METHODOLOGY TO ACCOUNT FOR CORROSIVE ENVIRONMENT ON ACCELERATED FATIGUE TEST ON MOORING CHAINS WITHIN THE CHAIN OUT OF PLANE BENDING (OPB) FATIGUE JOINT INDUSTRY PROJECT (JIP)

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Abstract. A Joint Industry Project (JIP), gathering 26 different companies, was started in 2007 to better address the Out of Plane Bending (OPB) mooring chain fatigue mechanism and propose some mooring chain fatigue design recommendations.
Within this project, full scale fatigue tests are in progress to mimic the OPB fatigue mechanism. To obtain results in a reasonable time-frame, these full scale tests are running on a dedicated fatigue bench at 1 Hz (instead of a normal offshore frequency of 0.1 Hz) in a corrosive seawater environment, on 2 different chain sizes. In parallel, tests on small samples, taken from mooring chains, have been done to better understand the influence of the corrosive environment on chain fatigue, by separately addressing the crack initiation and the crack propagation stages.
This paper will describe the tests done on small samples and the global methodology proposed to account for the higher frequency in the full scale tests (i.e. 1 Hz rather than the normal offshore frequency of 0.1 Hz) on the mooring chain OPB fatigue performance. This paper will also address the chain size effect.

1 INTRODUCTION

Eight years ago, several mooring chains of a deepwater offloading buoy failed prematurely within a very small time frame. These chains were designed according to conventional offshore fatigue assessment using API recommendations. With this first deepwater buoy application, a new mooring chain fatigue mechanism has been discovered. High pretension levels combined with significant mooring chain motions caused interlink rotations that generated significant Out of Plane Bending (OPB) fatigue loading. Traditionally, interlink rotations are relatively harmless and generates low bending stresses in the chain links. The intimate mating contact that occurs during the proof loading and the high pretension of the more contemporary mooring designs have been identified as aggravating causes for this phenomenon. Typical deepwater mooring pretension can be as high as 15% of the Minimum Breaking Load of the chain which is, as an example, for a 127 mm grade R4 studless chain, about 230 tonnes.

Out of Plane Bending (OPB) refers here after to the bending of a chain link out of its “main plane” (the one containing the oval shape, see figure 4). It is caused by the application of transverse forces and OPB moments which are resisted by friction forces at the contact between links.

Figure 1 : Chain Link Failure on deepwater buoy due to Out of Plane Bending (OPB)

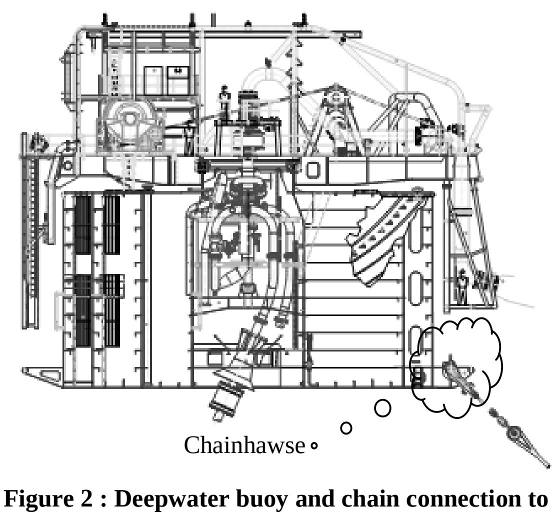

Figure 2 : Deepwater buoy and chain connection to the floating body

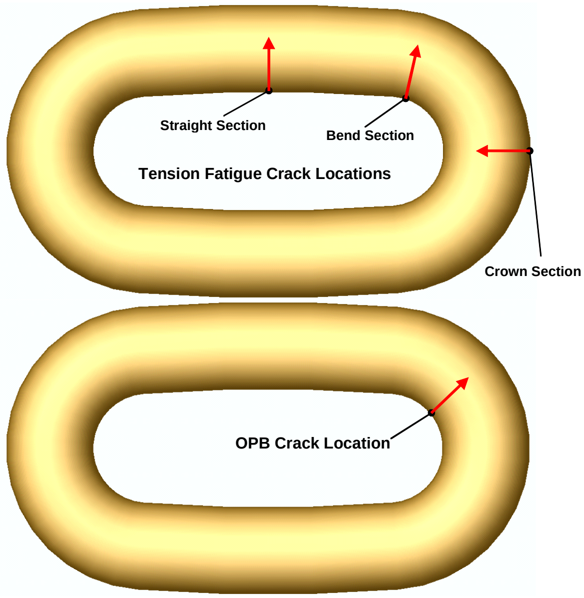

Figure 3 : Crack locations for Tension vs OPB Loading.

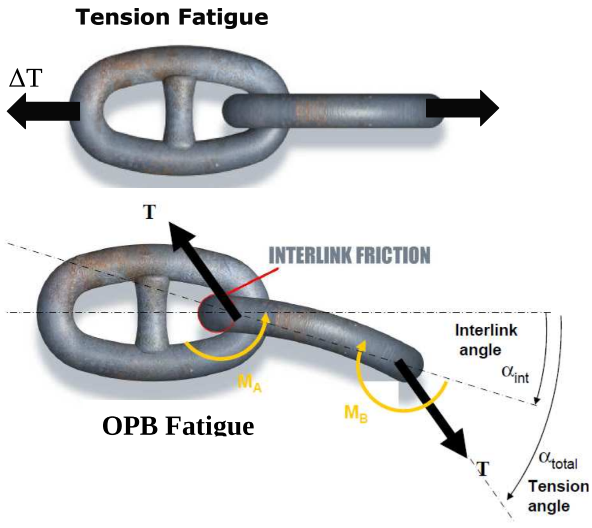

Figure 4: Out of Plane Bending (OPB) mechanism

Under high pretension, the friction is high and the moment that can be resisted at the contact between links can be significant. This rather unusual loading condition for a chain link arises from the combination of high pretension over MBL and poor articulation of the fairlead or chainhawse (chain connecting system with the floating body). The alternating OPB stresses may be large enough to cause the fatigue crack propagation in the first moving link starting from the chain connection at fairlead and failure can be quick. On particular case of the first deepwater buoy, 4 links have failed in less than 8 months always at the same location: on the first moving link.

A key difference between the traditional mooring chain-tension fatigue mechanism and the OPB fatigue is that chain tension fatigue uses the stress histogram applied to the mooring chain neglecting chain rotation effects, while the OPB fatigue uses the inter-link angular rotation converted to a stress (under constant chain tension) as a source of fatigue. Figure 1 shows the failure of a 81mm mooring chain in OPB. Figure 3 compares fatigue crack locations for tension loading and OPB loading.

Out-of-Plane Bending (OPB), explains why the mooring chains of the first off-loading buoy that failed (see Ref [1]) had such a short service life.
After this event, SBM undertook several different test campaigns to reproduce the OPB mechanism (see Ref [1] [2] [3] and [4]) and get the first laboratory demonstration of the Out of Plane Bending.
In 2007, a Joint Industry Project (JIP) was proposed to the offshore industry in order to implement a large chain testing program to better assess this new fatigue mechanism.
The main objectives from this JIP were to:

- Perform a quasi static test campaign to assess the interlink contact stiffness
- Implement a fatigue test program to get OPB endurance data points (S-N curve)
- Provide some design guidance to address the OPB chain fatigue mechanism

The fatigue domain of interest includes the high cycles regime (low stress range and large number of cycles, typically above 2 millions). Due to schedule constrain it was necessary to implement the fatigue tests at a higher frequency (1 Hz) than normal offshore conditions (about 0.1 to 0.2 Hz).
Moreover, it was initially proposed to do all fatigue tests in air and then to derive an S-N curve in seawater using the factors given by standard S-N curves. However, the validity of such extrapolation has been challenged by previous JIP results (T-T fatigues tests on chains, see Ref [5] showing a different trend (different slope) between tests in air and tests in a seawater corrosive environment (tests done in seawater at 0.2 Hz and 0.7 Hz showed the expected influence of frequency in seawater: 0.2 Hz fatigue performance was lower than that of 0.7 Hz; however, these seawater results were far superior to attempted extrapolated results from in air tests). Moreover, the ratio on life between S-N curves in air and in seawater can vary between factors of 2 to 5 depending on the standard codes used by the industry.

Consequently, it was decided to carry out most of the fatigue tests in seawater at 1 Hz (offshore mooring line loading frequencies are expected to be in the 0.1-0.2 Hz range), which is then introducing the question of the influence of the frequency increase on fatigue testing in a corrosive environment.

In addition, a test program on small samples has been implemented within the frame of this JIP in order to better assess the environmental parameter influence on fatigue test and its relation to the testing frequency by looking separately at fatigue initiation and crack propagation fatigue stages.

2 TESTS ON SMALL SAMPLES DEFINITION

2.1 Initiation and propagation fatigue mechanisms

The life time in fatigue may be split in 2 phases: an initiation phase (including initiation of microcracks, propagation and coalescence of microcracks and initiation of a macroscopic crack) and a crack propagation phase (propagation of the macroscopic crack), each corresponding to different damage mechanisms.

The following consideration, extracted from several references, provides a good insight for both fatigue mechanisms by addressing especially the crack nucleation, and small crack growth:

- "In flaw free material, a significant fraction of the total life is spent before the first detectable microcrack appears. At low amplitudes, the nucleation stage can occupy the majority of the fatigue life. Another fraction of the life time is needed for propagation of the microstructurally small cracks (i.e., crack of the size < 0.5 – 1 mm). Again this fraction can be quite high at low amplitudes. Propagation of physically small cracks and macrocracks can be quantitatively described by means of fracture mechanics. On the other hand, there is no generally accepted quantitative description of the nucleation process and there is no widely applicable description of the propagation of microstructurally small cracks". Ref [6]
- "Crack nucleation processes are associated with the generation and coalescence of excess vacancies along persistent slips bands… Clearly, propagation of small cracks is an important aspect of the initiation of a fatigue crack on the order of 1 mm" Ref [7]
- "The fundamental problem is that the customary linear elastic fracture mechanics (LEFM) parameter ΔK is strictly speaking an invalid representation of the crack driving force in the presence of enhanced near-tip plastically and microstructural inhomogeneity" Ref [8]
- Fatigue crack initiation parameters are reviewed by Mc Dowell in Ref [7] "Fatigue crack initiation parameters are reviewed, ranging from simple effective stress and strain concept to more recent critical plane theories. This approach is considered as distinct from fracture mechanics approach in view of the difficulties in applying the latter to small cracks in a rigorous fashion".

2.2 Effect of the frequency increase for both crack initiation and propagation stages

As explained in the following extracts, testing in a corrosive environment can be really sensitive to the testing frequency: "Because the environment induces a significant time dependency response, environment can vary markedly with loading frequency. At high frequency, it is common for the environmental enhancement to be substantially eliminated because of inadequate time available for associated chemical reaction and mass transport kinetics… Strong frequency effects are observed in most corrosion fatigue systems" (Ref [9])

The effect of the environment and of the frequency increase will affect each phase (initiation and propagation) differently. This can be summarized as follow:

- Influence of the environment and of the testing frequency on the crack initiation time:
    - Crack initiation is very sensitive to the surface finish of the chain link in terms of the depth of initial manufacturing crevice defects and other imperfections. Early occurrence of corrosion pitting in service can also create crack initiation sites.
    - Increasing the cyclic frequency up to 1 Hz (instead of a normal offshore cyclic loading of 0.1 to 0.2 Hz) will have an impact on the duration of exposure in a corrosive environment. Therefore, testing in seawater at 1 Hz should increase the crack initiation time.
    - Pre-soaking of samples in free corrosion conditions has been implemented before fatigue testing. However, it is difficult to assess if this enables to achieve a representative steel surface in terms of density of initial small defects (corrosion pits) and defect profile.

- Influence of the environment and of the testing frequency on the crack propagation time:
    - As defined by P.S. Pao in Ref [10] "crack growth rate can be substantially higher in a corrosive environment". The author defines different mechanism interactions between corrosion and fatigue like "hydrogen induced fatigue" (hydrogen embrittlement), "cracking and/or anodic dissolution at the crack tip" and "stress corrosion cracking".
    - The frequency may have an impact on the crack propagation rate (as may possibly interact on one of several of the corrosion - fatigue mechanisms above). This can be assessed separately by doing some tests on samples in air and in seawater for different frequencies.

2.3 Requirement for a multiaxial fatigue criterion for crack initiation stage

Some FEA work, that has been implemented within the frame of the JIP, has demonstrated that the stress state for a link subject to Out of Plane Bending is multiaxial at the OPB spot location. The OPB spot location is on the link curvature close to the border of the interlink contact area where most of the initial crack locations from tested chains have been found.
Therefore, a multiaxial fatigue criterion is appropriate to describe the OPB chain fatigue initiation stage.

Some recent multiaxial fatigue theoretical developments have been proposed by K Dang Van, based on critical plane theories (Ref [11] , [12] and [13]) that can help to assess the macroscopic flaw initiation stage.
In Dang Van method, the assumption is made that the structure is submitted to high cycles fatigue which implicitly means that the overall behavior remains elastic. The main hypothesis is that a fatigue crack will initiate if and only if the material doesn't reach elastic shakedown locally. The elastic shakedown at the mesoscopic scale (metallic grain size) may occur only if an elastically adapted mechanical state is reached at the scale of the structure.
A multiaxial fatigue criterion has been defined by K. Dang Van that gives the critical loading path in the diagram $\tau - p$ (shear stress as a function of hydrostatic pressure which is the hydrostatic part of the stress tensor):

- This criterion aims to deal with high cycle fatigue conditions where the damage occurs at a microscopic level. The formulation uses the current values of shear stress $\tau(t)$ and hydrostatic pressure p(t), at the mesoscopic scale, to calculate an "equivalent" stress and compare it to a threshold:
    - No damage will occur if: $\tau(t) + a * p(t) < b, \ t \in T$
    - a, b are material parameters calculated from two simple fatigue tests
    - T is the loading period.
- The initial Dang Van criterion defined for infinite lifetime has been extended for a finite lifetime based on a complete series of torsion and bending Wöhler curves for the material considered. For each finite number of cycles N, a limit amplitude in torsion and bending can be defined (denoted t_N and f_N respectively), each of these pairs defining a new Dang Van line that will form a bundle in the τ– p diagram. It states that over a finite number of cycles noted N of a T-periodic stress state, fatigue failure initiates if the Dang Van criterion fails as follows :
    - If it exists $t_0 \in [t, t+T]$ such $\tau(t_0) + a_N \cdot p(t_0) \geq b_N$

      where τ is the shear stress and p is the hydrostatic pressure
      a_N et b_N are material constants which depend on N.
    - $$a_N = \frac{t_N - \frac{f_N}{2}}{\frac{f_N}{3}} \ ; \ b_N = t_N$$

2.4 Small samples testing programs description

2.4.1 Crack propagation tests

- Tests objectives:

Crack propagation tests on small samples were performed at TWI (see Ref [18]). The objective from these tests was to determine the influence of cyclic loading frequency (in the range of 0.1 Hz to 1Hz) on rates of fatigue crack growth for high strength chain steel in seawater and assess the influence of environment (air / seawater) and of testing frequency on the crack propagation stage.

- Frequency scanning tests:

Six "frequency scanning" fatigue crack growth rate tests were conducted to determine the influence of cyclic loading frequency on observed fatigue crack growth rates. These tests were conducted under conditions of constant ΔK, with the frequency being varied in blocks to establish the influence of this parameter.
The following six frequency scanning tests were performed, using a stress ratio of 0.2:

- Two tests in air, at high ΔK
- Two tests in seawater, at high ΔK
- Two tests in seawater, at low ΔK

- Paris law definition:

Initially, two tests were performed in air, under conditions of increasing ΔK (constant load range), to determine a baseline Paris law for this material. These tests were carried out using a stress ratio of 0.2 and a frequency of 1 Hz and were used to select suitable low and high ΔK values (respectively of 380 and 800 $N/mm^{3/2}$).

2.4.2 Crack initiation testing program

- Tests objectives:

Full scale testing on chain links at higher frequency than the normal offshore frequency (1 Hz instead of 0.1 Hz) is reducing the time of exposure from chain links in a corrosive environment. This is assumed to have an influence on the corrosion status from these tested links.
To assess the influence of the corrosion status (density and profile from corrosion pits on chain links) on the crack initiation stage, the endurance limit for two types of loading (torsion and rotative bending) has been defined for both corroded and non corroded samples machined from chain links.
These 2 types of fatigue loading (torsion and rotative bending) have been selected to derive Dang Van curves for corroded and non corroded material.

- Preliminary study:

A preliminary study was contracted to CETIM to optimize the test program (see Ref [19]). Since typical offshore life time for mooring chains (over 20 years) would induce more than 50 millions of cycles, the question was to define if it was essential to get the endurance limit for at least $5*10^7$ cycles (very costly) and also to simulate the best way to get the standard deviation.
A theoretical approach has been implemented that has emphasized the following:

- A normal distribution from the fatigue life for a given load is generally admitted
- A constant standard deviation can be defined whatever the fatigue life
- The stair case testing method is recommended to derive the mean fatigue strength but is not suitable to derive the standard deviation
- The fatigue curve under load controlled (Wöhler / S-N curve) can be modeled as follow:
    - with an asymptote for steel tested in air
    - with no asymptote for tests under corrosive environment
    - with a downgraded asymptotic curve for corroded sample

Stair cases simulations have then been implemented (using Monte Carlo random function) based on an hyperbolic S-N curve (valid model for tests done in air on corroded or non corroded samples) calibrated to fit the chain material properties (grade R4). A large number of stair cases has been simulated that has shown that with an asymptotic curve, there was a significant overlap between the endurance level found at 10 millions of cycles and at 50 millions of cycles. Therefore, it was concluded that the results may not be statistically distinct.
Finally, simulations have been run to find the best way to get the standard deviation at lower cost. It was demonstrated that a few tests at constant stress level will provide less dispersion on the standard deviation than a large number of stair cases.

- Dang Van curves definition at 1 million and 10 millions of cycles:

The Dang Van curves (fatigue limit criteria for a given number of cycles in the τ / p diagram) are derived from Wöhler curves fatigue threshold for both torsion and rotative bending tests on samples. The same material grade (R4) as the crack propagation tests was tested at 2 different levels of corrosion (non corroded and corroded) and compared.
The endurance limit for one million of cycles and for 10 millions of cycles were extracted for torsion and rotative bending and for both corroded and non corroded material using nine samples for each stair case. Seventy two samples have therefore been used to build stair cases (9 samples * 2 number of cycles * 2 materials * 2 loading conditions) and to derive mean S-N curves.
The standard deviation for corroded S-N curves has then been defined using 10 samples tested at 2 constant load levels defined for a shorter number of cycles (5 samples for 2 load levels corresponding roughly to 10^5 cycles and $5*10^5$ cycles). Twenty samples were therefore used to derive the standard deviation on corroded material (5 samples * 2 loading conditions * 2 stress level). The standard deviation has been conservatively defined on corroded samples as the dispersion is assumed to be higher for corroded samples than for non corroded samples.

- Comprehensive testing program:

The samples have been machined from 84 mm studless chain links grade R4 manufactured by Vicinay.
The full crack initiation testing program (see Ref [20]) was done in 3 phases which were:

- Phase 1: Reproducing offshore corrosion state
- Phase 2: Fatigue tests to derive Dang Van curves on corroded and non corroded samples
- Phase 3: Comparative tests to see the influence of the samples size

3 TEST PROGRAM RESULTS

3.1.1 Crack propagation tests

- Testing protocol:

Fatigue crack growth rate tests were carried out using single edge notched bend (SENB) specimens machined from a supplied section of 84 mm chain link grade R4. Eight specimens (section of 15*30mm) were machined from sections located in the link straight part opposite to the flash weld to ensure crack growth in the parent material.

All tests have been carried out using standard servo-hydraulic testing machines with computer control and data logging. A direct potential drop technique was used to monitor the crack length. All tests have been carried out at ambient temperature using a sinusoidal waveform.

These frequency scanning tests were conducted under conditions of constant driving force ΔK by decreasing the applied load range as the crack grows from an initial crack of 3 mm up to a final crack of 15 mm. The cyclic loading frequency was varied in blocks to establish the influence of this parameter, as shown on the figure below. Five different blocks of testing frequency (0.1 Hz, 0.2 Hz, 0.5 Hz, 1Hz) were implemented using both increasing and decreasing conditions.

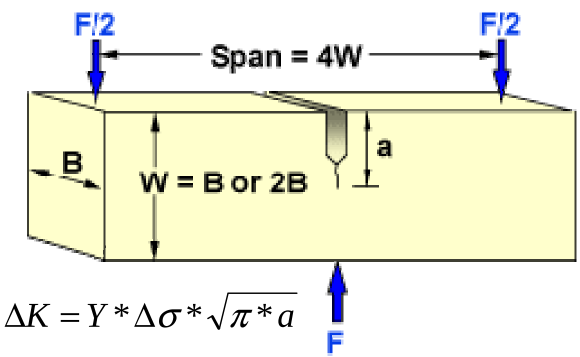

Figure 5 : SENB standard specimen machined from chain links

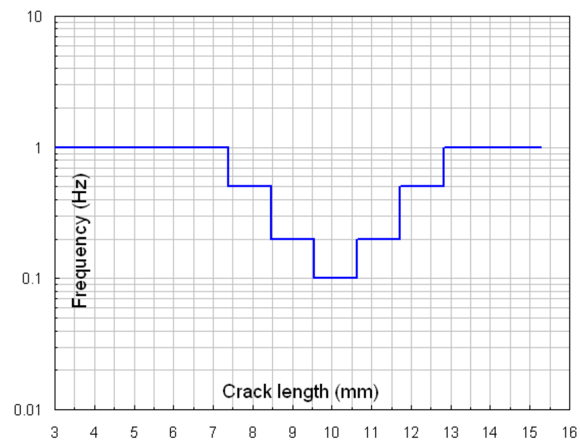

Figure 6: Frequency scanning tests block loading

Crack growth rate data from the frequency scanning tests was post processed by plotting the crack length versus the cycles data for each frequency test block and determining a linear fit. This provided a crack growth rate for each frequency block tested.

- Test results:

The following results and conclusions can be derived from these tests:

- There is a rather good consistency between both samples tested under the same conditions (more scatter for higher frequency values)
- The fatigue crack growth rate in air is not really dependant from the cyclic frequency (between 0.1 Hz and 1 Hz)
- For a high driving force ($\Delta K \approx 840$ N/mm$^{3/2}$):
  - The fatigue crack growth rate in seawater increases significantly (more than 50 %) when the testing frequency is reduced from 1 Hz down to 0.1 Hz.
  - The crack growth rate is higher in seawater than in air from a factor of 2 to 3 depending of the frequency (environmental factor close to 3 at 0.1 Hz and closer to 2 at 1Hz)
- For low driving force ($\Delta K \approx 400$ N/ mm$^{3/2}$):
  - The fatigue crack growth rate in seawater is not really dependent on the testing frequency
  - The crack growth rates in air and in seawater are very similar (no noticeable environmental effect in that case)
- Comparison with BS7910 (see Ref [15]) curves for steel (R<0.5), as illustrated by the Figure 7 below (conventional graph showing the crack growth rate function of the driving force):
  - For data in air, there is a good consistency with BS mean curve (slightly not conservative for results at low ΔK)

- The seawater tests results at high ΔK are consistent with BS mean curve. Crack growth rates are a little lower in the test at 1 Hz but BS mean curve is a little lower than the test results at 0.1 Hz
- Regarding the results for seawater tests at low ΔK, the BS mean curve crack growth is significantly higher

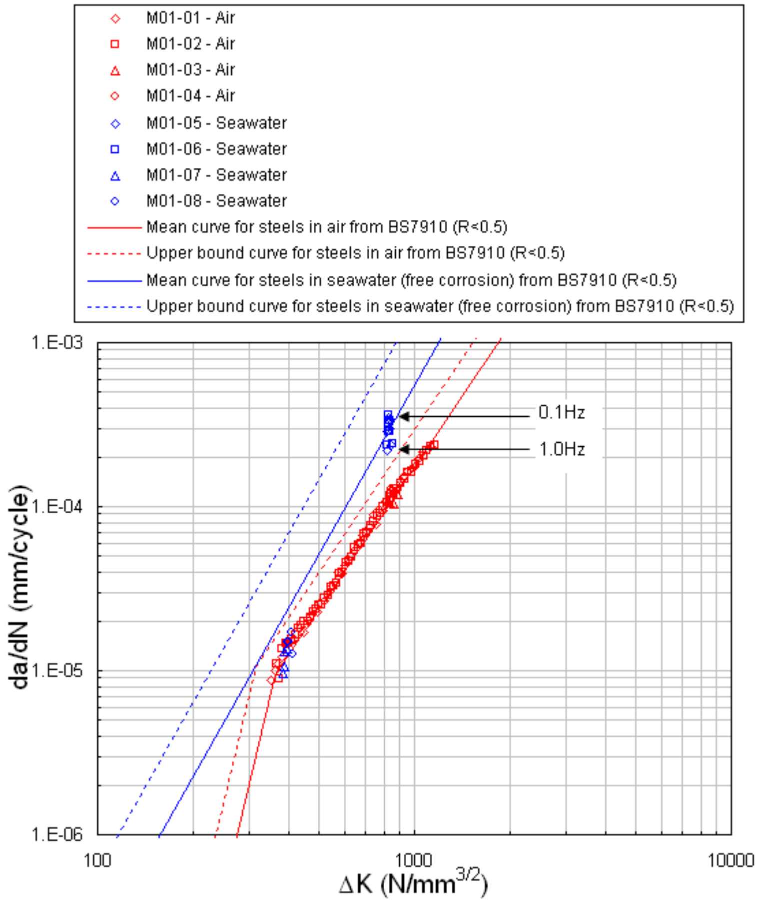

Figure 7 : Comparison of all fatigue crack growth rate data

3.1.2 Crack initiation testing program

- Phase 1: corrosion samples definition

In order to assess the influence of corrosion on fatigue crack initiation performance, the first step was to define a target corrosion profile that would be representative of offshore corroded chains after a couple of years.
Therefore, a couple of chain links retrieved from top mooring legs segment from a unit moored in North Sea have been analysed. These 157 mm chain links have spent about 9 years in seawater and have been taken as a reference.
Both metallographic examination and metrological inspection have been performed.
Both general corrosion (corrosion of the entire surface) and pitting corrosion under oxide deposit (localized crevice corrosion) were observed.
Corrosion mapping (see figure 9) was carried out by contact-free measurement of the surface of the link after chemical stripping as per standard given in Ref [16] . The aim was to obtain an image of the surface finish of a small zone.

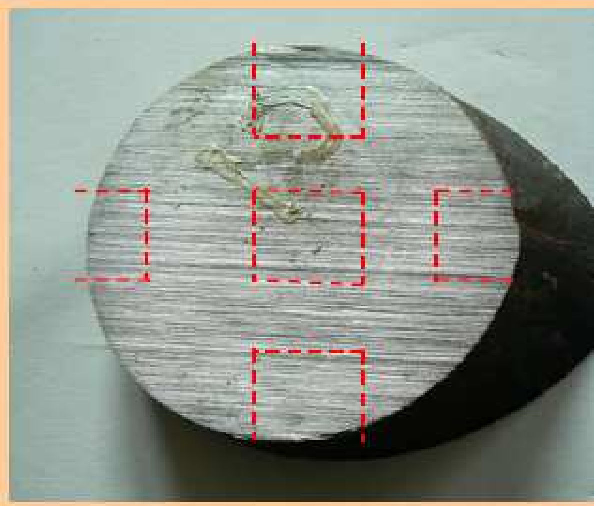

Figure 8 : Specimen cutting areas for morphological analysis (tubular section taken from chain link)

Figure 10 : Close view of a corroded area (chain link metallographic examination)

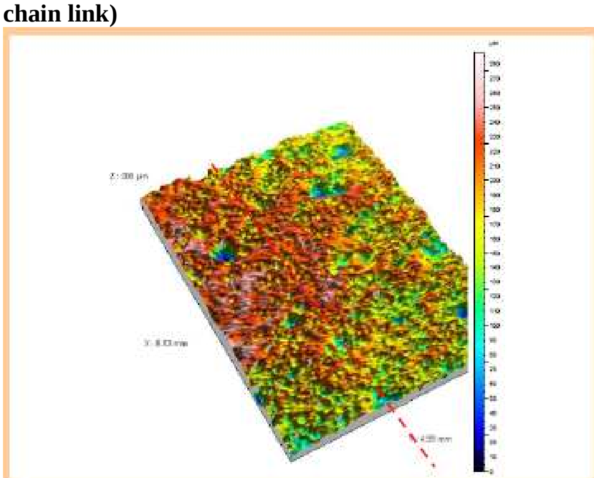

Figure 9 : Mapping of surface after chemical stripping of surface oxides

Figure 11 : Roughness profile along dotted line in figure 9

From these investigations, a target crevice corrosion depth was defined between 80µm and 150µm.
Two corrosion methods have been tested on samples (cylindrical specimen) and compared. These were:

- Salt spray method: the tests were carried out as per standard given in Ref [17] and samples were removed every 100 hours up to 840 hours.
- Corrosion by immersion in NaCl solution: the samples were immerged in a salted solution (NaCl concentration of 50g/L) for a maximum duration of 840 hours.

The samples were retrieved regularly and analyzed in the same way as was done for the reference chain links:

- Metallographic examinations

  For each cylindrical specimen taken during the tests, a metallographic section was taken in order to obtain an image of the state of corrosion. The maximum depth of the deposits in the area observed was measured.
- Characterization of the surface:

  Mapping of the surface of the cylindrical specimens (in 3 dimensions) was carried out. A clear image of the specimens' surface is produced. The specimens were cleaned as per standard given in Ref [16] before the mapping was done using a contact free measuring machine.

The result from this comparison was that the salt spray tests accelerated corrosion of the cylindrical specimen more significantly than the immersion tests. In the case of the salt spray tests, the presence of general corrosion was mainly observed together with incipient corrosion under deposits and 800 hours gave satisfactory results with respect to the corrosion state observed on the reference links.
Consequently, 800 hours salt spray test duration was considered sufficient to "simulate" corrosion degradation on fatigue samples:

- The whole surface is corroded: general corrosion with large crevices (depth ~ 100 µm)
- Corrosion does not affect the section of the sample ($\Delta S < 4\%$)

- Phase 2: fatigue characterization from chain links grade R4 material

Fatigue tests have been carried out in rotating bending and reversed torsion loading conditions (load ratio R=-1), on standard cylindrical fatigue specimens. According to results from the corrosion phase study, these specimens have been extracted from the periphery of the straight area of the chain links, opposite to the weld zone. The samples were typical fatigue samples with a nominal diameter of 5.9 mm for rotating bending and 7 mm for torsion. They were tested in air at 100 Hz for rotating bending and 50 Hz for torsion. These frequencies have no influence on the fatigue behaviour of steels, when tests are performed in air environment and ambient temperature.

Figure 12 : Standard torsion specimen (non corroded and corroded)

σ	Order of the tests								
(MPa)	1	2	3	4	5	6	7	8	9
370									
340	X								
310		X		X				X	
280			O		X		O		X
250						O			
220									
Number of Cycles	151000	167000	10000000	646000	288000	10000000	10000000	662000	468000

X : failure before Nr (Nb cycles to failure)
O : no failure at Nr
Figure 13 : Stair case example at 1E7 cycles

The endurance limit and standard deviations have been calculated from each stair case (corroded and non corroded samples for rotating bending and torsion and for 1 million and 10 millions of cycles).
The stair case method does not show a sensible difference between endurance limit at 1E6 and 1E7 cycles. The cut-off lives are in or very near the asymptotic part of the S-N curve. The whole results (stair cases at 1E6, stair cases at 1E7 and tests at constant stress levels) have then been processed and a reasonable fit has been obtained using a Stromeyer hyperbolic law.

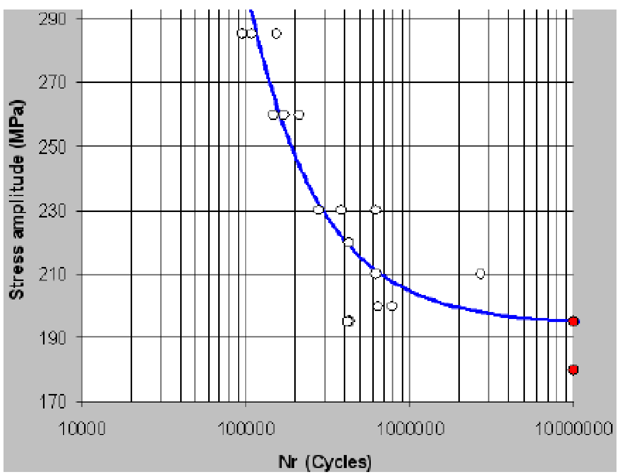

Figure 14 : Example from Woehler S-N curve obtained (torsional tests / corroded small samples)

Figure 15 : Typical failures observed on fatigue specimen (bending on top and torsion below)

For the endurance limits determination, the failure criterion corresponds to a macroscopic crack initiation, detected by a loss of specimen stiffness. However, conducting specimens to failure in this case showed that crack initiation phase represents the major part of specimen's total life compared to the propagation phase.

The main result from the comparison from endurance limits between corroded and non corroded samples is that the corrosion state on standard fatigue specimen reduces the endurance limit by about 40% in rotating bending and 35% in torsion.
Dang Van curves parameters were derived from fatigue tests using the rotating bending and torsion endurance limit (fatigue tests results from stair cases and Stromeyer asymptotic values). This is shown on the following figure.
For non corroded material state, the Dang Van threshold slope, a, was found to be in line with typical values for steel (around 0.3-0.35). In the case of corroded material state, the Dang Van slope (a) increases significantly, characteristic of a material fragilized or containing defects.

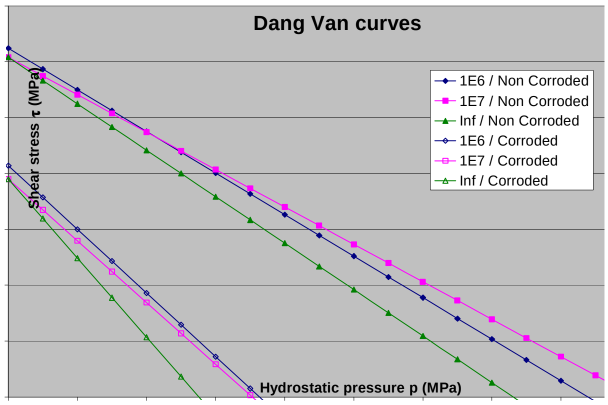

Figure 16 : Dang Van material limit diagram

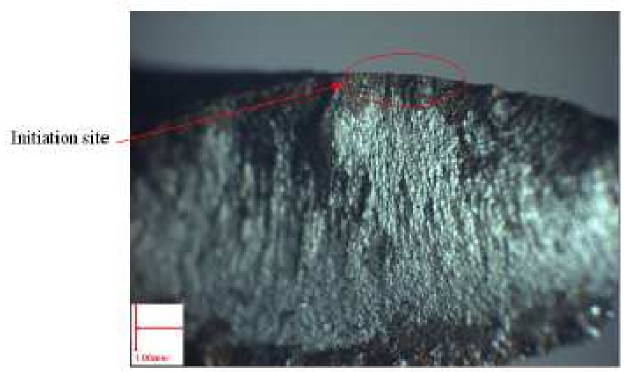

Figure 17 : Crack initiation location on corrosion crevice (corroded sample)

Finite Element Analyses have been done within the frame of the JIP, using 107 mm studless grade R3 chain links. Three cycles have been run in out of plane bending (up to sliding) at 25% MBL. These FE results were then post processed by CETIM to apply the Dang Van criteria using both non corroded and corroded material, at several locations.

The safety factor has been calculated using the following formula:

$$SF = \frac{b}{Max\left(\tau(t) + a \times p(t)\right)}$$

The results from this multiaxial stress state criterion have shown that:

- The smallest safety factor is achieved at location C (as shown on Figure 18) which was the worst shear stress location. Its safety factor is smallest than the one achieved at location B which has a highest maximum principal stress (B being close from location B' which is the worst location when looking at the maximum principal stress). Since OPB failure are more often associated to location C, the multiaxial criterion seems to be a better approach than a uniaxial criterion associated with the max principal stress for proper fatigue assessment for OPB.
- The results using corroded material curve are a lot more severe than results with non corroded material, showing that failure is occurring at a significantly lower load level with corroded material.
- A ratio of 1.85 can be derived between safety factors calculated at location C using non corroded and corroded material.
- Note that this ratio is applicable for the comparison of non corroded machined specimens to corroded specimens. The use of this scaling should be used with caution on actual mooring chains.

Similar results (calculated Dang Van safety factors) have been obtained when using the stresses recorded from strain gauges glued during tests at location B (about 20° inside the link curvature) and M (link straight part).

Node	Material Group	Safety factor	Tau critical	Ph critical
206253 C	link	1.114	191.8	238.3
206458 B	link	1.298	157.2	226.2
200006 M	link	5.022	21.05	116.1
201912 A	link	5.838	47.14	14.53

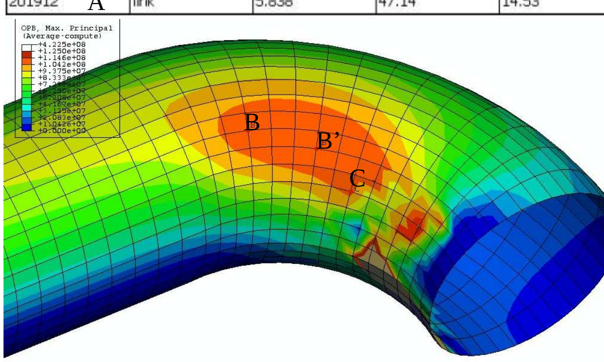

Figure 18 : Dang Van SF calculation using non corroded material curve at 1E7 cycles and FE results in OPB

Node	Material Group	Safety factor	Tau critical	Ph critical
206253 C	link	0.6039	191.8	238.3
206458 B	link	0.6924	157.2	226.2
200006 M	link	2.296	21.05	116.1
201912 A	link	3.537	47.14	14.53

Load path at critical node 206253:

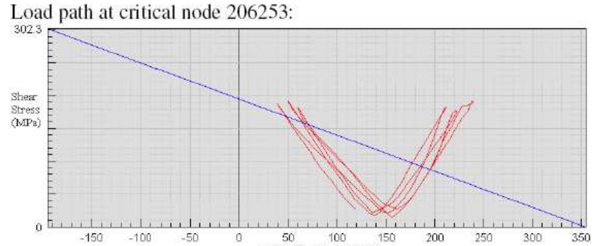

Figure 19 : Dang Van safety factors calculation using corroded material curve at 1E7 cycles

- Phase 3: large specimen testing

Size effect is one of the numerous factors influencing the fatigue strength of components. It is well known that for the same material, increasing the size of the specimen leads to a reduction in fatigue strength (for the same nominal stress) and this being due to a higher probability to have a defect for larger parts and also to a less steep stress gradient for these parts. In this case, tests have been carried out in torsion on specimens with a central diameter of 20mm compared to 7mm for the standard fatigue specimens, by a stair case with 5 specimens at 1E6 cycles. The same failure criterion was used (macroscopic crack initiation). Tests have been done using both non corroded and corroded samples.
The endurance limit found for non corroded and corroded samples at 1E6 cycle was found to be rather similar from the one found on smallest samples (7 mm diameter). No real performance degradation was found when increasing the sample size. This can be justified as follow:

- o The difference in specimen diameter (20mm vs 7mm) is probably too low. Results from the literature tend to confirm this observation, as illustrated by figure from work done by Sors (Ref [14]). It appears that fatigue strength reduction at 20mm is about 2.5% and significant reduction occurs only for diameters higher than 30mm.
- o In the case of corroded samples, the fatigue strength of large size corroded specimens was found even higher (about 10%) than that of small standard corroded specimens. This may be due to the fact that corrosion tests lead to similar maximum depth pits on both small and large specimens; which may make the corrosion effect more sensitive on the fatigue strength for smaller specimens.

Figure 20 : Large size corroded specimens

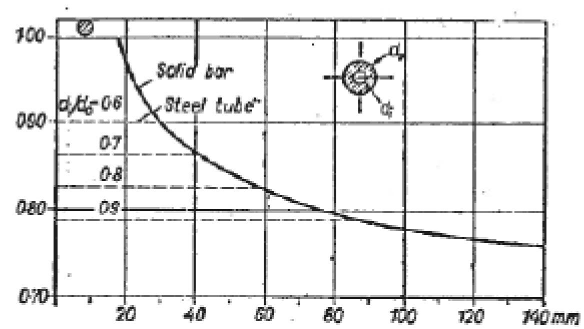

Figure 21 : Size effect in torsion for cylindrical specimen (see Ref [14])

4 FREQUENCY EFFECT CORRECTION FOR FATIGUE TESTS ON CHAINS

To account for loading frequency difference between the full scale fatigue tests on chains and the mooring environment, it is important to estimate for each test the contribution from both initiation and propagation stages. For this, it was initially foreseen to implement within the JIP Acoustic Emission measurements during testing which would have helped to assess when a crack is propagating. This was unfortunately not implemented due to budget constraint. However, some post failure crack investigations have been done using MPI (Magnetic Particle Inspection) on symmetrically loaded chain links to check the potential presence of cracks on similar OPB hot spot locations. This can provide valuable information on the time spent for a macroscopic crack to initiate.
Further work and discussion are in progress within the JIP to validate the correction proposed to account for the testing frequency difference. A potential correction factor (on life or on stress range) can be proposed for each full scale test on chain following the following guidelines:

- Estimate (based on recorded stress and NDT results) if the test is more dominated by crack initiation or crack propagation mechanism.
- The crack propagation stage can be assessed using fracture mechanics and established industry practice that enables to extract out the amount of fatigue life corresponding to propagation. Then, an average correction factor on life can be extrapolated, using a simple linear model and boundaries derived from the frequency scanning tests results (as per Figure 22).
- For a test dominated by crack initiation mechanism, the factor of 1.85 on stress (Dang Van Safety Factor ratio between non corroded and corroded material, as given in the previous chapter) provide a very conservative correction on stress that would apply on machined and uncorroded material and then is really severe to correct the corrosion effect on tested chains.

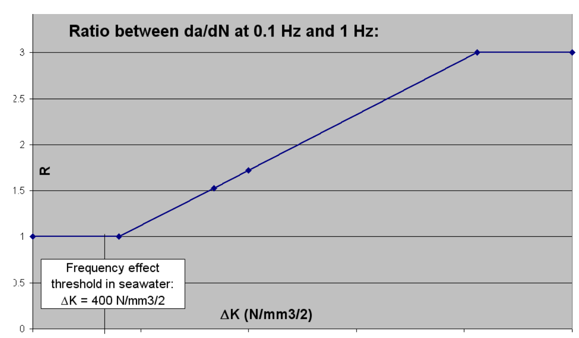

Figure 22 : Corr. factor / crack prop rate (1 to 0.1 Hz)

5 CONCLUSION

This paper summarizes the tests that have been done on small samples in the chain OPB fatigue JIP. These tests were intended to provide insight on the effect of frequency for the full scale fatigue tests (1Hz instead of a normal offshore frequency of 0.1Hz). This has been done by looking separately at the influence of the environment on crack propagation rate and by assessing the fatigue endurance threshold for corroded and non corroded material (crack initiation stage).

A simple correction model can be proposed for crack propagation stage and the effect of the corrosion status on crack initiation stage can be framed by fatigue endurance results comparison between corroded and non corroded samples. This provides an idea of the order of magnitude of the non conservatism for tests at higher frequencies in a corrosive environment.

For each individual full scale fatigue test on chain, the challenge is then to assess if there is one fatigue mechanism (crack initiation or crack propagation) which is dominating and then to propose a correction on the number of cycles to failure or on the stress range.

Further discussions are ongoing within this project to address case by case the result from each individual full scale fatigue test.

The crack initiation test on small samples have also enabled to get the Dang Van material curves based on corroded and non corroded material. Applying a multiaxial fatigue criterion did also confirm that the most fatigue sensitive location was within the chain link curvature in a multiaxial stress state location, showing that this criterion would be more suitable than an uniaxial criterion based on the maximum principal stress.

Finally, the sample size effect was assessed in this test program. The results did not show significant reduction in fatigue performance for the larger specimen likely due to insufficient difference between specimens diameter (7mm vs 20mm). Further investigation, within the full scale test fatigue program, is currently in progress to assess potential fatigue strength degradation for larger chain diameter directly from the large scale tests.

6 ACKNOWLEDGEMENTS

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