FATIGUE PERFORMANCE OF GRADE R4 AND R5 MOORING CHAINS IN
SEAWATER

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ABSTRACT

With more than 50,000 tons in service to date, the Oil&Gas Industry has the need to understand the tension fatigue performance of grade R5 chains in straight tension, and corroborate the validity of the existing design methods.

The chain fatigue design curves in API and DNV are based on fatigue tests obtained in the nineties and early two thousands. However the tests were performed on lower grades such as ORQ, R3 and R4, and small chains, 76 mm diameter being the largest studless chain tested.

The industry has moved towards the use of large studless chains, especially in permanent units, where chain diameters above 150 mm are not unusual.

This paper gathers information from a full scale fatigue test program on grade R4 and R5 studless chains, performed in seawater and with diameters between 70 mm and 171 mm. Therefore it covers the whole range of chain diameters used in the Oil&Gas industry, both in mobile and permanent mooring systems for any kind of floating unit.

INTRODUCTION

This paper presents results of a continuous fatigue test program on studless chains performed by Labein Research Centre, later part of Tecnalia. The program has been developed during 12 years and it has been sponsored by the chain manufacturer Vicinay Cadenas in Bilbao, Spain, who supplied the chain samples.

7 tests have been conducted in grade R4 and 12 in grade R5 studless chains of diameters between 70 mm and 171 mm. The chains were tested in pure straight tension conditions and in free corrosion conditions in absence of cathodic protection. Other degrading and loading mechanisms such as out of plane bending, in plane bending or torsion fatigue are not studied.

The paper analyses the data and determines tension-tension fatigue curves based on API and DNV methods for computation of cumulative fatigue damage, regardless of other damaging mechanisms. Improved fatigue capacity is obtained with respect to the above recommended design methods.
HISTORIC REVIEW

The first attempt to characterize the fatigue behaviour of chains was performed by Ramnas Bruks AB in the early seventies (Ref.1) with 2” studded chains tested in air.

Other studies were carried out in the eighties by DNV within a Joint Industry research project (Ref.2). Again small studded chains of 40 mm and 70 mm diameter grade ORQ were tested in air showing close agreement with the previous study.

API launched in 1991 a draft recommended practice for design, analysis, and maintenance of mooring for floating production systems (Ref.5), where a T-N fatigue curve was given for chains. The parameters of the curve for common links were \( m=3.36 \) and \( K=370 \), the test data relied upon is not public but it is thought that stud chain data was used. Studless chain was first used in 1989 and started gaining acceptance during the nineties (Ref.6). The design of 6d x 3.35d introduced by Vicinay in 1993 became the standard.

Later the API RP 2FP1 was first issued in 1993 (Ref.7). The same T-N curve was included in the first release of API RP 2SK (Ref.8) in 1995.

Between 1989 and 1992 a Joint Industry Project was conducted by BOMEL (Ref. 3 and Ref. 4). Fatigue tests were carried out on 54, 76 and 100 mm studded chains at Delft university of Technology. All the chains were of K3 grade (equivalent to ORQ), except for two tests in grade K4 and one early experiment of grade K5. All the tests were performed in air at various stress ranges, obtaining the following S-N curve parameters for the mean minus two standard deviations \( m=3.173 \) and \( a=5.78E11 \)

Also between 1989 and 1992 another Joint Industry Project was conducted by NDAI (Ref.10 and Ref.11). 76 mm and 102 mm ORQ and K4 grade studded chains were tested in air and water. A single studless chain was tested too but none of the links suffered failure though failures were expected. A reduced number of tests were performed on grade K4, being the results sometimes unexpected and also insufficient to draw firm conclusions about this grade and propose any fatigue curve. This study included the un-failed links to determine fatigue curves depending on the number of links in a chain, and also depending on a chosen probability of failure for a single mooring line (after being exposed to a normally failing number of cycles). These fatigue curves were derived from a combination of in-air and in-water tests of stud chains.

Between 1997 and 2001, another Joint Industry Study was conducted by Noble Denton (ND), consisting of a fatigue test program on 76 mm grade R3 and R4 studless chains (Ref.12). A recommended curve was defined by mean minus two standard deviations with an intercept of \( K=2084 \), and the load ranges being normalised to the minimum breaking load (MBL) of grade R3 chain. The correspondent recommended S-N curve had an intercept of \( 7.295E9 \) and the same slope \( m=2.396 \).

After the findings of the Deepmoor JIP, DNV presented, in 2001, the offshore standard Position Mooring, (Ref.13) with S-N fatigue curves for both studless and studded chains. The slope of these curves, today in full validity is \( m=3 \), and the intercepts \( 1.2E11 \) and \( 6E10 \) for stud and studless chains respectively, with a recommended safety factor of 5.

Later in 2005 API (Ref.9) presented different curves for stud and studless chains which were developed from the existing data available at that time and using a slope of \( m=3 \). The new curve for stud chain has a parameter of \( K=1000 \).
which gives a similar fatigue damage to API’s previous curve (for stud and studless). The intercept parameter for studless chain resulted in $K=316$. The recommended safety factor is 3 in this case.

The test rig has an approximate useful span of 4 metres. Since different diameters were tested, the number of links in the samples was variable as well as the number of links inside the tank.

The seawater was artificially created with a sodium chloride concentration around 35 grams per litre. The salt concentration and pH was controlled every two weeks, and the water temperature was monitored daily but left as per room demand without any action taken to control it. Normally the water temperature was in the range of 15 to 25 degrees centigrade.

The tank was oxygenated during the entire tests by means of an air flow induced by a hose with multiple holes. In addition the water leaks (normally small) are captured and re-circulated through a buffer tank, and causing some water movement.

The tests were conducted until first link failure occurred, and no kenter links were used to continue the tests to further failures. Multiple failures have been considered in previous works such as Refs.3, 10, 12.

**TEST PROGRAM**

The test program is considered to be very representative of the actual chains in mooring systems for permanent units in terms of chain sizes and steel grades. It is true, however, that grade R3 still has an important presence.

It is a low cycle, high load, program, the largest number of cycles obtained in one test being around 3 million. Actual chains can be however subjected to more than one hundred million of cycles during their lifetime offshore.

The test program has been conducted during a relatively long period of time, between 2000 and 2012, and one test was performed in 1995. In 2005 the beams of the rig were replaced by longer ones in order to accommodate a larger number of links per chain sample.

A total of 19 tests have been carried out on studless chains, 7 of them being made of grade R4 and 12 of grade R5. Different chain sizes have been tested between 70 and 171 mm, at different tests frequencies, according to table 1. The tests lasted between few days and five months, depending on the magnitude of the load applied and the frequency.

The chains are subjected to constant load ranges, being the shape of the load wave sinusoidal. The load ranges are normalised to the minimum breaking load of the grade ORQ chain. Different load ranges were applied between 10 and 33 per cent of this ORQ reference breaking strength. Also different wave frequencies between 0.2 Hz and 0.7 Hz were used. The last two chains were also pre-soaked for a period of two weeks in order to get a rust layer before cycling.

<table>
<thead>
<tr>
<th>Test</th>
<th>Dia (mm)</th>
<th>Design</th>
<th>Grade</th>
<th>Freq (Hz)</th>
<th>Failure location</th>
<th>Links in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>102</td>
<td>Studless</td>
<td>R4</td>
<td>0.6</td>
<td>bend</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>Studless</td>
<td>R4</td>
<td>0.4</td>
<td>bend &amp; crown</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>Studless</td>
<td>R4</td>
<td>0.4</td>
<td>bend</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>142</td>
<td>Studless</td>
<td>R4</td>
<td>0.5-0.7</td>
<td>crown</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>171</td>
<td>Studless</td>
<td>R4</td>
<td>0.5</td>
<td>crown</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>Studless</td>
<td>R4</td>
<td>0.3</td>
<td>bend</td>
<td>4</td>
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<tr>
<td>7</td>
<td>152</td>
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<td>R4</td>
<td>0.2</td>
<td>crown</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>149</td>
<td>Studless</td>
<td>R5</td>
<td>0.5</td>
<td>straight</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>127</td>
<td>Studless</td>
<td>R5</td>
<td>0.2</td>
<td>bend</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>157</td>
<td>Studless</td>
<td>R5</td>
<td>0.2</td>
<td>bend</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>70</td>
<td>Studless</td>
<td>R5</td>
<td>0.7</td>
<td>crown &amp; bend</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
<td>70</td>
<td>Studless</td>
<td>R5</td>
<td>0.7</td>
<td>straight</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>70</td>
<td>Studless</td>
<td>R5</td>
<td>0.5</td>
<td>crown &amp; bend</td>
<td>9</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>Studless</td>
<td>R5</td>
<td>0.5</td>
<td>crown</td>
<td>9</td>
</tr>
<tr>
<td>15</td>
<td>125</td>
<td>Studless</td>
<td>R5</td>
<td>0.2</td>
<td>bend</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>120</td>
<td>Studless</td>
<td>R5</td>
<td>0.2</td>
<td>bend</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>137</td>
<td>Studless</td>
<td>R5</td>
<td>0.2</td>
<td>straight</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>165</td>
<td>Studless</td>
<td>R5</td>
<td>0.3</td>
<td>bend</td>
<td>4</td>
</tr>
<tr>
<td>19</td>
<td>165</td>
<td>Studless</td>
<td>R5</td>
<td>0.3</td>
<td>no failure</td>
<td>4</td>
</tr>
<tr>
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<td>70</td>
<td>Stud</td>
<td>R5</td>
<td>0.7</td>
<td>bend</td>
<td>9</td>
</tr>
</tbody>
</table>

*Table 1. Tension-Tension fatigue program.*
RESULTS

Of the 19 tests, 9 failures occurred at a bend section, 6 at a crown section, and 3 at a straight section. One test was finished without failure. All the failures except for one occurred in submerged cross sections, confirming the importance of the corrosion-fatigue damage.

Nucleation and growth are the two stages governing the fatigue life of the chains. The duration of each stage was unknown in this test program because no inspections were performed during the tests, but generally longer duration is attributed to the nucleation process.

The results of the tests are represented in the graphics in figures 4 and 5. The double logarithmic graphics represent the number of cycles to failure in the horizontal axis and the applied nominal stress range or tension range ratio on the vertical axis.

A regression of logN on logR or logS is done since the number of cycles N is the measured variable from each test and therefore the dependent variable despite it is plotted in the horizontal axis.

The regression analyses have been performed enforcing the slope to 3 as it is the widely used slope, while the computed slope obtained without enforcement is 2.65.

Figure 4. S-N representation of results.

The following figures show examples of failures at three different locations. The fractures show a crack growing section followed by ductile collapse.

Figure 5. T-N representation of results.

Figure 6. Examples of link failures.
STATISTICAL APPROACH

The goal of this analysis is to develop T-N and S-N fatigue curves to characterise the average fatigue performance, and more important lower bound curves with sufficient safety margin to be used in design.

The R4 and R5 data is analysed separately and together. The mean curves, or best fit curves, are based on linear regression analysis of the data using the least squares method. Thus the fitted curve obtained this way represents the average of the failures.

This test program only considers the first failure on a chain string and no kenters are used to follow up the tests with the unfailed links. The ratio between failed and unfailed links is relatively small when compared to other test programs seeking for second or third failures on the same chain string. The only consideration of the first failure results in a lower fitted curve (more conservative).

Since a mooring line is as strong as its weakest link, the probability of line failure depends on the single link probability of failure and the number of links. If links are identically distributed and subject to the same load, the probability of line failure is

\[ P_{\text{line}} = 1 - (1 - P_{\text{link}})^k \]

where \( k \) is the number of links in the line.

Figure 7 shows the cumulative distribution function of the residuals of the failure points ordered from smallest to largest. The residuals are the horizontal difference between a test result and the fitted curve, defined as:

\[ \log N_i - \log N_f \]

where \( N_i \) is the number of cycles to failure and \( N_f \) the cycles predicted by the fitted curve. The ordered residuals of the failed links are associated with a probability plotting position (y axis) given by \( P = (i - 0.5)/n \) where \( n \) is the total number of links tested including runouts. The data is fitted to a Weibull distribution which allows estimating the line failure probability as a function of the number of links and a given probability of failure for a single link.

A link probability of failure of 1E-8 (or 1E-4 line probability for 10000 links) has been selected to get the following proposed S-N and T-N curves to be used together with the safety factors of 5 and 3 respectively.

Nominal stress format:

\[ N \times S^3 = 1.38 \times 10^{11} \]

Tension ratio format (with respect to ORQ chain breaking strength):

\[ N \times R^3 = 582 \]

It is obtained as a consequence of the analysis that the above curves approximately correspond to the fit minus 3 and fit minus 4 standard deviations respectively for the nominal stress and tension ratio formats.

In the fatigue program conducted the links are exposed to water for a much shorter period than in service. This is one of the uncertainties inherent to all fatigue test programs, which intends to be covered by using of a more conservative approach than a mean minus 2 standard deviations, together with reasonable fatigue safety factors.

TESTS ON SPECIMENS

Force controlled fatigue tests have been performed on 5 unnotched small specimens of grade R5 taken from actual links. The tests are performed in the fatigue regime where the strains are predominately elastic, both upon initial loading and throughout the test in accordance with the standard E466 (Ref. 14).

The specimens were subjected to a constant amplitude, and 0.5 Hz periodic forcing in seawater at room temperature. Next table shows the maximum and minimum stresses, the cycles obtained to failure and the cycles predicted by the B1 curve for free corrosion in seawater (Ref.15).

<table>
<thead>
<tr>
<th>Test number</th>
<th>Max stress</th>
<th>Min stress</th>
<th>Stress range</th>
<th>Cycles to failure</th>
<th>B1 predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>840</td>
<td>84</td>
<td>756</td>
<td>21967</td>
<td>6316</td>
</tr>
<tr>
<td>2</td>
<td>840</td>
<td>84</td>
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<tr>
<td>5</td>
<td>840</td>
<td>500</td>
<td>340</td>
<td>319863</td>
<td>69433</td>
</tr>
</tbody>
</table>

Table 2. Specimen test program.

These tests may be represented together with the full scale results dividing the stress range by the largest stress.
concentration factor of a studless link, which is obtained to be around 4, after finite element analysis and micro-strain measurements at hot spots.

This extrapolation is recognised not to be very scientific because the surface finish of the small specimens is machined and the cross section for crack propagation is much larger in actual chains. The latter fact can be a reason for a lower life obtained in the small coupons compared to the link results. Also there is an influence on the load type and probably a size effect. Nevertheless the extrapolated tests are plotted in figure 4 above in the S-N format.

CONCLUSIONS

The influence of seawater is very clear, confirming an expected decrease in the fatigue life due to the synergy of fatigue and corrosion in the so called corrosion-fatigue damage mechanism.

No significant differences have been identified in the fatigue performance between grades R4 and R5.

Based on test data from one manufacturer, fatigue equations have been developed with sufficient confidence to be used in mooring lines, considering the cumulative probability of failure of large number of links connected in series.

It is reasonable to think that the durability of chains has improved due to the advances in manufacturing, especially non-destructive testing and heat treatment. The former contributing to an improvement of the nucleation process, and the latter to an improvement of the microstructure and the crack growth rates under corrosion-fatigue.

REFERENCES