13 ALUMINIUM CONNECTIONS

In the past decades, a large number of studies have been carried out to enlarge the knowledge on the behaviour of aluminium structures. One of the main research areas except stability and fatigue was this one of connections between aluminium structural members (bolted, welded and adhesive bonded connections). All the results of these research efforts have been incorporated into Eurocode 9 (ENV 1999-01-01), which includes specifications and rules for the design of aluminium structures.

As far as the welding of aluminium structural members is concerned, welded connections have been widely established and developed during the years into an important joining method. The welds do not limit ductility of the connection, this being a great advantage compared to bolted and riveted connections. The design of welded connections is based on a method and assumptions similar to this one used for steel structures with necessary modifications. The instructions for welding provided in Eurocode 9 [ENV 1999-01-01, 1999] can be used when the following requirements are satisfied:

- The structures are loaded with predominantly static loads,
- The welding process MIG can be used for all thicknesses, while TIG is being used only for material thickness up to \( t = 6 \, \text{mm} \) and for repair, and
- The welding consumables should correspond to the aluminium alloy of the connecting members. The choice of filler metal has a significant influence on the strength of the weld metal, being usually lower strength than the strength of the basic material, see Tab. 13.1.

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c} \hline \text{Filler metal} & \text{3103} & \text{5052} & \text{5083} & \text{5454} & \text{6060} & \text{6061} & \text{6082} & \text{7020} \\ \hline \text{5356} & - & 170 & 240 & 220 & 160 & 190 & 210 & 260 \\ \hline \text{4043A} & 95 & - & - & - & 150 & 170 & 190 & 210 \\ \hline \end{array} \]

According to Chapter 6.6.1, lower partial safety factor \( \gamma_M = 1.65 \) instead \( \gamma_M = 1.25 \) should be used, if lower quality level of welding has been specified by the designer for partial or non-strength members.

**Resistance of fillet welds**

In the calculation of a fillet weld, what stresses need to be checked so that the demands of Eurocode 9 to be satisfied?

The stress in a fillet weld, see Fig. 13.1, can be decomposed into stress components in the most critical section at the weld throat.
The stress components are the following, see Fig. 13.2:

\( \sigma_{\perp} \) the normal stress perpendicular to the critical plane of the throat,

\( \sigma_{\parallel} \) the normal stress parallel to the axis of the weld, it should be neglected for design resistance of the fillet weld,

\( \tau_{\perp} \) the shear stress (in the critical plane of the throat) perpendicular to the weld axis,

\( \tau_{\parallel} \) the shear stress (in the critical plane of the throat) parallel to the weld axis.

The resistance of the fillet weld is sufficient if both the following conditions are satisfied:

\[
\sqrt{\sigma_{\perp}^2 + 3 (\tau_{\perp} + \tau_{\parallel})^2} \leq \frac{f_w}{\gamma_{Mw}} \tag{13.1}
\]

and

\[
\sigma_{\perp} \leq \frac{f_w}{\gamma_{Mw}}. \tag{13.2}
\]
Effective width and throat thickness of fillet welds

Which are the geometrical restrictions, concerning effective width and the throat thickness, when using fillet welding?

Effective width of the fillet weld should be at least eight times the throat thickness \( a \). The maximum length is limited by \( 100 a \). When the length is larger, effective length of the weld \( L_{w,\text{eff}} \) is used instead, which can be calculated as

\[
L_{w,\text{eff}} = \left( 1,2 - 0,2 \frac{L_w}{100 a} \right) L_w.
\]  

(13.3)

This reduction is used only in cases when stress in the welds of overlapping connection is not uniformly distributed, but reaches higher values at its ends, see Fig. 13.3a. Uniform stress distribution can be achieved by proper shape of the connected parts, see Fig. 13.3b.

Fig. 13.3 Stress distribution in welded overlapping joints with filled welds, a) non-uniform stress distribution, b) modification for uniform stress distribution

Throat thicknesses of double sided fillet weld loaded perpendicularly to the weld axis, see Fig. 13.3, should satisfy the following condition

\[
a > 0,7 \frac{t \gamma_{\text{hub}} f_w}{F_{\text{sd}}}.
\]  

(13.4)

where

\[
\sigma = \frac{F_{\text{sd}}}{t L}
\]  

(13.5)

and \( F_{\text{sd}} \) is applied force, \( t \) thickness of the connected element and \( L_w \) length of the weld.
Fig. 13.4  Double fillet welded joint loaded perpendicularly to the weld axis

Throat thickness of the weld loaded parallel to the axis, see Fig. 13.5, should be bigger than

$$a > 0.85 \frac{t \tau \gamma_{w}}{f_w},$$

(13.6)

where

$$\tau = \frac{F_{sd}}{t L_w}.$$  

(13.7)
Butt welds in aluminium joints

What information does EC-9 provide, with respect to the characteristics of butt welds between aluminium elements?

When butt welds are used for connection of aluminium elements, it is preferred to use full penetration butt welds for strength members. Partial penetration butt welds should be used only in cases, when verified by testing that no serious weld defects are apparent. In other cases partial penetration butt welds shall be only applied with higher partial safety factor $\gamma_M$ because of the high susceptibility for weld defects of partial penetration butt welds.

Effective thickness of full penetration butt weld is taken as thickness of the connected elements. When elements with different thicknesses are welded, the smaller shall be taken into account as weld thickness. For partial penetration butt welds an effective throat thickness should be applied, see Fig. 13.6. The effective length should be taken as total length of the weld when run-on and run-off plates are used. Otherwise the total length should be reduced by twice the thickness $a$.

![Fig. 13.6 Effective throat thickness of partial penetration butt weld](image)

The stress in butt welds should satisfy the following criteria:

The normal stress, tension or compression, perpendicular to the weld axis

$$\sigma_\perp \leq \frac{f_w}{\gamma_{Mw}},$$  \hspace{1cm} (13.8)

shear stress parallel to the weld axis

$$\tau \leq 0,6 \frac{f_w}{\gamma_{Mw}},$$  \hspace{1cm} (13.9)

and combination of normal and shear stresses

$$\sqrt{\sigma_\perp^2 + 3 \tau^2} \leq \frac{f_w}{\gamma_{Mw}}.$$  \hspace{1cm} (13.10)
Heat Affected Zones (HAZ)

How does the development of high temperatures in the vicinity adjacent to the welds affect the design of aluminium welded connections?

Structural aluminium material of many alloys and conditions is weakened in heat affected zones (HAZs) adjacent to welds. The affected region extends immediately around the weld, beyond which the strength properties rapidly recover their full values.

Eurocode 9 Chapter 6.6.2 deals specifically with heat-affected zones (HAZ), which need to be taken into account for the following classes of alloys:

- Heat-treatable alloys in any heat-treated condition above T4 (6xxx and 7xxx series)
- Non-heat-treatable alloys in any work-hardened condition (3xxx and 5xxx series)

In alloys in O or T4-condition, or when material is in the F-condition and design strength is based on O-condition properties, there is no weakening in the vicinity of welds [Dwight, 1999].

It is here underlined that the severity and extend of HAZ are different for TIG and MIG welding. For TIG welding, a larger HAZ area and more severe softening due to higher heat-input is considered [Mazzolani, 1985].

The two main aspects of HAZ softening are its severity and its extent. The characteristic strengths \( f_o, f_r, f_v \) in the HAZ are calculated in a way determined in the Eurocode 9 for the parent metal and reducing them by softening factor \( \rho_{haz} \). The other method is reducing the area over which the stress acts, see Fig. 13.7. Thus the design resistance of simple rectangular section affected by HAZ softening can be expressed as

\[
F_{rd} = \frac{A \left( f_a \rho_{haz} \right)}{\gamma_{Mw}} = \frac{A f_{a_haz}}{\gamma_{Mw}}, \tag{13.11a}
\]

or

\[
F_{rd} = \frac{(\rho_{haz} A) f_a}{\gamma_{Mw}}. \tag{13.11b}
\]

The values of \( \rho_{haz} \) are provided in Tab. 13.2.
Fig. 13.7  Heat affected zones at fillet weld

Tab. 13.2 Values of HAZ softening factor $\rho_{haz}$

<table>
<thead>
<tr>
<th>Alloy series</th>
<th>Condition</th>
<th>$\rho_{haz}$ (MIG welding)</th>
<th>$\rho_{haz}$ (TIG welding)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusions, sheets, plates, drawn tubes and forgings</td>
<td>Any O F</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>6xxx</td>
<td>T4</td>
<td>1.00</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6xxx</td>
<td>T5</td>
<td>0.65</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>6xxx</td>
<td>T6</td>
<td>0.65</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>7xxx</td>
<td>T6</td>
<td>0.80</td>
<td>0.60</td>
<td>applied when tensile stress acts transversely to the axis of butt or fillet weldpro tahové namáhání kolmo na osu svaru</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.00</td>
<td>0.80</td>
<td>applied for all other conditions</td>
</tr>
<tr>
<td>Sheets, plates, and forgings</td>
<td>5xxx H22</td>
<td>0.86</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H24</td>
<td>0.86</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>3xxx</td>
<td>H14</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H16</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H18</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>1xxx</td>
<td>H14</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
</tbody>
</table>

These values are valid from the following time after welding, providing the material has been held at a temperature not less than 10°C:

- 6xxx series alloys- 3 days,
- 7xxx series alloys- 30 days.

If the material is held at temperature lower than 10°C after welding, the recovery time will be prolonged. Advice should be sought from the manufacturer.

The heat affected zone is assumed to extend over a distance $b_{haz}$ in any direction from the weld, see Fig. 13.8 and Tab. 13.3. If the distance from the weld to the edge of the element is smaller than three times $b_{haz}$, then the HAZ extends to the full width of the element.

The measurement of $b_{haz}$ is taken as follows:

- transversely from the center line of an in-line fillet weld,
- transversely from the point of intersection of the welded surfaces at fillet welds,
- transversely from the point of intersection of the welded surfaces at butt welds used in corner, tee or cruciform joints,
in any radial direction from the end of the weld.

The HAZ boundaries should generally be taken as straight lines normal to the metal surface, particularly when welding thin materials. However, when surface welding is applied to thick material it is permissible to assume a curved boundary of radius $b_{haz}$.

**Tab. 13.3  Extent of HAZ for MIG and TIG welding**

<table>
<thead>
<tr>
<th>Thickness $t$</th>
<th>$b_{haz}$ (MIG welding)</th>
<th>$b_{haz}$ (TIG welding)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; t \leq 6$ mm</td>
<td>20 mm, *</td>
<td>30 mm, *</td>
</tr>
<tr>
<td>$6 &lt; t \leq 12$ mm</td>
<td>30 mm, *</td>
<td></td>
</tr>
<tr>
<td>$12 &lt; t \leq 25$ mm</td>
<td>35 mm, *</td>
<td></td>
</tr>
<tr>
<td>$t &gt; 25$ mm</td>
<td>40 mm, *</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 13.8 Heat affected zones at fillet weld](image)

Characteristic strength of the heat affected zones is reduced to $f_{a,haz}$

$$f_{a,haz} = f_a \rho_{haz}$$

for normal stress and to $f_{v,haz}$ for shear stress

$$f_{v,haz} = \frac{f_a \rho_{haz}}{\sqrt{3}}.$$  

The stress in heat affected zones should not exceed the following:

Tensile force perpendicular to the failure plane for full penetration butt welds

$$\sigma_{haz} \leq \frac{f_{a,haz}}{\gamma_{Mw}},$$

for partial penetration butt welds

$$\sigma_{haz} \leq \frac{f_{a,haz}}{t} \frac{t}{\gamma_{Mw}},$$

and for fillet welds at the toe of the weld and the fusion boundary respectively

$$\sigma_{haz} \leq \frac{f_{a,haz}}{\gamma_{Mw}},$$
\[ \sigma_{haz} \leq \frac{g_1}{t} f_{u, haz}. \] (13.17)

When the weld is loaded by a shear force, the stress in heat affected zone of butt welds is limited to

\[ \tau_{haz} \leq \frac{f_{v, haz}}{\gamma_{Mw}}. \] (13.18)

at toe of the weld and

\[ \tau_{haz} \leq \frac{t_e}{t} \frac{f_{v, haz}}{\gamma_{Mw}}. \] (13.19)

at the fusion boundary.

Similar condition apply for fillet welds

\[ \tau_{haz} \leq \frac{f_{v, haz}}{\gamma_{Mw}}. \] (13.20)

\[ \tau_{haz} \leq \frac{g_1}{t} f_{v, az}. \] (13.21)

For butt weld loaded by combination of shear nad normal stresses, the following apply

\[ \sqrt{\sigma_{haz}^2 + 3\tau_{haz}^2} \leq \frac{f_{u, haz}}{\gamma_{Mw}}. \] (13.22)

\[ \sqrt{\sigma_{haz}^2 + 3\tau_{haz}^2} \leq \frac{t_e}{t} \frac{f_{u, haz}}{\gamma_{Mw}}. \] (13.23)

Similar condition apply for fillet welds

\[ \sqrt{\sigma_{haz}^2 + 3\tau_{haz}^2} \leq \frac{f_{u, haz}}{\gamma_{Mw}}. \] (13.24)

\[ \sqrt{\sigma_{haz}^2 + 3\tau_{haz}^2} \leq \frac{g_1}{t} \frac{f_{u, haz}}{\gamma_{Mw}}. \] (13.25)

As a conclusion, it can be noted that the deformation capacity of a welded joint can be improved when the design strength of the welds is greater than that of the material in the HAZ.
References


List of symbols
HAZ       Heat Affected Zone

\(a\)       throat thickness of fillet weld
\(b_{\text{haz}}\)    width of heat affected zone
\(f_o\)      characteristic strength for bending and yielding in tension and compression
\(f_a\)      characteristic strength for local capacity in tension and compression
\(f_{a,\text{haz}}\) characteristic strength of heat affected zone
\(f_v\)      characteristic shear strength
\(f_{\text{v, haz}}\) characteristic shear strength of heat affected zone
\(f_w\)      characteristic strength of the weld metal
\(g_l\)      leg length of fillet weld
\(t\)        thickness
\(t_e\)      effective thickness of partial penetration butt weld

\(L_w\)      length of fillet weld
\(L_{w,\text{eff}}\) effective length of fillet weld
\(F_{\text{Sd}}\) applied force

\(\gamma_M\)  resistance of connection
\(\gamma_Mw\) resistance of welded connection
\(\rho_{\text{haz}}\) HAZ softening factor
\(\sigma\)    normal stress
\(\sigma_\perp\) normal stress perpendicular to the critical plane of the throat
\(\sigma_//\) normal stress parallel to the axis of the weld
\(\tau\)     shear stress
\(\tau_\perp\) shear stress (in the critical plane of the throat) perpendicular to the weld axis
\(\tau_//\) shear stress (in the critical plane of the throat) parallel to the weld axis