Fatigue of longitudinal connections under shear mode

November 2004

Rule Note
NR 515 DTM R00 E
MARINE DIVISION

GENERAL CONDITIONS

ARTICLE 1

1.1. - BUREAU VERITAS is a Society the purpose of whose Marine Division (the “Society”) is the classification (“Classification”) of any ship or vessel or structure of any type or part of it or system therein collectively hereinafter referred to as a “Unit” whether located to shore, river 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 wet 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 is 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 appraiser 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 appraiser 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 of any delay of circumstances which may affect the given appraiser or cause to modify its scope.

2.4. - The Client is to give to the Society all access and information necessary for the performance of the requested Services.

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 not a code of construction neither a guide for maintenance or a safety handbook.

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 Code of Ethics of the Members of the International Association of Classification Societies (IACS).

3.4. - The operations of the Society in providing its Services are exclusively conducted by way of its surveys and 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, respectively.

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 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 a half times the above mentioned fee.

The Society bears no liability for indirect or consequential loss such as e.g. 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 or were first known to the Client, except any claim which is not so presented shall be deemed waived and absolutely barred.

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. hereabove subject to compliance with 2.3. hereabove and Article 8 hereunder.

ARTICLE 8

8.1. - The Services of the Society, whether completed or not, involve 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 unfutile 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 Member of the International Association of Classification Societies (IACS) 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 are passed on to IACS according to the association working rules;
• the certificates, documents and information relative to the Units classed with the Society may be reviewed during IACS 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 life management plan.

ARTICLE 10

10.1. - Any delay or shortcoming in the performance of its Services by the Society arising from an event that is 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.

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.

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.

BV Mod. Ad. ME 545 | 16 February 2004
List of contents

1. INTRODUCTION 3

2. GENERAL 3
   2.1. Application 3
   2.2. Shear phenomenon 3
   2.3. Fatigue strength assessment 4

3. NOMINAL STRESS RANGE CALCULATION 4
   3.1. Nominal hull girder stress range 4
   3.2. Nominal local stress range 5
     3.2.1. Geometric parameters 5
     3.2.2. Calculation 6

4. DETERMINATION OF GEOMETRIC STRESS CONCENTRATION FACTORS 7
   4.1. Determination of stress concentration factors with FEM 7
     4.1.1. Hot spot stress location 7
     4.1.2. Hull girder geometric stress concentration factor 8
     4.1.3. Local geometric stress concentration factor 8
   4.2. Model extent 9
   4.3. Element 9

5. FATIGUE STRENGTH ASSESSMENT PROCESS 10
   5.1. Hot spot stress range 10
   5.2. Notch stress range 10
   5.3. Fatigue of welded parts 11
   5.4. Fatigue of flame-cut edges without weld 12
     5.4.1. SN curves 12
5.4.2. Mean notch stress

5.5. Fatigue damage calculation

REFERENCES

APPENDIX 1: NOMINAL LOCAL STRESS RANGE CALCULATION

APPENDIX 2: LIBRARY OF DETAILS

APPENDIX 3: EXAMPLE OF GEOMETRIC STRESS CONCENTRATION FACTORS CALCULATED WITH FEM FOR A SPECIFIC SHIP
1. INTRODUCTION

The purpose of this document is to give the methodology to assess fatigue strength of welded and non-welded connections of longitudinal ordinary stiffeners with transverse primary members under shear mode, with a simplified approach. This approach requires various calculations: nominal stress ranges, geometric stress concentration factors and the elementary damage ratios. Examples of connection details are shown in appendices.

2. GENERAL

2.1. Application

Fatigue strength assessment under shear mode is to be carried out for ordinary stiffeners connections with transverse primary members, located on side shell between 0.7TB and 1.15T, for oil tankers and FPSO more than 250 m in length.

Where:

TB = Ballast draught
T = Full load draught

2.2. Shear phenomenon

Cracks under shear mode are mainly due to both global and local phenomena:

- The bending of primary members is called hull girder phenomenon. Thus, according to beam theory, maximum shear stress appears at the neutral fibre which is usually closed to the cut out.
- The local phenomenon is due to the shear stress brought by the longitudinal under lateral pressure.

![Figure 1: Phenomenon of fatigue under shear mode](image)

Figure 1 : Phenomenon of fatigue under shear mode
2.3. Fatigue strength assessment

The fatigue strength assessment under shear mode is normally performed by use of very fine mesh with FEM analysis. However, due to the great number of connections, a simplified approach based on nominal stress ranges, allowing extrapolations may be very useful. It is then strongly recommended to recalculate the most critical details with accurate FEM. The different steps of the simplified approach are summarized below:

3. NOMINAL STRESS RANGE CALCULATION

3.1. Nominal hull girder stress range

The nominal hull girder stress range is due to the bending of the primary member. Thus, nominal stress in this case is based on the maximum principal stress in the effective section of the primary structure.

The nominal hull girder stress range, in N/mm², is to be calculated for each load case and each loading condition with the following formula:

$$\Delta \sigma_{\text{Nom}}^{\text{hg}} = \frac{h}{h'} \max \left[ \frac{\Delta \sigma_{\text{xx}} + \Delta \sigma_{\text{yy}}}{2} + \left( \frac{\Delta \sigma_{\text{xx}} - \Delta \sigma_{\text{yy}}}{2} \right)^2 + \Delta \tau_{\text{xy}}^2 \right]$$

with:

- $\Delta \sigma_{\text{Nom}}^{\text{hg}}$: Nominal hull girder stress range, in N/mm², due to hull girder shear stress in web frame
- $\Delta \tau_{\text{XY}}$: Shear stress range, in N/mm², in web frame calculated using a coarse mesh fatigue analysis.
- $\Delta \sigma_{\text{xx}}$: Compressive stress range, in N/mm², in web frame calculated using a coarse mesh fatigue analysis along the X local axis.
- $\Delta \sigma_{\text{yy}}$: Compressive stress range, in N/mm², in web frame calculated using a coarse mesh fatigue analysis along the Y local axis.
h : Web frame height, in mm (see Figure 2).

h' : Web frame height minus height of the cut out, in mm (see Figure 2 and Figure 3):

\[ h' = h - (d - v) \]

In case of opening such as manholes or lightening holes in primary members, the height of these openings should be deducted when determining h’ except if the opening is modelled in the FE model.

**Figure 2 : Definition of h and h’**

*Note*: a coarse model is a FEM with one element over the height of the web frame.

A fine mesh model, whose element size is around the value of the stiffener spacing, can also be used for determining the hull girder nominal stress but they should be considered on case by case basis. In case of double hull or double bottom they could be averaged over the distance h.

### 3.2. Nominal local stress range

#### 3.2.1. Geometric parameters

**Figure 3: definition of geometric parameters**
Dimensions of the cut-out, in mm, see Figure 3.

\[ c = \max(c_1; c_2), \]

\[ t_1: \] Thickness of the web frame, in mm, see Figure 3

\[ t_2: \] Thickness of the collar plate, in mm, see Figure 3

### 3.2.2. Calculation

The nominal local stress range, in N/mm², is to be calculated for each load case and each loading condition, depending on the side location (see Figure 3), with the following formulae:

\[
\Delta \sigma_{\text{Nom Loc Side 1}} = \frac{10^3}{u t_1} s l \left( 1 - \frac{s}{2l} \right) (1 - k) \Delta P \frac{K_2}{K_1 + K_2} \left[ \frac{3(c + 0.2d)}{2u} + \sqrt{1 + 9 \left( \frac{c + 0.2d}{4u^2} \right)^2} \right]
\]

\[
\Delta \sigma_{\text{Nom Loc Side 2}} = \frac{10^3}{v t_2} s l \left( 1 - \frac{s}{2l} \right) (1 - k) \Delta P \frac{K_1}{K_1 + K_2} \left[ \frac{3(b + 0.2d)}{2v} + \sqrt{1 + 9 \left( \frac{b + 0.2d}{4v^2} \right)^2} \right]
\]

with:

\[
K_1 = \frac{c + 0.2d}{G v t_1} + \frac{(c + 0.2d)^3}{2E t_1 u^3}
\]

\[
K_2 = \frac{b + 0.2d}{G v t_2} + \frac{(b + 0.2d)^3}{2E t_2 v^3}
\]

\[
\Delta P = \left| P_{\text{max}} - P_{\text{min}} \right|
\]

\[
P_{\text{max}}, P_{\text{min}}: \quad \text{Local lateral pressures, in N/mm², for each load case and each loading condition, cases “max” and “min”, constituted by still and dynamic local pressures.}
\]

\[
E: \quad \text{Young modulus of steel (206 000 Mpa)}
\]

\[
G: \quad \text{Coulomb modulus } G = \frac{E}{2(1 + \nu)}
\]

\[
\nu: \quad \text{Poisson coefficient } \nu = 0.3
\]

\[
s: \quad \text{Stiffeners spacing (see Figure 2), in m.}
\]
$l$ : Span, in m, of ordinary stiffeners (see Figure 4)

$k$ : Ratio of force taken by primary member stiffener, to be taken equal to 0, when there is no flat bar

4. DETERMINATION OF GEOMETRIC STRESS CONCENTRATION FACTORS

4.1. Determination of stress concentration factors with FEM

The following paragraphs give a simple methodology to calculate geometric stress concentration factors with FEM. Such factors are necessary to assess the hot spot stress range from the nominal stress range. They are calculated for the typical connection details and then, they are extrapolated to assess every details.

The simple extrapolation, as well as the way geometric stress concentration factors are calculated, enable a quick overview of the fatigue strength of every stiffener connections. It is then strongly recommended to recalculate the most critical details with FEM.

Three kinds of fine mesh model calculations are necessary to be performed. These calculations are to performed for the different loading conditions and load cases defined in BV rules, Pt B, Ch 7, sec 4.

4.1.1. Hot spot stress location

These calculations aim at locating the hot spot. Coarse mesh nodes displacements as well as coarse mesh loads are applied to the model.
4.1.2. **Hull girder geometric stress concentration factor**

These calculations aim at determining $K_g_{hg}$ of the studied detail, located at the previous hot spot location. Only coarse mesh nodes displacements are applied to the model. No pressure is applied.

To obtain $K_g_{hg}$, the stress ranges obtained from FE analysis are added, and then divided by the sum of the corresponding nominal hull girder stress ranges as follow:

$$K_g_{hg} = \frac{\sum_{i,j} \Delta \sigma_{ij,FEM_{hg}}}{\sum_{i,j} \Delta \sigma_{ij,Nomhg}}$$

where $i$ and $j$ correspond to the loading conditions and load cases.

4.1.3. **Local geometric stress concentration factor**

These calculations aim at determining $K_g_{Loc}$ of the studied detail, at the previous hot spot location. The nodes on the boundary of the model are fixed. The model is loaded with the coarse mesh pressure.

To obtain $K_g_{Loc}$, the stress ranges obtained from FE analysis are added and divided by the sum of the corresponding global nominal stress ranges:

$$K_g_{Loc} = \frac{\sum_{i,j} \Delta \sigma_{iy,FEM_{Loc}}}{\sum_{i,j} \Delta \sigma_{iy,NomLoc}}$$

where $i$ and $j$ correspond to the loading conditions and load cases.
4.2. Model extent

The models should span longitudinally at least over 4 frame spacings and vertically over 4 or 5 stiffeners, as shown on Figure 6.

![Figure 6: Extent of fine mesh model](Image)

4.3. Element

In the vicinity of the connection, element sizes are defined in accordance with BV rules, PtB, Ch7, App1, [6] and thus, they are taken between once and twice the thickness of the hot spot area. Flame cut edges are modelled with beam or rod elements whose section is equal to 0.1mm x 0.1mm. In case of hot spot in parent material, axial beam stress should be read as hot spot stress.

![Figure 7: Very fine mesh](Image)
5. FATIGUE STRENGTH ASSESSMENT PROCESS

5.1. Hot spot stress range

The hot spot stress range, in N/mm², is to be calculated for each load case and each loading condition, based on nominal stress ranges and geometric stress concentration factors, with the following formula:

\[ \Delta \sigma_{\text{Hot spot}} = K_{\text{Loc}} \Delta \sigma_{\text{Nom Loc}} + K_{\text{hg}} \Delta \sigma_{\text{Nom hg}} \]

Where:
- \( K_{\text{Loc}} \): Local geometric stress concentration factor calculated in 4.1.3
- \( \Delta \sigma_{\text{Nom Loc}} \): Nominal local stress range calculated in 3.2
- \( K_{\text{hg}} \): Hull girder geometric stress concentration factor calculated in 4.1.2
- \( \Delta \sigma_{\text{Nom hg}} \): Nominal hull girder stress range calculated in 3.1

5.2. Notch stress range

The notch stress range, in N/mm², is to be calculated for each load case and each loading condition with the following formula:

For a welded part:

\[ \Delta \sigma_{\text{Notch}} = 0.7 \cdot K_f \cdot K_{\text{overlap}} \cdot \Delta \sigma_{\text{Hotspot}} \]

For ground flame cut parts without weld:

\[ \Delta \sigma_{\text{Notch}} = K_f \cdot \Delta \sigma_{\text{Hotspot}} \]

Where:
- \( \Delta \sigma_{\text{Hotspot}} \): Hot spot stress range, calculated in 5.1
- \( K_f \): Notch coefficient, calculated according to BV rules, PtB, Ch7, Sec4, [4.3.1]. For a weld connection, \( \lambda \) is to be taken equal to the appropriate value in Table 1. In the case of ground flame cut without weld, \( K_f \) is to be taken equal to 1.4.
- \( K_{\text{overlap}} \): Overlap coefficient for collar plate. To be taken equal to 1 if overlap is modelled with FEM for the determination of geometric stress concentration factors. In this case, the welds between collar plate and web frame may be modelled by shell elements whose thickness is 1.25 times the web thickness, as shown in Figure 8. Otherwise, \( K_{\text{overlap}} \) is to be taken equal to 1.2
5.3. Fatigue of welded parts

For welded parts, the influence of compressive stress is to be considered. The correction applied on the stress range is described in BV Rules, PtB, Ch7, Sec4, [4.3.1].

The SN curve to be used is the one given in BV Rules, PtB, Ch7, Sec4.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Stress direction</th>
<th>Weld configuration</th>
<th>Not grinded weld</th>
<th>Grinded weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fillet weld</td>
<td>Continuous</td>
<td>Parallel to the weld</td>
<td></td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Perpendicular to the weld</td>
<td></td>
<td>2.15</td>
<td>1.9</td>
</tr>
<tr>
<td>Cruciform joint</td>
<td>Full penetration or partial penetration with toe cracking</td>
<td>Perpendicular to the weld</td>
<td></td>
<td>2.1</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>Partial penetration with root cracking</td>
<td></td>
<td></td>
<td>4.5</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Table 1: Coefficient $\lambda$
5.4. **Fatigue of flame-cut edges without weld**

5.4.1. **SN curves**

For flame-cut edges without weld, the influence of compressive stress is to be considered by taking into account the following SN curve, depending on the R ratio:

\[ \Delta S^m \cdot N = K \]

*with:*

\[ m = -\frac{1}{a} \]

\[ K = 0.4321 \cdot \frac{1}{b^{1/4}} \]

\[ a = -0.5 \cdot \log(\frac{546}{80 \cdot R + 230}) \]

\[ b = 546 \cdot 10^{-4 \cdot c} \]

\[ \sigma_{\text{mean}}: \text{mean notch stress, calculated in 5.4.2} \]

\[ \Delta \sigma: \text{notch stress range calculated in 5.2} \]

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

\[ \sigma_{\text{min}} = \sigma_{\text{mean}} - \frac{\Delta \sigma}{2} \]

\[ \sigma_{\text{max}} = \sigma_{\text{mean}} + \frac{\Delta \sigma}{2} \]

**Note 1:** When the maximum or minimum stress exceeds the yield strength, the correction has to be considered on case by case basis taking into account the \((\sigma, \varepsilon)\) material curve.

**Note 2:** For flame-cut edges, no correction is to be done due to the influence of plate thickness.

5.4.2. **Mean notch stress**

The mean notch stress, in N/mm², is to be calculated for each loading condition as follow:

\[ \sigma_{\text{mean}} = K_f (K_{\text{hg, loc}} \sigma_{\text{mean, loc}} + K_{\text{hg}} \sigma_{\text{mean, hg}}) \]

*Where:*

\[ K_f: \text{ Notch factor, defined in 5.2} \]

\[ K_{\text{hg, loc}}: \text{Hull girder geometric stress concentration factor calculated in 4.1.2} \]

\[ \sigma_{\text{mean, hg}}: \text{Hull girder mean stress, in N/mm², calculated based on the maximum principal stress in the effective section of the primary structure} \]

\[ K_{\text{hg}}: \text{Local geometric stress concentration factor calculated in 4.1.3} \]

\[ \sigma_{\text{mean, loc}}: \text{Local mean stress, in N/mm², calculated with the following formula:} \]

For side 1:

\[ \sigma_{\text{mean, loc, side 1}} = \frac{10^3}{u_t} \sqrt{1 - \frac{s}{2l}} (1 - k) P_s K_{z_2} \left[ \frac{3(c + 0.2d)}{2u} + \sqrt{1 + \frac{9}{4u^2} (c + 0.2d)^2} \right] \]
For side 2: \( \sigma_{\text{mean Loc Side 2}} = \frac{10^3 s l}{v t_2} \left( 1 - \frac{s}{2l} \right) (1 - k) P_s \left[ \frac{K_1}{K_1 + K_2} \left( \frac{3(b + 0.2d)}{2v} \right) \right] + \left( 1 + 9 \left( \frac{b + 0.2d}{4v} \right)^2 \right) \)

With:

- \( P_s \): Static local pressure, in N/mm², for the considered loading condition

### 5.5. Fatigue damage calculation

Elementary fatigue damage ratios are calculated for each loading condition and each load case, according to BV rules PtB, Ch7, Sec4, [3.1.1].

Elementary fatigue damage ratios are then combined according to BV rules PtB, Ch7, Sec4, [3.1.1].
REFERENCES

- Bureau Veritas Rules, edition February 2003, Pt B, Ch 7, Sec 4
- Bureau Veritas Guidance Note “Fatigue strength of welded ship structures” (Ref NI 393 DSM R01E – July 1998)
- Formulas for stress and strain, 5th edition, 7.10, p185 (Raymond J. Roark & Warren C. Young)
- Formulas of the engineer, Third part, chapter I p 418
- Review of Fatigue Assessment of FPSO Schiehallion, S.Madox, Report 14598/1/03 May 2003
APPENDIX 1: NOMINAL LOCAL STRESS RANGE CALCULATION

The behaviour of the longitudinal stiffener connection with the web frame, with or without collar plate and under local pressure, is to be modelled with an analytic function. The main geometric characteristics of the cut out and collar plate have to be taken into account.

One part of the shear force coming from the ordinary stiffener goes directly to the web frame. If there is a collar plate, the other part goes into it.

Thus two nominal local stress ranges may be considered: one for the web frame side (side1) and one for the collar plate side (side2), as shown on Figure 9.

![Figure 9: Nominal local stress range](image)

The detail shown in Figure 9 may be considered as a beam, fixed at ends and punctually loaded (see Figure 10, with a change of inertia (web frame/collar plate) at x =c with c = max(c1;c2) and guided at x=c.

![Figure 10](image)
The resulting deflection is composed about flexural deflection and shear deflection. Usually in straight beam theory shear deflection is negligible. For beams of relatively great depth (small span/depth ratio) shear stresses are likely to be high and the resulting deflection due to shear may be not negligible.

Thus at \( x = c \) the resulting deflection \( \delta \), in mm, is:

\[
\delta = \delta_f + \delta_s
\]

with

\( \delta_f \) = Flexural deflection, in mm

\( \delta_s \) = Shear deflection, in mm

at \( x = c \), the following equality between the deflection of the web frame side (1) and the collar plate side (2) may be written:

\[
\delta_1 = \delta_2
\]

\[
\delta_{f1} + \delta_{s1} = \delta_{f2} + \delta_{s2}
\]

\[
\frac{\Delta T_1 c}{Gut_1} + \frac{\Delta T_1 c^3}{24EI_1} = \frac{\Delta T_2 b}{Gtv_2} + \frac{\Delta T_2 b^3}{24EI_2}
\]

\[
\Delta T_1 \left( \frac{c}{Gut_1} + \frac{c^3}{24EI_1} \right) = \Delta T_2 \left( \frac{b}{Gtv_2} + \frac{b^3}{24EI_2} \right)
\]

\[
\Delta T_1 K_1 = \Delta T_2 K_2
\]

where:

\( \Delta T_1, \Delta T_2 \) : Shear force ranges, in N, at \( x = c \), respectively at the web frame side (1) and at the collar-plate side (2)

\( I_1, I_2 \) : Moments of inertia of the beams, in \( \text{mm}^4 \), respectively fixed in A and B

thus

\[
\Delta T_1 = \Delta T \frac{K_2}{K_1 + K_2}
\]

\[
\Delta T_2 = \Delta T \frac{K_1}{K_1 + K_2}
\]

\( \Delta T \) : Total shear force range, in N, equal to \( \Delta T_1 + \Delta T_2 \), also equal to

\[
10^3 sl \left( 1 - \frac{s}{2f} \right) (1-k) \Delta P , \text{ according to BV rules edition Feb 2003, PtB, Ch12, Sec1, [2.3.8]}
\]
The values of the shear stresses on both sides, are obtained as follow:

\[
\Delta \tau_1 = \frac{\Delta T}{ut_1} \frac{K_2}{K_1 + K_2}
\]

\[
\Delta \tau_2 = \frac{\Delta T}{vt_2} \frac{K_1}{K_1 + K_2}
\]

The value of the maximum flexural stress is evaluated, using straight beam theory at \(x=0\) and \(x=b+c\) as a function of shear stress:

\[
\Delta \sigma_1 = \frac{\Delta M_{x=0}}{I_1 \frac{2}{u}} = \frac{\Delta \tau_1 ut_1 \frac{c}{2}}{\frac{t_1 u^3}{12} \frac{2}{u}} = 3 \Delta \tau_1 \frac{c}{u}
\]

\[
\Delta \sigma_2 = \frac{\Delta M_{x=b+c}}{I_2 \frac{2}{v}} = \frac{\Delta \tau_2 vt_2 \frac{b}{2}}{\frac{t_2 v^3}{12} \frac{2}{v}} = 3 \Delta \tau_2 \frac{b}{v}
\]

The expression of the nominal local principal stress ranges are finally, at \(x=0\) and \(x=b+c\):

\[
\Delta \sigma_{\text{Nom,Loc Side 1}} = \frac{\sigma_1}{2} + \sqrt{\frac{\sigma_1^2}{4} + \Delta \tau_1^2} = \Delta \tau_1 \left[ \frac{3c}{2u} + \sqrt{1 + \frac{9c^2}{4u^2}} \right]
\]

\[
\Delta \sigma_{\text{Nom,Loc Side 2}} = \frac{\sigma_2}{2} + \sqrt{\frac{\sigma_2^2}{4} + \Delta \tau_2^2} = \Delta \tau_2 \left[ \frac{3b}{2v} + \sqrt{1 + \frac{9b^2}{4v^2}} \right]
\]

Which may be finally written as follow:

\[
\Delta \sigma_{\text{Nom,Loc Side 1}} = \frac{10^3}{ut_1} s f \left(1 - \frac{s}{2l}\right) (1-k) \Delta P \frac{K_2}{K_1 + K_2} \left[ \frac{3c}{2u} + \sqrt{1 + \frac{9c^2}{4u^2}} \right]
\]

\[
\Delta \sigma_{\text{Nom,Loc Side 2}} = \frac{10^3}{vt_2} s f \left(1 - \frac{s}{2l}\right) (1-k) \Delta P \frac{K_1}{K_1 + K_2} \left[ \frac{3b}{2v} + \sqrt{1 + \frac{9b^2}{4v^2}} \right]
\]

With:

\[
K_1 = \frac{c + 0.2d}{Gut_1} + \frac{c^3}{2Et_1u^5}
\]

\[
K_2 = \frac{b + 0.2d}{Gvt_2} + \frac{b^3}{2Et_2v^3}
\]
The calculation relies on the assumption that the span of the equivalent beam is \( b+c \). A verification made with a FEM calculation shows that it is more correct to replace \( b \) by \( b+w \) and \( c \) by \( c+w \) and then to take \( w = 0.2d \) where \( d \) is the cut out depth. Thus the nominal stress ranges become:

\[
\Delta\sigma_{\text{Nom, loc side 1}} = \frac{10^3}{u_1} s \left( 1 - \frac{s}{2l} \right)(1-k) \Delta P \left( \frac{K_2}{K_1 + K_2} \right) \left[ \frac{3(c + 0.2d)}{2u} + \sqrt{1 + \frac{9(c + 0.2d)^2}{4u^2}} \right]
\]

\[
\Delta\sigma_{\text{Nom, loc side 2}} = \frac{10^3}{v_2} s \left( 1 - \frac{s}{2l} \right)(1-k) \Delta P \left( \frac{K_1}{K_1 + K_2} \right) \left[ \frac{3(b + 0.2d)}{2v} + \sqrt{1 + \frac{9(b + 0.2d)^2}{4v^2}} \right]
\]

with:

\[
K_1 = \frac{c + 0.2d}{Gv_t_1} + \frac{(c + 0.2d)^3}{2Et_u^3}
\]

\[
K_2 = \frac{b + 0.2d}{Gv_t_2} + \frac{(b + 0.2d)^3}{2Et_v^3}
\]

\[
\Delta P = |P_{\text{max}} - P_{\text{min}}|
\]

\( P_{\text{max}}, P_{\text{min}} \): Local lateral pressures, in N/mm², for each load case and each loading condition, cases “max” and “min”, constituted by still and dynamic local pressures.

\( E \): Young modulus of steel (206 000 Mpa)

\( G \): Coulomb modulus \( G = \frac{E}{2(1 + \nu)} \)

\( \nu \): Poisson coefficient \( \nu = 0.3 \)

\( b, c_1, c_2, d, u, v \): Main dimensions, in mm, of the cut-out shown in Figure 9.

\( c = \max(c_1; c_2) \),

\( s \): Stiffeners spacing (see Figure 2), in m.

\( l \): Span, in m, of ordinary stiffeners, defined in 3.2.2

\( k \): Ratio of force taken by primary member stiffener, to be taken equal to 0 where there is no flat bar

\( t_1 \): Thickness of the web frame, in mm, see Figure 9

\( t_2 \): Thickness of the collar plate, in mm, see Figure 9
APPENDIX 2: LIBRARY OF DETAILS

- Collar

- Slot
• No collar

Side 1

\[ c = \max(c_1, c_2) \]

Side 2

• Full collar

Side 1

\[ c = \max(c_1, c_2) \]

Side 2
• Full slot

Side 1

\[ \text{c}_1 \]

\[ u \]

\[ t_1 \]

\[ d \]

\[ b \]

Side 2

• Watertight

Side 1

\[ u \]

\[ t_1 \]

Side 2
## APPENDIX 3: EXAMPLE OF GEOMETRIC STRESS CONCENTRATION FACTORS CALCULATED WITH FEM FOR A SPECIFIC SHIP

<table>
<thead>
<tr>
<th>Detail</th>
<th>Collar</th>
<th>Slot</th>
<th>No Collar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="HS1.png" alt="Diagram 1" /></td>
<td><img src="HS2.png" alt="Diagram 2" /></td>
<td><img src="HS1.png" alt="Diagram 3" /></td>
</tr>
<tr>
<td>Kg$_{hg1}$</td>
<td>1.24</td>
<td>1.30</td>
<td>1.76</td>
</tr>
<tr>
<td>Kg$_{hg2}$</td>
<td>1.69</td>
<td>1.74</td>
<td>1.27</td>
</tr>
<tr>
<td>Kg$_{Loc1}$</td>
<td>1.51</td>
<td>1.93</td>
<td>1.51</td>
</tr>
<tr>
<td>Kg$_{Loc2}$</td>
<td>1.97</td>
<td>1.26</td>
<td>0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detail</th>
<th>Full Collar</th>
<th>Full Slot</th>
<th>Watertight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="HS1.png" alt="Diagram 4" /></td>
<td><img src="HS2.png" alt="Diagram 5" /></td>
<td><img src="HS1.png" alt="Diagram 6" /></td>
</tr>
<tr>
<td>Kg$_{hg1}$</td>
<td>1.22</td>
<td>1.34</td>
<td>***</td>
</tr>
<tr>
<td>Kg$_{hg2}$</td>
<td>1.69</td>
<td>1.18</td>
<td>1.32</td>
</tr>
<tr>
<td>Kg$_{Loc1}$</td>
<td>1.51</td>
<td>2.45</td>
<td>***</td>
</tr>
<tr>
<td>Kg$_{Loc2}$</td>
<td>2.25</td>
<td>1.04</td>
<td>1.42</td>
</tr>
</tbody>
</table>