An assessment of proof load effect on the fatigue life of mooring chain for floating offshore installations

Mooring Integrity Joint Industry Project Phase 2

Prepared by the Joint Industry Project Steering Committee for the Health and Safety Executive
Mooring Integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).

Long lengths of steel chain links are used in the mooring lines of offshore floating installations. As an installation moves under wave, wind and current conditions, the chains are subject to high loads that can promote metal fatigue and line failure through the nucleation and propagation of defects in the steel. This report assesses the impact on the fatigue life of chains of the proof loading carried out after manufacture. Proof loading involves testing chains at about 66% of the minimum breaking load specified in offshore standards. Proof loading has been found to be beneficial for the integrity of chain and enhances fatigue life under tensile loading. The report identifies other implications for chains with out-of-plane bending and for twisted chains.

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An assessment of proof load effect on the fatigue life of mooring chain for floating offshore installations

Mooring Integrity Joint Industry Project Phase 2

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1  PREFACE

This sub-report has been produced under the auspices of Phase 2 of the GL Noble Denton led Mooring Integrity for Floating Offshore Installations Joint Industry Project, which has been sponsored by the following companies:

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- Petrobras
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- 2H Offshore
- Wood Group Engineering
- Single Buoy Moorings Inc.
- SOFEC
- Bluewater Energy Services
- Health and Safety Executive
- BG Plc
- Total
- Lloyds Register EMEA
- Det Norske Veritas
- Bureau Veritas
- ABS
- Welaptega
- Vicinay Cadenas S.A.
- TSC Inspection Systems
- Hamanaka Chain Mfg.Co., Ltd.
- Imes Group
- Sanmar Chain International Pte
- Viking Moorings
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2 INTRODUCTION

2.1 BACKGROUND

Traditionally residual stress has been used in the steel/manufacturing industry to improve fatigue life. Practices such as shot peening induce plastic deformation on the surface. Compressive stress on the surface due to plastic deformation is known to improve fatigue life. Imposing compressive stress on the surface reduces susceptibility to surface cracks.

The use of chain as a mooring component dates back to 1783. Mooring chain has witnessed several modifications in form and materials since then and is still evolving. In 1846, Lloyds introduced the requirement for proof testing. Since then it has been a requirement to test chains to a proof load specified by the Classification Societies. The specified proof load depends on the grade of the chain.

Proof loading requires testing to a load corresponding to a 0.2% or 0.1% permanent set following release of the load. The permanent set imposed by proof loading induces residual stresses in the mooring chain.

A twenty year design life at a five second characteristic period will result in 125 million cycles of applied loading. This is further compounded by the possibility of stress corrosion cracking in sea-water. A number of expensive chain fatigue failures have been experienced in the field.

It would be beneficial to the offshore industry if residual stress could be used to improve the fatigue life of mooring chains.

This report investigates the effect of the residual stresses from proof loading on the fatigue life for both Tension-Tension as well as Tension-Bending effects. If there is a relatively inexpensive way to improve the fatigue life, the high cost of mooring failures might well justify any additional manufacturing cost.

It may also be worth checking if the residual stress from proof loading has any detrimental effect on the life of mooring chain. So the effect of proof loading on bending and torsion also has been reviewed.
### 2.2 ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>BOMEL</td>
<td>Billington Osborne -Moss Engineering Limited</td>
</tr>
<tr>
<td>DNV</td>
<td>Det Norske Veritas</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>IACS</td>
<td>International Association of Classification Societies</td>
</tr>
<tr>
<td>JIP</td>
<td>Joint Industry Project</td>
</tr>
<tr>
<td>kN</td>
<td>kilo Newton</td>
</tr>
<tr>
<td>MBL</td>
<td>Minimum Breaking Load</td>
</tr>
<tr>
<td>MPa</td>
<td>Mega Pascal (N/mm²)</td>
</tr>
<tr>
<td>PL</td>
<td>Proof Load</td>
</tr>
<tr>
<td>SBM</td>
<td>Single Buoy Mooring.</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate Tensile Strength</td>
</tr>
</tbody>
</table>
### 3 PROOF TESTING

#### 3.1 CONCEPT OF PROOF LOADING

The typical stress strain curve for a ductile material appears as shown in Figure 3-1.

![Stress-strain curve](image1)

**Figure 3-1 Example of Terminology during a Tensile Test (courtesy of Ashby & Jones, [9])**

The exact position of the limit of proportionality is difficult to determine experimentally. To overcome this problem proof stress is defined; the 0.1% proof stress is the stress required to produce a permanent strain of 0.001 on removal of the stress. Proof load is generally defined as the load corresponding to a specified small value of permanent set usually 0.2% or 0.1%.

![Definition of proof stress](image2)

**Figure 3-2 Definition of Proof Stress**

For high-grade steels, the ratio of proof stress to tensile strength is higher. This means the proof load to achieve the permanent set is closer to the ultimate strength.

#### 3.2 PROOF LOADING OF CHAIN
Proof loading of chain is carried out for a number of purposes including to check the stiffness (elongation) of chain and to ensure the studs (where relevant) are fixed following heat treatment, which otherwise relaxes the initial clamping forces applied.

API [4] requires that “all chains shall withstand the applicable proof test load” equivalent to approximately 66% of the specified minimum break load. API Specification 2F [4] does not account for different grades of chain. The specified proof load is for a chain with minimum ultimate strength of 641 MPa.

In general, classification societies have specified proof loads for different grades of chain, which vary slightly. For example, the proof load requirement for DNV [3] varies between 70% for Grade R3 and 78% for Grade R5 stud link chain. For studless chain, it is uniformly 70% of the specified minimum break load.

DNV [3] allows the specified proof load to be exceeded by up to 15% to fasten studs or to adjust the chain dimensions.

The catalogue specified minimum break load (MBL) is actually an agreed specified minimum strength which has an associated testing requirement to ensure that this is achieved. Table 3-1 indicates the Minimum Breaking Load (MBL) and proof loads for various sizes and grades of chain supplied by Vicinay. The “d” in the expressions refers to the chain bar diameter in mm. It should be noted that a sample is not tested until breaking. As per DNV “each sample shall withstand the breaking load specified..”. “It shall be considered acceptable if the samples show no sign of fracture after application of the minimum specified load for 30 seconds”. It is possible that the tested sample may have a higher breaking strength and thus the applied proof load may not induce permanent set in the links.

![Figure 3-3 Proof Testing of Chain](image-url)
Table 3-1 Minimum Breaking Load and Proof Load (Courtesy of Vicinay)

<table>
<thead>
<tr>
<th></th>
<th>Stud Link</th>
<th>Studless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proof Load ORQ</td>
<td>kN</td>
<td>0.0140 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load ORQ</td>
<td>kN</td>
<td>0.0211 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load ORQ + 10</td>
<td>kN</td>
<td>0.0154 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load ORQ + 10</td>
<td>kN</td>
<td>0.0232 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load ORQ + 20</td>
<td>kN</td>
<td>0.0168 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load ORQ + 20</td>
<td>kN</td>
<td>0.0253 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load R3</td>
<td>kN</td>
<td>0.0156 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load R3</td>
<td>kN</td>
<td>0.0223 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load R3 S</td>
<td>kN</td>
<td>0.0184 <em>d^2</em>(44-0.08<em>d) 0.0174 <em>d^2</em>(44-0.08</em>d)</td>
</tr>
<tr>
<td>Minimum Break Load R3S</td>
<td>kN</td>
<td>0.0249 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load R4</td>
<td>kN</td>
<td>0.0216 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load R4</td>
<td>kN</td>
<td>0.0274 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load R4S</td>
<td>kN</td>
<td>0.02376 <em>d^2</em>(44-0.08<em>d) 0.0201 <em>d^2</em>(44-0.08</em>d)</td>
</tr>
<tr>
<td>Minimum Break Load R4S</td>
<td>kN</td>
<td>0.03014 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Proof Load R5</td>
<td>kN</td>
<td>0.0251 <em>d^2</em>(44-0.08*d)</td>
</tr>
<tr>
<td>Minimum Break Load R5</td>
<td>kN</td>
<td>0.03186 <em>d^2</em>(44-0.08*d)</td>
</tr>
</tbody>
</table>

The proof load and specified minimum break load of the different grades of chains based on IACS W22 [11] is compared in Table 3-2. It has to be noted that the ratio of yield strength to tensile strength for R4S and R5 is quite high and the plastic deformation of the links from proof loading will be limited.

Table 3-2 Comparison of Yield and Tensile Strength

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Stress</th>
<th>Tensile Strength</th>
<th>YS/TS</th>
<th>PL/MBL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/mm²</td>
<td>N/mm²</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>R3</td>
<td>410</td>
<td>690</td>
<td>0.59</td>
<td>66.4</td>
</tr>
<tr>
<td>R3S</td>
<td>490</td>
<td>770</td>
<td>0.64</td>
<td>72.3</td>
</tr>
<tr>
<td>R4</td>
<td>580</td>
<td>860</td>
<td>0.67</td>
<td>78.8</td>
</tr>
<tr>
<td>R4S</td>
<td>700</td>
<td>960</td>
<td>0.73</td>
<td>78.9</td>
</tr>
<tr>
<td>R5</td>
<td>760</td>
<td>1000</td>
<td>0.76</td>
<td>78.4</td>
</tr>
</tbody>
</table>

3.3 RESIDUAL STRESS FROM PROOF TESTING

When a chain is tested to proof load, the stress distribution generally is similar to Figure 3-4. The typical stress distribution is characterised by a very high compressive stress at the contact zone, which reverses to high tensile stress at the inner shoulders.
Once the load is released, the compressive residual stresses are set in at the inner shoulders of the chain link, see Figure 3-5. It should also be noted that the residual stress at the contact zone is tension. Proof testing induces local plastic deformation in areas of high stress concentrations. FE analysis carried out by Principia [12] for a 107mm studless link has noted that unloading from a 70% proof load results in a plastic deformation of 5.4% at the surface of the link. The study was carried out as a part of the SBM Out-of Plane Bending Joint Industry Project.

It is worth noting the rapid reversal of stress from tensile stress in the interlink contact zone to compressive residual stress at the half-crown area.
4 FATIGUE FAILURES IN CHAIN

To study the effect of residual stresses on proof loading, it is informative to review the hot spot stresses and the resultant fatigue failures reported in mooring chains. The highest tensile stress in a chain occurs at half-crown location. Most of the fatigue failures reported originate from the inner shoulder of the chain (intrados). Occasionally cracks originating at the peripheral of the interlink contact zone or crown (extrados) have been reported.

4.1 OBSERVATIONS FROM FATIGUE TESTING

Noble Denton initiated a joint industry project [7] in 1994 in an attempt to obtain information on the fatigue performance of large diameter chains. The tests were carried out at National Engineering Laboratory (NEL). Out of the 70 fatigue failures reported in this JIP, 52% occurred at an inner Half-Crown position, 34% at an inner Crown position and 14% at a mid leg position. The Crown refers to the area of maximum bend and Half-Crown essentially refers to the area of the link where bending commences, see Figure 4-1 below.

![Figure 4-1 Load regimes in a stud link for pure tension [7]](image)

Only two failures were observed by BOMEL (1992 JIP [6]) outside the bend area during their fatigue test programme; though for links from one batch of 54mm chain, the cracks have initiated consistently at the root of the stud weld. This has been attributed mainly to the welding procedures adopted.
From the observations from these fatigue tests, it is evident that normally the fatigue cracks emanate from the high tensile hot spot at the inner shoulder for a stud link chain subjected to tension loading. It should be noted that the stress concentration at the contact zone (crown) will be much higher than the inner shoulder (half crown), see Figure 4-3.

Out-of-plane bending fatigue tests have shown fatigue failures initiated at locations midway at the bend between the shoulder and crown.
4.2 DATA FROM CHAIN INSPECTIONS

Most of the cracks from tension fatigue are observed at the following locations -

- Crown (extrados) [See Figure 4-4]
- Half-crown (intrados), or
- At the straight section from the toe of the stud weld (less relevant today since studs are not held place by welding)

With the exception of damages from out of plane bending, field observation also have been similar to the fatigue damage observed during testing.

There have been instances when the cracks have been initiated at local pits at crown locations.

Figure 4-4 Fatigue cracks at the crown
Figure 4-5 Cracks at the weld

The failure location in out-of plane bending has been consistent (see Figure 4-6) with the hot spot identified from FE modelling (Figure 4-7). Both torsion and out-of-plane loadings are bending actions which result in tensile stresses that are a maximum well away from the tension hot-spot locations mid-way between the link bend-to-leg intersection and crown. These may also coincide with tensile residual stresses.

Figure 4-6 Chain failure in out-of plane bending [14]
Some mooring chain in very dynamic environments have exhibited fretting-type fatigue cracking around the interlink region. The wear pattern associated with these links suggests that there is significant sliding and rotating at the interlink region, see the smooth inner surface on Figure 4-8. It has been surmised that if links slide from the central axis (crown) towards the location of high tensile residual stress, this could lead to premature fatigue failure.
5 FATIGUE AND RESIDUAL STRESS

5.1 FACTORS AFFECTING FATIGUE

Fatigue is the mechanism whereby cracks grow in a structure, sometimes eventually resulting in a failure. The factors affecting the fatigue failure are:

- Stress range
- Mean stress, a mean tensile stress affects initiation of cracks
- Endurance Limit of the material.

Stress range is a function of the fluctuating loading on the system, related to the environmental loading - low frequency as well as wave frequency effects for a mooring system.

![Diagram showing stress and mean stress](http://www.fgg.uni-lj.si)

Mean load on a mooring chain is affected by the pre-tension or the working tension in the mooring line. Mean stress in the chain will be affected by the working load as well as the residual stress from proof loading. From the fatigue testing programmes, it emerges that mean stress is quite important for crack initiation [7], though the influence on crack propagation is limited.

5.2 INFLUENCE OF RESIDUAL STRESS

Compressive residual stress locked in at the inner shoulders of a mooring chain implies that the mean tensile stress for a load-cycle will be lower than for a chain link without compressive residual stresses. Since the magnitude of compressive stress during proof testing is much higher than the stress associated with a normal load-cycle, the mean stress may still be compressive. This can significantly influence the crack initiation and hence the fatigue life of the chain link in tension loading.
6 TENSION FATIGUE- PROOF LOAD TEST RESULTS

6.1 BOMEL JIP

Billington Osborne -Moss Engineering Limited (BOMEL) initiated a Joint Industry Project (JIP) for the design guidelines of anchor chains [1], [5]. As a part of the JIP, a series of tension fatigue as well as tension-bending fatigue tests were conducted. The test programme involved:

- Grade of Steel: K3, K4 and K5
- Mean tension- approximately 16% and 24% of breaking strength
- Stress range: various stress ranges from 16% up to 31% of breaking strength for Grade K3 and K4 and 40% of breaking strength for Grade K5
- Stud Welding; links with welded and un welded studs were tested
- Chain Size; 54, 76 and 100m diameter chain; and
- Link type; common chain link versus Kenter.

The fatigue lives of two of the chain specimens were exceptional and failures did not occur. Subsequent investigations revealed that these chains were subjected to excessive proof load during manufacture. One of the tests exceeded the number of cycles by 3 and the other one by 6, when the test was halted [6]. As discussed in Sec 3.2, it is allowed under Class specification to stretch under-length chain.

The test programme also involved bending fatigue. The tests were limited to only 54 diameter chain. Specimens from the batch of chain which exhibited unusual fatigue lives during the tension fatigue test were not tested for bending fatigue.

Evidence from the BOMEL JIP led to further investigation by one of the JIP partners, Amoco Production Company.

6.2 SHOUP, TIPTON AND SOREM WORK, 1992

Shoup et al. [2] [Amoco Production Company] used 10mm diameter grade 80 lifting chain manufactured according to ANSI-ASTM A391-36 Standard Specification for Alloy Steel Chain. 6.4mm diameter studs were fillet welded to the open link to make stud link chain. The chain links were heat treated to remove hopefully any form of residual stresses from welding of the studs.

The specified levels of proof loading were applied e.g. 0%, 70%, 76% and 82%. Fatigue testing was done on a closed loop servo hydraulic test machine. Each segment was tested until 3 failures out of 6 occurred.

The following test sequence was employed:

- Determine the break strength of the stud link and open link chain by loading the chains to failure
- Proof loading to various levels.
- Tension fatigue testing

Applied proof and mean loads were selected relative to the breaking load obtained from a break load test conducted. This ensured that the proof loading was referenced to the representative break strength from test rather than catalogue break strength.
This study concluded the following:

- Proof loading increases fatigue life substantially for both stud link as well as stud less chain.
- Higher the proof load, higher the improvement in fatigue life for the range of proof load applied.
- Residual compressive stress improves fatigue life.
- Higher applied stresses (mean + amplitude) accelerate the residual stress relaxation and hence reduce the fatigue life improvement.
6.3 NOBLE DENTON & ASSOCIATES, 2002

A Joint Industry Study led by Noble Denton [16] investigated the corrosion fatigue performance of studless mooring chain. 76mm diameter Grade R3 and Grade R4 mooring chain from three chain manufacturers were tested. The test variables were:

- Chain manufacturer
- Chain Grade
- Load range
- Load cycle frequency and
- Proof load.

Fatigue tests were carried out at UK National Engineering Laboratory (NEL). Chain from only one manufacturer used for to compare the effect of proof load. Fatigue lives for highly proof loaded (75% and 85%) chain are compared with chain with normal proof load (70% proof load).

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Manufact'r</th>
<th>Load Range (% of CBS)</th>
<th>Load Cycle Frequency (Hz)</th>
<th>No. of Cycles to Failure, N</th>
<th>Mean Cycles to Failure</th>
<th>Standard Deviation of N</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>675,851</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>714,463</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>714,463</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>865,301</td>
<td>821,867</td>
<td>127,470</td>
</tr>
<tr>
<td>16</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>959,998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>C (HP)</td>
<td>0.10</td>
<td>0.7</td>
<td>1,001,124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>C</td>
<td>0.10</td>
<td>0.7</td>
<td>597,319</td>
<td>645,145</td>
<td>47,826</td>
</tr>
<tr>
<td>20</td>
<td>C</td>
<td>0.10</td>
<td>0.7</td>
<td>692,970</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>C (HP)</td>
<td>0.20</td>
<td>0.7</td>
<td>171,761</td>
<td>179,811</td>
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</tr>
<tr>
<td>13</td>
<td>C (HP)</td>
<td>0.20</td>
<td>0.7</td>
<td>176,967</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>C (HP)</td>
<td>0.20</td>
<td>0.7</td>
<td>190,705</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>C</td>
<td>0.20</td>
<td>0.7</td>
<td>160,207</td>
<td>160,207</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>C</td>
<td>0.20</td>
<td>0.7</td>
<td>160,207</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(HP) in the above table indicate chains proof loaded to higher level. It is evident that the links subjected to higher proof load indeed had higher fatigue life. It can be seen that the effect diminish with higher load range (tests 13 and 19), which indicate the relaxation of residual stress.
7 BENDING, TORSION AND PROOF LOAD

7.1 SBM OUT-OF-PLANE BENDING JIP

As a part of the SBM out-of-plane bending (OPB) Joint Industry Project (JIP), Principia [12] has carried out a parametric Finite Element (FE) study on the impact of various factors on out of plane bending moment. The parameters included:

- Tension
- Interlink friction factor
- Proof Load
- Diameter

An elasto-plastic model has been studied for 107mm stud less link. Figure 7-1 below illustrates the residual stress (Principal Stress) from 70% proof load. Plastic strain at the elbow location is about 2.4% and the von Mises stress is around 530 MPa.

![Figure 7-1 Residual principal stress from proof loading [12]](image1)

It should be noted that immediately outside the interlink contact zone, the residual tensile stress is high. OPB principal stress at this region also happens to be tensile. The SBM/PRINCIPIA study has not drawn any conclusion in terms of the effect of tensile residual stress on OPB stresses. The focus has mostly been devoted to the effect of plastic deformation at the contact zone on interlink locking mechanism.

The SBM study has concluded that for a chain under tension loading, proof loading increases the out of plane bending stiffness and that the out-of-plane bending moment at the straight part has been significantly higher for proof loaded chains [12]. This has
been attributed to intimate mating surface from proof loading after manufacture of chain [14].

**Conclusions – FEA Scope 1**

- Sensitivity to the friction coefficient:
  - $\mu = 0.3; \mu = 0.5; \mu = 0.7$ with Proof Load
  - $\mu = 0.3; \mu = 0.5$ without Proof Load
  - $M_{OPB}$ calculated in the strait part

![Figure 7-3 Sensitivity to Friction Coefficient & Proof Load [12]](image)

### 7.2 TORSION

Ridge et al [15] carried out torsion tests on a 56mm stud link chain and 41mm stud less chain. The objectives of the test were

- To establish the torsional moment required to generate a given twist for a chain under axial load, and

- Response (torque) while applying an axial load to a twisted chain.

The results from the experimental study were compared with FE analysis. One of the FE models incorporated friction and reported stress levels in the chain, see Figure 7-4.

The highest principal stresses are reported at the half crown region, above 45° from the plane of the link. The tensile stress from torsional loads in this region may coincide with the tensile residual stress from proof loading (Figure 7-1).
Figure 7-4 Torsional stress in Stud Link Chain [15]
8 CONCLUSIONS

Numerical and test results confirm that proof loading is beneficial to tension fatigue. However, the effect of proof loading on chains under out-of-plane bending or torsional loads could be negative, since the regions with maximum tensile stress overlap with residual tensile stress following proof loading.

Proof loading leaves plastic deformation on the interlink contact zone. This may result in intimate mating surface between links thereby increasing the out of plane bending stiffness and stress.

Residual stress induces very high tensile strain at the contact zone surrounded by regions of minimum strain. The quick reversal of stress (and there by strain) within a short distance may induce surface cracks. Plasticity may not be induced uniformly along the surface. Assisted by corrosion, the cracks can develop and result in failure even under smaller working tensions.

To summarise, the issues identified;

- Proof load has been found to be beneficial for the integrity of chain and enhances fatigue life under tensile loading.
- Even though proof loading is proven beneficial to tension fatigue, it may reduce out of plane bending fatigue life or detrimental to twisted chains. Formulae that estimate non-tensile chain fatigue life based on the chain tension fatigue design curves should account for the distribution and effect of residual stresses and should be investigated.
- Any beneficial effect of proof loading may be confined to the period until the residual stresses are relieved- cyclic loading/higher working loads. This requires further investigations.
- Crack initiation is influenced by the mean tensile stress. Hence compressive residual stress is beneficial. However, once a crack is formed, crack propagation may not be influenced by the mean stress in the chain, and hence residual stress.
- A difficulty for high strength (e.g. R4) chain is that proof stress is cited with reference to specified minimum UTS/Break Load, not batch tested break load. It is difficult to ensure that there has been small permanent set to induce the beneficial compressive stress (in tension fatigue).
- If a batch has significantly higher UTS (which in many aspects is desirable) the degree of plasticity at the proof load level may be significantly less than the assumed with minimum specification material. A better definition of proof loading with respect to the actual break strength is required to make best use of the beneficial effect of proof loading.
- It has been noted that the rate at which break load is applied influence the outcome. The influence of the rate of proof loading is not known and deserves further discussion
- For stud link chain if the degree of plasticity under proof loading is less than anticipated, studs will be more likely to become loose in service.
- Plastic deformation at the contact zone due to proof loading has a detrimental effect due to a possible partial locking of the links, thereby increasing susceptibility to out of plane bending.
- Quick reversal of residual stress at the periphery of the interlink contact zone may initiate cracks. Assisted with sea-water and contact fatigue, the cracks may propagate faster.
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REFERENCES


An assessment of proof load effect on the fatigue life of mooring chain for floating offshore installations

Mooring Integrity Joint Industry Project Phase 2

Mooring Integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).

Long lengths of steel chain links are used in the mooring lines of offshore floating installations. As an installation moves under wave, wind and current conditions, the chains are subject to high loads that can promote metal fatigue and line failure through the nucleation and propagation of defects in the steel. This report assesses the impact on the fatigue life of chains of the proof loading carried out after manufacture. Proof loading involves testing chains at about 66% of the minimum breaking load specified in offshore standards. Proof loading has been found to be beneficial for the integrity of chain and enhances fatigue life under tensile loading. The report identifies other implications for chains with out-of-plane bending and for twisted chains.

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