Insights from the Load Monitoring Program for the 2014-2015 Volvo Ocean Race

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ABSTRACT

This paper describes insights into keel and rigging loads obtained through a data acquisition system fitted on the fleet of Volvo 65 yachts during the 2014-2015 Volvo Ocean Race. In the first part, keel fin stress spectra are derived from traces of canting keel ram pressures and keel angle; these are reviewed and compared against equivalent spectra obtained by applying methods proposed by Det Norske Veritas - Germanischer Lloyd (“DNVGL”) guidelines and the ISO 12215 standard. The differences between stress spectra and their validity are discussed, considering two types of keel: milled from a monolithic cast of steel, and fabricated from welded metal sheets. The second part discusses predicted and actual rigging working loads for the Volvo 65 yachts, and considers how safety factors vary between design loads proposed by DNVGL and actual recorded loads.

NOTATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\rho$</td>
<td>Density of water ($kg/m^3$)</td>
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<tr>
<td>$a_{sv}$</td>
<td>Vertical surface acceleration ($m/s^2$)</td>
</tr>
<tr>
<td>$CDR$</td>
<td>Cumulative damage ratio</td>
</tr>
<tr>
<td>$DAQ$</td>
<td>Data Acquisition</td>
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<tr>
<td>$FAT$</td>
<td>Classification reference to S-N curve</td>
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<tr>
<td>$GPS$</td>
<td>Global Positioning System</td>
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<tr>
<td>$H$</td>
<td>Wave height (m)</td>
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<tr>
<td>$IMU$</td>
<td>Inertial Measuring Unit</td>
</tr>
<tr>
<td>$LCG$</td>
<td>Location of Centre of Gravity</td>
</tr>
<tr>
<td>$LJB$</td>
<td>Lightweight Junction Box</td>
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<tr>
<td>$LLB$</td>
<td>Lightweight Logger Box</td>
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<tr>
<td>$n_i$</td>
<td>number of cycles at given stress level “i”</td>
</tr>
<tr>
<td>$N_i$</td>
<td>average number of cycles to failure at given stress level “i”</td>
</tr>
<tr>
<td>$TWA$</td>
<td>True wind angle (degrees)</td>
</tr>
<tr>
<td>$TWS$</td>
<td>True wind speed (knots)</td>
</tr>
<tr>
<td>$VO65$</td>
<td>Volvo 65 yacht</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>Wave encounter frequency (rad/s)</td>
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1. INTRODUCTION

For the first time in history, the 2014-2015 edition of the Volvo Ocean Race has been competed in with a fleet of one-design offshore racing yachts (the “VO65”). Green Marine, a specialist of high performance composite structures based in the United Kingdom, has coordinated the work of a consortium of composite builders including Decision S.A., Multiplast, and Persico S.P.A, while Farr Yacht Design (FYD) has been responsible for the design of the yachts, including the composite structure engineering. Gurit’s engineering team has been engaged by Farr Yacht Design to provide finite element analysis (FEA) to support the VO65 design.

Green Marine has also been responsible for assembling and fitting out the VO65s and providing overall quality control to guarantee that all the yachts would meet the strict “one-design” rule.

As part of their endeavour, Green Marine has taken the initiative to have bespoke data acquisition (DAQ) systems fitted to all seven Volvo 65 yachts that have entered the 2014-15 Volvo Ocean Race. The systems have recorded rig loads, keel ram pressure, keel angle, acceleration and sailing parameters obtained from the navigation instruments. Gurit has been responsible for specifying the data acquisition equipment, assisting Green Marine through the installation and commissioning stages, creating an algorithm to program the DAQ system, and for analysing all the recorded data and reporting the results to Green Marine and to the shore crew before and during the race.

The main purposes of the load monitoring system were:

- to monitor (and record continuously whilst sailing) the loads on all the main items of standing rigging, canting keel and rudder stocks, through-out the life of the yachts
- to provide the racing crew with real-time feedback on the load and slamming acceleration levels experienced while sailing
• to allow in depth analysis of loads at the end of each leg of the race to inform the decisions of the maintenance teams.

• to provide additional knowledge on the loads that VO65s are subject to and verify the validity of the design assumptions, with an aim to improving the reliability of offshore racing yacht structures.

In total, approximately 14030 hours of continuous recording were produced during the race and many more hours during the lead up including during the 2014 Round-Britain-and-Ireland race and multiple transatlantic crossings. This is believed to be the largest and most comprehensive set of data collected on offshore racing yachts to date (1) (2). It is a rare event for yacht builders and designers to have access to such an array of data. Green Marine has worked with Gurit to convert this wealth of information into useful insight about offshore racing yacht structures, so far focusing particularly on two subjects: fatigue loading of keel structures and maximum loads of rigging components measured while underway.

While there is a significant body of scientific literature and design guidelines covering the subject of fatigue loading for large commercial vessels (e.g. (3) and (4)), very little information has been published that applies to offshore sailing yachts. Fatigue in racing yachts is typically associated with failure of keels. Indeed, there are several reported cases of yachts capsizing due to keel loss or having to complete races under reduced sail as they lost their keel before reaching the finish line. Often, fatigue is quoted among the likely causes of these accidents (5); however historical records of the loads endured by keel structures are rarely available.

The first part of this paper focuses on the characteristics of stress spectra applicable to the keel structures of offshore racing yachts like the VO65s and delves into the different implications on the design of milled and fabricated metal keel fins. It compares a fatigue assessment achieved following existing guidelines and a fatigue assessment based on the fatigue loading recorded while sailing. In order to compare those methods, two hypothetical keels are considered, a milled and a fabricated keel, under the hypothesis that both are designed to meet the minimum static strength requirements to withstand the DNVGL static heeled loadcase (6).

Rig failure is another key factor that forces high performance sailing yachts to retire from racing. As well as disappointing and expensive, rig failure is a primary concern for the safety of the crew. Gaining a better understanding of the rig loads experienced during sailing is critical for increasing the reliability of racing yachts while continuing to improve their performance.

The second part of this study focuses on the maximum working rig loads measured during the 2014-2015 Volvo Ocean Race and presents a comparison between these, the typical design loads that Gurit would have used to design the structure supporting the rigging and the design loads recommended by the DNVGL (7).

2. VOLVO 65 DATA ACQUISITION SYSTEM

The primary function of the load monitoring system was to log selected data from force and motion sensors whenever the yacht is sailing. The data acquisition system was set up to start logging either when the boat speed sensor measured more than 1 knot or when the heel angle was greater than 20°; no intervention from the sailors was required to start or stop the acquisition. All of the yachts were fitted with the same set of sensors, shown in Figure 1, including:

• One triaxial accelerometer in way of the bow, measuring the three components of linear acceleration

• Inertial measurement unit (IMU), fitted close to the LCG, measuring heel and trim angle, roll, pitch and yaw angular velocity and the three components of linear acceleration

• Two pressure transducers fitted on the keel canting hydraulic system measuring pressures acting inside the keel rams with a pressure range from 0-700 bar and ±1% accuracy

• One sensor measuring the cant angle of the keel

• Strain gauges fitted on both rudder stocks measuring strains induced by lateral bending

• Eleven load cells measuring tension, each with an accuracy of ±2%, in way of the following rigging components:
  • ‘J1’ stay
  • ‘J2’ stay
  • ‘J3’ stay
  • ‘V1’ shrouds (port and starboard)
  • ‘D1’ shrouds (port and starboard)
  • Mainsheet
  • Runners (port and starboard)
  • Bobstay
A Cosworth lightweight logger box (LLB) logging unit was used, in combination with a Cosworth lightweight junction box (LJB), to process and store the data from all of the sensors; the unit had a storage capacity of 1Gb which allowed for the following variables to be logged continuously throughout the race:

- Sailing performance Data (Boat speed, TWS, TWA, GPS Latitude and Longitude, Rudder angle, Deflector settings), logged at a frequency of 1Hz
- Rigging loads, logged at a frequency of 10Hz
- Keel ram pressures, logged at a frequency of 2Hz

Besides the continuous logging, the LLB unit was programmed to perform “burst” logging when either accelerations, keel loads or rudder deflections exceeded set thresholds. Burst logs typically included all motion variables logged at 100Hz and keel ram and rudder loads logged at 50 Hz. The burst logs covered a period of time spanning between 4 seconds prior to the trigger event and 10 seconds after. The data was offloaded from the logging units at the end of every leg. In particular, the data was logged into buffer memory at the burst frequency and every minute a check was made to assess whether any value exceeded the threshold. If this was the case, the data points spanning 4 seconds before the event and 10 seconds after were kept while the other data points were decimated to the continuous acquisition frequency. In the case of acceleration measurements, the data was entirely erased if the threshold value was not met. This was done in order to obtain a record of all significant loads and events at high sampling frequency and for the entirety of each leg without exceeding the storage capacity of the logging unit.

3. KEEL LOADS ASSESSMENT

Some of the first insights that have been obtained from the complete data set are about the magnitude of the maximum loads experienced by the keel structures during the race and about the characteristics of fatigue loading that affects keels and their supporting structures.

3.1. Maximum Dynamic Keel Loads

The maximum dynamic load on the keel was calculated from the keel ram pressure. If a keel was designed to the maximum allowable of DNVGL static loadcase it would be designed for a 1g vertical acceleration with the yacht heeled 30 degrees and the keel fully canted (40 degrees) and material properties reduced with a partial material factor, with an additional partial load factor (“c_d”) of 1.4 to account for canting keel configuration (6).

The partial material factor (“\( q_m \)”) on steel properties is dependent on the yield strength of the steel used. It ranges from 1.96 to 2.74 for steel with yield stress ranging respectively from 235MPa to 900MPa. Thus for high strength steel (e.g. Weldox 900 with yield strength of 900 MPa) the overall static reserve factor relative to yield strength would be 3.842 (product of both partial material factor and partial load factor). The maximum force recorded in the canting keel rams would have corresponded
to a keel lateral acceleration of 1.897g. Thus, based on the keel forces measured across the entire fleet and for the duration of the whole race, the actual reserve factor between the minimum yield strength of the fin required by DNVGL and the largest estimated transient stress would have been of the order of 1.90. This number was obtained by dividing the product of partial material and load factors mentioned above by the maximum keel lateral acceleration.

$$RF = c_d \gamma_m \sin(40^\circ + 30^\circ) = \frac{1}{1.897} = 1.90$$

Note that the keels of the VO65s were designed by Farr Yacht Design for higher transverse bending strength requirements than those of the DNVGL rules; hence, their actual reserve factors relative to the highest measured transverse load were higher than the number quoted above.

3.2. Existing Standards for Keel Fatigue Assessment

3.2.1. DNVGL

Det Norske Veritas - Germanischer Lloyd (DNVGL) has published guidelines for the fatigue assessment of racing yacht keels (6). The DNVGL fatigue assessment is based on the assumption of a 5 year design life during which the yacht is expected to sail 15% of the time. During this design life the structure should not endure fatigue degradation leading to premature failure.

DNVGL considers two types of cyclic loads: inertial loads due to cyclic vertical accelerations when the yacht sails in a seaway heaving up and down, and full reversal order to establish a stress spectrum to be used for a fatigue assessment, DNVGL applies the following first principles approach:

- Stress cycles are distinguished between cycles due to motion through the waves and tacks/gybes.
- It is assumed that the yacht will spend a given percentage of its design life sailing at 4 different TWA: 45°, 90°, 135° and 180°.
- In each of these headings, a given percentage of the time sailed is spent in different sea conditions associated with a given wave length and amplitude, and at a given heel angle.
- The number of stress cycles due to waves is calculated from the encounter frequency and the time spent in each condition.
- The stress range is calculated based on the vertical acceleration, heel angle, keel cant angle and the nominal stress in the keel in the static “90 degree” load case.
- Vertical acceleration (“$$a_{vw}$$”) is calculated based on the relationship between wave height (“$$H$$”) and encounter frequency (“$$\omega$$”), given below:

$$a_{vw} = \frac{H \cdot \omega^2}{2}$$

- The yacht is considered to tack or gybe 30 times each day.
- The stress range due to tacks is calculated based on the nominal stress in the “90 degree” load case and the angle of the keel to vertical.
- All stress cycles are considered to be tension-tension, no consideration is made over the mean stress of each cycle. This remains a conservative assumption for metals and is reflected in the method by the choice of “S-N” curve.

3.2.2. ISO Standard 12215 PART 9

ISO standard 12215 part 9 (8) contains a simplified method for assessing keel fatigue strength. The method essentially stipulates a stress spectrum to be used for the fatigue assessment. It considers that over its operational life, the yacht will endure 8 million stress cycles which should cover tacking and gybing, rigid body motions and flutter or vibration related phenomena. The standard assumes that 8 million cycles should cover an operational life of 25-30 years of moderate to high usage recreational sailing or 5 years of very extensive ocean racing. The design life considered by ISO is thus very similar to that considered by DNVGL.

Similarly to the DNVGL guidelines, the stress range is established on the basis of a nominal stress obtained from the static transverse load case. The peak stress range is considered as 1.5 times the nominal stress and also includes a factor to take into account specific characteristics of the keel (i.e. with/without flange, design category, canting or fixed, fabricated or solid). The factor of 1.5 is explained as such: the largest cycle will have a peak stress equal to the nominal stress multiplied by the keel type factor and a trough equal to minus half the nominal stress multiplied by the keel type factor.

Hence, it considers cycles to be an intermediate case between full-reversal and unidirectional stress (no load reversal). This is reflected by the “S-N” curve specified by ISO (8).

3.3. Fatigue assessment based on actual recorded data

On the basis of the data recorded from the race, a fatigue assessment has been performed with the following approach:

- An actual stress spectrum was derived for the keel based on the assumption that it was designed to
meet the DNVGL static design criteria (6) and subjected to the same number and amplitude of cycles as recorded during the race.

- The set of cycles recorded during the race was extrapolated to provide an equivalent design life as used by DNVGL and ISO. That is, the numbers of cycles recorded during the race were multiplied by 274/141 where 141 was the number of days of recording during the race and 274 days is the DNVGL fatigue design life.

- The partial damage factors corresponding to the nominal load spectra obtained by applying the DNVGL and ISO methods were compared with those obtained from the extrapolation of measured data.

- The cumulative damage ratios (CDR) obtained with the DNVGL and ISO methods for both a fabricated (welded) and a milled keel design were compared with the CDR based on the measured data.

- Considerations have been made on how the DNVGL and ISO assumptions compare with actual measured data and how this affects the results of the fatigue assessment for different types of keels.

In order to compare the findings from the measured data with the predictions of the DNVGL and ISO methods, a measure of the stress cycles in the keel fin had to be derived from the data acquired during the Volvo Ocean Race. The method and its assumptions are described below.

### 3.3.1. From Ram Pressures to Accelerations

The force perpendicular to the head of the keel was obtained on the basis of the known keel structure geometry and from the logged keel cant angle and keel ram pressures. For the purpose of this investigation, the keel was considered as a rigid body and the acceleration perpendicular to the fin at its centre of gravity was derived from the force at the head of the keel (inferred from keel ram pressures) and the known weight of the keel fin and bulb.

### 3.3.2. From Acceleration to Stress

In order to translate acceleration amplitude into stress amplitude the following assumptions were made:

- When the keel is lying horizontal with 1g acceleration applied at its centre of gravity, the highest stress in the keel structure is equal to DNVGL’s allowable stress and is referred to as “nominal stress”. This assumption is legitimate for a racing yacht where the designer would typically optimise the structure to achieve the smallest acceptable reserve factor over the requirements of the design rules.

- The stress amplitude is equal to the nominal stress multiplied by the acceleration amplitude perpendicular to the keel expressed in “g”.

- Only stresses due to lateral acceleration are accounted for and the contribution of longitudinal acceleration is neglected, in-line with DNVGL provisions.

### 3.3.3. Stress Spectra

The number of stress cycles was obtained by applying a “rainflow counting” algorithm (9) on the measured accelerations. To allow direct comparison with the DNVGL method, a stress spectrum was derived from the measured data by counting stress cycles on the basis of stress amplitudes and independently from mean stress levels. In practice this means that the method did not make a distinction between tension-tension and tension-compression cycles.

### 3.3.4. Extrapolating Complete Design Spectra

The complete design spectrum that covers a design life corresponding to 15% usage during 5 years (equivalent to 274 days of continuous sailing) was obtained by scaling the number of cycles counted during the race by the ratio of design life over time logged. For reference, the total logged time over the nine VOR legs for one boat amounts to 141 days of continuous sailing, which is equivalent to 51% of DNVGL design life. The assumption is made that the data gathered during 141 days of continuous logging contain a representative sample of the stress cycles that the yacht will experience throughout its design life.

Only the data logged during offshore legs was used for the fatigue assessment. In comparison with inshore racing, the rate at which yachts tack and gybe when sailing offshore is lower. Tacks and gybes generate large amplitude stress cycles. Thus it could be argued that, by considering only the data recorded when sailing offshore, one would miss a high proportion of large amplitude stress cycles. However, Figure 6 demonstrates that the cycles with ranges of 400 MPa to 600 MPa (which are typically caused by tacks and gybes) only contribute to a CDR of 1%. Thus doubling the number of tacks would increase the CDR by 1%.

### 3.3.5. Reference S-N curves

To establish whether a keel is critical in fatigue rather than in static strength, the designer must compare the stress spectrum chosen with a reference “S-N” curve. “S-N” curves can be obtained from various sources (e.g. (10) and (8)) and are specific to a material and the detail under consideration (for example edge of a plate or butt weld).

For the present study, a fatigue assessment based on the three different stress spectra obtained as described in sections 3.2.1, 3.2.2 and 3.3.3 was performed for a
hypothetical fabricated (welded) keel and a milled keel. Four relevant S-N curves along with the three mentioned stress spectra are represented in Figure 2. The reference “S-N” curves were sourced from the International Institute of Welding (10) and from ISO standard 12215-9 (8). As “S-N” curves vary depending on the type of structural detail and alloy being considered (e.g. welded or solid plate, high or low yield strength, etc.), a curve for a “FAT” class of 140 was chosen for a milled keel fin (i.e. milled from a monolithic metal casting), and a curve for a “FAT” class of 90 was used for the assessment of a hypothetical fabricated keel. FAT 90 class corresponds to a continuous transverse butt weld which has been inspected with non-destructive testing (see (10) for a more detailed illustration of FAT classes).

3.3.6. Cumulative Damage Ratio
In a structure subjected to variable amplitude cyclic loading, the fatigue life is usually assessed using the “Palmgren-Miner” rule, which derives the “cumulative damage ratio” from the summation of the “partial damage factors”.

Partial damage factors are calculated as the ratio of the number of cycles (“n_i”) at a given stress range versus the allowable number of cycles (“N_i”) at that stress range before fatigue failure occurs. “k” is the number of sets of cycles at given stress range. This allowable number of cycles is typically sourced from the S-N curve that is relevant to the material and structural item under consideration.

Figure 3, Figure 4 and Figure 5 show plots of partial damage factors and their corresponding stress ranges, obtained for a milled keel respectively from DNVGL, ISO and measured VO65 stress spectra. Figure 6, Figure 7 and Figure 8 show similar plots, but for a fabricated keel. They are useful for assessing which type of cyclic loading has the greatest effect on the fatigue life of the structure. In the case of DNVGL, it is apparent that the high number of tacks and gybes assumed and the corresponding large amplitude stress cycles would be the primary contributor to fatigue of the milled keel fin.

However, Figure 5 shows that large amplitude stress cycles measured on the VO65 are not the main cause of fatigue, as these racing yachts complete much fewer tacks/gybes while racing offshore than the DNVGL method assumes. This confirms that the assumption made in 3.3.4 of scaling the number of cycles by the ratio of design life to
logged time is suitable: any very large amplitude cycle with small probability of occurrence that could have been missed would not have greatly influenced the CDR.

Figure 3: partial damage factor vs stress ranges obtained from DNVGL guidelines for a milled keel

Figure 4: partial damage factor vs stress ranges for ISO standard for a milled keel

Figure 5: partial damage factor vs stress ranges for extrapolated Volvo 65 measured data for a milled keel

Figure 6: partial damage factor vs stress ranges obtained from DNVGL guidelines for a fabricated keel

Figure 7: partial damage factor vs stress ranges for ISO standard for a fabricated keel
Figure 8: partial damage factor vs stress ranges for extrapolated Volvo 65 measured data for a fabricated keel

Figure 9: Cumulative damage ratios

Figure 9 displays the cumulative damage ratio (CDR) expressed as a percentage obtained for both a milled (solid) and a fabricated (welded) keel using the three different stress spectra described previously. A CDR of above 50% indicates a high likelihood of premature fatigue failure and indicates that further investigation is required and CDR of 100% indicates that fatigue failure will occur (6). It is interesting to note how the fabricated keel CDR exceeds the 50% limit, with both “nominal” (DNVGL and ISO) and “actual” (from VO65 data) stress spectra. Conversely the CDR of a milled fin is consistently below 25%, irrespective of which stress spectrum is used for the fatigue assessment.

From the data represented in Figure 9, one may also understand that:

- By applying the DNVGL fatigue assessment method, a milled keel designed for DNVGL static strength criteria would be appear to be adequate to perform 2 round-the-world races without experiencing fatigue failure.
- Based on the stress cycles actually recorded during the Volvo race, the same keel would be considered to be adequate for more than 4 round-the-world races.
- Based on actual Volvo race data and using a “S-N” curve for FAT class 90 for reference, a fabricated keel fin would not be considered to be suitable for more than one round-the-world race.

The CDR of the welded keel based on the DNVGL stress spectrum is significantly higher than the CDRs obtained from the VO65 and ISO stress spectra. An explanation for this can be found in Figure 2 and Figure 6: the reference S-N curves for the fabricated fins lie well below the ones for milled fins, and the number of low stress range cycles predicted by the GL method is close to the allowable level and contributes to a very large CDR.

Based on the recorded VO65 data, low stress range cycles appear to be less numerous than predicted by the DNVGL method and thus make a lower contribution to fatigue degradation. This shows how the assumption of the number of cycles due to wave encounters (usually associated with lower stress ranges) is critical in the assessment of keel fatigue life, particularly for fabricated keels, and highlights the importance of using stress spectra derived from experiments to improve the quality of fatigue assessments.

3.4. Discussion of DNVGL and ISO standard assumptions

It is of interest to consider how the assumptions contained in both the GL and ISO fatigue assessment methods compare with the data recorded on the VO65s and how this is likely to affect the results of these methods.

3.4.1. Discussion of DNVGL Assumptions

In comparison with the results obtained from the Volvo 65 data, the DNVGL method appears to lead to a rather conservative estimate of the cumulative damage factor, particularly for fabricated (welded) fins.

For the milled keel, this is due to the large contribution of the number of tacks predicted by DNVGL on the CDR. If CDR was recalculated following the DNVGL approach but using the actual rate of tacks or gybes per day, one would obtain 12.0%, which is close to what is obtained when using the Volvo stress spectrum (10.8%).

The fabricated (welded) keel CDR as calculated per DNVGL method is mainly driven by low stress range cycles as demonstrated in Figure 6. In the DNVGL method, low stress cycles are calculated based on the assumed percentage of time spent sailing at different true wind angles, design boat speed and nominal wave length. This method is conservative but the impact of those assumptions (6) on CDR compared with CDR obtained from test data is very large and again this highlights the importance of using...
experimental data to refine the analysis. Without experimental data, the method could be refined if the boat speed used to calculate the encounter frequency with the waves was a function of boat heading and sea state rather than being one single value. Similarly, the percentage of time spent at different TWA could be a function of the design: for instance, a VO65 yacht is clearly likely to spend more time sailing at TWA of 135° than 45°.

3.4.2. Discussion of ISO Assumptions
The ISO fatigue assessment appears to lead to a slightly optimistic conclusion when compared with the assessment conducted with the stress spectrum for the acquired VO65 data. The stress spectrum in the simple fatigue assessment proposed in ISO 12215 part 9 (8) is issued from a typical stress spectrum distribution for ships. The difference between the spectra reflects the fundamental differences in the motion of a ship and of a racing yacht in waves: there is less high amplitude cycles compared with the experimental data, typically caused by tacking or gybing. However, fatigue prediction is in good correlation with experimental data as it has been shown that tacks and gybes have a small impact on the fatigue life prediction according to the experimental data.

4. RIGGING LOAD ASSESSMENT

4.1. Nature of Rig Loads
The rig of a sailing yacht experiences continuously varying loads during sailing. A set of nomenclature to describe the different load states was proposed by McEwen and Belgrano (11) as described below:

W1: Maximum steady-state load
W2: Peak dynamic load
LIMIT: Elastic limit of supporting composite structure
ULTIMATE: Break load of supporting composite structure

W1 and W2 represent real or anticipated working loads. These are used for stiffness calculations and as an input into calculating LIMIT and ULTIMATE design loads. At the LIMIT load the supporting structure should continue to perform as designed without any sign of degradation. It is expected that beyond the LIMIT load the structure may begin to yield, crack etc. but should not fail catastrophically until the ULTIMATE load is surpassed. (11)

4.2. Analysis of Rig Loads
Unfortunately there were a relatively high number of instances throughout the race when particular load cells failed either intermittently or permanently due to loss of water-tight integrity by cable connectors that were exposed on deck, thus the data has been sanity checked and filtered to remove false readings prior to the analysis.

4.2.1. Working loads
The designer of the VO65 rigs has supplied the race teams with a table detailing allowable sailing load cases. The maximum load specified for each rigging component is referred to as the “nominal W1”.

The rigging data acquired during the Volvo Ocean Race has been post-processed to determine “VO65 W1” and “VO65 W2” loads. A moving average over 25 second windows (typically equivalent to at least 5-10 wave encounters) was calculated for each load cell and the maximum value for this moving average for each load cell across the whole fleet was determined as the “VO65 W1” load for that load cell. The maximum load for a given load cell across the whole fleet and throughout the entire race was determined as the “VO65 W2” load. Thus, it must be noted that “VO65 W1” and “VO65 W2” loads do not necessarily occur on the same boat or the same leg of the race.

Furthermore, transient peak loads were calculated as the “moving maximum” over 25 seconds for each load cell; these were used to calculate the ratio of transient peak to steady state load for “VO65 W1” loads greater than 80% of the nominal W1 load. Generally, the ratio of transient peak to steady state is expected to be larger at lower loads as the increase in load makes up a larger proportion of the initial load.

Figure 10 shows (1) the ratio of “VO65 W2” over “VO65 W1”, (2) the maximum calculated ratio of transient peak over steady state load, and (3) the ratio of “VO65 W2” over nominal W1.

![Figure 10: Working load ratios](image)
“VO 65 W1” is the smallest ratio. It should also be noted that the “VO65” loads often exceeded the nominal W1 loads. It is important to observe that the maximum W1 and W2 loads in each data set never occurred within the same 25 second window. This explains why the ratio of “VO65 W2” over “VO65 W1” shown in Figure 10 above, is smaller than the largest observed ratio of transient peak over steady state.

In other words, the largest dynamic responses did not occur when the rigging experienced the highest “steady state” loads and all observed values of transient peak/steady state ratio were in line with what is typically observed for structures subject to short transient excitations with low damping.

Figure 11 shows a comparison of the W2 loads predicted according to the standard Gurit design approach (referred to as “Gurit W2”) and the actual measured “VO65 W2” loads. The Gurit design approach involves applying a safety factor over the nominal W1 load of between 1.15 and 1.6 depending on the rigging component; these factors are based on historical data records.

It can be seen from Figure 11 that the Gurit W2 loads are consistently close to the “VO65 W2” loads. The prediction of all of the rigging loads is within ±12% of the measured “VO65 W2” loads except for the bobstay tension which would seem to be overestimated by 25%.

4.2.2. Theoretical LIMIT and ULTIMATE design loads

It is important when designing the rigging support structure to ensure that it does not break before the rigging itself. The LIMIT design load of the composite support structure, which must be greater than the W2 load by some safety factor, is typically determined by the break load of the rigging. An increasing number of modern high performance sailing yachts, such as the VO65, are equipped with composite rigging. As the specification of these rigging cables tends to be driven by stiffness rather than by strength requirements, composite rigging cables end up being significantly stronger than their “stiffness-equivalent” metal rods or cables.

This means that when designing composite support structure for composite rigging, the design load would typically be higher than for metal rigging by a significant amount. Hence, to avoid being overly conservative, Gurit typically takes the break load of the stiffness equivalent metal rigging as the LIMIT load for the supporting composite structure and applies a suitable safety factor between ULTIMATE and LIMIT loads to guarantee that the ULTIMATE load for the supporting structure is greater than the break load for the composite rigging by at least 10%. The reserve factor between the Gurit determined LIMIT design load, the break load of the cable and the Gurit determined ULTIMATE design load over the “VO65 W2” loads is shown by Figure 12.

4.3. DNVGL Guidelines

DNVGL guidelines (12) recommend that the rig is analysed using finite element analysis (FEA) with load cases accounting for four sailing conditions upwind and one spinnaker case, typically at 30° of heel.

For “Nitronic 50” rod rigging, provided the working loads have been calculated by static, geometric non-linear analysis, GL recommend a minimum safety factor of 2.5 for the transverse rigging and 2.0 for the fore and aft rigging between this load and the cable break load (7).

For composite rigging, again provided the working loads have been calculated by static, geometric non-linear analysis, GL recommend that the design working load should not exceed the cable’s maximum working load as specified by the cable supplier. This maximum cable working load must either be a GL-certified value as determined by testing (13) or, in lack of such proof, a
minimum safety factor of 4.5 is applied between cable break load and design working load for transverse rigging and of 3.6 for fore/aft rigging. (7) This highlights the importance of using approved test values when designing to GL guidelines.

Furthermore, DNVGL recommends a safety factor of 1.6 between the break load of the cable (6) (12) and the design load of the composite supporting structure (here referred to as “GL ULTIMATE” load). Figure 13 shows that the factor between the ULTIMATE load as determined by Gurit over “VO65 W2” is less conservative than the factor between “GL ULTIMATE” load and “VO65 W2”, but the minimum factor is still fairly conservative at 2.07. The minimum factor between “GL ULTIMATE” load and “VO65 W2” load is 2.76. This is due to the approach of Gurit effectively using a lower safety margin over the break load of the cable for composite rigging relative to metal rigging.

Figure 13: Factors of GL ULTIMATE and GURIT ULTIMATE over VO65 W2

5. CONCLUSIONS

Valuable insights could be obtained from data collected on the VO65 fleet during the 2014-2015 Volvo Ocean Race. This paper focused on some of the findings obtained through the analysis of keel and rigging load recordings, in particular:

- On the basis of the comparison between cumulative damage ratios (CDR) obtained from actual data with CDRs from the DNVGL fatigue assessment method, the latter appears to give a conservative result when designing for fatigue. With respect to an offshore racing yacht, a correct estimate of the number of tacks and gybes is critical to improving the accuracy of the prediction of fatigue life, particularly for solid keels. Equally, the DNVGL estimate of the number of cycles due to wave encounters (small stress amplitude) may be improved in order to provide more reliable indication of fatigue life for fabricated (welded) keels.

- The stress spectrum used by ISO for the keel simple fatigue assessment leads to results of CDR close to those obtained from using a stress spectrum derived from actual measurements on a VO65, and to a slightly optimistic prediction of fatigue life for the same type of yacht.

- Based on the results of the DNVGL fatigue assessment method and on the data recorded on the VO65s, one may conclude that designing a fabricated canting keel fin only to meet DNVGL static “knock-down” load case, would result in a significant probability of fatigue failure after less than 2 round-the-world races. To avoid this type of failure, extreme care should be taken by the structural designer in:
  a) carrying out adequate fatigue analysis for the keel structure and using an appropriate stress spectrum
  b) designing the welds with higher safety factors with respect to static loads than used for the continuous parts of the keel fin
  c) designing welds to be appropriately far away from high stress zones

- The approach used by Gurit to predict peak dynamic load (W2) from maximum steady-state load (W1) for rigging components shows good correlation with the data from the Volvo 65s, but in 4/7 cases underpredicts the maximum.

- For composite rigging, Gurit use the approach of taking the break load for metal stiffness equivalent rigging as the LIMIT design load and applying a safety factor to this to obtain the ULTIMATE design load, which must be greater than the composite cable break load. The minimum reserve factor above the peak dynamic load from the Volvo 65 data for Gurit LIMIT design load is 1.38, for cable break load is 1.73 and for Gurit ULTIMATE design load is 2.07.

- The reserve factor used by DNVGL between peak dynamic loads (W2) and minimum design break load of supporting composite structure (ULTIMATE) when using composite rigging is higher than using the approach taken by Gurit to determine the ULTIMATE design load. Both methods have a reserve factor greater than 2 between ULTIMATE and cable break load.
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