# Fatigue of Top Chain of Mooring Lines due to In-plane and Out-of-plane Bendings

October 2014

Guidance Note
NI 604 DT R00 E

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# MARINE & OFFSHORE DIVISION
# GENERAL CONDITIONS

### ARTICLE 1

**1.1.** - BUREAU VERITAS is a Society the purpose of whose Marine & Offshore Division (the "Society") is the classification (" Classification ") of any ship or vessel or offshore unit or structure of any type or part of it or system therein collectively hereinafter referred to as a "Unit" whether linked to shore, river bed or sea bed or not, whether operated or located at sea or in inland waters or partly on land, including submarines, hovercrafts, drilling rigs, offshore installations of any type and of any purpose, their related and ancillary equipment, subsea or not, such as well head and pipelines, mooring legs and mooring points or otherwise as decided by the Society.

The Society:

- "prepares and publishes Rules for classification, Guidance Notes and other documents (" Rules ");
- "issues Certificates, Attestations and Reports following its interventions (" Certificates ");
- "publishes Registers.

**1.2.** - The Society also participates in the application of National and International Regulations or Standards, in particular by delegation from different Governments. Those activities are hereafter collectively referred to as " Certification ".

**1.3.** - The Society can also provide services related to Classification and Certification such as ship and company safety management certification; ship and port security certification, training activities; all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board.

**1.4.** - The interventions mentioned in 1.1., 1.2. and 1.3. are referred to as " Services ". The party and/or its representative requesting the services is hereinafter referred to as the " Client ". **The Services are prepared and carried out on the assumption that the Clients are aware of the International Maritime and/or Offshore Industry (the "Industry") practices.**

**1.5.** - The Society is neither and may not be considered as an Underwriter, Broker in ship's sale or chartering, Expert in Unit's valuation, Consulting Engineer, Controller, Naval Architect, Manufacturer, Shipbuilder, Repair yard, Charterer or Shipowner who are not relieved of any of their expressed or implied obligations by the interventions of the Society.

### ARTICLE 2

**2.1.** - Classification is the appraisement given by the Society for its Client, at a certain date, following surveys by its Surveyors along the lines specified in Articles 3 and 4 hereafter on the level of compliance of a Unit to its Rules or part of them. This appraisement is represented by a class entered on the Certificates and periodically transcribed in the Society's Register.

**2.2.** - Certification is carried out by the Society along the same lines as set out in Articles 3 and 4 hereafter and with reference to the applicable National and International Regulations or Standards.

**2.3.** - **It is incumbent upon the Client to maintain the condition of the Unit after surveys, to present the Unit for surveys and to inform the Society without delay of circumstances which may affect the given appraisement or cause to modify its scope.**

**2.4.** - The Client is to give to the Society all access and information necessary for the safe and efficient performance of the requested Services. The Client is the sole responsible for the conditions of presentation of the Unit for tests, trials and surveys and the conditions under which tests and trials are carried out.

### ARTICLE 3

**3.1.** - **The Rules, procedures and instructions of the Society take into account at the date of their preparation the state of currently available and proven technical knowledge of the Industry. They are a collection of minimum requirements but not a standard or a code of construction neither a guide for maintenance, a safety handbook or a guide of professional practices, all of which are assumed to be known in detail and carefully followed at all times by the Client.**

Committees consisting of personalities from the Industry contribute to the development of those documents.

**3.2.** - **The Society only is qualified to apply its Rules and to interpret them. Any reference to them has no effect unless it involves the Society's intervention.**

**3.3.** - The Services of the Society are carried out by professional Surveyors according to the applicable Rules and to the Code of Ethics of the Society. Surveyors have authority to decide locally on matters related to classification and certification of the Units, unless the Rules provide otherwise.

**3.4.** - **The operations of the Society in providing its Services are exclusively conducted by way of random inspections and do not in any circumstances involve monitoring or exhaustive verification.**

### ARTICLE 4

**4.1.** - The Society, acting by reference to its Rules:

- "reviews the construction arrangements of the Units as shown on the documents presented by the Client;
- "conducts surveys at the place of their construction;
- "classes Units and enters their class in its Register;
- "surveys periodically the Units in service to note that the requirements for the maintenance of class are met.

**The Client is to inform the Society without delay of circumstances which may cause the date or the extent of the surveys to be changed.**

### ARTICLE 5

**5.1.** - **The Society acts as a provider of services. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty.**

**5.2.** - **The certificates issued by the Society pursuant to 5.1. here above are a statement on the level of compliance of the Unit to its Rules or to the documents of reference for the Services provided for.**

**In particular, the Society does not engage in any work relating to the design, building, production or repair checks, neither in the operation of the Units or in their trade, neither in any advisory services, and cannot be held liable on those accounts. Its certificates cannot be construed as an implied or express warranty of safety, fitness for the purpose, seaworthiness of the Unit or of its value for sale, insurance or chartering.**

**5.3.** - **The Society does not declare the acceptance or commissioning of a Unit, nor of its construction in conformity with its design, that being the exclusive responsibility of its owner or builder.**

**5.4.** - The Services of the Society cannot create any obligation bearing on the Society or constitute any warranty of proper operation, beyond any representation set forth in the Rules, of any Unit, equipment or machinery, computer software of any sort or other comparable concepts that has been subject to any survey by the Society.

### ARTICLE 6

**6.1.** - The Society accepts no responsibility for the use of information related to its Services which was not provided for the purpose by the Society or with its assistance.

**6.2.** - **If the Services of the Society or their omission cause to the Client a damage which is proved to be the direct and reasonably foreseeable consequence of an error or omission of the Society, its liability towards the Client is limited to ten times the amount of fee paid for the Service having caused the damage, provided however that this limit shall be subject to a minimum of eight thousand (8,000) Euro, and to a maximum which is the greater of eight hundred thousand (800,000) Euro and one and a half times the above mentioned fee. These limits apply regardless of fault including breach of contract, breach of warranty, tort, strict liability, breach of statute, etc.**

**The Society bears no liability for indirect or consequential loss whether arising naturally or not as a consequence of the Services or their omission such as loss of revenue, loss of profit, loss of production, loss relative to other contracts and indemnities for termination of other agreements.**

**6.3.** - All claims are to be presented to the Society in writing within three months of the date when the Services were supplied or (if later) the date when the events which are relied on of were first known to the Client, and any claim which is not so presented shall be deemed waived and absolutely barred. Time is to be interrupted thereafter with the same periodicity.

### ARTICLE 7

**7.1.** - Requests for Services are to be in writing.

**7.2.** - **Either the Client or the Society can terminate as of right the requested Services after giving the other party thirty days' written notice, for convenience, and without prejudice to the provisions in Article 8 hereunder.**

**7.3.** - The class granted to the concerned Units and the previously issued certificates remain valid until the date of effect of the notice issued according to 7.2. here above subject to compliance with 2.3. here above and Article 8 hereunder.

**7.4.** - The contract for classification and/or certification of a Unit cannot be transferred neither assigned.

### ARTICLE 8

**8.1.** - The Services of the Society, whether completed or not, involve, for the part carried out, the payment of fee upon receipt of the invoice and the reimbursement of the expenses incurred.

**8.2.** - **Overdue amounts are increased as of right by interest in accordance with the applicable legislation.**

**8.3.** - **The class of a Unit may be suspended in the event of non-payment of fee after a first unfruitful notification to pay.**

### ARTICLE 9

**9.1.** - The documents and data provided to or prepared by the Society for its Services, and the information available to the Society, are treated as confidential. However:

- "Clients have access to the data they have provided to the Society and, during the period of classification of the Unit for them, to the **classification file** consisting of survey reports and certificates which have been prepared at any time by the Society for the classification of the Unit ;
- "copy of the documents made available for the classification of the Unit and of available survey reports can be handed over to another Classification Society, where appropriate, in case of the Unit's transfer of class;
- "the data relative to the evolution of the Register, to the class suspension and to the survey status of the Units, as well as general technical information related to hull and equipment damages, may be passed on to IACS (International Association of Classification Societies) according to the association working rules;
- "the certificates, documents and information relative to the Units classed with the Society may be reviewed during certificating bodies audits and are disclosed upon order of the concerned governmental or inter-governmental authorities or of a Court having jurisdiction.

The documents and data are subject to a file management plan.

### ARTICLE 10

**10.1.** - Any delay or shortcoming in the performance of its Services by the Society arising from an event not reasonably foreseeable by or beyond the control of the Society shall be deemed not to be a breach of contract.

### ARTICLE 11

**11.1.** - In case of diverging opinions during surveys between the Client and the Society's surveyor, the Society may designate another of its surveyors at the request of the Client.

**11.2.** - Disagreements of a technical nature between the Client and the Society can be submitted by the Society to the advice of its Marine Advisory Committee.

### ARTICLE 12

**12.1.** - Disputes over the Services carried out by delegation of Governments are assessed within the framework of the applicable agreements with the States, international Conventions and national rules.

**12.2.** - Disputes arising out of the payment of the Society's invoices by the Client are submitted to the Court of Nanterre, France, or to another Court as deemed fit by the Society.

**12.3.** - **Other disputes over the present General Conditions or over the Services of the Society are exclusively submitted to arbitration, by three arbitrators, in London according to the Arbitration Act 1996 or any statutory modification or re-enactment thereof. The contract between the Society and the Client shall be governed by English law.**

### ARTICLE 13

**13.1.** - **These General Conditions constitute the sole contractual obligations binding together the Society and the Client, to the exclusion of all other representation, statements, terms, conditions whether express or implied. They may be varied in writing by mutual agreement. They are not varied by any purchase order or other document of the Client serving similar purpose.**

**13.2.** - The invalidity of one or more stipulations of the present General Conditions does not affect the validity of the remaining provisions.

**13.3.** - The definitions herein take precedence over any definitions serving the same purpose which may appear in other documents issued by the Society.

## GUIDANCE NOTE NI 604

# Fatigue of Top Chain of Mooring Lines due to In-plane and Out-of-plane Bendings

October 2014

**Section 1 General**

**Section 2 Mooring Analyses for Combined Fatigue Estimation**

**Section 3 Combined Fatigue Estimation**

## Appendix 1 Alternative Design Requirements

# SECTION 1 GENERAL

## 1 Scope

### 1.1 Application

**1.1.1** The present Guidance Note provides the methodologies, requirements and recommendations to be considered in the evaluation of top chain combined fatigue under tension loading, in-plane bending loading and out-of-plane bending loading for the classification of permanently moored offshore units.

**1.1.2** In the present Guidance Note, the top chain corresponds to the 20 first chain links of the mooring line after fairlead chain stopper.

**1.1.3** The requirements of the present Guidance Note are complementary to provisions of Rule Notes listed in [3.1.1] for granting the **POSA** notation to permanent offshore floating units.

**1.1.4** The evaluation of combined fatigue at top chain connection is to be performed when the pretension in mooring lines at intermediate draft is higher than 10% of the Minimum breaking strength of a chain of the same diameter in Oil Rig Quality (ORQ) grade and when the design life on site is higher than 2 years.

## 2 Definition

### 2.1 Top chain combined fatigue

#### 2.1.1 Loadings in Top chain

Chains in mooring lines are designed to resist tension loads in line with chain direction. Far from connection points, the angular variation between two chain links is negligible and the assumption of pure tension loading is valid. However, at connection points such as chain stoppers, when one link is forced to rotate with regards to the adjacent link, higher bending moments are imposed in the first following links, generating additional fatigue damage.

At fairlead/chain-stopper location, the motions and rotations of the vessel are imposed to the fairlead and the link retained in fairlead pocket whereas the motions of the mooring lines, following mooring line catenary, are imposed to the adjacent chain links.

Due to the angular differences between fairlead and chain and to friction between links, high bending moments are imposed to the first links of the top chain.

#### 2.1.2 Chain bending modes

Roll between chain links is largely prevented by the chain proofloading during fabrication (imprint of a pocket at contact area between links).

Between two links, the following two main behaviours in bending can thus develop:

- A sticking mode: static friction mode where adjacent links behave as locked.
- A sliding mode: dynamic friction mode when interlink moment is exceeding friction limit.

The different behaviours define a non-linear interlink stiffness.

#### 2.1.3 In-plane and out-of-plane bending of top chains

Three different bending modes can be defined depending on the direction of the bending moment:

- An in-plane bending (IPB) mode where the link is bent within its main symmetry plane.
- An out-of-plane bending (OPB) mode where the link is bent out of its main plane.
- A torsional mode where the link is in torsion around its main axis. This mode can generally be neglected for combined fatigue evaluation in the top chain.

The interlink stiffness naturally relates two adjacent links whose plane are at right angles.

#### 2.1.4 Combined stresses in top chain

Three loadings of the chain and resulting stresses are thus to be defined:

- Tension-tension (TT) loading due to axial tension loads in the link.
- In-plane bending (IPB) loadings due to bending in the main plane of the link.
- Out-of-plane bending (OPB) loadings due to bending out of the main plane of the link.

The loading of the chain can be decomposed within these three types of loading and the resulting stresses are to be combined in order to obtain the total stress for fatigue damage evaluation.

## 3 References

### 3.1

#### 3.1.1 Rule Notes

- NR445, Rules for the Classification of Offshore Units
- NR493, Classification of Mooring Systems for Permanent Offshore Units
- NR494, Rules for the Classification of Offshore Loading and Offloading Buoy.

#### 3.1.2 Other reference documents

- OTC 17238

  Failure of Chains by Bending on Deepwater Mooring Systems, P.Jean, K.Goessens, D.L'Hostis, Offshore Technology conference, May 2005

- OMAE 67353

  Out-of-Plane Bending Testing of Chain Links, C.Melis, P.Jean, P.Vargas, International Conference on Offshore Mechanics and Arctic Engineering, June 2005

- OMAE 67354

  FEA of Out-of-Plane Fatigue Mechanism of Chain Links, P.Jean, P.Vargas, International Conference on Offshore Mechanics and Arctic Engineering, June 2005

- OMAE 92488

  Fatigue Testing of Out-of-Plane Bending Mechanism of Chain Links, L.Rampi, P.Vargas, International Conference on Offshore Mechanics and Arctic Engineering, June 2006

- RR-M-86-007

  Chain Out of Plane Bending - JIP Report, L.Rampi, May 2013.

# 4 Methodology

## 4.1 General methodology

**4.1.1** The methodology for OPB calculation methodology can be divided into 3 steps:

- fatigue mooring simulations
- interlink stiffness computation
- fatigue damage evaluation.

Details of the methodology are presented in the following graphs.

**Figure 1 : General methodology**

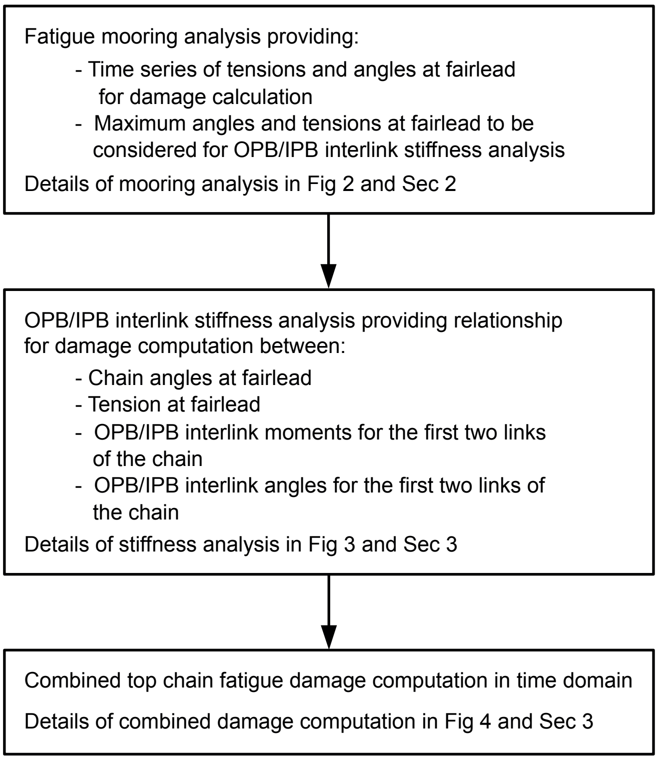


Figure 2 : Methodology for mooring analysis and post processing

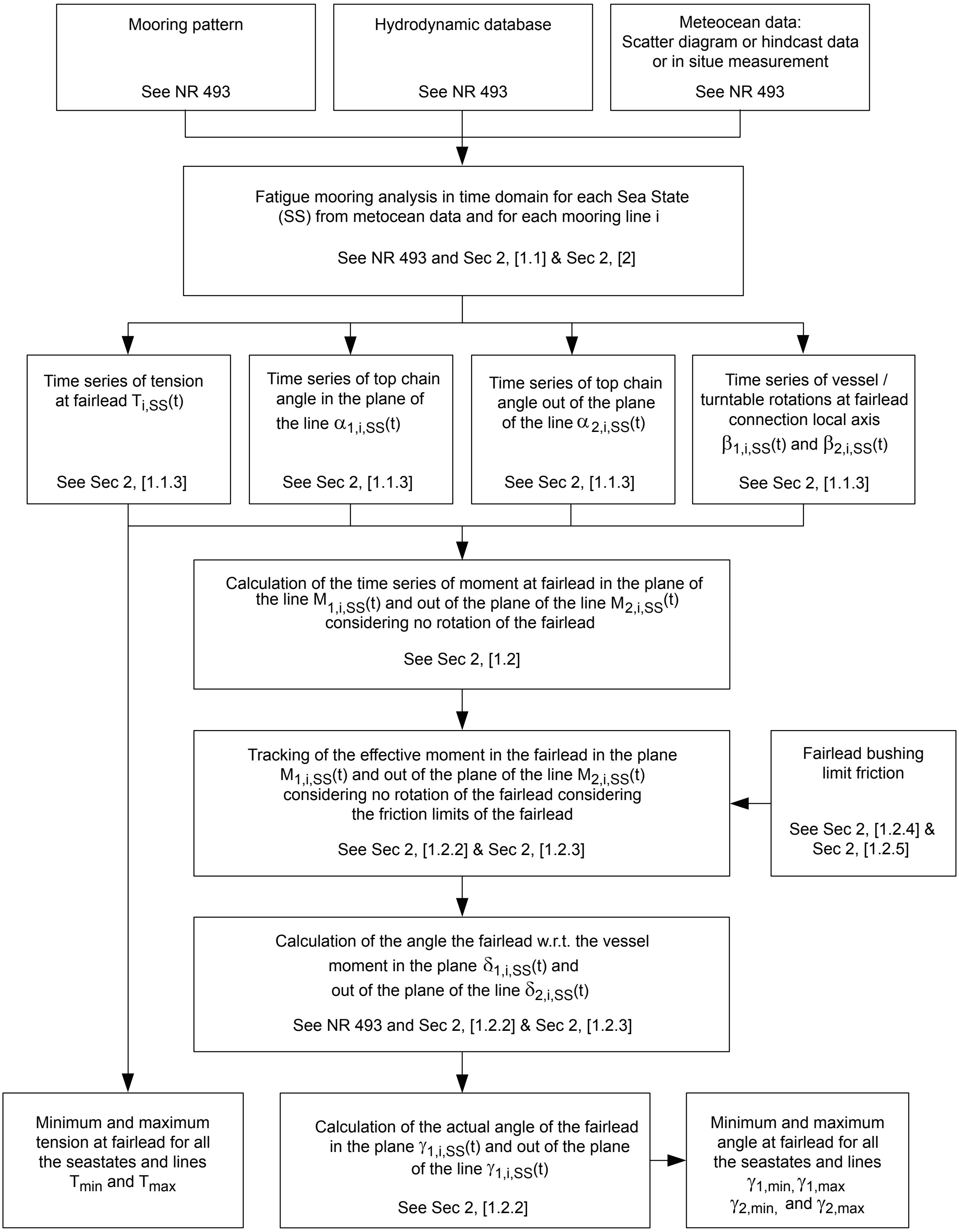


**Figure 3 : Methodology for OPB/IPB interlink stiffness analysis**

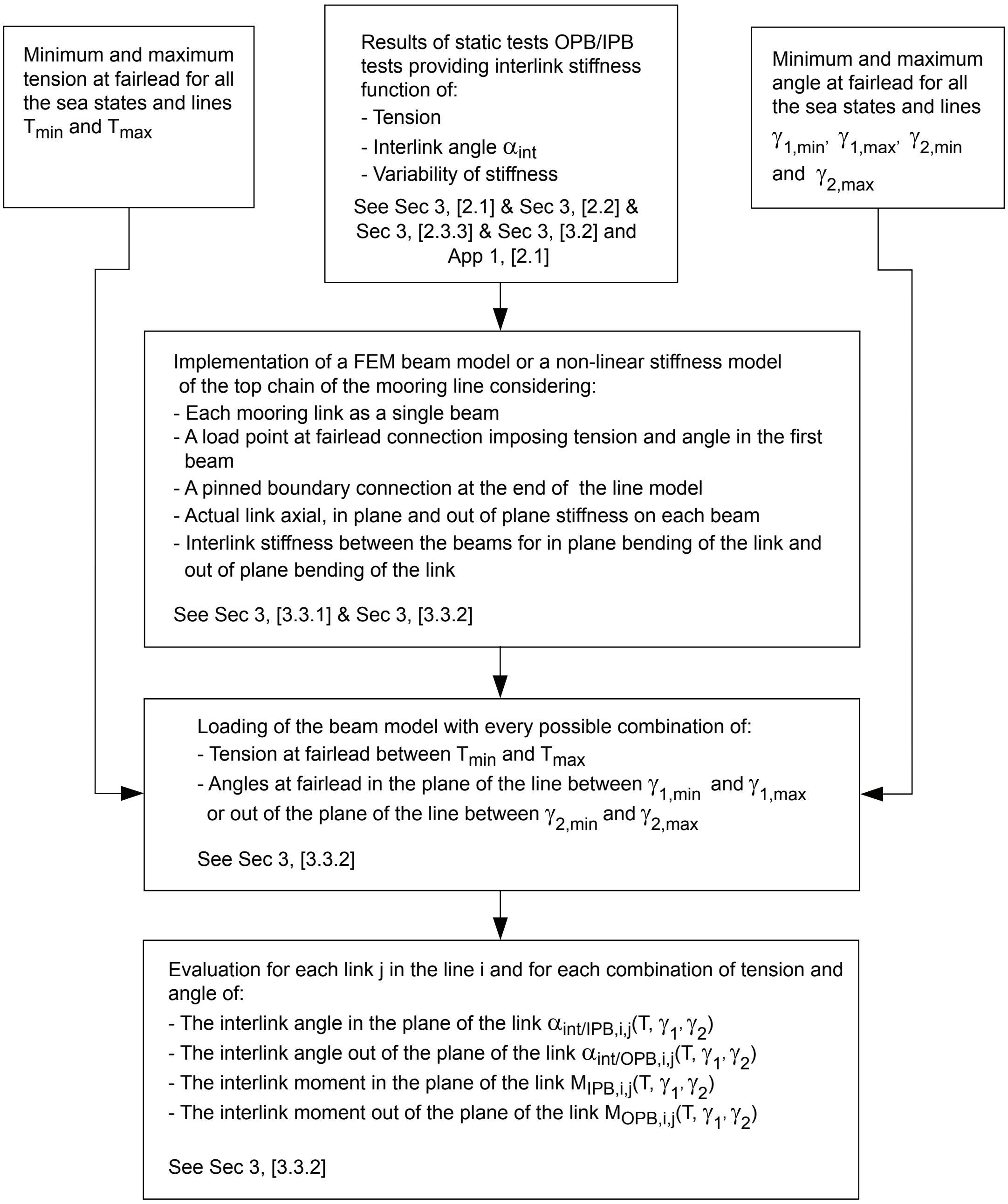
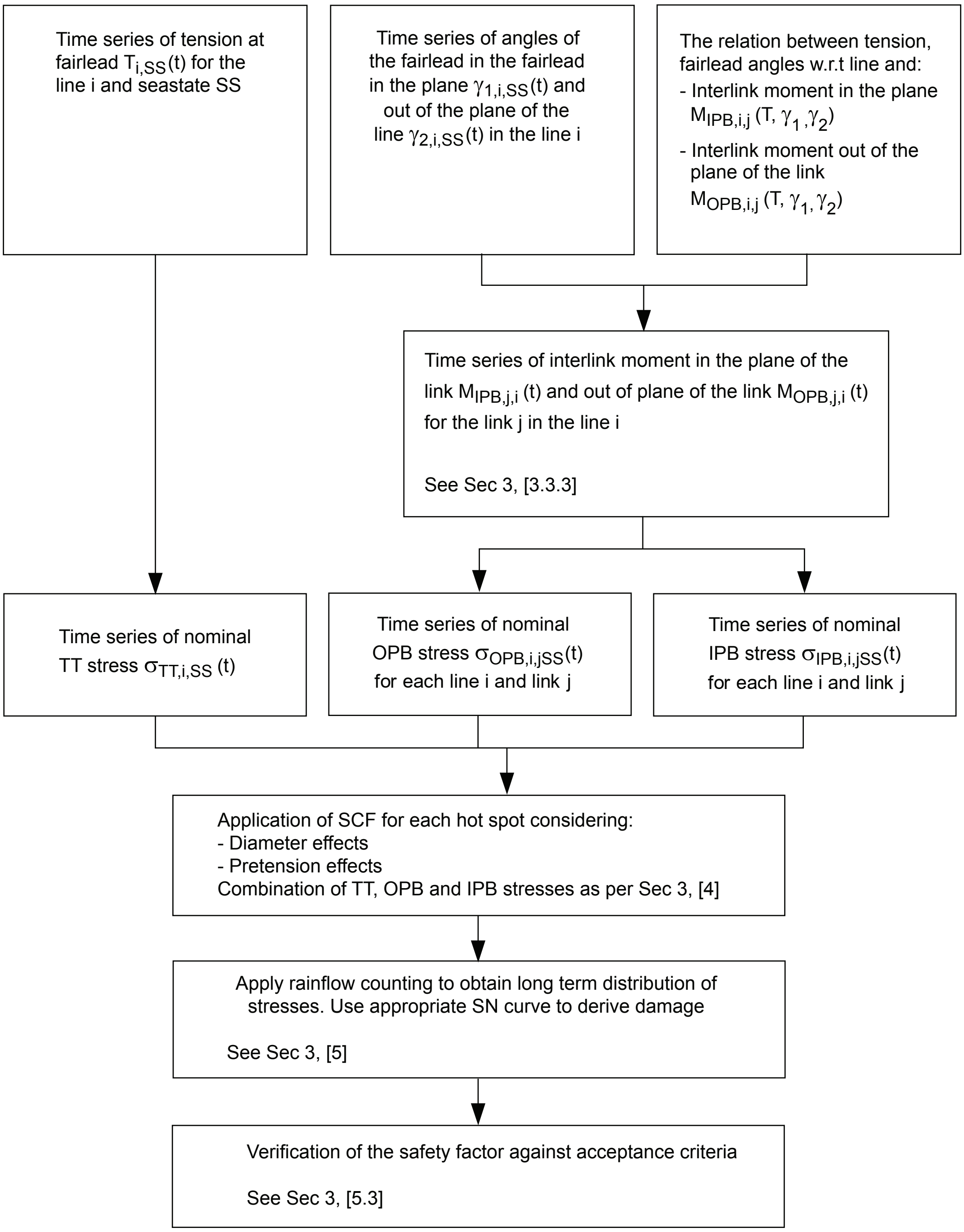


Figure 4 : Methodology for damage computation



# SECTION 2

# MOORING ANALYSES FOR COMBINED FATIGUE ESTIMATION

## Symbols

$T$ : Tension in the line at top chain attachment point
$P$ : Pretension in the line at top chain attachment point, for the simulated condition
$\alpha_1$, $\alpha_2$ : Chain angle at connection considering a perfectly pinned connection in fairlead global axis
$\beta_1$, $\beta_2$ : Vessel rotation in fairlead global axis
$\delta_1$, $\delta_2$ : Fairlead rotations in fairlead global axis
$\gamma_1$, $\gamma_2$ : Relative chain angle at fairlead
$\gamma_{TT}$ : Mean stress correction factor on multiaxial OPB SCF
$\mu$ : Friction coefficient between steel and steel
$\alpha_{int}$ : Interlink angle between the considered link and the next adjacent link
$d$ : Chain diameter
$D$ : Total fatigue damage
$D_i$ : Elementary fatigue damage
D-DAF : Dynamic Damage Amplification Factor
FCS : Fairlead - Chain stopper
FEM : Finite Element Methods
TT : Tension-Tension loading
IPB : In-plane bending of chain
OPB : Out-of-plane bending of chain
$M_{OPB}$ : Moment in chain at interlink contact area in OPB direction
$M_{IPB}$ : Moment in chain at interlink contact area in IPB direction.

## 1 Methodology for analysis

### 1.1 Global line assessment

**1.1.1** In order to assess combined fatigue of top chains at attachment points, the global line behaviour is to be assessed through dedicated mooring analyses considering detailed modelling of the vessel motions, of the line tension, of the angles between chain and fairlead at attachment point.

**1.1.2** The analyses methodology adopted for combined fatigue evaluation is to be in line with the provisions of NR493 Rules for the Classification of Mooring Systems for Permanent Offshore Units.

**1.1.3** Lines tensions and angles at attachment points are to be assessed through time-domain methodologies.

A pinned boundary condition of the chains at fairlead are to be considered.

Time series of chain angles and tensions at fairlead are to be provided for each metocean and loading conditions. These time series are to be post processed in order to obtain time series of relative chain angles in the plane and out of the plane of the fairlead, following the methodology defined in [1.2].

Interlink moments and combined stresses for fatigue evaluation are to be obtained through post-processing of these time series as defined in Sec 3.

**1.1.4** Alternative methodologies will be given consideration, on a case by case basis, provided they demonstrate to provide a Safety Level equivalent to that resulting from the application of the present document.

### 1.2 Local line assessment

#### 1.2.1 Chain relative angle assessment

Relative angle between chain and fairlead-chain stopper (FCS) is driven by chain motions, vessel motions and fairlead characteristics.

The angular motions on the chain and of the vessel are to be transposed in the FCS local axis system at chain connection, considering the abilities of rotation of the FCS.

Chain angle $\alpha$ is considered as the angle at chain connection when considering a perfectly pinned joint connection of the chain on the vessel at FCS connection in global axis.

The vessel rotations $\beta$ and the angle between FCS and vessel $\delta$ are to be considered in the global axis.

These chain and vessel angular motions are to be transposed in the FCS local axis, defining angles within the horizontal axis of the FCS ($\alpha_1$,$\beta_1$,$\delta_1$) and vertical axis of the FCS ($\alpha_2$,$\beta_2$,$\delta_2$).

The relative chain angle $\gamma$ at fairlead is then expressed as following, limited by FCS sliding abilities (see [1.2.2]):

$\gamma_1 = \beta_1 + \delta_1 - \alpha_1$

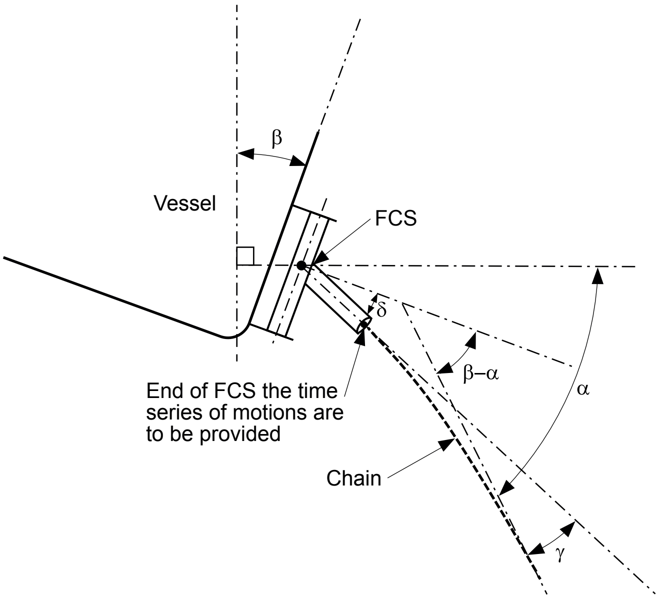
$\gamma_2 = \beta_2 + \delta_2 - \alpha_2$

#### 1.2.2 FCS rotations behaviour

Most modern FCS have rotation abilities around vertical and horizontal axes in order to reduce bending moments in mooring line top chains, so the angle between vessel and FCS is not constant.

These rotation abilities are limited by friction phenomena in bushings of axes of FCS, generating sliding limits of FCS axes under which the fairlead rotation is prevented, inducing bending fatigue of chain.

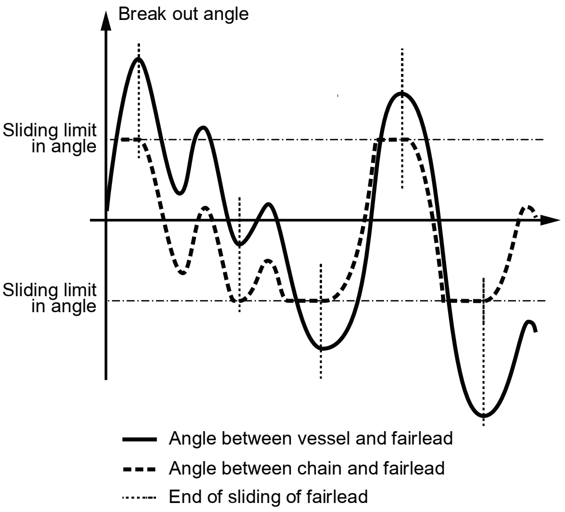
Figure 1 : Chain relative angles at FCS



This limiting moment is to be thoroughly investigated through testing. A sliding behaviour of the FCS as close as possible to effective fairlead behaviour is to be implemented in relative angle assessment.

The limiting moment can also be evaluated as a break-out angle above which the fairlead chain stopper starts sliding (see Fig 2).

Figure 2 : Sticking/sliding behaviour of the FCS



### 1.2.3 Evaluation of FCS rotations

The angle between vessel and FCS, δ, is to be evaluated along the time series, implementing a model of the sticking/sliding behaviour of the FCS bearings.

The resulting moment at fairlead connection is to be assessed depending on chain relative angle with fairlead and line tension, defining two working modes (see Fig 1):

- a sticking mode: when the moment is lower than the limiting moment, the angle δ remains constant
- a sliding mode: when the moment tends to be higher than the limiting moment, the angle δ varies in order to keep the moment at limiting value.

Simplified methodologies such as truncated angle time series are generally not allowed, except if demonstrated to provide a Safety Level equivalent to that resulting from the application of the present document.

### 1.2.4 Functional tests of FCS

Sticking/sliding behaviour of FCS is to be tested on full scale prototypes against imposed rotations of the FCS under fixed axial loads, unless the approach in [1.2.5] is followed. Testing is to be performed in seawater for submerged FCS.

The range of axial loads in tests is to be in accordance with maximum and minimum loads seen in fatigue mooring simulation time series.

The upper bound relation between load and limiting moment is to be assessed for the evaluation of FCS rotations.

The static friction coefficient of the bushing material is to be measured on the prototype.

### 1.2.5 Alternative evaluation of FCS sliding limits

Alternatively, the FCS sliding limits may be evaluated based on friction tests of the bushing material. The upper bound value of the static friction coefficient μ of the bearing material with steel is to be assessed in water for submerged FCS and in air for FCS above water for the range of loads seen in fatigue mooring simulation time series.

Test shall be conducted to evaluate the performance and suitability of the bearing material for this specific application, considering low motion and low sliding distance. The test will be perform with the bearing under sea water condition with controlled temperature. For each test the following results will be at least recorded: friction torque, displacement, continuous friction curve, continuous temperature curve.

Before and after each test, thickness measurement and surface roughness will be recorded for wear assessment. The rolling effect (if any) shall not be considered for the definition of sliding distance during the test.

The following moment limit $M_{lim}$ is to be considered:

$M_{lim} = 0{,}55\ \mu DF$

with:

F : Instantaneous axial load on the FCS

D : Diameter of the axis in the bearing.

This limiting moment can be expressed in general as a break-out angle.

### 1.2.6 Factory acceptance tests on bushing material

The static friction coefficient of the material from the actual production of the bushings of the FCS is to be measured for the tension range evaluated in mooring simulations and meet the values determined during the prototype tests in [1.2.4] or in [1.2.5].

# 2 Requirements for mooring analysis

## 2.1 Mooring Analysis Method

### 2.1.1 Dynamic analyses

Fatigue calculation is to be performed based on time-domain dynamic mooring analyses with fine representation of vessel characteristics and behaviour, riser characteristics and behaviour and mooring line characteristics and behaviour. The provision of NR493, Sec 3, [2.4] and NR493, Sec 3, [5.2] are to be fulfilled.

Coupling issues between vessel and mooring system are to be investigated. Dynamic mooring analysis may be limited to line dynamics when coupling effects are proven negligible.

### 2.1.2 Quasi-dynamic analyses

Quasi-dynamic time-domain analyses may be used as a first screening method for combined fatigue damage.

The designing environment are then to be reanalyzed through dynamic analysis. The extent of the environments to be reanalyzed through dynamic calculations and the methodology for integrating dynamic results will be evaluated by the Society on a case by case basis depending on the system and the metocean conditions of the site.

As a minimum for guidance purpose, the following seastates are to be assessed through dynamic analyses:

- the 10 most probable seastates
- the 10 most damaging seastates considering probability of occurrence, and
- the 10 seastates with highest damage without considering probability of occurrence.

The ratios between fatigue damage estimated through dynamic analyses and the fatigue damage estimated through quasi-dynamic analyses, called Damage Dynamic Amplification Factors DDAF obtained on these seastates are to be conservatively applied to the whole set of metocean conditions assessed for fatigue estimation. The DDAF, not being lower than 1, is estimated as following:

$DDAF = D_{Dyn} / D_{QS}$

with:

$D_{Dyn}$ : Fatigue damage obtained through dynamic calculation

$D_{QS}$ : Fatigue damage obtained through quasi-static calculation.

Note 1: Definition of quasi-dynamic analyses is provided in NR493, Sec 3, [2.3].

## 2.2 Selection of design conditions

### 2.2.1 Loading conditions

A set of representative configurations of the system is to be selected for the analyses, so as to cover all intended situations of operation of the Unit and to ensure that the most onerous configurations have been examined.

The whole range of variation of draft of the units is to be considered. As a minimum, the following drafts are to be considered:

- the ballasted draft or the minimum draft in operational conditions
- the maximum draft in operational conditions
- an intermediate draft maximizing the unit's rotations, obtained by scanning the different operational loading conditions from the unit's loading manual. As a guidance, this draft can be obtained by comparing roll and pitch natural periods with metocean data on site (wave peak periods).

Additional draft may be considered in order to represent the whole range of possible loading conditions. Realistic probability of the vessel to be in each condition is to be applied on fatigue damage in each configuration.

Other relevant conditions with realistic probabilities are to be assessed, such as operating/ survival conditions with corresponding drafts connected and disconnected conditions of exporting vessel.

### 2.2.2 Environment

For a given loading condition, a series of metocean conditions that are representative of the long term conditions of the intended site and of the operating limits in this condition is to be considered. This set of environmental conditions may be time series obtained by hind-casts data, or may be derived from available statistical data of waves (scatter diagrams) combined in an appropriate way with current and wind data to account for joint probabilities.

For each metocean condition, the fatigue damage is calculated by Rainflow counting and Palmgren-Miner sum on a the stress time series (see Sec 3, [4]) derived from the mooring analysis on a 3 hour long sea state in order to obtain a statistically stationary process.

Total damages have to be calculated taking into account the number of occurrence of the event over the total design life of the unit.

### 2.2.3 Corrosion

The following corrosion allowance of chain has to be considered:

- 0.4mm/year in the splash zone (+/– 110% of the relative wave elevation at mooring line location with a probability of occurrence of 5% or +/– 5 m around free surface, whichever greater)
- 0.3mm/year in the remaining length for under water FCS or fairlead high above the water surface.

For fatigue assessment, a minimum of half of the corrosion allowance on the design life of the unit is to be accounted.

Note 1: These corrosion rates seem relevant for cold seas but may be insufficient in tropical seas. Corrosion rates may be increased based on site conditions and relevant surveys or Operator's or local regulation specifications.

## 2.3 Sensitivity on loading conditions and mooring system model

**2.3.1** Within the set of representative configurations of the system to be accounted for the fatigue damage evaluation, sensitivity analyses on the different parameters of the analyses and the tolerances on fabrication, installations and in service conditions have to be performed. The most onerous conditions are to be considered to define the combined fatigue design damage of the top chain segment.

**2.3.2** In addition, the effect of all the simplifications and linearization used in the mooring analysis models are to be assessed and demonstrate to provide a Safety Level equivalent to a complete detailed fully coupled dynamic model.

**2.3.3** As a minimum, the effect of following sensitivities are to be performed, or justified by proper mean:

- effect on mooring line pretension of the whole range of tolerances defined in installation specifications
- effect of marine growth additional weight and drag area obtained from Metocean conditions at the mooring site
- effect of tolerances on mooring line components characteristics (stiffness and weight)
- effect of tolerances in bearing material on FCS behaviour
- effect of variations of friction coefficient of steel between links when the fairlead has a sliding limit higher than the chain links sliding limits.

# SECTION 3 COMBINED FATIGUE ESTIMATION

## Symbols

$T$ : Tension in the line at top chain attachment point

$P$ : Pretension in the line at top chain attachment point

$\alpha$ : Chain angle at connection considering a perfect ball-and-socket connection

$\beta$ : Angle between fairlead and vessel

$\gamma$ : Relative chain angle

$\gamma_{TT}$ : Mean stress correction factor on multiaxial OPB SCF

$\alpha_{int}$ : Interlink angle between the considered link and the next adjacent link

$d$ : Chain diameter

$D$ : Total fatigue damage

$D_i$ : Elementary fatigue damage

D-DAF : Dynamic Damage Amplification Factor

FCS : Fairlead - Chain stopper

FEM : Finite Element Methods

TT : Tension-Tension loading

IPB : In-plane bending of chain

OPB : Out-of-plane bending of chain

$M_{OPB}$ : Moment in chain at interlink contact area in OPB direction

$M_{IPB}$ : Moment in chain at interlink contact area in IPB direction

$\Delta\sigma_{TT}$ : TT stress variation due to tension variation at the considered hotspot

$\Delta\sigma_{OPB}$ : OPB stress variation due to OPB moment variation at the considered hotspot

$\Delta\sigma_{IPB}$ : IPB stress variation due to IPB moment variation at the considered hotspot

$\Delta\sigma_{TT,\ nom}$ : TT nominal stress variation due to tension variation

$\Delta\sigma_{OPB,\ nom}$: OPB nominal stress variation due to OPB moment variation

$\Delta\sigma_{IPB,\ nom}$ : IPB nominal stress variation due to IPB moment variation.

## 1 General

### 1.1 General

**1.1.1** Tension and bending cyclic loads are creating stress cycles in chain. This stress induced by TT, OPB and IPB loadings is to be estimated through the post processing of time series from mooring analyses.

**1.1.2** The stresses can be linearly decomposed in TT stresses, OPB stresses and IPB stresses that can be evaluated separately and recombined by proper means.

**1.1.3** The aim of the present section is to present the methodology to evaluate the stress cycle time series based on the results of the mooring analysis and to recombine them for the evaluation of combined top chain fatigue damaged.

**1.1.4** The methodology to be adopted to define and evaluate the design parameters such as interlink stiffness, stress concentration factors in the chain link or SN curves from full scale tests and FEM calculations are also presented in this Section.

**1.1.5** Available design parameters are presented in App 1. These parameters can be used within their range of applicability without additional full scale tests on chain.

**1.1.6** In the following part of the document, the "interlink stiffness" is defined as the range of moment at interlink for a given tension and a given range of interlink angle.

## 2 Definition of interlink stiffness

### 2.1 Tests on full scale chains

**2.1.1** Full scale tests are to be performed on chains from the actual manufacturer that will be retained for chain manufacturing.

Chains are to be in the same diameter as the one used in the project.

Chain configuration in test bench and attachment points in test bench have to be representative of combined loading phenomena occurring on the unit on site.

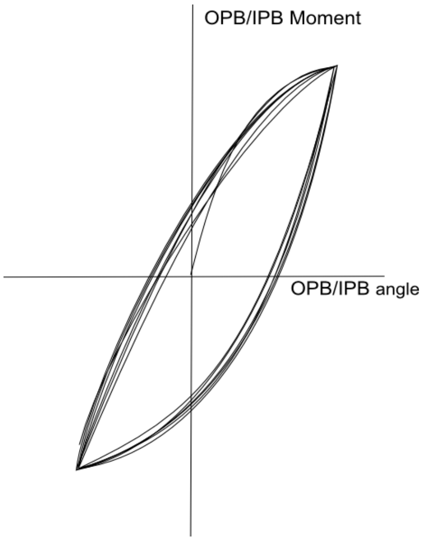
**2.1.2** Tests are to reproduce cycling for different tension and angular variations in accordance with the range of tension and relative angles sustained by the unit moored on site.

Due to the hysteresis of the bending moment during a loading range, chain has to sustain a sufficient number of cycles to assess non-linear bending moments and stresses and their variability, for each tension and angle variation (see Fig 1).

**2.1.3** Chain links in test bench are to be implemented with measurement device such as but not limited to inclinometers and strain gauges in order to validate and calibrate results of FEM calculations of stresses.

Testing program specification and test results are to be submitted to the Society for review.

Figure 1 : OPB/IPB Moment hysteresis loop



## 2.2 Results from other tests

**2.2.1** Results from previously performed full scale model tests on equivalent chain diameters and grade can be used in order to derive design parameters provided that the tested tensions and angles are in line with the requirement of the project.

The results of the tests will be reviewed by the Society on a case by case basis.

**2.2.2** Recognized design parameters can be used for the combined fatigue assessment, with prior agreement by the Society.

The test data used to derive these design parameters are to be documented and the domain of applicability of the design parameters is to be in line with the requirement of the project.

**2.2.3** Results from App 1 may be used for chains in R3, R3S and R4 grade with chain nominal diameter from 84 mm to 146 mm.

Out of this range of chains, these values are to be used with special care and extrapolation of results will be reviewed by the Society on a case by case basis.

## 2.3 Interlink stiffness from full scale tests

**2.3.1** Global best-fitted interlink stiffness law and variability around this average law has to be deduced from the testing program for the whole range of tension and angle variation sustained by the unit on site.

**2.3.2** A best fit model of interlink stiffness is to be evaluated from the results of the tests, providing the interlink moment as a function of the interlink angle and tension. Fitting methodology will be reviewed on a case by case basis by the Society.

Note 1: FEM analyses will not be deemed sufficient to assess the interlink stiffness due to the fact that the material properties and the effective contact area cannot be modelled accurately. This has been confirmed by full scale tests and the corresponding FEM calculations have shown unconservative results for the interlink stiffness.

**2.3.3** The coefficient of variation around this best fit law is to be provided.

# 3 Evaluation of bending moments

## 3.1 Bending moment threshold

### 3.1.1 Friction parameter

The friction coefficient of chain in air generally is between 0,5 and 0,6 and the coefficient of friction in seawater is between 0,25 and 0,35.

As a basis for design a coefficient of 0,5 in air and 0,3 in seawater can be considered.

In case of non-rotating fairlead, or when the fairlead sliding limit is higher than chain links sliding limits, sensitivity analyses on friction parameters are to be considered.

### 3.1.2 Sliding threshold in chain

It has been demonstrated that the same bending stiffness curve can be used in air and in seawater. However, in seawater, bending moment in chain links are limited in each link to a sliding threshold where the two links begins to slide one on the other. This threshold is to be implemented in interlink stiffness law.

When the sliding threshold is exceeded, the moment remains constant while the angle is increasing. When the angle reaches a local extremum, the chain sticks back. This is creating hysteresis loops of moment versus interlink angle (see Fig 1).

The sliding threshold $M_{threshold}$ is defined as follows:

$M_{threshold} = \mu \, T \, d/2$

with:

T : Actual tension

$\mu$ : Friction coefficient

d : Chain nominal diameter.

## 3.2 Stiffness variability

**3.2.1** The variability on stiffness curve is to be considered in OPB and IPB stiffness.

This variability, corresponding to the variability of the contact area after the sliding of one link on the other, is considered as statistically independent of the other parameters of the stiffness law.

It can thus be represented as an independent variable factoring the stiffness law.

In absence of more detailed statistics of variability based on larger sets of data, the variability of the stiffness with regards to best fit stiffness curve can be considered as following a log normal distribution.

The shape factor, $\delta$, of the distribution of the stiffness variability can be linked to the coefficient of variation (COV) of the stiffness by the following formula:

$$\ln(1 + COV^2) = \delta^2$$

where the coefficient of variation is defined by the ratio between the standard deviation and the mean value of the stiffness.

As the fatigue damage evaluation corresponds to an integration of the stresses and thus of the moments in the time domain, this independent variable is equivalent to a constant factor $Z_S$ on the stiffness law, only depending on the shape factor $\delta$ and the fatigue SN-curve exponent m.

$$\ln Z_S = \frac{m\delta^2}{2}$$

This factor $Z_S$ is to be applied on OPB and IPB stress range (see [4.3.2]).

## 3.3 Static OPB/IPB moments evaluation

### 3.3.1 Chain interlink angles

The interlink angle between two adjacent links of the top chain section is only related to chain relative angle with fairlead and the tension at fairlead by the chain interlink stiffness.

The interlink angle drops regularly from one link to the next one in the top chain and interlink angle is negligible after 20 links.

### 3.3.2 Implicit formulation between chain tension and angles and interlink moments

An implicit formulation of the relation between interlink angles on the first links of the line and fairlead relative angle and tension can be drawn that is only dependent on the formulation of the interlink stiffness, i.e. of the chain diameter, grade and manufacturer.

This relation is independent of dynamic and memory effects and can be estimated by static calculations.

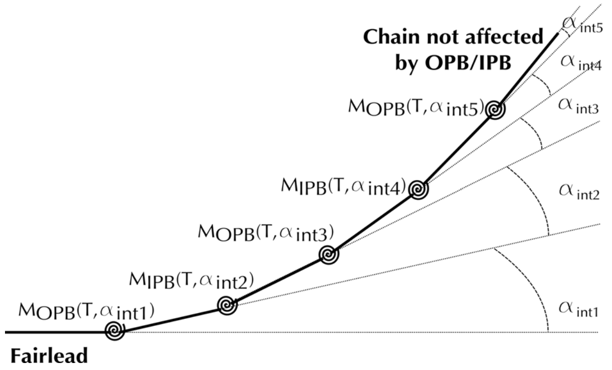
This evaluation is to be done through non-linear static finite element analysis of the first 20 links.

Each link is to be represented as a beam with the same stiffness as a link and the interlink stiffness with bending moment threshold is to be implemented between the links.

The model is to be loaded with line tension and in plane and out-of plane relative angles at fairlead combinations covering the whole range of tension and angles obtained from the mooring analysis (see Fig 2). The twentieth link of the model can have pinned boundary conditions.

For each loadcase, interlink angles and moments in plane and out of the plane of the link are to be evaluated for each link of the model.

Figure 2 : Example of beam model of chain for interlink angle estimation



### 3.3.3 Time series of interlink angles and moments

The time series of interlink angles/moments is to be obtained by applying the relation obtained by static beam analysis on time series of tensions and relative chain angles at FCS.

Simplified methodologies are generally not allowed, except if demonstrated that an equivalent Safety Level is provided.

More advanced methodologies will be reviewed on a case by case basis by the Society, in particular, methodologies accounting for link stiffness in the mooring analysis.

# 4 Combined stress estimation

## 4.1 Stress concentration factor estimation

### 4.1.1 FEM calculations for stress concentration factors

Mooring analyses and static OPB/IPB simulations provides time series of tension loads and interlink moments at contact area.

In order to obtain stresses due to TT, OPB and IPB loadings, stress concentration factors on TT load and OPB interlink moments and IPB interlink moments are to be evaluated through FEM calculations. These calculations and their post processing are to be submitted for review.

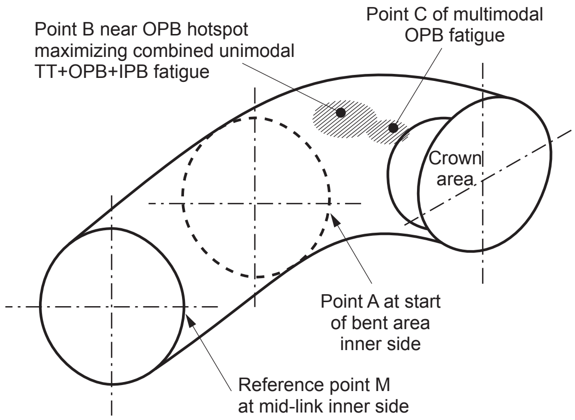
### 4.1.2 Requirements on FEM model

A volumic FEM model of a part of the top chain is to be built. The software and the type of FEM element used for in the calculation is to be qualified for elastic-plastic calculations with contacts.

The model of the chain is to consider at least one complete chain link connected with two half links. A realistic definition of contact behaviours, considering a friction in air for comparison to full scale tests on chains. Chain geometry is to be in accordance with the manufacturing data in terms of chain dimensions and tolerances at the end of heat treatment manufacturing step.

One of the half links are to be fully constrained on the midlink plan (plane of the welding area see Fig 3). The loading of the model is to be performed by applying tensions and displacements or tension and moments on the other half link.

**Figure 3 : Critical hotspot on chain link for combined fatigue of top chain**



Material stress-strain (hardening) law used in the calculation has to be representative of the effective material properties in the manufactured chain. Bilinear material laws are not recommended. Ramberg-Osgood or more advanced hardening laws are to be considered.

### 4.1.3 Loading of the FEM model

The loading is to be performed for different axial tensions covering the whole set of possible axial tensions contributing to top chain fatigue and full scale test values.

The interlink angles in the model are to cover the whole set of possible interlink angles variations on site and in the full scale test values.

All the loading conditions in full scale tests are to be computed on FEM model. FEM results are to be compared with the results of the tests.

For each loadcase, the following load sequence is to be performed on the FEM model. The loading is to be performed on unconstrained chain half-link:

- loading of the model in-line up to Rules proof load value as defined in NR216, Ch 4, Sec 2
- unloading of the model
- axial loading of the model up to specific line tension
- applying to the model a succession of cycles of angular displacement or moments.

After proofloading step, the chain dimensions are to be in line with Rules requirements and manufacturers factual data.

Stresses and displacement are to have reached a stable behaviour between the cycles at the end of the succession of angular cycles.

### 4.1.4 Comparison with test results

Results of model tests calculations are to be compared with the results of full scale tests (measures of load cells, strain gauges, inclinometers, etc.)

Discrepancies between FEM calculations and test results have to be justified.

### 4.1.5 Determination of critical hotspots

As the TT, OPB and IPB hotspot stress are located in different part of the chain link, the fatigue failure location may vary depending on the magnitude of each loading. Thus different stresses at different hotspots have to be assessed in fatigue.

OPB hotspot is spread on a wide area with a slow gradient in stresses thus different location in OPB hotspot area could be defined. The point maximizing additional TT loading effects and IPB effects in this area has to be retained as fatigue failure location instead of maximum OPB location in order to maximize combined stress.

Additionally in OPB hotspot area, when approaching interlinks contact area, stresses are not uniaxial anymore and multiaxiality of stresses is to be addressed by appropriate multiaxial fatigue methods such as Dang Van criterion. This defines another critical hotspot location.

As guidance, the following hotspot stresses are generally identified as the most critical in term of combined loading (see Fig 1):

- pure TT hotspot hereafter called hotspot A
- uniaxial OPB hotspot maximizing TT, OPB and IPB effects called hotspot B
- multiaxial OPB hotspot with multiaxiality effects closer to contact area called hotspot C.

### 4.1.6 Stress concentration factor definition

Cyclic stresses and corresponding stress concentration factors for the different loadings are defined as follows with d the un-corroded nominal diameter of chain:

$$SCF_{TT} = \frac{\Delta\sigma_{TT}}{\Delta\sigma_{TT,\,nom}}$$

and

$$SCF_{OPB} = \frac{\Delta\sigma_{OPB}}{\Delta\sigma_{OPB,\,nom}}$$

with:

$$\Delta\sigma_{TT,\,nom} = \frac{2\Delta T}{\pi d^2}$$

$$\Delta\sigma_{OPB,\,nom} = \frac{16\Delta M_{OPB}}{\pi d^3}$$

For studless chain, IPB stresses and corresponding stress concentration factors is defined as following:

$$SCF_{IPB} = \frac{\Delta\sigma_{IPB}}{\Delta\sigma_{IPB,\,nom}}$$

with:

$$\Delta\sigma_{IPB,\,nom} = \frac{2{,}33\ \Delta M_{IPB}}{\pi d^3}$$

For studlink chain, IPB stresses and corresponding stress concentration factors is defined as following:

$$SCF_{IPB} = \frac{\Delta\sigma_{IPB}}{\Delta\sigma_{IPB,\,nom}}$$

with:

$$\Delta\sigma_{IPB,\,nom} = \frac{2{,}06\;\Delta M_{IPB}}{\pi d^3}$$

These stress concentration factors can be estimated through adequate FEM calculation calibrated by full scale model tests on chain.

## 4.2 Corrosion effect

### 4.2.1 Nominal stresses modification in chain due to corrosion

Stress for fatigue damage computation are to be calculated considering the material loss due to corrosion at mid life of the unit.

The hypothesis or uniform corrosion can be considered as valid in the top chain. The effect of a uniformly spread loss of material on the link can be estimated as an increase of the TT, OPB and IPB nominal stresses as follows:

$$d_{corroded} = d_{uncorroded} - \frac{L_d}{2} r_{corr}$$

$$\Delta\sigma_{TT,\,nom} = \frac{2\Delta T}{\pi d_{corroded}^{\;2}}$$

$$\Delta\sigma_{OPB,\,nom} = \frac{16\Delta M_{OPB}}{\pi d_{corroded}^{\;3}}$$

$$\Delta\sigma_{IPB,\,nom,\,studless} = \frac{2{,}33\;\Delta M_{IPB}}{\pi d_{corroded}^{\;3}}$$

with:

$L_d$ : Design life of the unit

$r_{corr}$ : Loss of diameter due to corrosion per year.

### 4.2.2 Stress concentration factors modification in chain due to corrosion

When FEM calculations are performed on chains in as-new conditions, a geometrical corrosion factor is to be applied on SCF to account to the variation of the chain link geometry due to material loss.

For chain reductions at mid design life lower than a 5% diameter loss, this geometrical corrosion factor $Z_{corr}$ can be taken as 1,08, to be multiplied to the SCF for new chain, accounting for corrosion and manufacturing tolerances. This factor can be replaced by an evaluation of the SCF on a chain link with corrosion at mid-life.

For chain reduction at mid-life higher than a 5% diameter loss, SCF have to be calculated by proper FEM analyses based on corroded model with corrosion at mid-life (as per [4.1.2]).

When the FEM calculations are performed on corroded models, close attention is to be made on the proofload applied in order to obtain representative deformations of the proofloaded chain links. These calculations are to be submitted to the Society for review.

## 4.3 Stresses combination

**4.3.1** Fatigue damage calculation is to be performed on combined stresses. Fatigue calculation by simple summation of fatigue damage from each loading is not allowed as proven not conservative. As response period of TT loading, OPB loadings and IPB loadings are in the same order of magnitude, statistical damage combination methods are not applicable for combined fatigue calculation.

**4.3.2** Stresses are to be combined by proper means, by summation of time series.

As the chain link has 2 symmetry planes, four possible location of fatigue crack initiation exists on each side of the link.

Due to the symmetry planes and to the phase difference between the loadings, the loads in the four locations are anti-symmetric and combined stresses and fatigue calculation is to be performed in each of the four locations in Fig 4.

The combined stress is defined as following with the sign before OPB and IPB stress range depending on the location in the link.

$$\Delta\sigma_{combined} = Z_{corr}(\Delta\sigma_{TT} \pm Z_S\Delta\sigma_{OPB} \pm Z_S\Delta\sigma_{IPB})$$

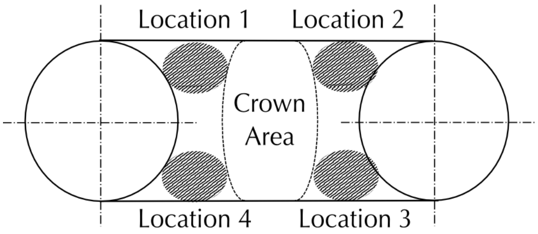
where:

$Z_{corr}$ : Defined in [4.2.2]

$Z_S$ : Defined in [3.2.1].

Note 1: Based on our experience, none of the four resulting combined stress can be discarded from the analysis.

**Figure 4 : The four anti-symmetrical fatigue failure location**



# 5 Design fatigue damage calculation

## 5.1 SN-curve

### 5.1.1 Environmental conditions to be considered

As a general matter for OPB calculations, SN curves for free corrosion in sea water are to be considered.

SN curves in air may be considered, when the FCS is positioned in air far from the splash zone, i.e. higher than:

- 110% of the relative wave elevation at mooring line location with a probability of occurrence of 5%
- 5 meters above free surface, whichever more critical.

SN curve in sea water with cathodic protection is generally not to be considered for OPB calculations. Should cathodic protection be considered in the calculation, a detailed inspection and maintenance plan with regular verification of cathodic potential in the 6 first links of the chain is to be provided for approval.

Calculations in seawater with and without cathodic protection are to be provided in order to define inspection and maintenance minimum frequency.

**Table 1 : SN curves for combined fatigue calculation**

| Environmental Case | First slope | | Second slope | | |
|---|---|---|---|---|---|
| | log $K_1$ | $m_1$ | log $K_2$ | $m_2$ | $\Delta\sigma$ at N = $10^7$ cycles |
| Seawater free corrosion | 12,436 | 3 | No second slope | | |
| Seawater under cathodic protection | 14,917 | 4 | 17,146 | 5 | 106,97 |
| Air | 15,117 | 4 | | | |
| **Note 1:** Other SN curves may be defined by the designer provided they are documented by a sufficient amount of fatigue tests. | | | | | |

#### 5.1.2 Basis SN curve

The design fatigue SN curves for OPB computations are defined as follows, with K and m parameter in Tab 1:

$$K = N\Delta\sigma^{m}_{combined}$$

Other SN curves may be defined provided they are documented by a sufficient amount of fatigue tests on the actual steel material from the same chain grade of the same manufacturer. These design SN curves have to be defined with a survival probability of 97,7% (i.e. mean SN curve minus 2 standard deviation).

## 5.2 Fatigue damage calculation

**5.2.1** Fatigue stress cycles for each seastate are to be obtained by Rainflow counting on combined stress time series.

Fatigue damage on the seastate is to be obtained by Miner sum of individual cycle damage. The individual damage for a single cycle of combined stress $d_i$ can be computed as following:

$$d_i = \frac{\Delta\sigma^{m}_{combined}}{K}$$

By applying miner sum, the damage on one seastate $d_{ss}$ is thus:

$$d_{ss} = \sum_{cycles}\frac{\Delta\sigma^{m}_{combined}}{K}$$

The computed total fatigue damage $D_{total}$ during the design life $L_D$ , in years, of the unit on the whole set of seastate with a probability of occurrence $p_{ss}$ of each seastate is obtained as follows, considering $N_{SY}$ as the number of seastate per year (equal to 2922 seastates for 3 hour long seastates):

$$D_{total} = \sum_{SeaStates} p_{ss}N_{SY}L_Dd_i$$

## 5.3 Design criteria

**5.3.1** The design service life is the duration, in years, that the unit is intended to stay on site. The combined fatigue of mooring lines top chain is to be assessed for service lives higher than 2 years when the mooring line pretensions are higher than 10% of the Minimum breaking strength of a chain of the same diameter in Oil Rig Quality (ORQ) grade.

**5.3.2** The safety factor is defined as the inverse of the maximum combined damage computed on the total service life of the unit.

**5.3.3** The minimum safety factor, for the top chain of each mooring line, is depending on the maximum slope parameter m of the SN-curve used for fatigue calculation and equal to:

- 3 for single slope free corrosion SN-curve when m = 3
- 5 for dual slope SN curve when m = 4 or m = 5, such as typical SN-curves in air and under cathodic protection.

Should part of the sensitivity analyses be omitted or less advanced computation methods such as frequency domain simulations be used for damage computation, the minimum safety factor is 10, with prior agreement by the Society.

Higher safety factors may be applied, if specified by the unit's operator or local regulations.

# APPENDIX 1 ALTERNATIVE DESIGN REQUIREMENTS

## 1 General

### 1.1 Tension-tension, in-plane bending and out-of-plane bending modes

**1.1.1** The recognized design parameters defined in this Appendix may be used for the calculation of the combined fatigue of top chain under tension-tension (TT), in-plane bending (IPB) and out-of-plane bending (OPB).

This formulation is limited to chain diameters from 84 mm to 146 mm. Out of this diameter range, the formulation is to be considered with special care and the approval by the Society is to be dealt with on a case-by-case basis.

Note 1: This range of diameters is based on the static tests performed during the considered testing programs.

Note 2: This formulation is based on tests on chain grades QR3 to QR4. The formulations can be extended to higher grades provided no limitation of the validity of this formulation has been identified by the industry.

## 2 Evaluation of stresses in mooring line

### 2.1 OPB and IPB stiffness and moments

#### 2.1.1 General

A non-linear evaluation of the interlink stiffness between the links is provided as a relationship between the interlink angle, the tension in the line and the interlink moment in OPB and in IPB.

This stiffness can be considered equal for both OPB and IPB phenomena, as both OPB and IPB phenomena are symmetrical: one link works under out-of-plane bending mode when the adjacent one works under in-plane bending mode.

The global moment of the mooring line can be derived from the interlink stiffness in OPB and IPB, providing the interlink angle of each link as a function of the tension in the line and the global angle of the mooring line with regard to the fairlead. This procedure can be performed by finite element analyses on beam models as per Sec 3, [3.3].

The OPB and IPB stresses can be derived from the interlink moments and angles in OPB and IPB for fatigue calculation as per Sec 3, [4].

#### 2.1.2 Interlink bending moment and stiffness curve

The interlink bending moment $M_i$ ($\alpha_{int}$ ,T, d), in N.mm, for both OPB and IPB, can be evaluated using the following parametric function:

$$M_i(\alpha_i, T, d) = \frac{\pi d^3}{16} C \frac{P(\alpha_{int})}{G + P(\alpha_{int})} \left(\frac{T}{0{,}14\ d^2}\right)^{a(\Delta\alpha_i)} \left(\frac{d}{100}\right)^{2a(\Delta\alpha_i) + b(\Delta\alpha_i)}$$

where:

$\alpha_{int}$ : Interlink angle, in degree

T : Mooring line tension, in kN

d : Chain diameter, in mm

$C = 354$

$G = 0{,}93$

$P(\alpha_{int}) = \alpha_{int} + 0{,}307\ \alpha_{int}^3 + 0{,}048\ \alpha_{int}^5$

$a(\alpha_{int}) = a_1 + a_2 \tanh(a_3\ \alpha_{int})$

$b(\alpha_{int}) = b_1 + b_2 \tanh(b_3\ \alpha_i nt)$

In seawater, the value of $M_i$ ($\alpha_{int}$ ,T, d) is limited by the sliding moment between links (see Sec 3, [3.1.2]).

Note 1: The Best Fit model of interlink moment using least square method developed in JIP Chain OPB can also be used.

**Table 1 : Parameters $a_1$, $a_2$, $a_3$, $b_1$, $b_2$ and $b_3$**

| | | |
|---|---|---|
| $a_1 = 0{,}439$ | $a_2 = 0{,}532$ | $a_3 = 1{,}020$ |
| $b_1 = -0{,}433$ | $b_2 = -1{,}640$ | $b_3 = 1{,}320$ |

### 2.2 OPB and IPB stresses

#### 2.2.1 Stress concentration factors for studless chains

Stress concentration factors (SCF) are based on the formulation given in Sec 3, [4].

For studless chains, the stress concentration factors for locations A (pure TT), B and B' (uniaxial OPB) and C (multiaxial OPB) are defined in Tab 2.

**Table 2 : Stress concentration factors**

| Loading mode | Location | | | |
|---|---|---|---|---|
| | A | B | B′ | C |
| TT | 4,48 | 2,08 | 1,65 | 1,04 |
| OPB | 0 | 1,06 | 1,15 | 1,21 $\gamma_{TT}$ |
| IPB | 1,25 | 0,71 | 0,66 | 1,50 |

Due to multiaxiality of stresses at location C, the mean stress effect cannot be neglected for OPB loading and a mean stress correction factor $\gamma_{TT}$ is to be introduced on multiaxial OPB SCF, as follows:

$$\gamma_{TT} = 1 + 0{,}9\left(\frac{P}{MBL} - 0{,}15\right)$$

not being less than 0,95.

Where:

P : Mooring line pretension, in kN

MBL : Mooring line breaking strength, in kN.

For studlink chain, it is recommended to perform a detailed FEM analysis under TT, OPB and IPB loading modes.

### 2.2.2 Variability of the stiffness and the stress on one cycle

The variability of the stiffness curve and thus of the stress, during an OPB/IPB cycle is to be accounted (see Sec 3, [3.2]). This stress variability can be modeled as a constant factor on the interlink stiffness curve, equal to:

$$Z_s = \exp\left(\frac{m\delta^2}{2}\right)$$

where:

m : Exponent parameter of the SN-curve

$\delta$ : Standard deviation of the ratio between the measured interlink stiffness and the modeled one.

The variability of the stiffness can be considered as a factor $Z_S$ on the interlink moment, taken equal to 1,06 in seawater free-corrosion and 1,10 in air or under cathodic protection.

### 2.2.3 Effect of the diameter

In order to account for the effect of the material thickness (chain bar diameter) on the fatigue resistance, the combined stress cycle is to be factored as follows:

$$\Delta\sigma_{factored} = \Delta\sigma_{combined}\left(\frac{d}{d_{ref}}\right)^k$$

where:

d : Chain diameter, in mm

$d_{ref}$ : Reference chain diameter equal to 84 mm

k : Thickness exponent equal to 0,15.

### 2.2.4 S-N curve

When using the methodology in App 1, the following single slope design SN curve may be used in sea water under free corrosion instead of values in Sec 3, Tab 1:

- log K = 12,575 and
- m = 3.