ABSTRACT

One year full scale measurements available from Victoriaborg, a general cargo/container vessel with hull flare and bow flare, were analyzed to determine the effect of whipping on fatigue. The measurements utilized comprise the global strains in the midship region. From the global strains and ship’s geometric properties the hull girder bending moments were determined using a simple beam model. The wave and whipping induced hull girder bending moments and stress records were analyzed in detail.

In order to distinguish the wave frequency loads and the whipping loads, Fast Fourier Techniques were applied in order to obtain a high frequency part (whipping response), a low frequency part (wave frequency response) and the original response. Various sailing speeds up to 20 knots with a step of 4 knots were also considered.

Information on the contribution of whipping to the wave induced vertical hull girder bending moment was obtained. The horizontal hull girder bending moment with respect to the vertical hull girder bending moments was also determined.

This paper addresses the full scale monitoring campaign. Furthermore it describes the calculation methods of the measured data applied to obtain the fatigue damage originating from whipping and the wave frequency loads.

Assuming the low amplitude cycles contribute to fatigue, due to whipping the fatigue damage induced by the vertical hull girder bending moment increases with about 30%.

KEYWORDS

Full Scale Measurements; Cargo/Container Vessel; Whipping; Hull Girder Loads; Statistics; Fatigue Damage

1 INTRODUCTION

Wave and slamming induced hull girder vibrations and their fatigue effect has been an ongoing matter of concern to the industry. This paper focuses on the effect of the wave and slamming induced hull girder vibrations on the fatigue damage.

To investigate the effect of hull girder vibrations on fatigue, full-scale measurements obtained from a one year monitoring campaign onboard the Victoriaborg, a general cargo/container vessel, owned and operated by Wagenborg Shipping, was utilized. The monitoring campaign was performed within the Joint Industry Project ‘Monitoren 9000t’, which was aiming to improve the
performance of the double-hull general cargo ship, by monitoring the structure, propulsion and engine in service conditions. The monitoring campaign started during the sea trials of the Victoriaborg in December 2001, and followed by the long term measurements during service, which was completed in January 2003. The measurements comprise local stresses, hull girder stresses, propeller and slamming induced hull pressures, accelerations and ship’s wave frequency motions together with the environmental conditions like waves and wind. The study on fatigue presented in this paper only uses the stresses and hull girder loads in midship section. In the calculation of design bending moment of a ship, some assumptions were made in Classification Society rules regarding to the relationships of horizontal hull girder bending moment and whipping moment with respect to the vertical hull girder bending moment. Therefore joint statistics between the horizontal and vertical hull girder bending moments and between the wave and whipping induced hull girder bending moments were made. Furthermore the relation between whipping induced responses and the wave induced responses with respect to their effect on fatigue life was addressed.

2 PARTICULARS OF VESSEL AND MEASUREMENT ARRANGEMENT

The main particulars of the vessel are as follows:

Length over all : 132.20 m
Length between perpendiculars : 123.84 m
Breadth, moulded : 15.87 m
Depth : 9.65 m
Draft abt. : 7.73 m
Dead weight abt. : 9900 t
Class : BV ICE 1A Finnish/Swedish

Four Long Base Strain Gauges (LBSGs) were installed in the midship section between the bulkhead at frame 99 and the bulkhead at frame 102 (midherft) to obtain the hull girder bending moments. A LBSG consists of a displacement sensor installed on a pipe, which measures the lengthening (or shortening) of the hull over the pipe length (about 2 m). The LBSGs were installed in longitudinal direction, two at the tank top (port and starboard) and two in void spaces at main deck (port and starboard). By applying these sensors the overall axial membrane stresses were measured.

A review of the sensors and their locations in the global coordinate system are summarized in Table 1. The x-axis of the global coordinate system directs from aft to fwd, the y-axis directs from starboard side to port side and the z-axis directs upwards. The origin is located at the intersection of the centerline/keel/aft.

Table 1: Location of sensors

<table>
<thead>
<tr>
<th>No.</th>
<th>Sensor</th>
<th>Frame</th>
<th>X-coordinate [mm]</th>
<th>Y-coordinate [mm]</th>
<th>Z coordinate [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LBSG1</td>
<td>100.5</td>
<td>72250</td>
<td>6210</td>
<td>1150 (tanktop)</td>
</tr>
<tr>
<td>2</td>
<td>LBSG2</td>
<td>100.5</td>
<td>72250</td>
<td>-6210</td>
<td>1150 (tanktop)</td>
</tr>
<tr>
<td>3</td>
<td>LBSG4</td>
<td>100.5</td>
<td>72250</td>
<td>7000</td>
<td>9650 (main deck)</td>
</tr>
<tr>
<td>4</td>
<td>LBSG5</td>
<td>100.5</td>
<td>72250</td>
<td>-7000</td>
<td>9650 (main deck)</td>
</tr>
</tbody>
</table>

The signals of the Long Base Strain Gauges were measured directly with a central data acquisition system with large storage and processing capacity. Ship’s speed was obtained from the ship’s network and was transmitted into the measurement system via a serial line. The strains were measured with the sampling rate 200 Hz. The measurement system allows storage of the data with either 10 Hz or 200 Hz. During the measurement campaign the system was configured in the alternating way that the two sampling modes, 10 Hz and 200 Hz,
succeeding each other, with the 10 Hz mode continued for 15 minutes, followed by the 200 Hz mode continued for 2 minutes. Both the 10 Hz and 200 Hz data files were used in the analyses. The 200 Hz data files were submitted to a software post filter in order to filter the higher frequency components. The speed of the ship was sampled and stored with 2.5 Hz. During the one year monitoring campaign the vessel was sailing in the North Atlantic, Baltic Sea and one voyage to the Mediterranean Sea.

3  CALCULATION PROCEDURE FROM STRESS TO FATIGUE DAMAGE

In this chapter the method used to obtain the fatigue damage from the stress records is described. It does not concern the absolute fatigue damage, but the fatigue damage when whipping is taken into account with respect to the fatigue damage when only the wave frequency response is considered.

The signals summarized in Table 2 are input for the fatigue calculation.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Base Strain Gauge 1 (LBSG1)</td>
<td>Microstrain</td>
</tr>
<tr>
<td>Long Base Strain Gauge 2 (LBSG2)</td>
<td>Microstrain</td>
</tr>
<tr>
<td>Long Base Strain Gauge 4 (LBSG4)</td>
<td>Microstrain</td>
</tr>
<tr>
<td>Long Base Strain Gauge 5 (LBSG5)</td>
<td>Microstrain</td>
</tr>
<tr>
<td>Vertical hull girder bending moment</td>
<td>kNm</td>
</tr>
<tr>
<td>Horizontal hull girder bending moment</td>
<td>kNm</td>
</tr>
</tbody>
</table>

From the strain measurements amidships in tank top and main deck the hull girder bending moments were calculated.

3.1 Hull girder bending moments

Assuming a uniform stress distribution and uniaxial stress state at measured locations, the stresses were calculated with Hook’s law:

\[ \sigma = E \varepsilon \]  (1)

Where:

\( \sigma \) : Stresses [MPa]

\( E \) : Modulus of elasticity (210 [GPa])

\( \varepsilon \) : Strain [-]

Using the geometric properties of the ship hull girder, the hull girder bending moments were determined from the stresses. Since the positions of the LBSGs are symmetric with respect to the centre line of the ship, the vertical and horizontal hull girder moment were calculated by the following relations.

\[ M_y = \frac{I_{yy}}{4} \left( \frac{\sigma_{LBSG 1} + \sigma_{LBSG 2} + \sigma_{LBSG 4} + \sigma_{LBSG 5}}{z_{LBSG 1} - z_{LBSG 2}} \right) \]  (2)

\[ M_z = \frac{I_{zz}}{4} \left( \frac{\sigma_{LBSG 1} + \sigma_{LBSG 4} + \sigma_{LBSG 5} + \sigma_{LBSG 2}}{y_{LBSG 1} - y_{LBSG 2}} \right) \]  (3)

where:

\( M_y, M_z \) : Vertical and horizontal hull girder bending moment in midherft respectively [Nm]

\( I_{yy}, I_{zz} \) : Section moments of inertia with respect to the y-axis and the z-axis respectively [m^4]
\( \sigma_{LBSGi} \): Longitudinal stress at long base strain gauge \( i \), to be obtained from the measured strain using Hooke's law [Pa]

\( y_0, z_0 \): Coordinates ship's neutral axis [m]

\( y_{LBSGi}, z_{LBSGi} \): Coordinates LBSGi [m]

The locations of the ship’s neutral axis was obtained from Finite Element analysis performed by Bureau Veritas. The z-coordinate \( z_0 \) of the neutral axis was also calculated from the measured responses induced by the still water bending moment at the sensor locations using the following formula.

\[
\frac{z_m - z_0}{z_0 - z_t} = \frac{d\sigma_m}{d\sigma_t}
\]

where:

\( z_m \): Vertical co-ordinate of the main deck above base (\( z_m = 9650 \) [mm])

\( z_t \): Vertical co-ordinate of the tank top above base (\( z_t = 1150 \) [mm])

\( d\sigma_m \): Increment of the global stresses at the main deck [MPa]

\( d\sigma_t \): Increment of the global stresses at the tank top [MPa]

This calculated value was within 2.5% of the value obtained from the Finite Element analysis.

### 3.2 Wave frequency and whipping induced responses

In order to distinguish the wave frequency responses and the slamming induced responses, the signals summarized in Table 2 were filtered in frequency domain using Fast Fourier Techniques in a low and high frequency part. The natural frequency of ship’s first vertical bending mode equals about 1.3 Hz. Therefore the boundary was chosen such that the low frequency part (wave frequency responses) contains the signals lower than 0.67 Hz and the high frequency part (whipping responses) contains the signals above 0.67 Hz. The various signals obtained in this way are summarized in Table 3.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Total</td>
<td>Original response/load</td>
</tr>
<tr>
<td>2 Low frequency</td>
<td>Wave frequency response/load (&lt; 0.67 Hz)</td>
</tr>
<tr>
<td>3 High frequency</td>
<td>Whipping induced (&gt; 0.67 Hz)</td>
</tr>
</tbody>
</table>

All signals were filtered to remove noise. The upper cut was defined at 5 Hz. Figure 1 shows an example where extreme whipping was measured. The significant wave height during the voyage from the Baltic to Canada was about 4 meter.

### 3.3 Cycle counting distributions

In order to establish the time history of nonlinear stress with a wide band wave frequency response and a narrow band high frequency response, a cycle counting procedure is necessary. There exist a number of counting methods, but only the rainflow counting procedure is considered as appropriate, because with this method all reversal points are counted which correspond to the local elastic-plastic stress-strain behavior of the material. Each closed hysteresis loop represents a cycle \( z, 3 \).

The counting method of the variations is based on rainflow counting according the Cloormann/Seeger method. This method gives all closed hysteresis loops and is identical to the French AFNOR recommendation and the ASTM standard (variant called simplified version). The initial settings in the rainflow calculation of the hull girder bending moments and responses are summarized in Table 4.
Variations less than 2 microstrain were not counted. Also variations less than 1700 kNm vertical bending moment and 3000 kNm horizontal bending moment were not counted. For the rainflow distribution calculations, only those measurements were selected in which the ship was sailing with more than 1 knot in stable conditions. A measurement is considered as stable when the ship's speed does not vary more than 3 knots within 15 minutes (data file length).

In order to analyse the effect of ship's speed on the hull girder bending moments and responses, the distributions were calculated for different speeds. The speed ranges considered are 0-4 knots, 4-8 knots, 8-12 knots, 12-16 knots and 16-20 knots.

### 3.4 Fatigue damage

Fatigue resistance calculation is based on S-N curves which are obtained from fatigue tests. Those curves present the allowable number of cycles per stress range. They are presented in a log-log scale by one-slope lines for a corrosive environment and by two slope lines for a non-corrosive environment (air with cathodic protection). The slope of the one-slope line is defined by a parameter $m$ which equals 3. For the two slope lines $m$ equals 3 and 5 \(^{1}\).

The fatigue damage is calculated by Palmgren-Miner summation, which assumes linearity implying that history effects are neglected. This is not accurate, but is standard procedure in the industry.

To quantify the relative fatigue damage of signal $x$ the Cubic Weighted Value ($CWV$) was envisaged, which is defined as:

$$CWV = \sqrt[3]{\sum_{i=1}^{k} \frac{x_i^3}{N_i}}$$

(5)
Where:

\[ CWV : \text{Cubic weighted value} \]
\[ n_i : \text{Number of cycles in bin i} \]
\[ N : \text{Total number of cycles} \]
\[ k : \text{total number of bins} \]

This formula is based on a one slope S-N curve with \( m = 3 \) which corresponds to a corrosive environment. A non corrosive environment (air) corresponds to a two-slope S-N curve. The calculation procedure is based on the one-slope S-N curve and is therefore slightly conservative. The two slope S-N curve \((m = 3 \text{ and } m = 5)\) would give a lower fatigue damage ratio (Total divided by Low frequency) than that based on a one slope S-N curve with \( m = 3 \). The reason is that the high frequency cycles are in general of low amplitudes and hence applicable to the S-N curve with \( m = 5 \). Therefore it would give lower contribution to fatigue damage.

To quantify the fatigue damage the \( CWV \) to power three were multiplied with the number of cycles per minute to form the fatigue loading factor:

\[ L \approx CWV^3 N \] (6)

where:

\[ L : \text{Fatigue loading factor} \]
\[ N : \text{Number of cycles per unit time} \]

4 ANALYSES RESULTS

In order to determine the fatigue loading factor, the rainflow count distributions and \( CWVs \) were calculated based on the signals in Table 2.

4.1 Statistics

In order to gather information on the contribution of whipping to the design bending moment, joint statistics were established between the total wave induced load/response (without still water loading) and the low frequency load/response (without whipping).

Figure 2 shows the joint statistics, comprising the maximum, minimum and standard deviation of the total and low frequency vertical hull girder bending moment. The results show that the effect of whipping on the standard deviation of the total response/load is small. The maximum and minimum values are affected by whipping considerably. The results show:

— The short term extreme whipping responses/loads are linear with the short term extreme low frequency (wave induced) responses/loads
— The extremes of the total responses/loads (wave induced and whipping) are up to about 150% of the extremes of the low frequency (wave induced) responses/loads and occasionally even higher.

In Figure 3 the standard deviation of the horizontal hull girder bending moment as a function of the standard deviation of the vertical hull girder bending moment is presented. It concerns the standard deviation of the total load (wave and whipping induced). The results show:

— The relation between the dynamic horizontal hull girder bending moment \( M_z \) and vertical hull girder bending moment \( M_y \) is linear.
— \( M_z \) is roughly 35 per cent of \( M_y \).
— The horizontal hull girder bending always occurs, even in head sea conditions.
— \( M_z \) varies between \( M_y \) and \( M_y/8 \), or even higher for low sea states.

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4.2 Rainflow distributions

The rainflow counts were calculated for the responses (LBSG 1, LBSG 2, LBSG 4 & LBSG 5) and for the hull girder bending moments $M_y$ and $M_z$. The total signal, the low frequency signal and the high frequency signal were distinguished at different ship velocities varying between 0 and 20 knots with step of 4 knots. The variations of the still water bending moments of the hull girder induced by varying loading conditions were not considered, since the cycle counts were determined for the duration of 15 minutes per data file and within this short period the variations of loading conditions are small.

The cumulative rainflow distributions of the vertical hull girder bending moment obtained from the measurements of the ship sailing with the speed between 12 and 16 knots are shown in Figure 4. For sailing speeds above 4 knots, the amplitudes of the total responses and loads are 10 to 20 \% higher than the amplitudes of the low frequency responses and loads. For the measurements of the speed 0–4 knots, the whipping contribution is significantly smaller.

Table 5 presents the counted total number of cycles of the responses and hull girder bending moments for the ship traveling at different velocities. It shows that the total number of cycles for all responses and loads over the whole velocity range (0–20 kn) are within 1,000,000 and 1,540,000 except that for LBSG 1. The later is exceptionally about 4 times higher, might be resulting from the higher noise level of the measurement system.
Table 5: Number of cycles of the total responses and loads

<table>
<thead>
<tr>
<th>Ship’s speed [kn]</th>
<th>LBSG 1</th>
<th>LBSG 2</th>
<th>LBSG 4</th>
<th>LBSG 5</th>
<th>M_y</th>
<th>M_z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4</td>
<td>41112</td>
<td>3043</td>
<td>1975</td>
<td>1379</td>
<td>1575</td>
<td>1888</td>
</tr>
<tr>
<td>4 – 8</td>
<td>62966</td>
<td>12817</td>
<td>13399</td>
<td>9936</td>
<td>12069</td>
<td>8255</td>
</tr>
<tr>
<td>8 – 12</td>
<td>562991</td>
<td>214915</td>
<td>224687</td>
<td>187609</td>
<td>211965</td>
<td>136132</td>
</tr>
<tr>
<td>12 – 16</td>
<td>5005468</td>
<td>1272716</td>
<td>1269908</td>
<td>1051651</td>
<td>1149089</td>
<td>841154</td>
</tr>
<tr>
<td>16 – 20</td>
<td>221675</td>
<td>37398</td>
<td>29643</td>
<td>15096</td>
<td>21346</td>
<td>16019</td>
</tr>
<tr>
<td>0 – 20</td>
<td>5894212</td>
<td>1540889</td>
<td>1539612</td>
<td>1265671</td>
<td>1396044</td>
<td>1003448</td>
</tr>
</tbody>
</table>

Table 6 and Table 7 show similar results for the low frequency and high frequency responses and loads respectively. The tables show that the cycle counts of the low frequency responses and loads are about 65% of the total responses and loads. This means 35% is originating from whipping.

The sum of the low frequency responses and loads and the high frequency responses and loads is considerably higher than the counts of the total responses and loads. Even the cycle counts of the high frequency responses and loads are higher than the cycle counts of the total response and loads. This is because the rainflow counting method does not count all small cycles. This means that the calculation of the lifetime is conservative when it is based on the separated low and high frequency responses and loads.

Table 6: Number of cycles of the low frequency responses and loads

<table>
<thead>
<tr>
<th>Ship’s speed [kn]</th>
<th>LBSG 1</th>
<th>LBSG 2</th>
<th>LBSG 4</th>
<th>LBSG 5</th>
<th>M_y</th>
<th>M_z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4</td>
<td>2254</td>
<td>1484</td>
<td>1298</td>
<td>1151</td>
<td>1201</td>
<td>1301</td>
</tr>
<tr>
<td>4 – 8</td>
<td>6532</td>
<td>6093</td>
<td>5136</td>
<td>5008</td>
<td>5027</td>
<td>6047</td>
</tr>
<tr>
<td>8 – 12</td>
<td>87923</td>
<td>89317</td>
<td>79890</td>
<td>82404</td>
<td>81047</td>
<td>77102</td>
</tr>
<tr>
<td>12 – 16</td>
<td>757557</td>
<td>821699</td>
<td>775419</td>
<td>709490</td>
<td>739558</td>
<td>633539</td>
</tr>
<tr>
<td>16 – 20</td>
<td>16855</td>
<td>18007</td>
<td>15145</td>
<td>9389</td>
<td>11744</td>
<td>8996</td>
</tr>
<tr>
<td>0 – 20</td>
<td>871121</td>
<td>936600</td>
<td>876888</td>
<td>807442</td>
<td>838577</td>
<td>726985</td>
</tr>
</tbody>
</table>

Table 7: Number of cycles of the high frequency responses and loads

<table>
<thead>
<tr>
<th>Ship’s speed [kn]</th>
<th>LBSG 1</th>
<th>LBSG 2</th>
<th>LBSG 4</th>
<th>LBSG 5</th>
<th>M_y</th>
<th>M_z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4</td>
<td>45635</td>
<td>5084</td>
<td>5123</td>
<td>3181</td>
<td>3727</td>
<td>777</td>
</tr>
<tr>
<td>4 – 8</td>
<td>86031</td>
<td>34208</td>
<td>37211</td>
<td>35158</td>
<td>36008</td>
<td>14565</td>
</tr>
<tr>
<td>8 – 12</td>
<td>774042</td>
<td>366839</td>
<td>415949</td>
<td>416535</td>
<td>408904</td>
<td>201072</td>
</tr>
<tr>
<td>12 – 16</td>
<td>6643979</td>
<td>2315388</td>
<td>3028849</td>
<td>2787679</td>
<td>2769262</td>
<td>560687</td>
</tr>
<tr>
<td>16 – 20</td>
<td>245772</td>
<td>39375</td>
<td>39575</td>
<td>27761</td>
<td>30950</td>
<td>10427</td>
</tr>
<tr>
<td>0 – 20</td>
<td>7795459</td>
<td>2760894</td>
<td>3526707</td>
<td>3270314</td>
<td>3248851</td>
<td>787528</td>
</tr>
</tbody>
</table>

Table 8: Time of the ship sailing within the specified speed limits

<table>
<thead>
<tr>
<th>Speed [kn]</th>
<th>Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>699</td>
</tr>
<tr>
<td>4-8</td>
<td>1314</td>
</tr>
<tr>
<td>8-12</td>
<td>12498</td>
</tr>
<tr>
<td>12-16</td>
<td>114184</td>
</tr>
<tr>
<td>16-20</td>
<td>4314</td>
</tr>
<tr>
<td>0-20</td>
<td>133009</td>
</tr>
</tbody>
</table>

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Table 8 shows the total time in which the ship was sailing with different speeds. They were calculated for similar data files for determining the rainflow counts. The mean cycle periods for the hull girder bending moments were calculated from Table 5 to Table 8. The results are presented in Table 9. The natural frequency of the first mode of vertical hull girder bending equals 0.8 seconds. As the lowest mean cycle period (1.8 seconds) was obtained between 8 and 12 knots, it can be concluded that whipping occurs most often for this particular sailing speed. There may exist certain relationship among the ship speed, the probability of whipping and the wave condition. When encountering heavy sea state, the captain would intend to reduce the ship speed. This might be the situation, which could explain why the highest whipping occurrence appears between 8 and 12 knots, rather than at other higher speed region. It can also be concluded that at the sailing speed between 8 and 12 knots, whipping occurs in about half of the time (0.8 divided by 1.8).

Table 9: Mean period of loads

<table>
<thead>
<tr>
<th>Ship’s speed</th>
<th>$M_y$</th>
<th></th>
<th>$M_x$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Low frequency</td>
<td>High frequency</td>
<td>Total</td>
</tr>
<tr>
<td>0~4 kn</td>
<td>26.6 s</td>
<td>34.9 s</td>
<td>11.3 s</td>
<td>22.2 s</td>
</tr>
<tr>
<td>4~8 kn</td>
<td>6.5 s</td>
<td>15.7 s</td>
<td>2.2 s</td>
<td>9.6 s</td>
</tr>
<tr>
<td>8~12 kn</td>
<td>3.5 s</td>
<td>9.3 s</td>
<td>1.8 s</td>
<td>5.5 s</td>
</tr>
<tr>
<td>12~16 kn</td>
<td>6.0 s</td>
<td>9.3 s</td>
<td>2.5 s</td>
<td>8.1 s</td>
</tr>
<tr>
<td>16~20 kn</td>
<td>12.1 s</td>
<td>22.0 s</td>
<td>8.4 s</td>
<td>16.2 s</td>
</tr>
<tr>
<td>0~20 kn</td>
<td>5.7 s</td>
<td>9.5 s</td>
<td>2.5 s</td>
<td>8.0 s</td>
</tr>
</tbody>
</table>

Global vibrations were recorded on board a large ocean-going bulk carrier by the DNV structural monitoring system. It was found that the 2-node global vibrations are basically continuous and are linked to the wave and wind conditions (increase with wave height and wind strength) and to wave and wind headings (reduce for stern wave and wind heading) and to the ship conditions (reduce for cargo compared to ballast). Their studies indicate that the hull girder vibrations may be caused by slamming at the bow or stern in moderate seas. When the damping is small and a moderate slam at the stem occurs for almost every encountered wave, the resulting hull girder vibrations will be more or less continuous \(^6\) and \(^7\).

The pressure transducer fitted to the bottom forward at 0.94L did not indicate the emergence of the bottom out of the water. However, the records of bottom pressure show time variations, which coincide with the ship’s vibration frequency. It was concluded that stern slamming causes this global vibration.

The low frequency loads are induced by the waves. The lowest mean period for the low frequency loads is 9.3 seconds for a sailing speed between 8 and 16 knots. The mean periods for sailing speed between 16~20 and 0~4 knots are considerably higher. This is because, when ship’s speed is above 16 knots, the ship is most often sailing in still water and therefore the loads induced by waves may be too low to be counted. When the ship is sailing between 0 and 4 knots it is usually sailing near harbours where the waves are also negligible.

### 4.3 Fatigue damage

Cubic Weighted Values ($CWV$) were calculated for all signals (LBSG1, LBSG2, LBSG4, LBSG5 and the hull girder bending moments), including the low frequency, high frequency and total signals. In Figure 5 the joint $CWV$s are shown for the hull girder bending moments. The $CWV$s of the low and high frequency signals were plotted against the $CWV$s of the total signal. The results show that the $CWV$s of the total signal are equal or lower than the $CWV$s of the low frequency signal. The $CWV$ of the high frequency signal is the lowest, since although slamming induces considerable responses, it is only an incident.

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The number of cycles per unit time was computed for all signals. The number of cycles per unit time for the high frequency signal is highest. The maximum number of cycles for the responses and vertical hull girder bending moments are equal to about 80 cycles per minute, indicating a mean period of 0.75 seconds, which is the natural period of the first global bending mode. The maximum number of high frequency cycles for the horizontal hull girder bending moment is around 65, corresponding to the natural period of the horizontal hull girder bending mode of about 1 second. This means that the ship in mid-ship section (midherft) is less stiff around the z-axis than around the y-axis.

The mean period of the low frequency signals varies between 4 and 6 seconds. The mean period of the total signal varies between the mean periods of the high frequency and the low frequency signals.

In the left plot of Figure 6 the so-called fatigue loading factors are presented for the vertical hull girder bending moment. It shows the fatigue loading factors of the low frequency signals against the fatigue loading factors of the total signals. The results illustrate that the damage originated from the low frequency (wave frequency) signals is 75% of the damage originated from both the wave and whipping induced total signals. Due to the contribution of whipping, the damage originated from the vertical hull girder bending moment increases with 33%.

The right plot of Figure 6 shows a similar graph for the horizontal hull girder bending moment. The results show that due to the contribution of whipping the damage originated from the horizontal hull girder bending moment increases with 20%.

The fatigue loading factors of the low frequency signals and the high frequency signals were added and compared with the fatigue loading factors of the total signal. The results show that the damage obtained from the summation of the low and high frequency responses calculated separately is about 20 % lower than the damage calculated from the total signal. This means when the summation is taken the calculated damage is not conservative.

5 RELATIONSHIP WITH CLASS RULES

Fatigue and whipping induced fatigue have been a research topic with Bureau Veritas since the early seventies. One of the first full scale measurement campaigns was undertaken on the cable
layer “Marcel Bayard”. Later an ULCC, container ship and Ro-Ro ferry have been outfitted with measuring equipments and among other issues the contribution of whipping to fatigue was investigated. These studies did not find large contribution of whipping to overall fatigue damage as described in this paper.

The verification of fatigue strength of the structure of seagoing ships has been developed and based on a probabilistic law methodology. In the early 1980s, this methodology was introduced with the purpose to assure that the seagoing ships could respect a fatigue life of 20 years in North Atlantic sea conditions, with a cumulative damage ratio of 1, taking into account the SN curve at minus two standard deviations.

These ships were mainly verified by considering two draughts: full and ballast loading. At that time, a guidance note for fatigue assessment was developed by BUREAU VERITAS. Later on fatigue assessment for ships of the length more than 170m became mandatory, which are carried for structural details as:
— Connection of longitudinals with transverse web frames,
— Hopper knuckles,
— Stringer connection.

5.1 Fatigue on ships L<170m
As mentioned above for ships with length below 170m, fatigue analysis is not requested by rules. This however does not mean that for ships under this length fatigue is not considered.

Construction rules in general consider two limit states, an ultimate limit state and a serviceability limit state. In the rules for ships $10^{-5}$ loads are considered equal to a load which would be encountered once each voyage, with $10^{-8}$ being the highest expected load in 25 years. The step from $10^{-5}$ to $10^{-8}$ and from local to global strength can be seen as a multiplication of the loads by a factor of 1.6. This factor partly addresses ultimate strength and partly addresses fatigue.

In the latest classification rules for Bulk Carriers and Oil Tankers all loads for yielding evaluated using a $10^{-8}$ probability level, against $10^{-5}$ with the previous rules. The related maximum stress level has been increased by 25%.

![Figure 6: Fatigue loading factors for $M_y$ and $M_z$](image)
Fatigue is not only incorporated in the global strength criteria but also in the k-factor for the material. This factor is not simply an adjustment for the higher yield strength but includes the limit of fatigue characteristics valid for higher tensile steels as well as ordinary steel (Table 10).

**TABLE 10: The k-factor for the material**

<table>
<thead>
<tr>
<th>ReH, in N/mm²</th>
<th>235/ReH</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
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<td>1</td>
</tr>
<tr>
<td>315</td>
<td>0.746</td>
<td>0.78</td>
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<tr>
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<tr>
<td>390</td>
<td>0.603</td>
<td>0.68</td>
</tr>
</tbody>
</table>

5.2 Discussion of measurement results on the Victoriaborg

Previous research on whipping induced fatigue was initiated due to cracks⁴,⁵. On the Victoriaborg no fatigue cracks have been reported. The measurement campaign was performed within the Joint Industry Project ‘Monitoring 9000t’, which was aiming to improve the performance of the double-hull general cargo ship, by monitoring the structure, propulsion and engine in service conditions.

In a second step the obtained data has been analyzed in order to see how the high frequency stress cycles contribute to fatigue damage. This analysis has delivered valuable information for the research departments at both Marin and Bureau Veritas. It was found that the measured first modal frequencies of 3 ships of similar length were between 2.0 and 2.5 Hz. However the Victoriaborg design resulted in a evidently lower frequency (1.2 Hz). Being more flexible this ship suffered more whipping and the fatigue component was greater than other ships built in the past. This was due to the relative large open hold and heavy short aft and fore-ship structure.

Bureau Veritas has registered 1287 General cargo ships ranging between 1000 to 20000 ton dwt, most of which have a similar design as the Victoriaborg. Up to now no systematic fatigue damage has been reported on these ships. A fatigue analyses with MARS software shows a safety margin of more than 2 with respects to normal fatigue life time (20 years), generally expressed as 40+ years fatigue life. It should be noted that the measurements are usually taken to obtain the global strength level, but the fatigue calculations are generally based on the stress level in the detail structure. Furthermore although the result of fatigue calculations is often represented in an absolute number of years we should not forget the uncertainties which are included in fatigue calculation ⁸.

This means that no direct rule changes are foreseen as a result of this study however on a research level we will continue to participate in new investigations into whipping induced fatigue in order to continuously scrutinize the present rules & regulations.

6 CONCLUSIONS

Based on four Long Based Strain Gauges the hull girder bending moments of the Victoriaborg, a general cargo/container vessel, were determined with the simple beam model. From one year strain measurements and calculated hull girder bending moments the statistics and rainflow counts were computed. In the calculations the total, whipping (high frequency) and wave induced (low frequency) responses and loads were distinguished. Different sailing speeds were also considered. In the conclusions it should be considered that the Victoriaborg has a hull form with a very moderate flare.

From the one year measurements onboard the Victoriaborg, the following conclusion may be drawn:
—The wave induced horizontal hull girder bending moment is roughly 35% of the wave induced vertical hull girder bending moment.
—The wave induced horizontal hull girder bending moment varies from one eighth of the vertical hull girder bending moment (head waves), indicating that there is always a horizontal hull girder bending moment.
—Hull girder vibration occurs in all sea conditions.
—The short term extreme whipping responses and loads are linear with the short term extreme low frequency (wave induced) responses and loads.
—The whipping amplitudes vary up to 70% of the wave induced strain and hull girder loads.
—The extremes of the total responses and loads (wave and whipping induced) equals to about 150% of the extremes of the low frequency (wave induced) responses and loads.
—As expected the influence of whipping on the standard deviation of the responses and loads is negligible.
—About 35% of the number of cycles of the total responses and loads, counted with the rainflow method, originates from whipping. The remaining 65% originates from wave induced responses.
—When dividing ship’s speed in bins from 0 to 20 knots with step of 4 knots, whipping occurs most often within the sailing speed from 8 to 12 knots, relating to sea conditions.
—For a vessel with a hull form and bow flare similar to the Victoriaborg, the occurrence of whipping and the responses would be significant.
Assuming also the low amplitude cycles contribute to fatigue based on a one-slope S-N curve,
—Due to the contribution of whipping the fatigue damage originated from the vertical hull girder bending moment increases about 30% in comparison with the calculations of only the low frequency responses.
—The fatigue damage calculated from the summation of individual wave and whipping induced responses is about 20% lower than the damage calculated from the total response. This means when the summation is taken the calculated damage is not conservative.

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REFERENCES