Section 1: LR Design S-N Curves

1.1 FDA Level 3 procedures adopt a hot spot stress approach in conjunction with the Palmgren-Miner cumulative damage rule to determine the fatigue damage of structural details. The hot spot stress reference mean and design S-N curves in air for conventional steel are defined as follows:

\[
\log N = \log K_{hs} - m' \log (\Delta S)
\]

where
- \( N \) is the number of cycles to failure at stress range \( \Delta S \)
- \( \log K_{hs} \) is the intercept of the hot spot stress S-N curve on with the log N-axis
- \( \Delta S \) is the hot spot stress range obtained using the FE analysis procedure described in Ch 6, including any additional stress concentration factors from Section 3.2
- \( m' \) is the negative slope of the hot spot stress S-N curve

The hot spot stress S-N curves for other steels and materials are to be specially considered.

1.2 The hot spot stress reference design S-N curves used for the fatigue assessment represent two standard deviations below the mean curve, which corresponds to a 97.5 per cent probability of survival.

1.3 The hot spot stress reference S-N curves for weld toes represents the fatigue strength of the welded material in air, including the weld geometrical stress concentration due to the local notch at the weld toe, if applicable, but it does not include stress concentration factor due to gross geometry.

1.4 The reference hot spot stress S-N curves are consists of two slopes S-N curves modified as per the Haibach correction at the 10^7 stress cycle, with the values of the inverse slopes, \( m' \), are defined in Table 7.1.1.

1.5 The reference mean S-N curve applicable for fillet weld, for normal or high strength steel, is defined with a stress range of 75,62 N/mm^2 at 10^7 stress cycles.

1.6 The reference mean S-N curve applicable for flame cut edge, for normal or high strength steel, is defined with a stress range of 102,22 N/mm^2 at 10^7 stress cycles.

1.7 The parameters of the hot spot stress reference S-N curves in air are summarised in Table 7.1.1.

<table>
<thead>
<tr>
<th>Table 7.1.1 Hot spot stress reference S-N Curves Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \log K_{hs} )</td>
</tr>
<tr>
<td>Mean curve</td>
</tr>
<tr>
<td>Fillet weld</td>
</tr>
<tr>
<td>Free edge</td>
</tr>
</tbody>
</table>

1.6 Where a weld connection or structural detail is located in a wet, high humidity or corrosive environment, the fatigue life is to be determined by the hot spot stress reference S-N curves in air with the following correction applied:

\[
FL_{\text{corrected}} = T_c + f \cdot (FL_{\text{air}} - T_c) \quad \text{for} \quad FL_{\text{air}} > T_c
\]

\[
FL_{\text{corrected}} = FL_{\text{air}} \quad \text{for} \quad FL_{\text{air}} \leq T_c
\]

where
- \( FL_{\text{corrected}} \) is the fatigue life corrected for the corrosive effect in wet or high humidity environment
- \( FL_{\text{air}} \) is the fatigue life in air calculated using the hot spot stress reference design S-N curves in air
- \( T_c \) is the effective life of the applied coating, \( T_c \) is to be taken as zero if no coating is applied
- \( f \) is the fatigue life reduction factor for operational environment, see Table 7.1.2
Table 7.1.1  Hot spot stress reference S-N curve parameters

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Log ($K_{hs}$)</th>
<th>$m'$ $N \leq 10^7$</th>
<th>$m'$ $N &gt; 10^7$</th>
<th>Stress range $\Delta S_o$, N/mm$^2$ at $10^7$ cycles</th>
<th>Standard deviation of log $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free edge$^1$</td>
<td>A and D for all yield stress$^{(3)}$, E$^{(3)}$, EH27$^{(4)}$</td>
<td>14,03</td>
<td>13,64</td>
<td>3.5</td>
<td>5.5</td>
</tr>
<tr>
<td>A &amp; D for all yield stress$^{(3)}$, E$^{(3)}$, EH27$^{(4)}$</td>
<td>15,29</td>
<td>14,89</td>
<td>4</td>
<td>6</td>
<td>117,87</td>
</tr>
<tr>
<td>EH32 and FH32$^{(2)}$</td>
<td>15,18</td>
<td>14,78</td>
<td>4</td>
<td>6</td>
<td>111,12</td>
</tr>
<tr>
<td>EH36 and FH36$^{(2)}$</td>
<td>15,38</td>
<td>14,98</td>
<td>4</td>
<td>6</td>
<td>124,46</td>
</tr>
<tr>
<td>EH36 and FH36$^{(4)}$</td>
<td>15,28</td>
<td>14,88</td>
<td>4</td>
<td>6</td>
<td>117,71</td>
</tr>
<tr>
<td>EH40 and FH40$^{(2)}$</td>
<td>15,53</td>
<td>15,13</td>
<td>4</td>
<td>6</td>
<td>135,68</td>
</tr>
<tr>
<td>EH40 and FH40$^{(4)}$</td>
<td>15,33</td>
<td>14,93</td>
<td>4</td>
<td>6</td>
<td>121,14</td>
</tr>
<tr>
<td>Weld toes$^{(2)}$</td>
<td>All grades</td>
<td>12,64</td>
<td>12,19</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

NOTES
1. Applicable to plates which are free from weld butts & seams and any other weld attachment.
2. Applicable to the toe region of all weld types. For partial penetration welds and fillet welds; weld size is to be such that the possibility of crack initiation from the weld root rather than the weld toe is eliminated. In principle for welds that comply with the requirements given in the Rules for Ships and have not been subjected to weld improvement methods, consideration of root cracking is not required. Where weld improvement is planned, full penetration welds or increased weld throats are to be used to eliminate the possibility of cracking at the weld root.
3. Any cutting of edges by machine flame cutting with a controlled procedure.
4. Applicable to cut edges of plate with thickness up to 100 mm. All visible defects, such as drag lines, should be removed from the flame cut edges by grinding or machining. Any flame cut edges are to be subsequently machined or ground smooth. Where the corners of the plate are removed in accordance with Lloyd’s Register’s, ShipRight Fatigue Design Assessment – Level 3 Procedure, Ch 2.2.4.3, the additional fatigue life improvement factor as specified in the ShipRight Fatigue Design Assessment – Level 3 Procedure, Table 2.4.5 in Chapter 2, can be applied.

The hot spot stress S-N curves are only applicable for the calculation of fatigue damage due to the action of 1st order wave induced loads, except where permitted by Lloyd's Register procedures.

Table 7.1.2  Fatigue life reduction factors for operational environment

<table>
<thead>
<tr>
<th>Surfaces/spaces</th>
<th>$f$ factor, see 1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water ballast tank</td>
<td>0.5</td>
</tr>
<tr>
<td>Fresh water tank</td>
<td>0.5</td>
</tr>
<tr>
<td>Crude oil tank</td>
<td>0.67</td>
</tr>
<tr>
<td>Hold carrying high sulphur cargo (e.g. coal)</td>
<td>0.5</td>
</tr>
<tr>
<td>Hold space with independent tanks, such as LNG and LPG tanks</td>
<td>1.0</td>
</tr>
<tr>
<td>Ship structure within hold space of membrane LNG ship</td>
<td>1.0</td>
</tr>
<tr>
<td>Container hold</td>
<td>1.0</td>
</tr>
<tr>
<td>Fuel oil tank</td>
<td>1.0</td>
</tr>
<tr>
<td>Surface exposed to weather</td>
<td>1.0</td>
</tr>
</tbody>
</table>

NOTE
The value of $f$ is to be specially considered for corrosive environments not listed in the Table.
Section 2: Additional Stress Concentration Factors

2.1 General

2.1.1 Where appropriate, additional stress concentration factors to account for construction tolerances and plate thickness effects may be applied. The following Sections are provided for information purposes only. Application of any additional stress concentration factors is to be done in consultation with Lloyd’s Register Research and Development Department.

2.2 Plate thickness effect

2.2.1 Plate thickness primarily influences the fatigue strength of welded joints through the effect of geometry, and through-thickness stress distribution. The stress concentration factor, \( K_T \), for plate thickness effects may be taken as:

\[
K_T = \begin{cases} 
1,0 & \text{for } t \leq 22 \text{ mm} \\
1 - \frac{1}{n} \left( \frac{t}{22} \right) & \text{for } t > 22 \text{ mm}
\end{cases}
\]

For \( t \leq 22 \text{ mm} \), \( K_T = 1,0 \)

For \( t > 22 \text{ mm} \), \( K_T = \frac{1}{n} \left( \frac{22}{t} \right) \)

where

- \( t \) = thickness of the plate member where the crack is likely to initiate,
- \( t_1 \) = thickness of the member where the crack is likely to initiate
- \( n \) = thickness exponent provided in Table 7.2.1

2.3 Weld flank angle

2.3.1 The normalised weld stress concentration factor, \( K_W \), for a fillet weld may be taken as:

\[
K_W = \begin{cases} 
0,7304 \left( \frac{\theta}{30} \right) & \text{for } 1 \leq \theta < 30 \\
0,785 \left( \frac{\theta}{30} \right) & \text{for } \theta \geq 30
\end{cases}
\]

where

- \( \theta \) = average weld flank angle, not to be taken as less than 30° for calculation purposes. If a weld flank angle of less than 30° is used in the calculations, the weld flank angle used is to be shown on the CM plan and the weld flank angle is to be verified during survey.

2.4 Undercut

2.4.1 The maximum acceptable undercut depth in any thickness of material is 1 mm. The maximum acceptable SN value (stress range at 10^7 stress cycle), \( SN_\mu \), for a fillet weld with an undercut depth to plate thickness ratio, \( \mu \), may be taken as the lesser of 75,625 and:

\[
SN_\mu = 75,625 \left( 1.451 - 25.925\mu + 306.964\mu^2 - 1387.887\mu^3 \right)
\]

2.5 Misalignment

2.5.1 Stress concentrations arising from the effect of misalignment is not explicitly accounted for in the FDA Level 3 finite element analysis procedures, where median procedures, Median line alignment is assumed.

2.5.2 Existing procedures, such as those suggested in BSI PD6493 [Ref 8] which account for the stress increase due to axial and angular misalignment, are primarily applicable to simple cruciform joints. For complex cruciform joints, such as a welded hopper knuckle connection, additional finite element analysis will need to be performed to determine the additional stress increase due to misalignment.
2.5.3 In general, two-dimensional finite element models may be used to obtain the hotspot stress where the infinite extent assumption can be justified, for example, the welded hopper knuckle connection away from the web floor. Otherwise, three-dimensional finite element models with solid elements are to be used.

2.5.4 The structural detail is to have two independent models, one with a perfect alignment and with the other with the misalignment. Misalignment is to be individually modelled. The additional stress concentration factor is to be obtained calculated as the ratios of the hot spot stress with the misalignment to that with a perfect alignment, results from the misaligned model to the perfect alignment model. Dominant loading modes, which are considered to have a significant contribution to the fatigue damage, are to be investigated. It is not necessary to carry out such investigations for structural details which comply with the fit up criteria contained in Lloyd’s Register’s Construction Monitoring procedure.

2.5.5 The procedure for deriving the additional stress concentration factors is to be submitted for approval by Lloyd’s Register.

Table 7.2.1 Exponent for thickness correction

<table>
<thead>
<tr>
<th>Joint category</th>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruciform joints, transverse T-joints, plates with transverse and longitudinal attachments</td>
<td>as-welded</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>toe ground</td>
<td>0.2</td>
</tr>
<tr>
<td>Transverse butt welds</td>
<td>as-welded</td>
<td>0.2</td>
</tr>
<tr>
<td>Transverse butt welds ground flush</td>
<td>any</td>
<td>0.1</td>
</tr>
<tr>
<td>Cut edges of non-welded material (see Table 7.1.1, Notes 3 and 4)</td>
<td>any</td>
<td>0.1</td>
</tr>
<tr>
<td>Longitudinal welds</td>
<td>any</td>
<td>0.1</td>
</tr>
<tr>
<td>Stiffener end connections</td>
<td>$t_1 \leq 0.75 \cdot t_2$</td>
<td>any</td>
</tr>
<tr>
<td></td>
<td>$t_1 &gt; 0.75 \cdot t_2$</td>
<td>Any</td>
</tr>
</tbody>
</table>

Section 3: Fabrication Stage Improvement

3.1 Fabrication stage improvement, such as grinding, thermal stress relief, dressing and peening of weld toes, may be applied to enhance the fatigue strength of structural details. The application of fabrication stage improvement methods and the achievable degree of improvement in fatigue strength are explained in Ch 2.2.4 of Lloyd’s Register’s, ShipRight Fatigue Design Assessment, Level 1 Procedure, Structural Detail Design Guide.

3.2 Fabrication stage improvement methods should usually be considered as remedial measures, and are to be subjected to strict quality control procedures. The operational environment and inspection regime should be considered which can reduce the effectiveness of the improvement over time.
3.3 The calculated fatigue life of any welded structural detail at the design stage, prior to applying any fabrication stage improvement methods, must not be less than 20 years for all trading routes considered.

3.4 For plate free edge where the required fatigue design life cannot be achieved practically after consideration of all design options, fabrication improvement may be applied provided that the calculated fatigue life at the design stage, excluding the fabrication improvement, is not less than 17 years for all trading routes considered.

3.5 The quantitative improvement in the fatigue life by the application of any fabrication stage improvement methods should be agreed with Lloyd’s Register.

3.6 Where a fabrication stage improvement method is planned at the design stage, it is to be specially considered by Lloyd’s Register and subjected to enhanced survey procedures to ensure that a consistent level of fatigue strength improvement is achieved.

3.7 The use of improvement methods should be considered in association with the Construction Monitoring (CM) procedure to ensure that the benefits to be gained by the use of the improvement method are achieved. Adequate inspections are to be carried out.

3.8 Where a fabrication stage improvement method is used as a means to achieve the required design fatigue life of a structural detail, the improved fatigue life is to be calculated in accordance with Table 2.4.6 in Chapter 2, of ShipRight Fatigue Design Assessment – Level 1 Procedure.