Degradation of mooring chains of floating offshore installations: chain measurement, estimation of wear, corrosion rates, and their effect on break load

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).

Mooring chains inevitably degrade over time leading to loss of strength of individual mooring lines and the mooring system as a whole. This report describes how the reduced dimensions of the chain may be measured by various techniques, both underwater or when brought above the surface. It investigates typical wear and corrosion rates experienced in the field, and the change in the minimum break load of used mooring chains. The report provides: practical guidelines on likely wear and corrosion rates to inform decisions at the design stage on chain diameter allowance; indicative wear and corrosion rates to inform judgements on whether rates seen in use are typical or anomalous; and guidelines on how the minimum break load will change with degradation.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.
Degradation of mooring chains of floating offshore installations: chain measurement, estimation of wear, corrosion rates, and their effect on break load

Mooring Integrity Joint Industry Project Phase 2

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1  PREFACE

This sub-report has been written to provide operators and those involved in designing, verifying and integrity management of offshore floating production units with guidelines on:

• Above water / on shore chain measurement;
• Cross-sectional area estimation;
• Chain measurement analysis techniques;
• Typical wear and corrosion rates for offshore mooring chains;
• Break testing of aged mooring chains;
• Down rating of aged offshore mooring chains.

These guidelines have been produced under the auspices of Phase 2 of the GL Noble Denton lead Mooring Integrity Joint Industry Project (JIP) and as such should be read in conjunction with the other reports that have been produced under its auspices. It should be noted that wire rope, spiral strand and fibre rope is not covered in this report, although some of the principles discussed may be applicable to them.

The GL Noble Denton lead Mooring Integrity Joint Industry Project (JIP) Phase 2 has been sponsored by the following companies:

- Maersk Oil
- Petrobras
- BP
- Chevron
- Statoil ASA
- Exxon Mobil
- A/S Norske Shell
- Conoco Philips
- Husky Energy
- 2H Offshore
- Wood Group Engineering
- Single Buoy Moorings Inc.
- SOFEC
- Bluewater Energy Services
- Health and Safety Executive
- BG Plc
- Total
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- Lloyds Register EMEA
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- Welaptega
- Vicinay Cadenas S.A.
- TSC Inspection Systems
- Hamanaka Chain Mfg.Co., Ltd.
- Imes Group
- Sanmar Chain International Pte
- Viking Moorings
- International Mooring Systems
- Ramnas Bruk AB
- Mooring Systems Limited
- Bruce Anchors Limited
- Inpex
- Delmar
- Film Ocean Limited
2 INTRODUCTION

Given that Floating Production Systems (FPSs) stay on location year after year their mooring systems will inevitably degrade over time leading to a loss of strength of individual lines and the system as a whole. With explicit regard to mooring chains such degradation is likely to take three principle forms, namely:

1. Wear;
2. Corrosion;
3. Fatigue damage.

To account for items 1 and 2, an allowance is typically added to the chain size so that at the end of the intended design life the degraded chain still has sufficient strength to be able to resist the loadings imposed by the design survival condition. Guidance on such a combined wear and corrosion allowance can be found in a number of mooring codes such as API RP 2SK [1], DNV OS-E301 [2], and LR: Rules and Regulations for the Classification of a Floating Offshore Installation at a Fixed Location [3]. For example Table E1 of DNV’s Offshore Standard for Position Mooring [2] states that:

<table>
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<th>Part of mooring line</th>
<th>Corrosion allowance referred to the chain diameter</th>
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<tr>
<td></td>
<td>No inspection (mm/year)</td>
</tr>
<tr>
<td>Splash zone 3)</td>
<td>0.4</td>
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<tr>
<td>Catenary 4)</td>
<td>0.3</td>
</tr>
<tr>
<td>Bottom 5)</td>
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1) Regular inspection e.g. in accordance with the Classification Societies or according to operators own inspection programs approved by the National Authorities if necessary. The mooring lines have to be replaced when the diameter of the chain with the breaking strength used in design of the mooring system is reduced by 2%.
2) The increased corrosion allowance in the splash zone is required by NORSOK M-001 and is required for compliance with NPD, see DNV-OS201.
3) Splash zone is defined as 5 m above the still water level and 4 m below the still water level.
4) Suspended length of the mooring line below the splash zone and always above the touch down point.
5) The corrosion allowance given in the table is given as guidance, significant larger corrosion allowance should be considered if bacterial corrosion is suspected.
6) Investigation of the soil condition shall be carried out in order to document that bacterial corrosion is not taking place.

There have, however, been a number of cases of wear and corrosion greatly exceeding these figures, as well as some systems where the combined wear and corrosion has been much less, and the origin of these figures and those in other mooring codes appears to have become somewhat lost in the annals of time. As a consequence, this report sets out to investigate typical wear and corrosion rates that have been experienced in field, as well as investigating the change in the minimum break load of used mooring chains.

The intention of this report therefore is threefold:

- Firstly, to provide designers and operators with practical guidelines during the design phase as to likely wear and corrosion rates. As such it is intended that this report be read in conjunction with the aforementioned Classification Society Rules and API guidance, as well as the Mooring Integrity JIP Phase 2 sub-report entitled "Practical Method for Calculating
Mooring Chain Wear for Floating Offshore Installations, Mooring Integrity Joint Industry Project Phase 2" [4], such that an informed decision can be made about the allowance to be added to the chain at the mooring system design stage;

- Secondly, to provide operators and integrity management personnel with indicative wear and corrosion rates to assist them in making informed judgements as to whether the rates that they are seeing, on the mooring system that they are managing, are typical or anomalous;
- Thirdly, to provide guidelines, in general terms, on how the minimum break load of a mooring chain will change with degradation.

As a consequence, this report is broken up into four sections, namely:

- Data Survey and Collection (Section 3), including some guidelines on above water/on shore chain measurement, which are intended to supplement the guidance given in the classification rules and the likes of API RP 2I [5];
- Indicative Wear and Corrosion Rates (Section 4), which includes information on how chain measurement data sets can be used in integrity management;
- Break Testing of Aged Mooring Chains Guidelines (Section 5), including guidelines on some of the issues that need to be taken into account and useful data that could be collected when break testing mooring chains in order to maximise the worth of the break tests;
- Down Rating of Aged Offshore Mooring Chains Guidelines (Section 6), which outlines the factors that need to be taken into account when deriving a minimum break load for an operational mooring chain.

In using these guidelines, it should always be borne in mind that the information presented is from a relatively small data set and so the data should never be seen as anything more that indicative and should only form one part of a decision making process.
3 DATA SURVEY AND COLLECTION

3.1 DATA SURVEY

The very essence of a study such as this is data, hence as part of the Mooring Integrity JIP Phase 2 a data survey and collection exercise was undertaken in 2008. At the time, there were a total of 11 members of the JIP that were operators, all of whom were sent pre-filled in spreadsheets with regard to:

- FPS type;
- Mooring system type and configuration;
- Design Conditions;
- Whether the mooring systems were part of Class;
- Whether they surveyed their mooring systems;
- If they did survey them how often;
- Whether they took measurements of their mooring chains;
- If they did measure them how often;
- Whether they would be willing to release that measurement data to the JIP in an anomalous fashion;
- Whether they had undertaken any break tests of used mooring equipment;
- Whether they would be willing to release that break test data to the JIP in an anomalous fashion.

Out of these 11 operators, seven provided responses that resulted in a basic data survey population of 25 units worldwide, as these operators were also unable between them to provide details of four of their units. Their assistance in answering the surveys and filling in missing details from the spreadsheets is gratefully acknowledged. From these responses it was found that approximately 45% of the units surveyed worldwide had mooring systems that formed part of Class and, from this it can be inferred in general, that the units themselves are also likely to be classed. In addition, it was found that around 80% of the units surveyed undertook regular mooring system surveys, with this figure likely to rise due to a number of the units having yet to decide their mooring system integrity strategy.

The time between surveys varied enormously between different operators and even between different units under the same operator. The spread of periods between surveys ranged from four months to five years, with the mean survey time being around two and a half years. This means that unless the FPS is fitted with line failure detection equipment, such as that discussed in the "Mooring Failure Detection Systems for Floating Offshore Installations, Mooring Integrity Joint Industry Project Phase 2" [6], or the lines are visible from the unit then these units could, in theory, end up in a one line failed condition for nearly two and a half years on average, or up to nearly five years in some cases. The implications with this, in regard to exposure of the mooring system to higher loads, higher than designed for fatigue loads, and the theoretical decrease in reliability of the mooring system due to the "joint probability" of the unit encountering a design storm with a failed line [7] cannot be over emphasised.

Of the 25 units for which details were received only approximately 30% have undertaken any form of measurement campaign on their chains despite over 95% of
the subject units having mooring systems containing chain. Of this 30%, no operator had measured their chains more than twice and only 25% of those units had been subjected to more than one chain measurement programme. As a consequence overall, only two out of 25 units, or around 8% of the surveyed units, can truly assess their wear and corrosion rates. Particularly given that it did not appear that any of the operators had taken pre- or post-installation base line surveys of their chains to give them a starting point.

Around half of the units that have undertaken chain measurement programs agreed to release data in an anomalous fashion to the JIP and grateful thanks are expressed to those units and operators. This data set has been supplemented by data from the GL Noble Denton Archives to give a useable data set covering eight different units, of three different types, and twelve individual data sets of varying quality and usefulness. Data was also available for several other units but not in a form that could be readily used to derive indicative wear and corrosion rates. This was typically due to the data being related to particular design aspects of the subject mooring system eg wear measurements for parallel weighted chain sections, which if used to calculate indicative wear and corrosion rates for main mooring line would resulted in skewed figures.

3.2 ABOVE WATER / ON SHORE CHAIN MEASUREMENT

3.2.1 Overview

One of the problems encountered with the data that was collected during the data survey is that often full measurements have not been taken. Whilst measuring the same inter-grip double diameters over time can give the wear and corrosion rate, a single set of inter-grip double diameters is of less value. Unless for instance the perpendicular diameter and the parent bar diameter so that the reduction in cross sectional area due to wear can be calculated. This section therefore puts forward some suggestions as to how the “worth” of a chain inspection can be greatly increased with only minimal impact on the schedule and cost of undertaking the chain inspection. It should therefore be seen as a supplement to existing guidance on chain measurement, such as API RP 2I [5], that enables the measurement to be taken from measurement to “best practice” measurement.

As discussed in Section 2, in general terms the loss of section of a mooring chain over time is caused by two basic mechanisms, namely corrosion and wear. In broad terms, although this can vary on a case by case basis, corrosion will lead to an uniform loss of cross-sectional area, as illustrated in Figure 3-1, and wear will lead to a concentrated loss of section which tends to be either curved, as in inter-grip wear (see Figure 3-2), or flat, such as wear due to contact between a hawse pipe and chain link (see Figure 3-3). It is important that these basic mechanisms are understood when chain measurements are being specified and undertaken in order that the most beneficial measurements can be taken. For instance the minimum cross section due to inter-grip wear may be off the centreline and so specifying that the chain will be pulled straight and then the inter-grip measurements taken may miss this data. Therefore the chain inspection specification and procedure needs to include provision for measuring each of these degradation processes, as well as a clear understanding of the purpose of the measurement data. Hence, in order for the measurement program to be correctly specified, the person responsible for it needs to have a fair understanding of what they expect to see when the chain is examined and what use the data is going to be put to.
Figure 3-1: Section Loss due to Corrosion

Figure 3-2: Section Loss Typically due to Inter-Grip Wear

Figure 3-3: Section Loss Typically due to Contact Wear
3.2.2 Manual Measurement Specification

As previously stated the following should be seen as supplementing the guidance given in the likes of API RP 2I [5] and as such they only cover certain areas in detail. In general terms, any chain measurement program should aim to get information on:

- Link Length;
- Link Straightness;
- General cross-sectional area, normally due to corrosion;
- Inter-grip cross-sectional area, normally due to corrosion plus inter-grip wear;
- Damaged section cross-sectional area, normally due to corrosion plus contact damage and as such is not always present.

These guidelines deal with the latter three points as the first two are adequately covered within API RP 2I [5], which also, if covered closely, gives reasonable guidance on cross-sectional area measurement. It is this area though that this section is intended to add to.

In general terms, as noted in API RP 2I [5], diameter measurements should be taken in pairs with one measurement in plane and one out of plane of the link as shown in Figure 3-4. By using these two diameters an ellipse can be fitted to the diameters to give a reasonable approximation of the cross sectional area in most instances, unless otherwise noted herein.

![Figure 3-4: Measurement Axis](image)

Therefore to determine the general cross-sectional area and the corrosion loss associated with it, as shown in Figure 3-1, then such diameter measurements should be taken on Section A-B of Figure 3-5 for studless chain, or Section A-C in Figure 3-5 for studded chain, with between one and four sets of measurements being taken. When taking these measurements on studded chain, the measurement location should be just before the expansion of the chain bar before the stud but as far away from the shoulder of the link as possible. In addition, when more than one set of Section A-C measurements is taken on a link, then the cross-sectional areas should be calculated individually and compared rather than the diameters simply being average in order to check for any uneven corrosion or erroneous measurements. When using the data in later calculations, it would normally be acceptable, after comparing the individual cross-sectional areas, to simply use the average of them for each link.
When considering the measurement of inter-grip wear, typically on Section A-A in Figure 3-5, although the measurement location should be in the middle of the wear patch and not always on the centre line, since the asymmetric nature of inter-grip wear, as shown in Figure 3-2, needs to be considered. To take this into account then the minimum and maximum diameters of the section need to be taken, which will typically lie perpendicular to each other, field experience has shown. However, the minimum and maximum diameters may not lie in line with the chain axis and as such care needs to be taken to find them. Hence all measurement operations need to be carefully specified and suitably supervised.

Due to the deformation of the parent bar as it is bent round the mandrel during manufacture, the cross-section in the inter-grip area tends to be more oval than round. Hence the only simple way to approximate the inter-grip cross-sectional area is to fit an ellipse to the minimum and maximum diameters, as per Equation 3-1. The conservative error that such an approximation causes, in relation to a perfectly round bar, is illustrated in Figure 3-6. Given that the bar tends to be more oval in shape then in reality the error will be much smaller than illustrated and therefore acceptable. This does not preclude the use of other shapes where these can be justified, the use of an ellipse is simply seen as the best approximation in the circumstances and lends itself well to the actual shape of the chain bar after the link has been formed.

\[ CSA_{\text{general}} = \frac{\pi D_{\text{min}} D_{\text{max}}}{4} \]

Equation 3-1: Ellipse Approximation of Cross-Sectional Area
When dealing with a flat wear zone, such as that illustrated in Figure 3-3, there are a number of measurements that need to be taken to allow the cross-sectional area to be calculated as accurately as possible. First and foremost the 'wear width', as illustrated by the dimension 'W' in Figure 3-3, needs to be taken along with the minimum diameter of the bar at that point, marked 'D_w'. In addition, the diameter perpendicular to the minimum diameter i.e. parallel to the wear face, should also be taken marked as 'D_m' in Figure 3-3, along with the two diameters one either side of the wear zone, marked as 'D_1' and 'D_2' in Figure 3-3. With these four diameter measurements, plus the width of the wear zone, an approximation of the cross-sectional area can be fairly accurately calculated using Equation 3-2.

$$\text{CSA}_{\text{flat}} = \frac{1}{2} \pi D_w \left( D_1 + D_2 \right) - \frac{1}{2} \pi \left( D_1 + D_2 \right)^2 + W \left( D_w - \frac{1}{2} \left( D_1 + D_2 \right) \right)$$

Equation 3-2: Flat Wear Zone Cross-Sectional Area Approximation

Where:

$$\theta = 2 \tan^{-1} \left( \frac{W}{2(D_w - \frac{1}{2}(D_1 + D_2))} \right)$$

Equation 3-3: Flat Wear Zone Angular Width
3.3 PHOTOGRAMMETRIC MEASUREMENT TECHNIQUES

3.3.1 Introduction

When a component has visually gross wear, such as the chain link in Figure 3-8, then finding the cross-sectional area of the link, so a strength assessment can be undertaken, can be quite difficult as illustrated by Figure 3-9 and Figure 3-10. In such situations, visual photogrammetric or laser scanning measurement techniques can be utilised to build a three dimensional model of the component in terms of a Surface Elevation Map (SEM). From such a model, after suitable manipulation, measurements can be taken of the component in common CAD packages, or the model can be used as a basis for Finite Element Analysis (FEA). Regardless of the analysis technique, the basis is still the visual photogrammetric or laser scanning measurement techniques, of which visual photogrammetric measurement is the most commonly technique and is described in this section.

Figure 3-8: Chain Link / Boulder Contact Causing Gross Wear
Figure 3-9: Chain Link against Boulder with Scaled Background Sheet

Figure 3-10: Standard Measurement Gauge over Worn Chain in an Attempt to Find Diameter
3.3.2 Equipment

Whilst a 3D video system, such as that shown in Figure 3-11, requires:

- 3D Camera System mounted on ROV pan-and-tilt, complete with suitable high intensity lighting;
- Topside 3D viewing suite, comprising of:
  - Polarising Control Box,
  - LCD Polarising Screen in front of standard CRT monitor,
  - Polarising Glasses for operators.
- Digital recording system;
- Control PC.

A system to capture the data for photogrammetric modelling techniques (see Section 3.3.3) on the other hand only requires:

- Two high-resolution digital stills cameras mounted on a deployment frame;
- Suitable high intensity lighting;
- Acoustic range finder;
- Topside control PC.

It should be noted though that this surface of the area to be modelled must be cleaned of marine growth so that surfaces are visible. This can be achieved using high pressure water jet, stiff nylon or similar rotary brushes.

Figure 3-11: 3D Video System (Courtesy of Welaptega Marine Limited)
3.3.3 Outline Photogrammetric Modelling Methodology

The basis of creating Surface Elevation Maps, to generate geometrically accurate 3D models, is pixel matching between pairs of high resolution digital images. Such a pair of images, from the chain wear from boulder contact discussed in Section 3.3.1, can be seen in Figure 3-12, whilst Figure 3-13 illustrates pixel matching in action.

Once a series of pixels have been matched on a pair of images then the three-dimensional location of these points can be calculated using stereo-photogrammetry. This basically involves constructing theoretical lines (or rays) from the camera location to each identified point on the object and it is the intersection of these lines that determines the three-dimensional location of the point through triangulation. As illustrated by the SEM in Figure 3-14 that shows the chain damage illustrated in Figure 3-12.

After a SEM has been created using triangulation then it can be used to build a wire frame polygon, as illustrated in Figure 3-15, from which a full solid CAD model can be built, as shown in Figure 3-16 for the same boulder damaged chain link. The solid CAD model can then be used to investigate areas of interest, such as the three sections highlighted in Figure 3-17, in industry-standard CAD packages. Such an investigation is illustrated in Figure 3-18 and Figure 3-19 for two of the worn sections. Similarly, the models can also typically be formatted to be compatible with Finite Element Analysis programs, thus allowing strength assessment of the worn or damaged components to be made.

![Figure 3-12: Pair of High Resolution Images (Courtesy of Welaptega)](image-url)
Figure 3-13: Pixel Matching Example (Courtesy of Welaptega)

Figure 3-14: Surface Elevation Model Assembly (Courtesy of Welaptega)

Figure 3-15: 3D Polygon Wire Frame Model (Courtesy of Welaptega)
Figure 3-16: Full 3D Solid CAD Model (Courtesy of Welaptega)

Figure 3-17: Areas of Interest on Subject Chain Link (Courtesy of Welaptega)
Figure 3-18: Section A-A of Subject Chain Link (Courtesy of Welaptega)

Figure 3-19: Section B-B of Subject Chain Link (Courtesy of Welaptega)
4 INDICATIVE WEAR AND CORROSION RATES

4.1 INTRODUCTION

Dr Laurence Johnston Peter, the educator and "hierarchiologist", best known for the formulation of the “Peter Principle”, from which the following famous quotation comes:

“In a hierarchy every employee tends to rise to his level of incompetence ... in time every post tends to be occupied by an employee who is incompetent to carry out its duties ... Work is accomplished by those employees who have not yet reached their level of incompetence.”.

Once stated that:

“If you don't know where you are going, you will probably end up somewhere else.”.

Something that is very applicable to chain measurement data analysis techniques ie if you don’t know what you are trying to find by analysing the data then you will just find something out but not necessarily what you are looking for. Thus it is important from the outset of a measurement programme to decide what the purpose of the measurement programme is and how the results will be analysed. This is very similar to the principle put forward in "Guidelines for Monitoring the Service and Behaviour of Mooring Systems for Floating Offshore Installations, Mooring Integrity Joint Industry Project Phase 2" [9] that “in order for a monitoring campaign or permanent system to be deemed a success, then the purpose of the campaign or system needs to be decided from the outset, thus allowing the campaign or system to be planned and tailored to meet the requirements”.

This section describes the various techniques that have been applied to the chain measurement data sets that have been made available to the JIP and the results that have been obtained from them and how these can be practically applied.

4.2 CHAIN MEASUREMENT DATA ANALYSIS TECHNIQUES

4.2.1 General

As stated in Section 3.1, 10 chain measurement data sets, covering six different units, and four different unit types, have been made available to the JIP. Some of the measurement sets have been taken subsea, some on the back of an anchor handling tug and others on shore, all of which has an influence on the measurements taken and the analysis techniques available. Within the individual data sets the number of inter-grip measurements for instance ranges from 15 to 580. Therefore given that the chain segment of each mooring line, let alone mooring system, can be made up of hundreds, if not thousands of links, then the statistical significance of the sample size is obvious.

One of the problems often faced in the analysis of chain measurement data is the lack of base line data for the actual chain being measured, to which the chain measurements can be compared so allowing the corrosion and wear loss rates to be calculated. The majority of the chain measurement data sets made available to the JIP are no exception, with only one set having baseline measurements and the other actually being the base line measurement for a new chain. Both of these data sets only occurred because the personnel involved in operations were mooring specialists and specifically requested that base line measurements be taken. As a
consequence operators should always request that baseline measurements be taken on all chains before they are installed and chains suitably marked so that follow up measurements can be tied back to the base line measurements. Given that typically chain links are measured during manufacture to ensure that the links, or at least a sample of links, are within the specified requirements then integrating baseline measurements with this should not add significantly to the cost or time spent manufacturing the chains.

In essence three different analysis techniques have been applied to the data sets in order to calculate either:

- The nominal inter-grip wear and corrosion rate; or
- The nominal inter-grip cross-sectional area loss rate; or
- The nominal chain bar corrosion loss and inter-grip wear loss;
- The actual inter-grip wear and corrosion rate;

dependant on the data available within the data set. ‘Nominal’ refers to comparison to the nominal chain size and ‘actual’ refers to measurements that have been compared to base line data. These methods are described in the following sections. In addition to which the probabilistic use that can be made of the data, if the data set is large enough to be significant, is also described based on the work of Ahilan and Luo [10].

4.2.2 Nominal Inter-Grip Wear and Corrosion Rate Method

This method is the simplest of all of the analysis methods, and is the only method that can readily applied when only in-line inter-grip diameter or double diameter measurements, see Figure 4-1 below, have been taken.

![Figure 4-1: In-line Double Diameter Measurement](image)

In essence it compares the inter-grip measurements back to the nominal diameter of the chain in order to assess the wear and corrosion loss. Given the following tolerance information from DNV OS-E302 [11] for new chain that:

“The diameter shall be measured at the crown. The average diameter based on two perpendicular measurements must have no negative tolerance and the plus tolerance shall not exceed 5% of nominal
diameter. As a result of being bent around the anvil, however, a particular diameter may be smaller than the nominal:

- for nominal diameter up to 84 mm: - 2 mm
- for nominal diameter 85 through 122 mm: - 3 mm
- for nominal diameter 123 through 152 mm: - 4 mm
- for nominal diameter 153 through 184 mm: - 6 mm
- for nominal diameter 185 through 210 mm: - 7.5 mm”.

Then it can be seen that for links where the starting inter-grip was below nominal then this method would give a conservative wear and corrosion rate, whereas for links above nominal the calculated rate would under estimate the actual rate. Although this error rate would drop for the longer the chain had been in service as the error would be spread over a larger number of years.

In practical terms the nominal inter-grip wear and corrosion rate \( \text{NIG}_{\text{Rate}} \) is calculated using:

\[
\text{NIG}_{\text{Rate}} = \left( \frac{D_{\text{mean, min}} - D_{\text{in, min}}}{N_{\text{ave}}} \right)
\]

Equation 4-1: Nominal Inter-Grip Wear and Corrosion Rate

Where the mean In Line Diameter \( \overline{D}_{\text{hlw}} \) is given by:

\[
\overline{D}_{\text{hlw}} = \frac{\sum D_i}{n}
\]

where:

\( D_i \) = Individual Diameter measurements
\( n \) = Number of Diameter measurements in sample

Equation 4-2: Inter-grip mean Diameter

Although this can be calculated in isolation, it is also normally useful to calculate the standard deviation of the diameters and the range of the diameter, in addition to the mean diameter in order to establish how significant the mean is within the sample. This can usefully be achieved by calculating the Coefficient of Variation \( \text{COV}_{\text{NIG}} \) and the Coefficient of Range \( \text{COR}_{\text{NIG}} \), using:

\[
\text{COV}_{\text{NIG}} = \left( \frac{\sum (D_i - \overline{D}_{\text{hlw}})}{n \overline{D}_{\text{hlw}}} \right) \times 100\%
\]

Equation 4-3: Coefficient of Variation

\[
\text{COR}_{\text{NIG}} = \left( \frac{D_{\text{max, hlw}} - D_{\text{min, hlw}}}{\overline{D}_{\text{hlw}}} \right) \times 100\%
\]

Equation 4-4: Coefficient of Range

Thus allowing an assessment to be made of how applicable the average diameter is to all the links within the chain, and from this how representative the nominal inter-grip wear and corrosion rate is to the whole of the mooring system.
4.2.3 Nominal Inter-Grip Cross-Sectional Area Loss Rate Method

If perpendicular inter-grip diameter measurements are taken, as discussed in Section 3.2.2 and shown schematically in Figure 3-4, then a slightly more informative analysis than that described in Section 4.2.2 can be undertaken. As with a pair of inter-grip measurements an approximate cross-sectional area can be calculated, as discussed in Section 3.2.2, and then compared to the nominal cross-sectional area for the chain.

For a theoretically round bar, which is likely to give a higher cross-sectional area error in relation to an ellipse than an oval bar, Figure 4-2 shows the cross-sectional area calculated using an ellipse and the actual cross-sectional area for a range of wear depths. Although the deviation of the actual and ellipse calculated areas looks fairly dramatic, when the actual error is plotted, as shown in Figure 4-3, it is found that it is quite acceptable particularly given the wear depth range, which for a 120 mm link would be up to 12 mm. Given this, applying Equation 3-1 to the average in-line and out of plane inter-grip diameter measurements is an acceptable way in which to find the average cross-sectional area.

The nominal inter-grip cross-sectional area loss rate (NIGCSA\text{Rate}) can then be determined from:

\[
NIGCSA_{\text{Rate}} = \frac{\pi \left(D_{\text{nominal}}^2 - D_{\text{actual, plane}}^2\right)}{4N_{\text{plane}}}
\]

Equation 4-5: Nominal Inter-Grip Cross-Sectional Area Loss Rate

As with the method described in Section 4.2.2, it is good practice to also calculate the Coefficient of Variation and Coefficient of Range in order to assess the applicability of the calculated cross-sectional area loss rate to the mooring system as a whole.
Figure 4-2: Calculated cross-sectional area versus wear depth

Figure 4-3: Ellipse Calculated Cross-Sectional Area Error Versus Wear Depth
4.2.4 Nominal Chain Bar Corrosion Loss and Inter-Grip Wear Loss Method

This method can only be used where in addition to perpendicular inter-grip diameter measurements the parent bar diameter (‘BD’) is measured at a non-distorted position, as discussed in Section 3.2.2. With this additional diameter, preferably pair of perpendicular diameters, then the nominal corrosion loss can be calculated. This in turn allows the starting out of plane diameter to be calculated and so the starting in-line diameter. From this the nominal in-line wear rate can be calculated as well as the nominal cross-sectional area loss in the inter-grip area due to wear and corrosion, as follows:

1. Calculate nominal corrosion rate (NCRate) using Equation 4-6;
2. Calculate average in-line and out of plane inter-grip diameters, as well as standard deviations and ranges for reasons previously discussed;
3. Calculate nominal out of plane inter-grip starting diameter (ND_{out of plane}) using Equation 4-7;
4. Calculate nominal in-line inter-grip starting diameter (ND_{in-line}) using Equation 4-8;
5. Calculate nominal in-line wear and corrosion rate (NIGWCRate) using Equation 4-9;
6. Calculate nominal in-line minimum wear rate (NIGWRate) using Equation 4-10;
7. Calculate nominal inter-grip cross-sectional area loss rate (NIGCSARate) using Equation 4-11.

\[
NC_{rate} = \frac{D_{nominal} - BD}{N_{year}}
\]

Equation 4-6: Nominal Corrosion Rate

\[
ND_{out of plane} = \overline{D}_{out of plane} + \left( D_{nominal} - BD \right)
\]

Equation 4-7: Nominal Out of Plane Inter-Grip Starting Diameter

\[
ND_{in-line} = \frac{D_{in-line}}{ND_{out of plane}}
\]

Equation 4-8: Nominal in-Line Inter-Grip Starting Diameter

\[
NIGWC_{rate} = \frac{ND_{in-line} - \overline{D}_{in-line}}{N_{year}}
\]

Equation 4-9: Nominal in-Line Inter-Grip Wear and Corrosion Rate

\[
NIGW_{rate} = NIGWC_{rate} - NCR_{rate}
\]

Equation 4-10: Nominal in-Line Inter-Grip Minimum Wear Rate

\[
NIGCSA_{rate} = \pi \left( ND_{in-line} ND_{out of plane} - \overline{D}_{in-line} \overline{D}_{out of plane} \right) / 4N_{year}
\]

Equation 4-11: Nominal Inter-Grip Cross-Sectional Area Loss Rate

This method when employed over a large number of samples, so as to be as representative as possible and so minimise the error rate, will yield fairly accurate
results. Although the results can never be as accurate or robust as those calculated using the base line measurement data or multiple data sets for the same links. As with other methods discussed, it is good practice to look at the applicability of the calculated rates by also calculating the Coefficient of Variation and Coefficient of Range of the measured diameters.

### 4.2.5 Actual Inter-Grip Wear and Corrosion Rate Method

Where two sets of measurements are available for exactly the same links i.e. pairs of measurements, whether this be base line plus a set of field measurements or two sets of field measurement spaced several years apart, then the actual wear and corrosion rates can be directly determined, by the basic equations:

\[
DC_{\text{rate}} = \frac{BD_2 - BD_1}{N_{\text{years}}}
\]

Equation 4-12: Actual Corrosion Rate

\[
DWC_{\text{rate}} = \frac{D_{\text{in-line,2}} - D_{\text{in-line,1}}}{N_{\text{years}}}
\]

Equation 4-13: Actual Inter-Grip wear and Corrosion Rate

\[
DW_{\text{rate}} = DWC_{\text{rate}} - DC_{\text{rate}}
\]

Equation 4-14: Actual Inter-Grip Wear and Corrosion Rate

Where the subscripts ‘1’ and ‘2’ refer to the first and second sets of measurements for a particular link. As with the other methods discussed in Section 4.2, it is good practice to calculate the Coefficient of Variation and Coefficient of Range in order to assess the significance of the results gained in relation to the mooring system as a whole. Such statistical analysis also allows the probabilistic analysis methods discussed in Section 4.2.6 to be applied, either on their own or in conjunction with the aforementioned methods in this section and Sections 4.2.2 and 4.2.3.

### 4.2.6 Outline Probabilistic Analysis Methods

As discussed by Luo and Ahilan in their OTC paper on “Probabilistic Chain Cable Strength and Mooring Reliability” [10] “a chain is only as strong as its weakest link”.

In addition, DNV for instance, allow “a mooring system to be designed by direct application of structural reliability analysis, as long as such analyses are at least as refined as the reliability analysis used to calibrate the design procedure and have been checked against the results of the calibration for at least one relevant test case” [2]. Where “the probability levels given in Table H1 (see Figure 4-4 below) have been applied in the calibration, and should also be applicable in a comparable reliability analysis”:
This therefore raises the possibility of using a number of inter-grip diameter measurements, from a chain section, to calculate the probability of any one inter-grip diameter, within that section, being less than the minimum allowable inter-grip diameter ($D_{\text{maig}}$). In theory, this then allows the reliability of the chain section to be gauged and compared against the target reliability levels given in Figure 4-4 in terms of annual probability of failure by taking into account the probability of the design storm occurring and a link being less than the minimum allowable inter-grip diameter.

Where the minimum allowable inter-grip diameter can be based on:

- Tabulated minimum break load versus diameter, see references [12][13] and [14] for instances;
- Finite Element Analysis of a nominal diameter chain link with the inter-grip diameter suitably reduced;
- Break test results of used chain from the same system with varying inter-grip diameters, thus allowing a curve to be fitted to break load versus inter-grip diameter. A minimum of three, but preferably five break tests is required to achieve this.

There are a number of statistical methods and probabilistic models that could potentially be put together to calculate the minimum diameter probability and the overall reliability of the line based on it, using either Frequentist or Bayesian methods. As such, the following example method is just one of a myriad of possibilities that the reader could use. The reader should therefore make up their own mind about its relative merits before using it, modifying it or developing their own method for their particular mooring system.

**Example Method**

**Definitions:**
\( D_{\text{nom}} \) = Nominal manufacturing diameter of chain  
\( \text{tol} \) = Manufacturing tolerance  
\( D_{\text{nom}} \) = Nominal diameter of chain minus manufacturing tolerance  
\( D_{\text{nom}} \) = Nominal diameter of chain plus manufacturing tolerance  
\( n \) = Number of years in service  
\( \Delta D \) = Wear and corrosion allowance per year  
\( R \) = Return period of design storm  
\( \mu_0 \) = Average manufacturing diameter  
\( \mu_n \) = Assumed priori average diameter after \( n \) years  
\( \sigma_n \) = Assumed / calculated / known manufacturing diameter standard deviation  
\( \mu_n \) = Sample average diameter at time \( n \) years  
\( \sigma_n \) = Sample diameter standard deviation at time \( n \) years  
\( m \) = Number of measurements taken in sample  
\( \mu \) = MAP estimate of average diameter of full chain section after \( n \) years  
\( \sigma \) = MAP estimate of standard deviation of diameter of full chain section after \( n \) years  
\( D_{\text{min}} \) = Minimum allowable inter - grip diameter
Method:

If, for the purposes of the example, we assume that:

- The distribution of inter-grip diameters at the time of manufacture and thereafter follows a Gaussian (Normal) distribution; and
- In the absence of specific manufacturing statistics, that 99.9% of the inter-grip diameters lie within the $D_{\text{lower}}$→$D_{\text{upper}}$ range;

then the standard deviation of the manufactured diameters will be given by:

$$\sigma_t = \frac{\text{tol}}{3.2906}$$

**Equation 4-15: Standard Deviation of the Manufactured Diameters**

The above equation also implies that average manufacturing diameter $\mu_0$ is equal to the nominal chain diameter $D_{\text{nominal}}$.

Given the system included a wear and corrosion allowance of $\Delta D$ per annum, then by design, it can be assumed that the priori mean of diameters of the chain section, will be given by:

$$\mu_n = \mu_0 - n\Delta D$$

**Equation 4-16: Assumed Average Diameter after n – Years**

Whilst, if the diameters are all wearing and corroding at a constant rate in line with the wear and corrosion allowance, then the shape of the distribution will remain unchanged and so the priori standard deviation will be the manufacturing standard deviation given by Equation 4-15.

Given this, then the Maximum Posteriori Probability (MAP) estimates of the average diameter and standard deviation of diameters of the full chain section in the $n^{th}$ year, when the chains are measured, can be found using:

$$\mu_n = \frac{m\sigma^2 \mu + \sigma^2 \mu_0}{m\sigma^2 + \sigma^2}$$

**Equation 4-17: MAP Average Diameter after n – Years**

$$\sigma_n = \frac{m\sigma^2 + \sigma^2}{m\sigma^2 + \sigma^2}$$

**Equation 4-18: MAP Standard Deviation of Diameter after n – Years**

Based on the assumption that the inter-grip diameters of the worn and corroded chain still follow a normal distribution, then the probability of an inter-grip diameter being less than the minimum allowable inter-grip diameter $D_{\text{maig}}$ is then given by:

$$P(D \leq D_{\text{maig}}) = \Phi\left(\frac{D_{\text{maig}} - \mu_n}{\sigma_n}\right)$$

**Equation 4-19: Probability of Inter-Grip Diameters being Less than $D_{\text{maig}}$**

The reliability of the line, in terms of inter-grip diameter only, can then be found using:
Equation 4-20: Reliability of Full Chain Section based on Inter-Grip Diameters (only)

This method gives a linear interpolation between the priori mean and the sample mean weighted by their respective co-variances, which should allow for measurements not being taken evenly throughout the length of the chain. It could, however, inadvertently mask areas of the chain where high wear is taking place if it is not used in conjunction with raw data examination and visual examination of the chain in service.

4.3 INDICATIVE WEAR AND CORROSION RATES FOR OFFSHORE MOORING CHAINS

As discussed in Section 3.1, data sets covering eight different units, of three different types, and 12 individual data sets of varying quality and usefulness have been collated in order to give indicative wear and corrosion rates. Table 4-1 overleaf, presents this data in terms of normalised rates, where the rates have been normalised in relation to the nominal chain diameter so as to make the data both anonymous and as much use as possible.

As might be expected Table 4-1 shows that the wear and corrosion rates can vary wildly, even on chains from the same unit, due to sample size and measuring specific areas of the chain length, in addition to the normal variation between lines due to environmental directionality. The following points though can be drawn from Table 4-1, which has used a parent bar diameter one chain size above nominal:

- For North Sea Turret Moored FPSOs the Nominal Cross Sectional Area Loss Rate appears to lie in a range of 0.22% to 0.74% per annum, if the Nominal Diameter Loss Rate is converted to a Nominal Cross Sectional Area Loss Rate for comparative purposes. See Figure 4-5 for practical application.

- For North Sea Spread Moored Semi-submersibles the Nominal Cross Sectional Area Loss Rate appears to lie in a range of 0.1% to 1.39% per annum, if the Nominal Diameter Loss Rate is converted to a Nominal Cross Sectional Area Loss Rate for comparative purposes. See Figure 4-6 for practical application.

- Due to the prevailing environmental conditions in Africa, in combination with the heat from flair stacks, high levels of corrosion can be seen above the water line in some instances. As a consequence Nominal Corrosion Rates between 0.3% and 0.9% per annum have been experienced. It might reasonably be expected that similar results could be seen in other regions that experience similar environmental conditions. See Figure 4-7 for practical application.

- Due to the nature of spread moored FPSOs and the swell dominated environmental conditions in general around the African coast, high levels of wear have been experienced by at least one FPSO, that recorded an average Nominal Wear only rate of 0.39% per annum. See Figure 4-8 for practical application.
<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Region</th>
<th>Years Service</th>
<th>Mean $D_{\text{in line}}$</th>
<th>CoR $D_{\text{in line}}$</th>
<th>Mean $D_{\text{out of plane}}$</th>
<th>CoR $D_{\text{out of plane}}$</th>
<th>Nominal Corrosion Rate</th>
<th>Nominal Wear &amp; Corrosion Rate</th>
<th>Nominal CSA Loss Rate</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turret Moored FPSO</td>
<td>North Sea</td>
<td>9</td>
<td>99.0%</td>
<td>6.2%</td>
<td></td>
<td></td>
<td>0.11% p.a.</td>
<td></td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>Turret Moored FPSO</td>
<td>North Sea</td>
<td>11</td>
<td>97.5%</td>
<td>7.4%</td>
<td>102.5%</td>
<td>3.2%</td>
<td>0.62% p.a.</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Turret Moored FPSO</td>
<td>North Sea</td>
<td>13</td>
<td>100.6%</td>
<td>6.7%</td>
<td>106.4%</td>
<td>4.4%</td>
<td>0.34% p.a.</td>
<td></td>
<td></td>
<td>47</td>
</tr>
<tr>
<td>Turret Moored FPSO</td>
<td>North Sea</td>
<td>10</td>
<td>99.4%</td>
<td>3.8%</td>
<td>99.6%</td>
<td>3.8%</td>
<td>0.06% p.a.</td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Turret Moored FPSO</td>
<td>North Sea</td>
<td>9</td>
<td>97.0%</td>
<td>3.9%</td>
<td>101.8%</td>
<td>4.51%</td>
<td>0.61% p.a.</td>
<td></td>
<td>0.13% p.a.</td>
<td>9</td>
</tr>
<tr>
<td>Semi-submersible FPU</td>
<td>North Sea</td>
<td>15</td>
<td>99.3%</td>
<td>7.1%</td>
<td></td>
<td></td>
<td>0.05% p.a.</td>
<td></td>
<td></td>
<td>580</td>
</tr>
<tr>
<td>Semi-submersible FPU</td>
<td>North Sea</td>
<td>17</td>
<td>95.1%</td>
<td>9.2%</td>
<td>102.2%</td>
<td>3.2%</td>
<td>0.83% p.a.</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Semi-submersible FPU</td>
<td>North Sea</td>
<td>16</td>
<td>90.5%</td>
<td>7.2%</td>
<td>98.2%</td>
<td>4.4%</td>
<td>1.39% p.a.</td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>Semi-submersible FPU</td>
<td>North Sea</td>
<td>19</td>
<td>91.8%</td>
<td>13.0%</td>
<td></td>
<td></td>
<td>0.4% p.a.</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Spread Moored FPSO</td>
<td>Africa</td>
<td>12</td>
<td>95.3%</td>
<td>5.6%</td>
<td>100.0%</td>
<td>7.4%</td>
<td>0.3% p.a.</td>
<td></td>
<td>0.39% p.a.</td>
<td>22</td>
</tr>
<tr>
<td>Turret Moored FPSO</td>
<td>Africa</td>
<td>9</td>
<td>100.6%</td>
<td>3.2%</td>
<td>101.4%</td>
<td>2.1%</td>
<td>0.9% p.a.</td>
<td></td>
<td></td>
<td>66</td>
</tr>
<tr>
<td>New Studded Chain</td>
<td></td>
<td>0</td>
<td>100.6%</td>
<td>3.2%</td>
<td>101.4%</td>
<td>2.1%</td>
<td></td>
<td></td>
<td></td>
<td>28</td>
</tr>
</tbody>
</table>

**Table 4-1: Normalised Indicative Wear and Corrosion Rates**

**Notes**

a. As per the method given in Section 4.2.2.

b. As per the method given in Section 4.2.3.

c. In relation to bar diameter away from inter-grip area rather than out of plane inter-grip measurement.

d. In relation to parent bar diameter rather than nominal chain diameter due to application of method given in Section 4.2.4.

e. Nominal wear rate rather than nominal wear and corrosion rate due to application of method given in Section 4.2.4.

f. Corrosion of chain that was intermittently submerged and in splash zone due to normal operations of FPSO. The corrosion was found over the whole link with the exception of the inter-grip area which reportedly showed a lower corrosion and wear rate.
Figure 4-5: North Sea Turret Moored FPSO Advisable Nominal Wear and Corrosion Allowance

Figure 4-6: North Sea Spread Moored Semi-Submersible FPU Advisable Nominal Wear and Corrosion Allowance
Figure 4-7: Africa Spread and Turret Moored FPSOs Advisable Nominal Corrosion Allowance

Figure 4-8: Africa Spread Moored FPSO Advisable Nominal Corrosion Allowance
5 BREAK TESTING OF AGED MOORING CHAINS GUIDANCE

5.1 INTRODUCTION

As stated in Section 18.8 of the FPS Mooring Integrity Phase 1 report [16]:

“As mooring lines and connectors wear, corrode and fatigue it is likely that there will become a stage when the true Minimum Break Load (MBL) of the line is no longer known with any real confidence. With the desire to sometimes extend field lives beyond the original design life there is a need to confirm that the as installed system is still fit for purpose.”.

To confirm the minimum break load of the worn system either Finite Element Analysis (FEA) or actual physical break tests can be utilised. Of these two options only the latter will give definitive results. However, it should always be borne in mind that the break test will be for a sample, or a number of samples, from the system and inference to the system as a whole should be done cautiously. The other issue that has to be addressed with break testing is that fundamentally it requires part of the mooring system to be changed out, and the risk and costs associated with that may mean that changing out the entire system rather than just one part of the system for break testing is ultimately more economic.

This section though, through the use of actual break test data examines how the ultimate loading bearing capacity of chain appears to change through use, with the overall aim of providing guidelines as to how this capacity could potentially be treated over time.

5.2 INDICATIVE ULTIMATE LOAD CAPACITY RESULTS FOR WORN CHAINS

Table 5-1 below, contains the results of a number of break tests that have been carried out and made available in an anonymous manner. As such, gratitude is expressed to the companies and units that have made the data set available, which covers four different units, three grades of chain, and thirteen individual break tests.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Type</th>
<th>Service</th>
<th>BL/MBL Ratio</th>
<th>BL/MBL Ratio Loss Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>98.5%</td>
<td>0.15% per annum</td>
</tr>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>100.0%</td>
<td>No Loss</td>
</tr>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>98.8%</td>
<td>0.12% per annum</td>
</tr>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>100.3%</td>
<td>No Loss</td>
</tr>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>100.3%</td>
<td>No Loss</td>
</tr>
<tr>
<td>R4</td>
<td>Studless</td>
<td>10years</td>
<td>100.3%</td>
<td>No Loss</td>
</tr>
<tr>
<td>R3</td>
<td>Studless</td>
<td>12years</td>
<td>97.1%</td>
<td>0.24% per annum</td>
</tr>
<tr>
<td>R4</td>
<td>Studded</td>
<td>20years</td>
<td>83.5%</td>
<td>0.83% per annum</td>
</tr>
<tr>
<td>R4</td>
<td>Studded (stud removed)</td>
<td>20years</td>
<td>84.9%</td>
<td>0.76% per annum</td>
</tr>
<tr>
<td>R4</td>
<td>Studded (stud misplaced)</td>
<td>20years</td>
<td>88.1%</td>
<td>0.60% per annum</td>
</tr>
<tr>
<td>ORQ+20%</td>
<td>Studless</td>
<td>4years</td>
<td>97.4%</td>
<td>0.65% per annum</td>
</tr>
<tr>
<td>ORQ+20%</td>
<td>Studless</td>
<td>4years</td>
<td>90.7%</td>
<td>2.33% per annum</td>
</tr>
<tr>
<td>ORQ+20%</td>
<td>Studless</td>
<td>4years</td>
<td>94.7%</td>
<td>1.33% per annum</td>
</tr>
</tbody>
</table>

Table 5-1: Normalised Chain Break Test Results
**Notes**

a. *Chain sustained this load for 30 seconds before test was curtailed without link actually failing.*

b. *Notch with a length equivalent to 13% of the nominal diameter was introduced on the shoulder of the link to investigate the effects of this.*

c. *Notch with a length equivalent to 17% of the nominal diameter was introduced on the shoulder of the link to investigate the effects of this.*

In real terms the following graphs illustrate how the ultimate load capacity of the various chain grades and types appear to as the number of years of service increase.

![Ultimate Load Capacity versus Years in Service - Grade R4 Studless Chain](image-url)
Figure 5-2: Ultimate Load Capacity versus Years in Service - Grade R4 Studded Chain

Figure 5-3: Ultimate Load Capacity versus Years in Service - Grade R3 Studless Chain
Figure 5-4: Ultimate Load Capacity versus Years in Service - Grade ORQ+20% Studless Chain
6 DOWN RATING OF AGED OFFSHORE MOORING CHAINS

6.1 GENERAL PRINCIPALS

As stated in the FPS Mooring Integrity Phase 1 report [16]:

“The catalogue specified minimum break load (MBL) is actually an agreed specified strength which has an associated testing requirement to ensure that this is achieved.”

For different grades and types of chains there are agreed formulas based on the nominal diameter of the chain in millimetres that determine the catalogue Minimum Break Load. The equations are not repeated here for simplicity, but are readily available in chain manufacturers’ catalogues or the FPS Mooring Integrity Phase 1 report [16]. As a base case, it has for many years been a widespread practice for a first pass estimate to be made of the residual capacity of a measured chain or the minimum required chain bar diameter to meet code requirements to be based on a simplistic application of these MBL equations. This, however, negates the fact that the chain bar in the inter-grip region does not start off as a pure circle and nor does it wear and corrode evenly. Thus a better application of the MBL equations would be in terms of cross sectional area versus minimum break load, as a first pass estimate as shown in the figure below:

![Minimum Break Load versus Cross Sectional Area at Crown of Links](image)

**Figure 6-1: Minimum Break Load versus Cross Sectional Area at Crown of Links**

In theory, such a figure in conjunction with the Wear and Corrosion Loss Rates given in Section 4.3 can then be used to get a first pass estimate of the residual life of a mooring chain after a number of years service. This estimate can then be compared against the Ultimate Load Capacity versus number of years service data given in Section 5.2 to draw some conclusions about the remaining capacity of the chain. Such a method could, of course, be further enhanced by including measurement data, but the first pass estimate may be necessary in order to justify
the expense of gathering such data, although the cost is very loss in comparison to the costs involved in a mooring replacement program.

6.2 DOWN RATING EXAMPLE

In order to see the above method might be applied, in theory, the following fictitious example will be worked through for a North Sea Turret Moored FPSO:

<table>
<thead>
<tr>
<th>Nominal Chain Diameter</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain Grade</td>
<td>R4</td>
</tr>
<tr>
<td>Chain Type</td>
<td>Studless</td>
</tr>
<tr>
<td>Number of Years in Service</td>
<td>15</td>
</tr>
<tr>
<td>Catalogue MBL</td>
<td>9864kN</td>
</tr>
</tbody>
</table>

Table 6-1: Down Rating Example Data

Based on the nominal chain diameter of 100mm the Cross Sectional Area at the Crown of the Links will be 7854mm². In Section 4.3, it was stated that the "Nominal Cross Sectional Area Loss Rate appears to lie in a range of 0.22% to 0.74% per annum". Given this and the 15 years of service stated in Table 6-1, then it could be expected that the worn links would have a Cross Sectional Area in the range 6982 mm² to 7,595 mm² at the end of 15 years. Based on Figure 6-1, this would imply that the Ultimate Load Bearing Capacity of the chain lay in the range 8,880 kN to 9,574 kN. If on the other hand, Figure 5-1 is examined, it can be seen that after 15 years of service a Grade R4 Studless chain is expected to have an Ultimate Load Bearing Capacity to MBL ratio in the range 97.75% to 100%, or in real terms for the subject chain 9,646 kN to 9,864 kN. This is therefore implying that the system has somewhere between its original design strength and 90.0% of it. Whilst this may seem like a wide range in this case, given the number of links and variability with regard to original and worn dimensions then this may not be that unrealistic. Therefore using the median of the range would perhaps be a sensible first pass figure.

Indeed, if the outline methodology and the median principle are applied to one of the units that appears in both data sets contained in Table 4-1 and Table 5-1 then the calculated Ultimate Load Bearing Capacity of the chain is only 1.5% away from the actual Ultimate Load Bearing Capacity of the chain samples tested.

6.3 DOWN RATING

Therefore as a first pass assessment method, the following would appear to yield indicative results that can then be used to plan the 'next step' :

1. Establish / collate the Nominal Chain Diameter, Chain Grade, Chain Type, Number of Years in Service and Catalogue Minimum Break Load.
2. Calculate the Nominal Cross Sectional Area of the Crown of the Chain Links.
3. Find the Nominal Cross Sectional Area Loss Rate (ΔCSA) Range from the appropriate figure in Section 4.3.
4. Calculate the Minimum and Maximum likely worn Cross Sectional Areas using:

   \[ CSA_{worn} = CSA_{nominal} - \left( \Delta CSA \times N_{years} \right) \]
5. Look up the Minimum and Maximum likely Ultimate Load Capacities for the Minimum and Maximum likely worn Cross Sectional Areas calculated in Step 4 using Figure 6-1.

6. Find the Minimum and Maximum likely Ultimate Load Capacity versus Minimum Break Load Ratio for the number of years in service from the appropriate figure in Section 5.2.


8. Collate and find the Median value for the Minimum and Maximum likely Ultimate Load Capacities of the Chain found in Steps 5 and 7.

9. Compare Minimum, Maximum and Median Ultimate Load Capacity values against design loading conditions.

If this method raises concerns about the strength of the chain then the next logical step would be to obtain dimensional data from the chain itself so that the assessment can be refined. If such a refinement still gives cause for concern, in the short or long term, then the logical next step would be to undertake a Finite Element Analysis of a worn link to give some indication of its strength, excluding fatigue effects. This refined assessment though should also take into account the predicted wear of the chain over the remaining field life.

Hence overall the following need to be taken into account when assessing the residual strength of a used mooring component:

- Chain grade and original strength variability;
- Date of manufacture;
- Corrosion loss, including any MIC loss or damage eg severe pitting;
- Wear loss;
- Strength loss estimate;
- Fatigue damage;
- Other physical damage eg notching.

Not all of which are easy to quantify, hence any assessment should be piecewise and following the old adage of ‘keeping it simple’ ie undertaking simple first pass assessments. Before assessing the applicability and impact of these assessments, before moving onto more complex assessment methods if concerns are raised by the simplistic techniques.
This report is intended for the sole use of the person or company to whom it is addressed and no liability of any nature whatsoever shall be assumed to any other party in respect of its contents.

GL NOBLE DENTON

Signed: ___________________________ Signed original on file ________________

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Countersigned: ___________________________ Signed original on file ________________

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Dated: Aberdeen, 10 March 2011
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Degradation of mooring chains of floating offshore installations: chain measurement, estimation of wear, corrosion rates, and their effect on break load

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).

Mooring chains inevitably degrade over time leading to loss of strength of individual mooring lines and the mooring system as a whole. This report describes how the reduced dimensions of the chain may be measured by various techniques, both underwater or when brought above the surface. It investigates typical wear and corrosion rates experienced in the field, and the change in the minimum break load of used mooring chains. The report provides: practical guidelines on likely wear and corrosion rates to inform decisions at the design stage on chain diameter allowance; indicative wear and corrosion rates to inform judgements on whether rates seen in use are typical or anomalous; and guidelines on how the minimum break load will change with degradation.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.