13. Lamellar tearing

13.1 Description of lamellar tearing

Lamellar tearing can occur beneath the weld especially in rolled steel plate, which has poor through-thickness ductility. The characteristic features, principal causes and best practice in minimising the risk of lamellar tearing are described. Finally, some design examples on steel quality chosen are given.

![Fig. 1. BP Forties platform lamellar tears were produced when attempting the repair of lack of root penetration in a brace weld.](image)

Lamellar tearing is a cracking phenomenon, which occurs beneath welds, and is principally found in rolled steel plate fabrications. The tearings always lies within the parent plate, often outside the transformed (visible) heat-affected zone (HAZ), and is generally parallel to the weld fusion boundary.

![Fig. 2. Schematic view and some examples on lamellar tearing.](image)

For tearing to occur, three conditions must be satisfied:

- **Strains must be developing in the short transverse direction of the plate.** These strains arise from external loads (load distribution) and/or from weld metal shrinkage in the joint, which can be greatly increased by strains developed from reaction with other joints in restrained structures.
- **The weld orientation must be such that the strains act through the joint across the plate thickness, i.e. the fusion boundary is roughly parallel to the plate surface.**
- **The material must be susceptible to tearing,** e.g. in figure 3 shown the horizontal plate must have poor ductility in the short transverse (through thickness) direction so-called occurrence of poor short transverse (ST) ductility.

![Fig. 3. Appearance of fracture face of lamellar tear.](image)

Thus, the risk of lamellar tearing will be greater if the stresses generated on welding act in the through-thickness direction. The risk will also increase the higher the level of weld metal hydrogen. As lamellar tearing is associated with a high concentration of elongated inclusions oriented parallel to the surface of the plate, tearing will be transgranular with a stepped appearance.

13.2 Lamellar tearing characteristics

Lamellar tearing occurs at certain critical joints usually within large welded structures involving a high degree of stiffness and restraint. Restraint may be defined as a restriction of the movement of the various joint components that would normally occur as a result of expansion and contraction of weld metal and adjacent regions during
welding. The following points characterize tearing and enable it to be distinguished from other forms of cracking:

- In section it has a stepped appearance with long horizontal portions and sort vertical steps
- It often lies just outside the visible HAZ, parallel to the weld fusion boundary and the plate surface
- It can be completely subsurface and difficult to detect even using non-destructive methods
- The surfaces of the cracks are fibrous, woody and characteristic of low ductility fractures
- It is not often associated with hydrogen-induced HAZ cracking and may well occur even when adequate precautions against hydrogen-induced cracking have been taken

**Fig. 4. Fracture face.**

Metallography
The main reason for low ST ductility lies in the inclusion content of the plate. All the steels in common use in structural and pressure vessel applications contain considerable number of inclusions, mainly of the manganese sulfide, manganese silicate, and oxide types.

The inclusion content of as-cast steel depends on numerous factors such as the type of steel, deoxidization practice, composition, position in the ingot, etc. The inclusions are usually formed as spheres, eutectic films, of small angular particles in the solidifying ingot.

When the ingot is rolled to form steel plate, the inclusions deform into plates or discs parallel to the plate surface. Different types of inclusions deform to different degrees relative to the steel matrix and some may fragment during rolling.

High concentrations of elongated and/or fragmented inclusions seen here on a fracture surface are responsible for poor ST ductility and the incidence of lamellar tearing in steels.

It’s important to understand that only a small percentage of steel plates are susceptible to tearing, even though all steel contain deformed inclusions. Only in certain plates are the concentrations of inclusions, couples with unfavorable shape and type, sufficient to give a risk of tearing. Also, of the potentially susceptible steel plates, only a further small percentage is incorporated into the critical joints and structures that satisfy the other two conditions (transverse strains and weld orientation) necessary for lamellar tearing to occur.

### 13.3 Factors to be considered to reduce the risk of tearing
The choice of material, joint design incl. restraining condition, welding process, consumables, preheating and welding technique can all help reduce the risk of tearing.

**Material**
Tearing is only encountered in rolled steel plate and not forgings and castings. There is no one grade of steel that is more prone to lamellar tearing but steels with a low Short Transverse Reduction in Area (STRA) will be susceptible. As a general rule, steels with STRA over 20% are essentially resistant to tearing whereas steels with below 10 to 15% STRA should only be used in lightly restrained joints.

**Fig. 5. Relationship between the STRA and sulphur content for 12.5 to 50 mm thick plate.**
Steels with a higher strength have a greater risk especially when the thickness is greater than 25mm. Aluminium treated steels with low sulphur contents (<0.005%) will have a low risk. Steel suppliers can provide plate, which has been through-thickness, tested with a guaranteed STRA value of over 20%.

**Joint design incl. restraining condition**

Lamellar tearing occurs in joints producing high through-thickness strain, e.g. T joints or corner joints. In T or cruciform joints, full penetration butt welds will be particularly susceptible. The cruciform structures in which the susceptible plate cannot bend during welding will also greatly increase the risk of tearing. Restraint may be defined as a restriction of the movement of the various joint components that would normally occur as a result of expansion and contraction of the weld metal and adjacent regions during welding. Some major types of structures commonly associated with the problem are:

- **Stiffeners or end closure plates in cylindrical structures.**
- **Stiffened joints and box structures.**
- **Flange to web joints in fabricated I-beams.**

**Fig. 6. Major types of structures associated with lamellar tearing.**

In butt joints, as the stresses on welding do not act through the thickness of the plate, there is little risk of lamellar tearing. As angular distortion can increase the strain in the weld root and or toe, tearing may also occur in thick section joints where the bending restraint is high. Most fabricators have experienced tearing in plates in the range 12-60 mm in thickness, but the majority of these feel that there are few problems with plates below 25 mm in thickness.

Several examples of good practice in the design of welded joints are illustrated.

As tearing is more likely to occur in full penetration T butt joints, if possible, use two fillet welds.

Double-sided welds are less susceptible than large single-sided welds and balanced welding to reduce the stresses will further reduce the risk of tearing especially in the root. This is only a marginal improvement mainly caused by reducing the volume of the weld material and balancing the strains.

Large single-side fillet welds should be replaced with smaller double-sided fillet welds. This because balanced double-sided welds appear to present less risk than large single side-welds.

Corner joints are common in the single-sided form in box sections, etc. and the double form in more complex fabrications. Redesigning the joint configuration so that the fusion boundary is more normal to the susceptible plate surface will be particularly effective in reducing the risk.
Lamellar tearing is more likely to occur in large welds typically when the leg length in fillet and T butt joints is greater than 20mm. As restraint will contribute to the problem, thinner section plate, which is less susceptible to tearing, may still be at risk in high restraint situations.

**Welding process**
As the material and joint design are the primary causes of tearing, the choice of welding process has only a relatively small influence on the risk. However, higher heat input processes that generate lower stresses through the larger HAZ and deeper weld penetration can be beneficial.

As weld metal hydrogen will increase the risk of tearing, a low hydrogen process should be used when welding susceptible steels.

**Consumable**
Where possible, the choice of a lower strength consumable can often reduce the risk by accommodating more of the strain in the weld metal. A smaller diameter electrode, which can be used to produce a smaller leg length, has been used to prevent tearing.

A low hydrogen consumable will reduce the risk by reducing the level of weld metal diffusible hydrogen. The consumables must be dried in accordance with the manufacturer's recommendations.

**Preheating**
Preheating will have a beneficial effect in reducing the level of weld metal diffusible hydrogen. However, it should be noted that in a restrained joint, excessive preheating could have a detrimental effect by increasing the level the level of restraint produced by the contraction across the weld on cooling. Preheating should, therefore, be used to reduce the hydrogen level but it should be applied so that it will not increase the amount of contraction across the weld.

**Welding techniques**
A number of welding techniques can be applied as precautionary measures in order to minimise the risk of tearing:

**Buttering**
Buttering the surface of the susceptible plate with a low strength weld metal has been widely employed. As shown for the example of a T butt weld the surface of the plate may be grooved so that the buttered layer will extend 15 to 25mm beyond each weld toe and be about 5 to 10mm thick.

![Buttering with low strength weld metal.](image)
*Fig. 7. Buttering with low strength weld metal.*
*Left: general deposit on the surface of the susceptible plate.*
*Right: in-situ buttering.*

In-situ buttering i.e. where the low strength weld metal is deposited first on the susceptible plate before filling the joint, has also been successfully applied. However, before adopting this technique, design calculations should be carried out to ensure that the overall weld strength would be acceptable.

**Balanced welding**
In T butt welds made with susceptible plate lamellar filling up the two welds can occasionally prevent tearing initiating from the weld root in a symmetrical manner, depositing several runs in one weld.

**Peening**
Peening weld runs at intermediate stages during welding has been attempted in order to lower residual stresses and lessen the risk of tearing. No real measure of success can be claimed.

**Intermediate stress relief**
Several fabricators have attempted reduction of residual stresses by thermal means. This has not been particularly successful, probably because the thermal treatment by itself can increase the incidence of defect indications seen by ultrasonic techniques.
Detection and remedial action
If surface-breaking, lamellar tears can be readily detected using visual examination, liquid penetrate or magnetic particle testing techniques. Internal cracks require ultrasonic examination techniques but there may be problems in distinguishing lamellar tears from inclusion bands. The orientation of the tears normally makes them almost impossible to detect by radiography.

In-situ buttering ie where the low strength weld metal is deposited first on the susceptible plate before filling the joint, has also been successfully applied. However, before adopting this technique, design calculations should be carried out to ensure that the overall weld strength would be acceptable

13.4 Acceptance standards
The rules given in prEN 1993-1-10 “Eurocode 3: design of steel structures: part 1.10 selection of materials for fracture toughness and through-thickness properties” are for the determination of whether steel products with improved deformation properties perpendicular to the surface of the steel product are necessary in order to avoid lamellar tearing in a particular application. The suitability of the material should be based on the through-thickness ductility to EN 10164, which is expressed in terms of quality classes identified by Z-values representing the percentage short transverse reduction of area (STRA) in a tensile test.

The STRA-value (Z in %) given by EN 10002-1:1990 is defined as:

\[
\frac{(S_o - S_u)}{S_o} * 100
\]

with

\[
S_o = \text{cross section original area;}
\]

\[
S_u = \text{cross section after failure.}
\]

The code NEN-EN 10164 “Steel products with improved deformation properties perpendicular to the surface of the product; Technical delivery conditions” specifies three Z-classes, namely Z15, Z25 and Z35. As an example: Steel EN 10113-2 S355N + EN 10164 – Z35

The suitability of the material for through thickness-requirements should be based on the through-thickness ductility quality criterion to EN 10164, which is expressed in terms of quality classes identified by Z-values.

Limit State equation
The Limit State of lamellar tearing is expressed by the following formula

\[
\frac{Z_{Sd}}{Z_{Rd}} \leq 1.0
\]

where

\[
Z_{Sd} = \text{the design value of the Z-requirement from the magnitude of strains from restrained metal shrinkage under the weld beads.}
\]

\[
Z_{Rd} = \text{the design value of the material capacity to avoid lamellar tearing expressed by the Z-classes for material according to EN 10164.}
\]

The local straining which may exhaust the ductility of the material depends on the following influences

a. effective weld depth between through plate and incoming plate
b. shape and position of weld, weld bead sequence
c. effect of material thickness of the through plate
d. remote restraint of shrinkage from welding due to stiffness of other portions of the structure
e. influence of preheating

The requirement \(Z_{Sd}\) has been allocated to the influences \(a\) to \(e\) in the form

\[
Z_{Sd} = Z_a + Z_b + Z_c + Z_d + Z_e
\]

using partial requirements \(Z_i\) for each influence \(i\).

The allocation is given in table 1 on the basis of damages reported.
Of the value of \(Z = 10\) steel to EN 10164 need not be used.
Z<sub>a</sub>-value; Influence of the effective weld depth a<sub>eff</sub>

<table>
<thead>
<tr>
<th>a&lt;sub&gt;eff&lt;/sub&gt; ≤ 7 mm</th>
<th>a = 5 mm</th>
<th>Z&lt;sub&gt;a&lt;/sub&gt; = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 &lt; a&lt;sub&gt;eff&lt;/sub&gt; ≤ 10 mm</td>
<td>a = 7 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 3</td>
</tr>
<tr>
<td>10 &lt; a&lt;sub&gt;eff&lt;/sub&gt; ≤ 20 mm</td>
<td>a = 14 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 6</td>
</tr>
<tr>
<td>20 &lt; a&lt;sub&gt;eff&lt;/sub&gt; ≤ 30 mm</td>
<td>a = 21 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 9</td>
</tr>
<tr>
<td>30 &lt; a&lt;sub&gt;eff&lt;/sub&gt; ≤ 40 mm</td>
<td>a = 28 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 12</td>
</tr>
<tr>
<td>40 &lt; a&lt;sub&gt;eff&lt;/sub&gt; ≤ 50 mm</td>
<td>a = 35 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 15</td>
</tr>
<tr>
<td>a &gt; 50 mm</td>
<td>a &gt; 35 mm</td>
<td>Z&lt;sub&gt;a&lt;/sub&gt; = 15</td>
</tr>
</tbody>
</table>

Table 1. Relation between weld size and Z-value.

Z<sub>b</sub>-value; Influence of the shape and position of weld and weld bead sequence

Table 2.
Criteria affecting the required value of Z.
**Zc-value; Thickness ‘s’ of the plate with through thickness strains**

<table>
<thead>
<tr>
<th>S</th>
<th>Zc-value *</th>
</tr>
</thead>
<tbody>
<tr>
<td>s ≤ 10 mm</td>
<td>Zc = 2</td>
</tr>
<tr>
<td>10 &lt; s ≤ 20 mm</td>
<td>Zc = 4</td>
</tr>
<tr>
<td>20 &lt; s ≤ 30 mm</td>
<td>Zc = 6</td>
</tr>
<tr>
<td>30 &lt; s ≤ 40 mm</td>
<td>Zc = 8</td>
</tr>
<tr>
<td>40 &lt; s ≤ 50 mm</td>
<td>Zc = 10</td>
</tr>
<tr>
<td>50 &lt; s ≤ 60 mm</td>
<td>Zc = 12</td>
</tr>
<tr>
<td>60 &lt; s ≤ 70 mm</td>
<td>Zc = 15</td>
</tr>
<tr>
<td>70 &lt; s</td>
<td>Zc = 15</td>
</tr>
</tbody>
</table>

*Table 3. Relation between plate thickness and Z-value.*

- Reduced by 50% for material stressed, in the through-thickness direction, by predominantly static loads only or compression only (such as base plates).

**Zd-value; Influence of remote restraint to shrinkage due to stiffness of other portions of the structure**

<table>
<thead>
<tr>
<th>Gradation</th>
<th>Example</th>
<th>Z-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low restraint</td>
<td>T-joint</td>
<td>Zd = 0</td>
</tr>
<tr>
<td>Medium restraint</td>
<td>diaphragms in box girders</td>
<td>Zd = 3</td>
</tr>
<tr>
<td>High restraint</td>
<td>stringers in orthotropic</td>
<td>Zd = 5</td>
</tr>
</tbody>
</table>

*Table 4. Relation between remote restraint of shrinkage after welding by other portions of the structure.*

**Ze-value; Influence of preheating**

| Without preheating    | Ze = 0                      |
| Preheating (= 100 °C) | Ze = -8                     |

*Table 5. Relation between preheating and Z-value.*

It should however be noted that where the shrinkage of the preheated material after completion of welding can provide additional strain to that arising from cooling of the weld itself, the bonus from preheating should be applied. The choice of quality according to EN 10164 (the minimum required \( Z_{Sd} \)) is defined according to table 6.

<table>
<thead>
<tr>
<th>Required value of ( Z_{Sd} )</th>
<th>Z-quality according to EN 10164</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_{Sd} \leq 10 )</td>
<td>-</td>
</tr>
<tr>
<td>11 &lt; ( Z_{Sd} \leq 20 )</td>
<td>Z15</td>
</tr>
<tr>
<td>21 &lt; ( Z_{Sd} \leq 30 )</td>
<td>Z25</td>
</tr>
<tr>
<td>( Z_{Sd} &gt; 30 )</td>
<td>Z35</td>
</tr>
</tbody>
</table>

*Table 6. Choice of quality class according to EN 10164.*

### 13.5 Design examples

Table 7 gives examples for the determination of \( Z_{Sd} \) values and allocations to Z-classes according to EN 10164 for bridges.

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Structural detail</th>
<th>( s_i )</th>
<th>( Z_a )</th>
<th>( Z_d )</th>
<th>( Z_c )</th>
<th>( Z_d )</th>
<th>( Z_{Sd} )</th>
<th>Required ( Z_{Rd} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flange-web-connection of a beam</td>
<td>15</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>“low restraint”</td>
<td>Flange-web-connection of a beam</td>
<td>20</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>“low restraint”</td>
<td>30</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>“low restraint”</td>
<td>50</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 7. Examples for determining $Z_{Sd}$ and allocation to the $Z_{Rd}$-classes in EN 10164.

Fig. 9. Example anchor detail of a cable-stayed bridge.

Fig. 10. Example hanger detail of an arch bridge.

REFERENCES

http://www.fhwa.dot.gov