micrograph (original image captured at X25), specimen etched in Nital. Starboard side fillet weld root crack originating from slag or silica entrapment.

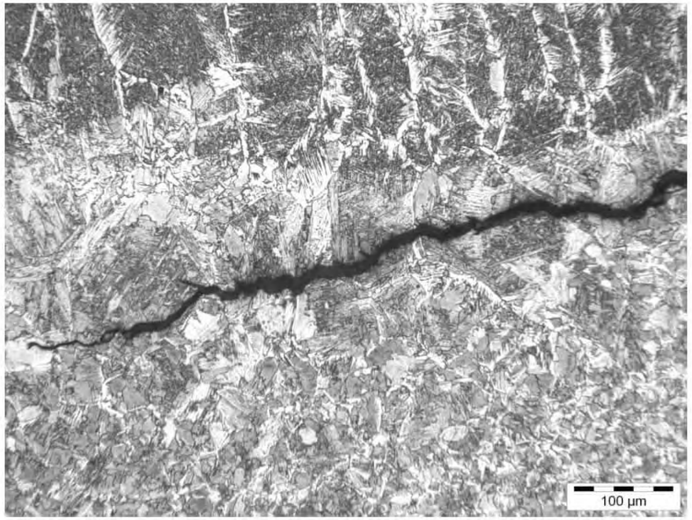


Figure 71: Micrograph (original image captured at X200), specimen etched in Nital. Detail of fillet weld root cracking shown earlier in figure 70 and including features more consistent with hot cracking originating during the original welding.

Wolfson Unit Report – No 1958 dated March 2007

WOLFSON UNIT
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Report No. 1958 **March 2007**

Marine Accident Investigation Branch (MAIB)

Investigation into the Keel Failure of the Max Fun 35 Yacht - Hooligan V

1 INTRODUCTION

This review has been conducted at the request of the Marine Accident Investigation Branch (MAIB) in accordance with the Wolfson Unit M.T.I.A. proposal 3091, dated 14th March 2007, to support the investigation into the Keel Failure of the sailing yacht "Hooligan V", a Max Fun 35 designed by Simonis Voogd Design B.V (SV Design).

2 SCOPE OF THE REVIEW

The Wolfson Unit have reviewed drawings, pictures, supporting calculations and the related design data of the Max Fun 35 yacht "Hooligan V" to provide an expert opinion and assess the suitability of the structural design of the keel as specified by the designer and as built. The yacht keel was modified in 2005 and this modification has also been assessed for the as designed and as built configurations.

The analysis includes calculations to determine whether or not the keel conforms with the criteria of the ABS Guide for Building and Classing Offshore Racing Yachts 1994, hereby referred to as the ABS Guide. The ABS Guide has two basic requirement scenarios for assessing the keel fin structure and keel bolts:

1. Sailing Knockdown Case (90 degree heel)
2. Grounding Loads

The suitability of the use of the ABS Guide in this instance is also discussed.

The report also includes a comparison of keel fabrication methods including laminated, cast and prefabricated designs.

Fatigue is discussed in the role of the structural failure and also related to other recent keel failures such as those in the Open 60 racing yacht class.

3 CONFIDENTIALITY

This report is confidential to the Wolfson Unit M.T.I.A. and their client shown in the title and may be made public at the discretion of the client.

4 SUMMARY OF FINDINGS OF THE REVIEW

4.1 Method

Values have been calculated for the construction shown on the drawings and data provided. The results have been compared with the requirements taken from analytical beam bending theory and the requirements and criteria set out in the ABS Guide. A list of the drawings and any other documentation is given in Table 1 of the report.

4.2 Conclusions

In the opinion of the Wolfson Unit, the design does not conform to the bending stress criteria of the ABS Guide under any of the presented configurations.

The keel fin and keel bolts both pass the ABS requirement for the grounding case.

The as built design is considered to be below acceptable safety factors. The arrangement of the as built specification increases the risk of fatigue failure greatly over that originally designed. This combined with the addition of the extra bulb weight, lower fin section mechanical properties and the low safety factor over the allowable stress contributed to the failure of the keel at the keel fin root.

4.3 Comments

The ABS Guide has been a recognised standard in yacht structural design for many years and provides a basis for safe design. From information supplied by the MAIB it is understood that the Max Fun 35 (Design 150) has been designed to the ABS Guide. On this basis the Wolfson Unit has used the ABS Criteria for assessing the design.

In the case of light displacement, high performance yachts, designs may be optimised to the minimum safety factors in hull and keel design. Thus, to avoid compromising safety, the designer’s specification should be most strictly adhered to by builders and fabricators or changes referred to the designer for approval.

With failed structure of keels and rudders representing a notable proportion of the loss of yachts at sea, the question could be asked if new and type approved boats in RCD Category A and B should be assessed for structural integrity in these areas?

ISO standards involving appendage attachments; ISO12215, Parts 8 and 9 are in draft form and should hopefully be harmonised within 2008. The design of “Hooligan V” could not be based on an unpublished standard but it may provide an alternative basis of assessment to the ABS Guide.

5 DESIGNERS' RESPONSIBILITIES

It is understood that this yacht was designed and constructed to meet the Essential Safety Requirement of the Council of European Communities Recreational Craft Directive 94/25/EC (RCD) for Boat Design Category B.

For RCD Category B boats a Notified Body certificate will be needed in respect of its stability and/or buoyancy, but there is no requirement for Notified Body involvement in regards to the structural integrity of the boat. Instead this remains the manufacturer's responsibility with the requirement to maintain a technical file.

The designer and fabricators produced drawings and associated documentation showing the construction of the yacht. The Wolfson Unit have reviewed these drawings and corresponding documentation.

6 DOCUMENTATION

The drawings and documentation related to this review are listed in Table 1. Copies of all drawings and related documentation will be retained in a file at the Wolfson Unit until at least the completion of the MAIB investigation.

7 DESIGN REVIEW

7.1 Structural Assessment Requirements and the ABS Guide

The calculations for the structural assessment are based upon standard analytical beam bending theory incorporating methods and safety factors detailed in the ABS Guide.

In the past many designers have used the ABS Guide and its use was stipulated in certain Safety Regulations and some Class Rules such as the Volvo Ocean 60s. The Guide is considered the standard for determining scantling dimensions and loadings for offshore racing yachts and whilst racing yachts have not been failure free, the ABS Guide has provided a basis for developing satisfactory service experience.

The ABS Guide includes requirements for the keels, their supporting structure and bolts. The keel has to be designed to resist sailing transverse loading, which is based on the weight and centre of gravity of the fin and bulb under sailing knockdown conditions. The knockdown situation is used in the ABS Guide as it endeavours to cover the complete envelope of loading conditions the keel will see during service.

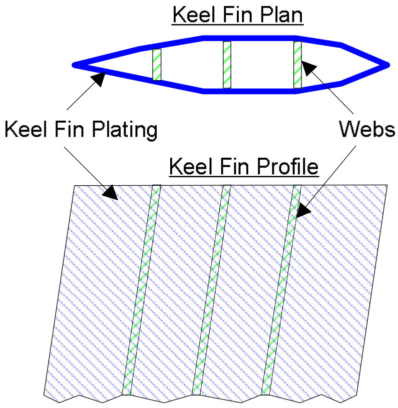
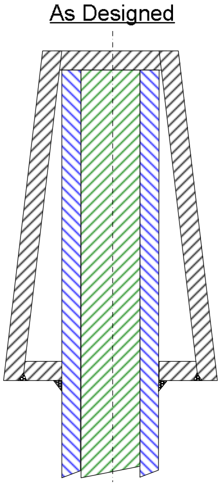
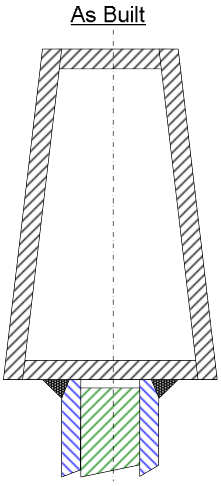
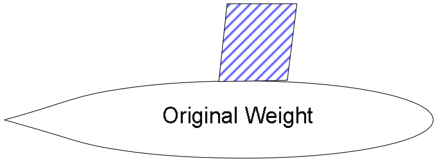
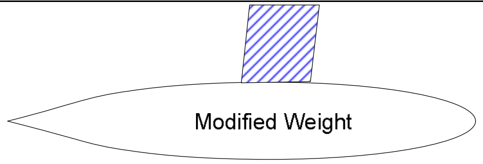
The keels also have to resist grounding loads and the guide contains specific clauses concerning the design of ballast keels or fins and their attachments so provides a good basis for building robust structures. Indeed there were reports of Volvo 60 yachts grounding at speed and sustaining little serious damage. The grounding load cases are notional and are assessed using a quasi-static analysis, which will not represent actual dynamic behaviour in real instances. Nevertheless they provide a useful method for ensuring that the ballast keel is designed to cope with impact loads and the high accelerations associated with the performance ballast keel yachts in ocean racing conditions.

The ABS Guide's grounding load cases are stated to use the yacht's displacement including the bulb weight.

It is worth noting that the new ISO 12215 standard: "Hull construction – Scantlings" is due to be published in 9 parts. Part 6: "Structural Arrangement and Details" and Part 9: "Appendages and Rig Attachments", which are in draft form, will be relevant to keel construction and attachment.

7.2 Assessment of Design Configurations

There are four presented design scenarios within the investigation. It is not deemed necessary within this report to recount the history of any changes or modifications to the original design, simply analyse the various design configurations presented by the MAIB and discuss their suitability to cope with the in service loads. The design configurations are as follows:

		
	1. As designed with original bulb weight of 1325kg.	3. As built with original bulb weight of 1325kg.
	2. As designed with modified bulb weight of 1488kg.	4. As built with modified bulb weight of 1488kg.

See also Figure 1 for a schematic of the as designed vs. as build configurations.

The blue hatched area represents the steel keel fin plating. The green hatched area represents 3 steel webs running down the length of the fin. Importantly, the as built configuration shows no sign of the vertical webs being attached to the underside of the plate where the keel fin plating is welded. This has been confirmed following inspection and discussions with The Welding Institute (TWI) on the 15th March 2007 who are carrying out the material inspection of the failed area.

The section modulus of the fin is therefore different for the as designed compared to the as built case, primarily due to the attachment of the transverse webs. The bending moment varies for the original bulb weight and the modified bulb weight due to the addition of the estimated 163kg of lead material to the bulb.

7.3 Sailing knockdown case

Review calculations were performed to check the design of the keel and associated structure to resist the sailing loads within the allowable stresses. Standard beam bending theory was utilised to ratify the design. An example calculation is detailed in Table 2 for the as designed configuration with a summary of the results for the various design configurations in Table 3.

Calculations for the as designed, original bulb weight, sailing knock down case are presented by SV Design in the documentation and the independent Wolfson Unit calculations correspond very well with those, including a full calculation of the structural properties and estimation of the bending moment. It is noted that SV Design used a safety factor of 2 over the ultimate tensile strength whereas the ABS Guide requires a safety factor of 2 over the yield strength.

Calculations for the as built configuration are also presented by J. de Jong. The calculations assume a maximum stress in the fin of 150 MPa, yet the Wolfson Unit's independent calculation suggests a maximum stress of 284 MPa as built. The subsequent calculations do not appear to check the structure in way of the keel fin root or its welded attachment; there are only checks for the steel box insert into the hull. The keel bulb weight, moment arm and material properties are not evident in the calculations so it is difficult to establish from where the 150 MPa was derived.

All the design scenarios are assumed that the keel fin structure does not contain any water. In the case where water ingress may have occurred the added weight of the keel would further reduce the safety factors in the assessment as it would increase the bending moment and hence the design bending stress.

The ABS Guide sets out a bending requirement for the allowable stress to be half the yield stress for the sailing knockdown case, this is a factor of safety of two over the yield strength. The ABS Guide also states the yield strength is not to be taken as greater than 70% of the ultimate tensile strength of the material and not greater than 390 MPa where steel is used. The steel used in the design is quoted as having a maximum ultimate tensile strength of 510 MPa, therefore the ABS Guide value for the yield strength is 357 MPa and the allowable bending stress is 178.5 MPa. These factors of safety relate to the onerous sailing knockdown case. There are no explicit factors for fatigue associated with cyclic loading that every keel experiences during its lifetime so it is inferred that compliance with the knockdown case will ensure that stresses arising from sailing will not cause fatigue problems.

The ABS Guide also has a shear requirement for the sailing knockdown case; this is based on the bending moment coupled with the torsion of the bulb on the keel root. The ABS Guide has a requirement that the shear stress should not be greater than half the shear strength. The shear strength should not be taken as greater than 40% of the ultimate tensile strength; therefore the ABS allowable shear stress is 204MPa.

Table 3 shows that for all four configurations the design did not pass the bending or shear requirements set out in the ABS Guide. The as designed with the original bulb weight shows a margin of safety of 1.4 over the ABS yield stress requirement and 1.6 over the ABS allowable shear stress. The as built with the modified bulb shows a margin of safety of 1.1 over the ABS allowable bending stress and 1.3 over the ABS allowable shear stress. For comparison, in all cases the requirement in the ABS Guide was a factor of 2.

7.3.1 As Designed

SV Design's original design presented a safety factor of two over the ultimate tensile strength. This does not, however, meet the ABS requirement.

7.3.2 As Built

The as built design combined with the original bulb and modified bulb shows a safety factor of 1.3 and 1.1 respectively over the yield strength. These safety factors are deemed too low for this type of racing yacht. In particular these are very low in respect to the method of fabrication where a weld is directly in the line of load and a safety factor of 2.5 to 3 over yield may have been more appropriate for this method of attachment. For example the ESDU (Engineering Science Data Unit) code suggests an initial estimate of the allowable stress of 0.4 times the ultimate tensile strength for welded joints experiencing fatigue loading; this is a safety factor of 2.5.

7.4 Grounding cases

Review calculations were performed to check the design of the keel pin, fin, flange and internal structure to resist the grounding loads within the allowable stresses. These calculations were based on the requirement given in the ABS Guide. It was further assumed that the grounding load was reacted by forces acting in the plane of the bulkheads. The ABS Guide has a requirement that the grounding bending stress should not be taken as greater than 1.33 of the yield stress; therefore the ABS allowable grounding bending stress is 289 MPa.

Standard beam bending theory was utilised to ratify the design, with an example calculation shown in Table 2. A summary of the results for the various design configurations in Table 3 and this shows that for grounding the original and modified design would pass the ABS Requirement with a allowable stress safety factor of 2 and 1.9 respectively. The results are not presented for the as designed vs. as built configuration as the longitudinal section modulus of the fin does not change significantly for these configurations.

The keel bolts are also checked for compliance with ABS guide and the calculation is detailed in Table 4 for the worst case with the modified bulb weight. In the as designed and as built configurations the bolts are not designed to take the bending moment in the knockdown sailing case. The bolts are therefore only checked for grounding and tension. The bolt allowable stress factors are the same as the keel fin steel. For both scenarios the bolts pass the ABS Requirement.

7.5 Fatigue

In his email dated 15/3/07, David Ellin of TWI confirmed that: “The two fracture surfaces exhibited features consistent with failure by a mechanism of reversed bending fatigue.” This is also consistent with the calculated low safety factors of the allowable stress for the as built together with the original and modified bulb design configuration. With evidence of pictures of the boat at the time of the bulb modification and other unmodified identical design boats exhibiting cracking around the keel fin junction with the hull it is suggested that significant fatigue and cracking of the weld could have occurred before the additional weight of the bulb was added.

In Reference 3, written by an eminent and well respected racing yacht designer, under a section regarding fatigue the following statement is made: “Important criteria in the design of the fin are to keep stress concentrations to a minimum. With this in mind all sharp corners, areas of high stiffness and welds in line with the load action are kept to a minimum.”

The change from the as designed configuration to the as built configuration greatly reduced the fatigue life of the keel fin junction with the keel. The original design had little or no welding in line with the load action whereas the as built had a weld supporting the whole load from the weight of the keel fin and bulb. It is recognised that the fatigue life of a weld is lower and higher safety factors should be used for the allowable stress in this case.

Also in Reference 3, under a section entitled fatigue, it is stated that “…keels have a practical life of 60,000 miles of offshore racing on Open class designs. After this they are inspected more frequently, or replaced before a long offshore race. We strongly recommend replacing keels at this stage…”. It is noted that evidence presented by the MAIB suggests this boat had done in the region of 50,000 miles of offshore sailing and thus had experienced significant number of load cycles to warrant replacement or careful inspection such as ultrasound or other forms of non-destructive testing.

7.6 Keel Fin Construction and Open 60 design

7.6.1 Steel: Cast and Fabricated

Steel fins can be either solid cast or fabricated most often from high tensile alloys. Steel is often considered a conservative design and used especially in offshore racing yachts. Cast fins have quite a large weight penalty but are considered the best in terms of strength and fatigue life; it is notable that the Volvo70 Ocean racing yacht rules require the keel fins to be solid cast. Steel fabricated fins often rely on welds and therefore fatigue can be a problem. As mentioned previously, in designing a steel fin a weld should be avoided in the load path.

As an example let us consider three Open 60s with fabricated steel fins. The Open 60, Ecover, had a keel failure at 40,000 miles in service. The Open 60s Kingfisher and Hexagon had no keel failure and lasted 60,000 miles. All the keels were built by the same manufacturer. It is mentioned in Reference 3 that Kingfisher and Hexagon were designed with a stress safety factor of 20% more than Ecover, this is significant in terms of the failure of Hooligan V as the as built, modified bulb had a safety factor of 20% less than the as designed, original bulb. It is also mentioned that the crack that caused the keel failure of Ecover propagated from a weld that did not exist in the Kingfisher or Hexagon design.

7.6.2 Composite

Composite or fibre reinforced plastic (FRP) fins are often made from carbon reinforcement. Composite keels have a tendency to flutter and because the materials used in keel fins are often highly orthotropic, this can pose problems with torsion and can make the fins prone to delamination. It is mentioned in Reference 3 that delamination of carbon fins was a problem in two Open 60 boats in the last Vendee Globe.

8 REFERENCES:

1. ABS Guide for Building and Classing Offshore Racing Yachts 1994.
2. Safety considerations in developing the stability and structural requirements in the Volvo Open 70 rule. RINA 2nd High Performance Yacht Design Conference, Auckland NZ, 14-16 February, 2006. Ian M. C. Campbell , Andrew R. Claughton, Barry Deakin.
3. Practical aspects of canting keel design, construction and analysis. RINA 2nd High Performance Yacht Design Conference, Auckland NZ, 14-16 February, 2006. L. Tier, M. Owen, T. Sadler.
4. Heavy Weather Sailing, K Adlard Coles, Revised by Peter Bruce.

9 TABLES

Table 1 Documentation and drawings reviewed by the Wolfson Unit MTIA

Drawing/Document Title	Drawn By / File Number	Date
Construction Plan and Elev.	SV / 150-200	October 2001
Sail and Rigging Plan	SV / 150-310	April 2002
Construction Interior Liner	SV / 150-202	March 2002
Keel Construction Details	SV / 150-230	October 2002
Keel Root and Fin Deflection Calcs	SV / 150-	N/A
Konstruktiebedrif de Jong BV	JJ	19 March 2007
4x kiel Max Fun 35	BH / 02064	8 April 2002
RORC Rating – IRM Certificate 2003	RORC	2003
RORC Rating – IRM Certificate 2005	RORC	
RUUKKI Hot Rolled Steel Plates, Sheets and Coils. Comparison Tables	RUUKKI	N/A
Sketch of Presumed Keel/Hull Arrangement	MAIB / --	March 2007
Original design by SV vs. As built (also see Figure 1)	MAIB / --	March 2007
Pictures: various: Keel failure area	MAIB/TWI / --	March 2007
Pictures: various: Keel and bulb during modification	N/A	N/A
Pictures: various: Other Max Fun 35 keels	N/A	N/A

Key:
SV = Simonis Voogd Design B.V. (Max Fun 35 yacht designer)
JJ = J. de Jong
BH = Breehorn BV (keel fabricator)
RORC = Royal Ocean Racing Club Rating Office
RUUKKI = Rautaruukki Corporation, Finland
MAIB = Marine Accident Investigation Branch
TWI = The Welding Institute, Cambridge

Table 2 Example keel structure sailing and grounding load calculations for configuration 1.

Keel fin bending and torsion under transverse loading to ABS 9.13.3a

Hooligan V as Designed, Original Bulb **T keel**

Chord	ch	550	mm
Thickness	t	64	mm
Location	l	40	%
t/c ratio	t/c	11.6	%
Inertia	I	285	cm^4
Area	A	47	cm^2
Section modulus	Z	89	cm^3
Torsional stiffness	K	1106	cm^4
Curvature	r	921	cm
πt^4/16A^2		4717	
Torsion factor	Cf	9.6	cm
Keel and bulb weight	W	1426	kg
Vertical distance	zcg	1649	mm
Lateral distance	xcg	110	mm
Bending moment	M	23.070	kN.m
Torsion moment	T	1.54	kN.m

DISTANCES

Bulb centroid to root	1710	mm
Fin centroid to root	851	mm
Fillet	10	mm
Flange	10	mm

WEIGHTS

Bulb		1325	kg	Additional Weight	0	kg
Fin		101	kg			
Ult. Tensile strength	σ UTS	510	MPa			
Bending stress	σb	259	MPa			
Torsion shear stress	τs	13	MPa			
				ABS allowable stresses 9.13.3a		
Principal stresses	σ1	259.42	MPa	178.5	MPa	**Fail**
Max shear stress	τ	130	MPa	102	MPa	**Fail**

Grounding load

Section modulus Fore & Aft	450	cm^3
Max. displacement	3	tonnes
Scantling length	10.7	m
Grounding load	4.8	tonnes
Dist. Root section to bulb CL	1710.0	mm
Bending moment	80.8	kN.m
bending stress	179	MPa
allowable stress	289	MPa
ABS requirement	**Pass**	

Table 3 Calculation results for sailing and grounding loads.

Configurations

	Condition	Mechanical/Material Properties			Loading		Safety Factor(s)		Pass/Fail
Keel Fin Bending. Sailing knockdown case	Bulb weight	Section Modulus	Ultimate Tensile Strength, UTS	ABS Yield Strength	Bending Moment	Bending Stress	UTS Safety Factor	Yield Safety Factor, S.F.	Pass ABS Yield S.F.=2?
	kg	cm^3	MPa	MPa	kN.m	MPa			
1. As designed original	1325	89.2	510	357	23.07	259	1.97	1.38	**Fail**
2. As designed modified	1485	89.2	510	357	25.84	290	1.76	1.23	**Fail**
3. As built original	1325	81.4	510	357	23.07	284	1.80	1.26	**Fail**
4. As built modified	1485	81.4	510	357	25.84	318	1.60	1.12	**Fail**

	Bulb weight	Torsional Stiffness		ABS Shear Stress	Torsion Moment	Shear Stress		Shear Safety Factor, S.F.	Pass ABS Shear S.F.=2?
Keel Fin Shear	kg	cm^4		MPa	kN.m	MPa			
1. As designed original	1325	1106		204	1.54	130		1.57	**Fail**
2. As designed modified	1485	1106		204	1.72	146		1.40	**Fail**
3. As built original	1325	994		204	1.54	142		1.44	**Fail**
4. As built modified	1485	994		204	1.72	160		1.28	**Fail**

	Bulb weight	Section Modulus		ABS Yield Strength	Bending Moment	Grounding Bending Stress		Yield Safety Factor, S.F.	Pass ABS Yield S.F.=1.33?
Grounding Loads	kg	cm^3		MPa	kN.m	MPa			
1. Original	1325	450		357	80.8	179		1.99	**Pass**
2. Modified	1485	450		357	85.2	189		1.89	**Pass**

Table 4 Keel bolt load calculations

Actual bolt root dia.	18.5	mm
Bolt Tension		
Mean bolt tension	16	kN
Bolt stress	19	MPa
Grounding allowable stress	191.3	MPa
ABS requirement	Pass	
Grounding loading		
Max. displacement	3.163	tonnes
Scantling length	10.7	m
Grounding load	5.1	tonnes
Dist. flange to bulb CL	1730.0	mm
Grounding allowable stress	191.3	MPa
Max. bolt tension	48	kN
Bolt stress	178	MPa
ABS requirement	Pass	

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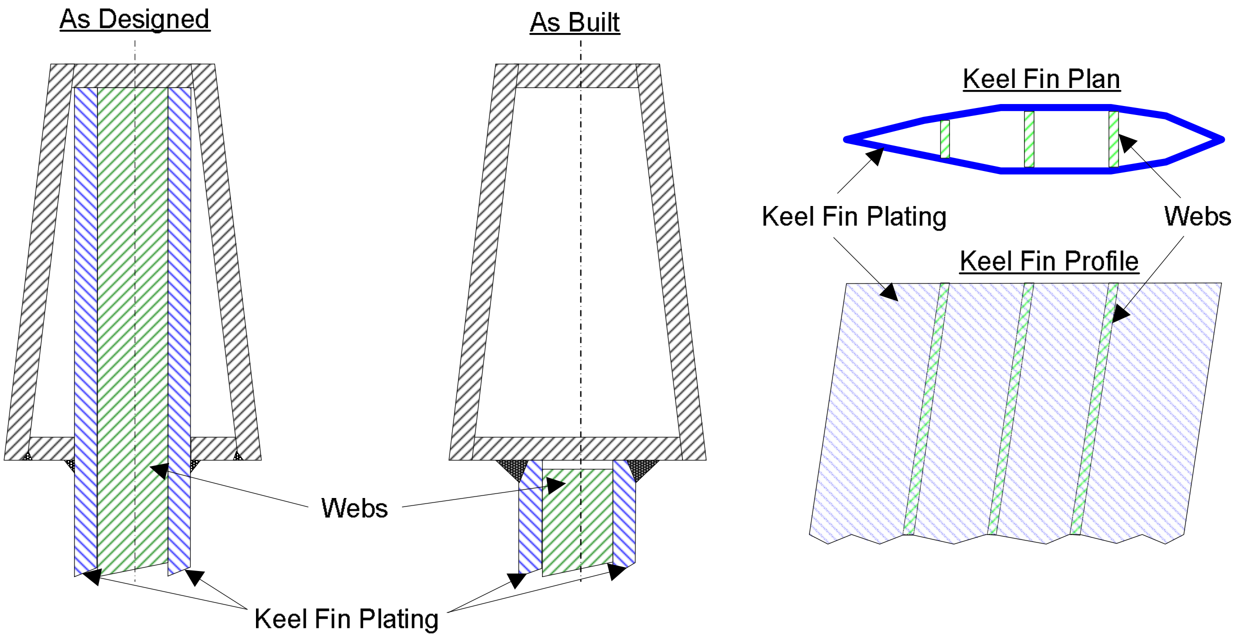
10 FIGURES

Figure 1 – Schematic of Original design by SV vs. As built. Assumed Configuration from Drawings and Information supplied by MAIB



Max Fun Boats BV’s letter dated 6 February 2007 – advising owners not to use the Max Fun 35 yachts

maxfun
PERFORMANCE YACHTS

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<u>Subject: Incident Max Fun 35 Hooligan V</u>

Enkhuizen, 6 February 2007

Dear Owner,

As you might have heard by now the Max Fun 35 "Hooligan V" (built no:01) capsized after losing its keel in the English Channel near Salcombe on the 3rd of February 2007 at 3 A.M. local time.
The exact cause of the accident is unknown at this time and an official investigation by the Maritime Accident Investigation Board (MAIB) is currently underway.

Max Fun Boats B.V. will keep you informed about any conclusions coming out of the MAIB report which affects your particular production number.
Pending the outcome of this investigation, we recommend that your Max Fun 35 no:4 remains in port.

Yours Sincerely,

Max Fun Boats B.V.

M Voogd

Maarten Voogd,