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THROUGH LIFE LOAD MONITORING OF SUPERYACHT CARBON FIBRE RIGS EXPERIENCE AND NEW APPLICATIONS

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SUMMARY

Monitoring sailing loads on highly loaded rigs allows design, ownership, operation and maintenance of these structures with confidence they are being operated within their design load envelopes. This enables the manufacturer to offer conditional warranties and can reduce build and insurance costs. Insight from load data is invaluable for design refinements on subsequent projects.

The radical Dyna-rigged three-masted superyacht, Maltese Falcon, was fitted with an embedded fibre-optic load monitoring system providing real-time feedback on rig loads to the operational crew. The installation and aims were presented at HISWA, Roberts, Dijkstra (2004). The system continues to record data, providing a lifetime history covering 10 years since commissioning.

This paper updates the position of such systems by reference to this unique dataset, including a general review of the lifetime load history and a focus on selected high load events, across a range of sailing conditions.

Data obtained justifies ongoing use of lifetime and extreme load monitoring as a useful tool, for owners, insurers, designers and classification societies. A development of the system is installed in several recent megayacht build projects, including the 146m Sail Yacht “A” and a 106m Dyna-rigged sailing vessel. The application of this system and the data will be discussed.

1. INTRODUCTION

The Maltese Falcon superyacht (Figure 1) introduced many novel technologies to yacht design, including an automated sailing system and through life load monitoring of the rigs. This vessel was the largest yacht built with freestanding spars. The Dynarig, based on a 1960s concept by W. Prolls, was put forward by the naval architect G. Dijkstra, championed by prospective owner Tom Perkins and developed and engineered by Insensys, led by D. Roberts (Perkins et al (2004)).

Figure 1 *Maltese Falcon under sail*

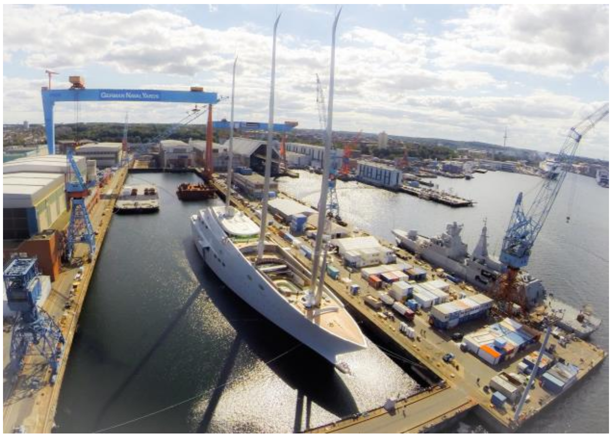

Figure 2 *Sail Yacht A during build*

The Dynarig development overcame a number of structural challenges in the design of the spar, not least due to the bending and torsional loads unsupported by rigging, the slots in the front face for in-mast furling and the actuation of rig rotation from the base of the mast (Roberts et al (2004)).

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To ensure the rig was sailed safely at all times within its operational envelope, a system was developed to monitor, display and record the strains and loads in the masts. The load monitoring provides several benefits for owners, insurers, designers and classification societies, which will be discussed in detail.

The partnership between Magma Structures, with D. Roberts as technical advisor, and Dykstra Naval architects has given birth to two new equally ambitious freestanding superyacht rig build projects. The first, sail yacht A (Figure 2), is as radical in concept and scale as Maltese Falcon was at the time of build. The second is a Dyna-rigged vessel, a step up in size from Maltese Falcon, that draws on the knowledge and experience gained from the success of the Maltese Falcon. Both of these new rigs are equipped with a monitoring system which has benefitted from further development.

The extensive data gathered from through life load monitoring of Maltese Falcon feeds into the design of the latest Dynarig, by informing the development of new loadcases based on the way the vessel has been sailed in real operation. Summary data and selection of the highest load events has been prepared for presentation in this paper, including a deep-reefed reaching case in over 50kts of wind, and two upwind cases with 26knots and one reef, and 19 knots and full sail respectively.

2. BENEFITS OF THROUGH LIFE LOAD MONITORING

The primary function of rig load monitoring is to provide real-time feedback to the sailing system operator on the bridge (Figure 3). A percentage (%) value is displayed for each mast, representing the operational capacity used for that mast. The sailing master is empowered with knowledge either that they are operating the rigs within the designed operational envelope for the spar, or given an indication that they should be considering action to reduce loads, perhaps to ease or furl sails away.

Maintaining the condition of an un-instrumented rig on a large vessel relies on the experience of the crew to intuit that the rig is becoming over-pressed, and to further recognize when a significant event has occurred that would warrant an inspection. Although the sailing manual and crew training are clear on acceptable operation of the sailing systems, the displays provide a feedback mechanism to reinforce these limits and a backstop against unintentional misuse.

Benefits accrue to the owner. The first is the assurance that their sailing rig is being operated within its limits, increasing safety and reducing the risk of damage, insurance loss and associated downtime. Cost savings can be made on insurance and warranties, due to these reduced risks. The design can have a reduced margin for misuse loadcases so the manufacturer will see lower labour and material costs, due to the same safety levels being achieved with reduced material and time costs and can pass this on to the customer. Insurance companies could be willing to reduce premiums based on the installation of a rig load monitoring system. Two year warranties are in place from Magma Structures for the two rigs discussed in this paper, conditional on the recorded data showing no misuse.

An additional benefit to the owner is the reduced requirement for sailing crew training and experience. This complements the advantages of the automated sailing system, whereby all of the vessels sailing functions can be controlled by one operator. A similar sized conventional rig might require a crew of twenty. This manifests as a reduced operating cost. The load monitoring systems can provide performance benefits for superyacht owners intending to race, or aiming to reduce fuel costs. For both Dynarigs a readout is displayed showing the driving force developed, the simultaneous heeling moment and the ratio between them. Using these metrics, the operator can find the optimum trim of the rigs for the conditions.

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The continual recording and archiving of load data and contextual information provides a history for deciding fault in insurance and warranty claims. If benign, it may permit a reduced requirement for rig lift-out and inspection. This is particularly the case for freestanding rigs with low risks from rigging terminal failure. The cost of a full inspection can be very high, as large rigs are typically craned out onto the dock for access. Magma Structures are working with classification societies and insurance companies to promote inspections without craning out, supported by load data history. The load data from transport, craning and mast stepping operations is also important, as these can impose unusual loads on the structure and are also of interest to insurers, manufacturers and classification societies.

Lastly for the rig engineers on these huge, multi-sparred yachts the load history is a valuable dataset. Part of the trade off in agreeing a warranty is access to the load data for the warranty period. Mining the dataset for significant load events can feed into loadcases for future projects, as will be shown in this paper. This allows savings on build costs for these projects, and provides supporting evidence when seeking to obtain approval from classification societies and influence future design guidelines. In the event of a failure, access to the data would provide vital information to understand what has gone wrong. The Maltese Falcon is as advanced today as she was when launched and her systems are designed in such a way as to allow the latest computations, server, communications and archiving technologies to be updated on her, as they become available, something that the continuous technical investment on the Maltese Falcon achieves, in order to stay at the forefront and cutting edge of her genre of automated superyachts

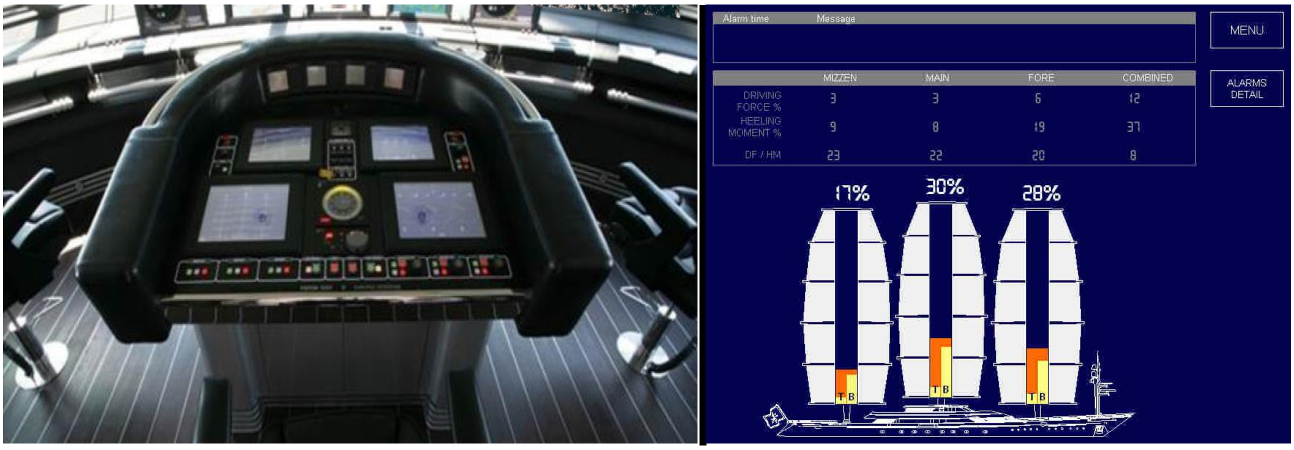

Figure 3 *Maltese Falcon bridge sailing control panel (Left) and mast load display graphic (Right)*

3. LOAD MONITORING SYSTEM DESIGN

A through life load monitoring system has been developed for the superyacht application. A minimal outline system specification is presented here. Each system is customized and integrated with the vessel systems.

3.1 Specification

The load monitoring system shall

- provide simple and stable load indicators and alarms for the bridge operator for each mast;
- endure a marine environment with an operational life of 10 years, with minimal maintenance;
- measure strains in the mast structure using sensors that provide longevity, accuracy, repeatability, corrosion resistance, are temperature compensated, non-conductive and can be surface bonded to the composite structure;
- assemble from modular, supportable components, to ensure similarity between systems and simplify maintenance;
- calculate load and strain outputs in real time from measurements based on rig structural parameters;
- operate through the life of the vessel and log data continually, accumulating the data on an archive disk;
- collect and log contextual data from the ship systems and log them alongside the strains and loads;
- send a daily email of condensed data to the design office, for warranty purposes;
- send an email snapshot of data to the design office in the event of an alarm, for warranty purposes;
- monitor and record strains during lifting and transport operations, when the rigs are separated from the vessel.

3.2 Fibre Optic Strain Sensing

Key to load monitoring in composite structures such as these is the use of Fibre Bragg Grating (FBG) sensor technology for measuring strain. This technology was originally an offshoot from telecommunications research and development. The FBG sensor itself is an interference pattern marked into an optical fibre by laser. This is read by a Fibre Sensor Interrogator (FSI), an opto-electronics device which emits a pulse of light that is reflected from the sensors and measured when it returns to the FSI. Sensors can be distinguished along the same fibre by the time delay. This is known as Time Division Multiplexing (Lloyd et al (2004)). As an FBG attached to the structure shortens or lengthens with strain, the spacing of the grating pattern changes, and therefore the reflected wavelength changes, indicating the strain.

The Maltese Falcon was a pioneering application for the technology as a permanent system, although sea trials had been carried out on other large yachts e.g. Read et al (2000) & Everall et al. (2000). The longevity and ability to measure reliable, absolute strains even in harsh environments with cyclic loading is essential, and it would not be feasible to rely on conventional metallic strain gauges, which fatigue, corrode and drift all to a much greater extent. There are no other commercially available practical alternatives.

A custom array of FBG sensors, along a fibre, is embedded within composite patches which are connected together by clad cables (Volanthen et al (2006)). For a superyacht rig these patch arrays are then adhesively bonded to the inside surface of the mast for protection and aesthetics. Sensors are located in order to pick up particular structural strains, so that global loads can be calculated. An FSI is located at the base of each mast and connected to the fibres. The FSI digitally transmits the sensor wavelength to the processing system, where the strains are calculated.

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3.3 System Architecture

A typical system architecture is shown in Figure 4.

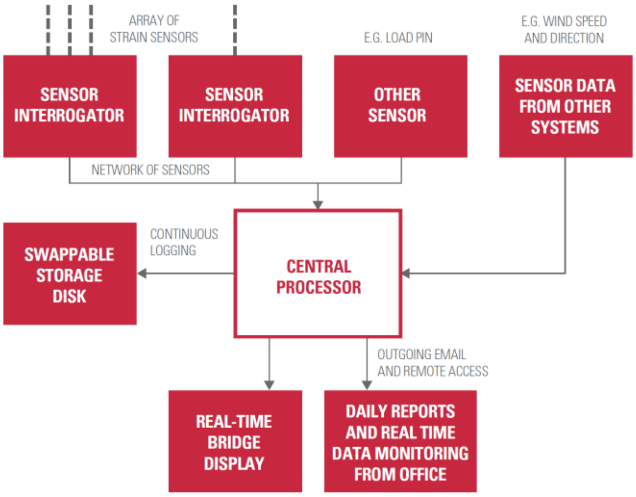

Figure 4 *Typical System Architecture, power distribution network not shown*

4. INSTALLED LOAD MONITORING SYSTEMS

4.1 Maltese Falcon

The SY Maltese Falcon is an 87m sailing superyacht, the first of the Dyna Rigs, with three freestanding 57m tall carbon fibre masts, each supporting cross-yards and sails. She has, since launch in 2006, covered over 100,000 miles at sea, mostly under sail, including a number of transatlantic and transpacific cruises. She has engaged in short course racing in over 10 regattas, has been victorious in three Perini Navi cups, and has scored numerous race wins. She has raced in the Atlantic Superyacht Race. The easy handling enables the vessel to sail where otherwise rigged vessels would motor. Full sail can be set, or recovered, within 6 minutes by automated systems. The vessel can be manoeuvred under sail by one person and it can tack, gybe and alter course at any time without preparation. She can even be sailed off her moorings (Perkins et al (2004)).

Fibre optic strain monitoring systems were used, not only on the finished yacht, but also for design validation and testing. A one-sixth scale model of the mast section in bending was instrumented with FBG sensors and tested to failure, a full size yard was monitored in a structural test and the data from the complete rigs was used to ratify loads (Perkins et al (2004)).

The innovative use of fibre optic sensors to provide loads to the bridge fitted the revolutionary design philosophy of the vessel. The system was included in order to improve safety by giving advance warning to the crew that the operational limits are near (Perkins et al (2004)), to provide the basis of post event evaluation of loadcases and to help ascertain the probability of damage (Roberts et al (2004)). A total of 60 FBG sensors measure torsion and bending at the deck, plus bending at higher stations.

The system installed on Maltese Falcon has proved to be reliable, and has operated continuously with no failures of sensors or other components to date.

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4.2 Sail Yacht A

Sail Yacht A (Figure 2) will be the world's largest private sailing yacht. She is 143m in length with three carbon fibre freestanding masts over 90m in height, the largest in the world, supporting a total sail area of 4558m^2. The masts have now been stepped in the hull and the complete vessel will be delivered in 2017. She also features an automated sailing system.

The mast load monitoring system is similar to that of the Maltese Falcon, but with design starting from a clean sheet. The fibre optic patches are now a mature, ruggedized technology and the FSIs are refined production units. The processor and communication terminals are built from upgraded, industrial components with a low expected failure rate. Due to the enormous size of the vessel, cable runs between masts are longer than the 100m range of copper cables and so use fibre optic links. To make the data more easily available to the designers, an email function has been introduced to send out daily emails and immediate event based emails to the office, over the vessel satellite link.. A new set of loading calculations were derived for the novel rig concept.

A loading bar with percentage design capacity will be displayed on the bridge for each mast. The operator will use this, along with other readouts, such as vang and mainsheet loads, to decide how the vessel is sailed. Warnings and alarms will trigger if critical thresholds are reached.

4.3 Second Dynarigged vessel

This, three-masted Dyna Rigged vessel being built is a step up in size from the 89m Maltese Falcon, with the rig scaled in proportion. This vessel will also be launched in 2017.

The mast load monitoring system is the same model as installed in Sail Yacht A. Architecture and major components are identical and only the load calculations are different. This has allowed economy of scale savings in design, production, installation and (eventually) support and maintenance. The long manufacturer support lifetimes and modularity of the components used means that future systems will need minimal changes to the design.

5. MALTESE FALCON DATA INVESTIGATION

The data collected from Maltese Falcon covers 8 years from 2006 to 2014 and totals 39GB. This data includes loads, strains, sail set data, performance metrics, apparent wind speed and direction as well as display percentages and alarm status. Over this time period the vessel has experienced a huge variety of conditions, sail sets and manoeuvres. Data has been captured for tacks, gybes, steady state sailing at all wind angles and strengths over 50kts, racing, passage making, motoring and tied to the dock. The system continues to display , record and archive as required.

We consider some summary data as a starting point: From the sail counter summary in Table 1 we can see that the main lower topsail has been used for the longest total duration of 5121 hours, understandably because it is low down in the center of the sail plan, but that the course (the lowest sail) on the foremast, has been set and furled 1105 times, by far the most often, perhaps because it is unfurled for short periods to blow the bow off the wind. This information is available to the crew in real-time and is used like a mileage indicator for the nominal life of each sail. This output is also important feedback to the rig designers and sailmakers on the longevity of the sails and rig components.

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Table 1 *Maltese Falcon individual sail sets and usage hours between 06/2006 and 03/2014*

	Course	Lower Topsail	Upper Topsail	Topgallant	Royal	
Mizzen	879	784	862	745	599	**Sail Sets**
Main	735	789	906	858	630	
Fore	1105	755	794	670	692	
Mizzen	4395	4922	4440	3426	2246	**Usage, hours**
Main	4699	5121	4760	3528	2648	
Fore	5042	4734	4660	3175	2900	

In order to extract useful load cases from the large volume of data, it is necessary to first mine the data for events causing high structural strains. It is these high strain events that indicate the edge of the operational envelope in practice. In general, the structure will be designed based on loadcases that reflect such infrequent marginal events, rather than the loads from everyday sailing conditions. They will also dominate any accumulated damage; this is particularly so for carbon fibre since it has a high theoretical fatigue exponent (Harris (2003)).

The process is described as follows: 1) Rank the 24 hour data files in order according to their maximum absolute strain values. 2) Starting from the file with highest strain, plot the strain and identify the highest strain events. 3) Continue through the files until the 5 highest strain events have been found.

This process is repeated for each mast and strain channel. Table 2 shows the maximum strain value seen in each channel over the time period investigated. Bending strains are related to the extreme 0° fibre perpendicular to the moment. Torsion strains are related to the axial strain in the 45° fibres. Station 1 is mid span between yard 1 and 2, Station 2 between 2 and 3, etc. From the high strain load cases found, three have been selected as case studies for this paper.

Table 2. *Maximum Absolute Strains (με) for each strain channel, between 07/2006 and 06/2008*

Max Abs Strains (με)	Mizzenmast	Mainmast	Foremast
My Bending @ Deck	649	662	342
Mx Bending @ Deck	720	817[2]	897[3]
Mx Bending @ Station 1	412	686	770
Mx Bending @ Station 2	674	694	751
Mx Bending @ Station 3	516	675	636
Mx Bending @ Station 4	393	460	415
Mx Bending @ Station 5	258	307	166
Mz Torsion @ Deck	182	217[1]	132

/[1]/[2]/[3] Selected for case studies 1-3

The wind conditions, sailing trim and load values for each case are summarised in Figure 6 and Table 2. Sign conventions are consistent with Figure 5. Case 1 is deep-reefed broad-reaching with apparent wind up to 52 knots. Case 2 and 3 are upwind in 19 knots apparent with full sail and in 26 knots apparent with royal off. One mast is considered for each case in isolation, and the data is examined for a minute before and after the peak. For all cases the load value calculated for the bridge is in the order of 100%, which corresponds to maximum operational, rather than survival loadcases.

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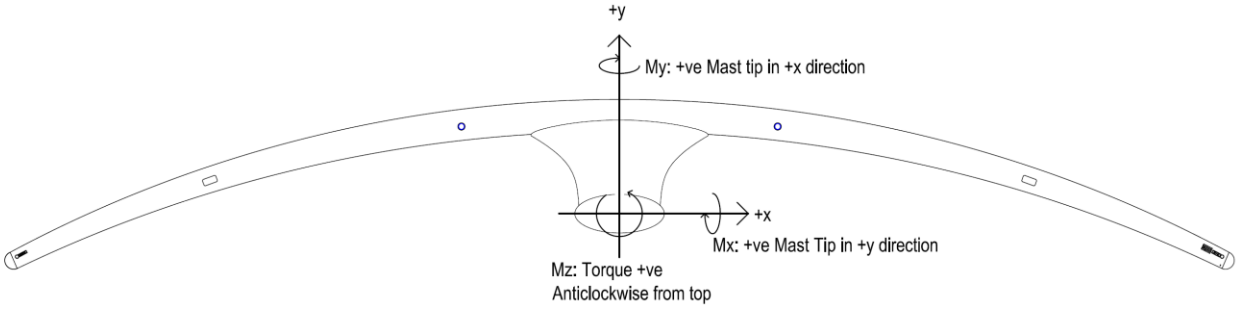

Figure 5 *Dyna Rig bending and torsion sign conventions, in mast reference frame*

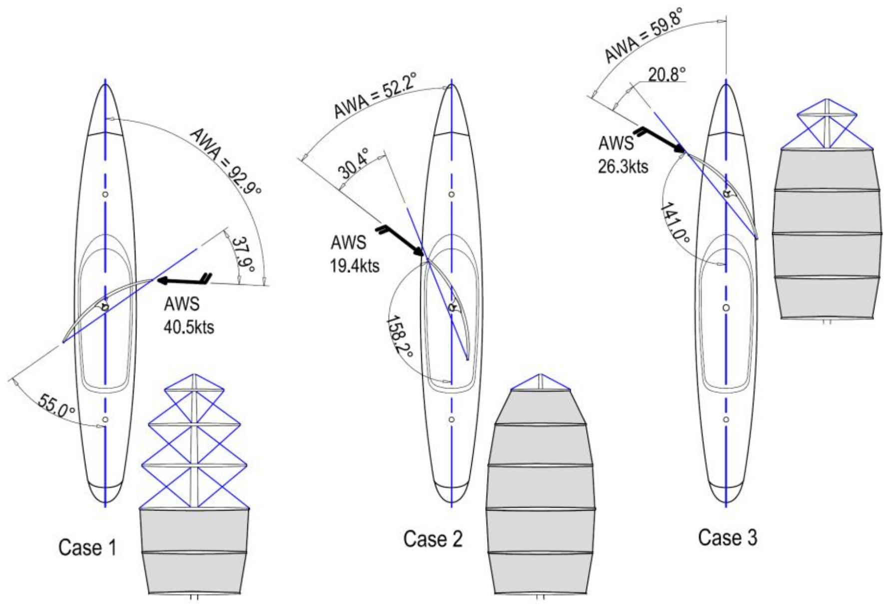

Figure 6 *Apparent wind, sail set and trim conditions for 3 cases (2 minute average*)

Table 3. *Peak load and windspeed information for 3 cases*

	Case 1	Case 2	Case 3
Date	12/11/2006	02/08/2006	02/02/2007
Mean Apparent Wind Speed, kts	40.5	19.4	26.3
Peak Apparent Gust Speed, kts	52.2	21.9	28.6
Peak Load Display Value…	110%	86%	83%
…for Loading Bar	Mainmast Torque	Mainmast Combined Bend & Torque	Foremast Combined Bend & Torque

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5.1 High Load Case 1

The Maltese Falcon was in passage in a strong mistral wind. The torsion strain at mainmast deck peaks at 217µε, plotted in Figure 7. This corresponds to 442kNm of torque, which is above the operational limit of 403kNm set for the mast rotation actuator (with safety margin!), hence the 110% displayed. In the minute beforehand the torsion strain, bending strain (Figure 8) and apparent wind speed (Figure 9) oscillate in phase with a consistent period of 11s. It is likely that the vessel is rolling and that the inertia of the yards and sails acting at a horizontal offset from the mast contribute the varying component on top of the torsion due to wind loading. The average torsion strain over 2 minutes is only 111µε. The gust load factor from the average 40 knots to peak 51 knots is $(51/40.5)^2$ = 1.6, which is not sufficient alone to cause the observed increase in bending or torsion. To clarify such situations data from later systems is to include heel and pitch channels.

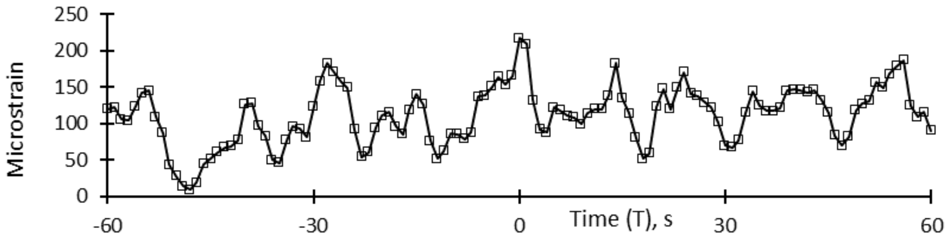

Figure 7 *Case 1 Torsion strain: Axial strain in mainmast deck +45 fibre sensors*

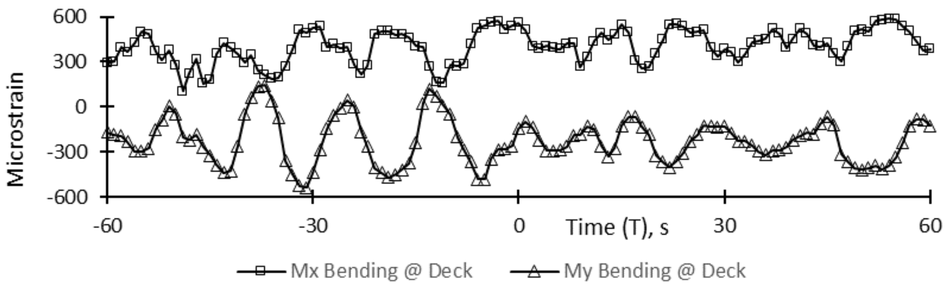

Figure 8 *Case 1 Bending strain: Axial strain in mainmast deck 0° fibre sensors for both axes*

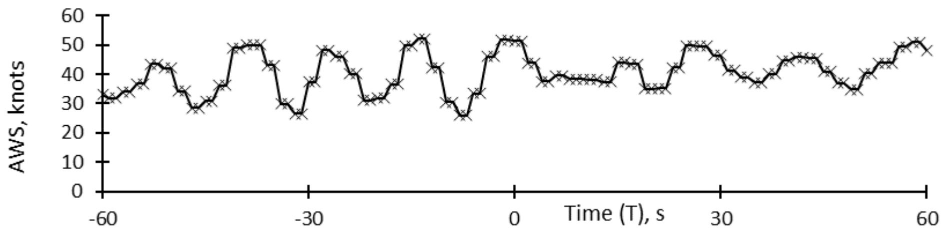

Figure 9 *Case 1 Apparent Wind Speed: Apparent wind measured at mainmast head*

5.2 High Load Case 2

The Maltese Falcon is sailing upwind with full sail in a mean apparent wind speed of 19.4 knots, which remains steady. The Mx bending strain at deck in Figure 10 gradually increases from 500µε until a peak of 817µε. The apparent wind angle moves aft by around 10° in Figure 11, increasing the angle of attack of the rig and probably causing the peak load. The effects of smaller oscillations in wind angle can be seen in the bending data from T=-60 to T=-40s. This may be due to either wind shifts or changes in heading. Following the peak load, the wind moves forward and the mast rotation angle is eased from 160° to 149° by T=+40s, possibly an operator response to the high displayed load. The bending strain drops to 450µε as a result.

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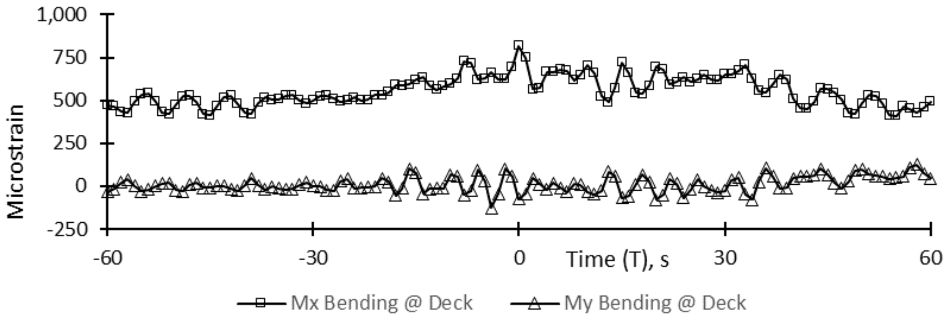

Figure 10 *Case 2 Bending strain: Axial strain in mainmast deck 0° fibre sensors for both axes*

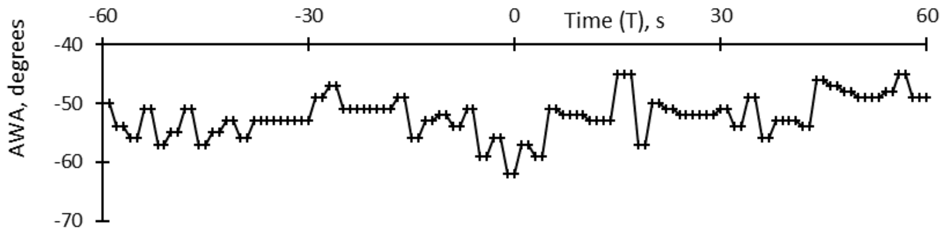

Figure 11 *Case 2 Apparent Wind Angle: Apparent wind measured at mainmast head*

5.3 High Load Case 3

Case 3 is similar to Case 2, the clear differences being a higher windspeed and a reefed royal. Figure 12 shows how the Mx bending strain varies in concert at all stations up the mast, due to changes in inflow conditions. Like Case 2, the windspeed is steady and the peak in Mx strains, up to 897με at the deck, is synchronized with a large oscillation of apparent wind angle.

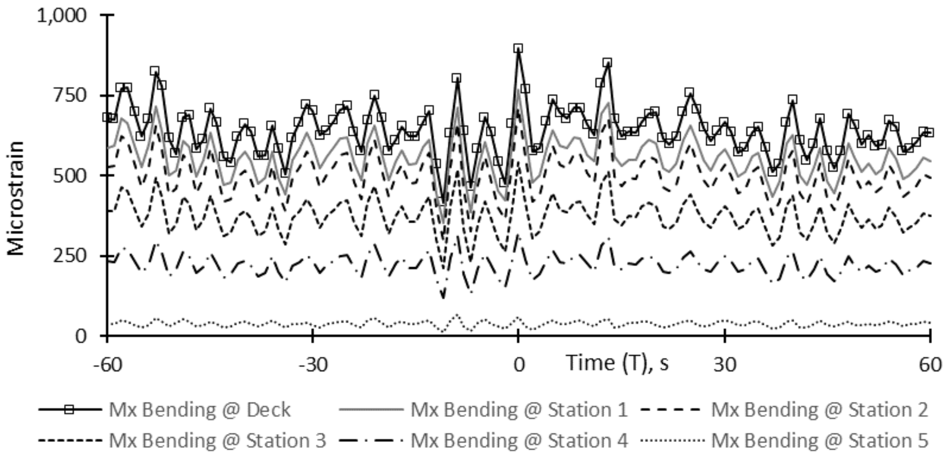

Figure 12 *Case 3 Bending strain: Axial strain in foremast 0° fibre sensors measuring bending about x axis*

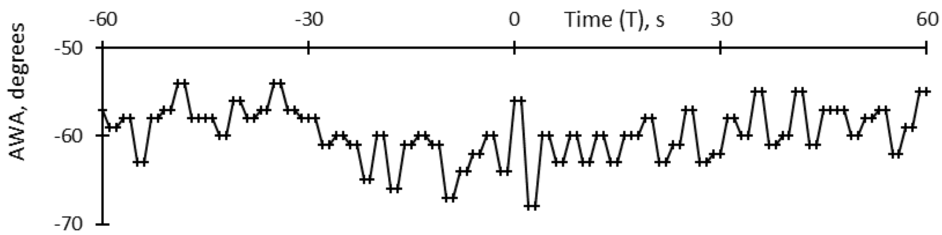

Figure 13 *Case 3 Apparent Wind Angle: Apparent wind measured at foremast head*

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5.4 Comparison with Theory

It is instructive to compare the sailing strains against some theoretical calculations. All channels are averaged over the two minutes to approximate steady state values. The predicted sail forces are then calculated from the averaged wind speed and rig incidence inputs, applying sail plan geometry and wind tunnel lift, drag and centre of effort calculations from wind tunnel tests, plus estimated wind shear profile. The resulting moments are fed into beam section calculations, using mast structural and material parameters to predict a strain at each station.

The comparisons are made in Figure 14 to Figure 16 for Cases 1-3. In general the profile of Mx strain up the mast is a good match. For Cases 2 and 3 the My strain parallel to the yard is predicted and measured as close to zero. However for Case 1 the measured value is nearly double, although still a low value. It is possible that some of these differences seen in deck bending strain are due to steady-state vessel heel and the self-weight of the rig, which is not included in the predictions. In particular for Case 1 the mast is rotated so that the self-weight will bend the mast to induce an My moment.

The high torsion strain for Case 1 is close to prediction, suggesting a centre of effort not far from the 43% chord assumed from wind tunnel data for full sail, despite a lower aspect ratio. For Cases 2 and 3 the torque is much lower than predicted, implying a center of effort closer to mid chord than the 40% and 37% from wind tunnel data. A possible explanation is that the rig and sail deformations act to soften the leading edge and move the camber and centre of pressure aft under load.

This agreement of theory and measurement is sufficient for design purposes, given that these global strain values are significantly below the typical microcracking level of around 4000με in composites (Harris (2003)). However to understand where the errors are introduced it would be necessary to take each link in the chain and separately validate them: wind measurement, strain measurement, aerodynamics, wind shear profile, material properties, vessel motions and structural parameters. This is part of the ongoing development process.

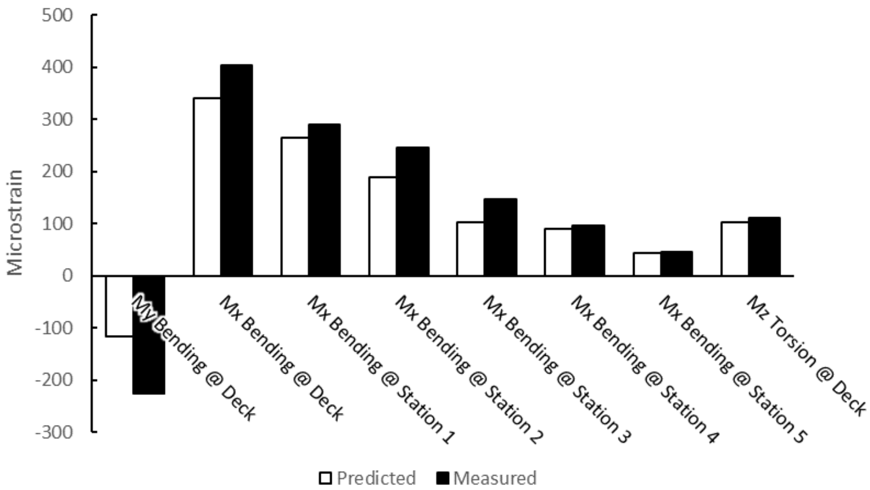

Figure 14 *Case 1 Comparison of Predicted vs. Measured averaged strain*

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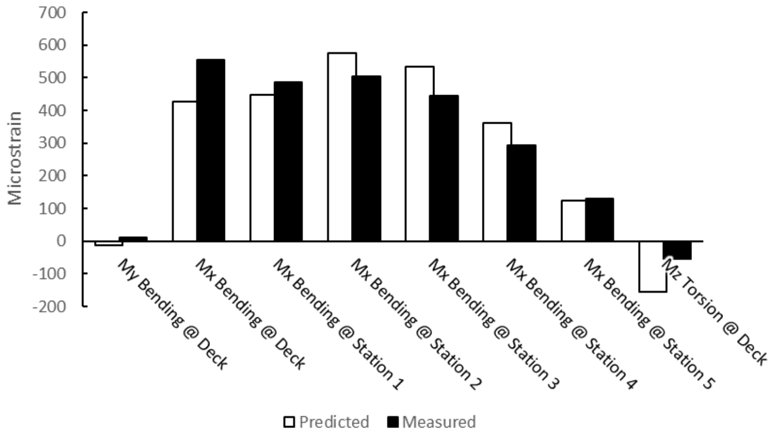

Figure 15 *Case 2 Comparison of Predicted vs. Measured averaged strain*

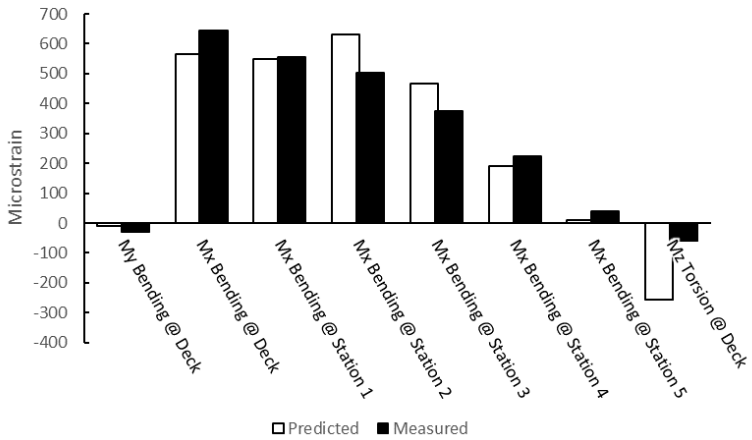

Figure 16 *Case 3 Comparison of Predicted vs. Measured averaged strain*

6. CONCLUSIONS

The data analysis from the Maltese Falcon has shown the value of through life load monitoring for superyacht applications. Sail set data over the lifetime of the vessel can be used for planning maintenance and understanding component life. By mining through the load history, some major load events experienced by the rigs have been identified and analyzed. These can be lifted from anywhere out of the long-term data, not just an initial sailing trial of a few weeks when designers might be on board. Contextual data collected from the other ship systems has been used to suggest causes of the high strains. Operator actions before and after the high strain occurred can be seen in the data, helping to understand how the vessel is being sailed. These load cases help the designers to define where the edges of the operational envelope occur in practice, and to compare and validate with design calculations. This encourages questions to be asked about, for example, centre of effort position and whether the real rig corresponds with the model test results. The mast load monitoring system has been compared to a "real-life wind tunnel model" (Roberts et al (2004)).

Through life monitoring systems have been installed on two of the largest new sailing superyachts, soon to enter operation. These new monitoring systems have additional features and have been developed with mature and robust technologies. Their presence has allowed the rig to be warrantied, may lower rig insurance costs, and will reduce the sailing risk with clear bridge displays of load relative to operational limits. The data downloaded from these systems will be welcomed by owners, insurers, designers and classification societies.

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