***TRY*** **TERÄSNORMIKORTTI** **N:o 24/2018**

# Design Resistance of One-sided Welds to EN 1993-1-8:2005

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**Menetelmän kuvaus:**

Normikortissa esitetään yksipuoleisen hitsin mitoittaminen, kun hitsin juureen aiheutuu taivutuksen aiheuttama vetojännitys.

Teräsrakenneyhdistys ry:n Normitoimikunta on käsitellyt tämän Teräsnormikortin 22.11.2018 kokouksessa ja todennut sen täyttävän standardin SFS-EN 1993 ja niihin liittyvien Suomen kansallisten liitteiden vaatimukset.

Teräsnormikortin käyttäjällä on vastuu kortin ohjeiden käytöstä.

Tämä Teräsnormikortti on voimassa toistaiseksi.

Helsingissä helmikuun 7. päivänä 2019

TERÄSRAKENNEYHDISTYS r.y.

Aki Vuolio
Hallituksen puheenjohtaja

Janne Tähtikunnas
Toimitusjohtaja

## 1. BACKROUND

EN1993-1-8:2005 clause 4.12 sets out the basic position of the European Standard in relation to the adoption of eccentrically loaded single fillet and single-sided partial penetration butt welds

Standard EN 1993-1-8, clause 4.12:

*(1) Local eccentricity should be avoided whenever it is possible.*

*(2) Local eccentricity (relative to the line of action of the force to be resisted) should be taken into account in the following cases:*

- *Where bending moment transmitted about the longitudinal axis of the weld produces tension at the root of the weld, see Figure 4.9(a);*
- *Where the tensile force transmitted perpendicular to the longitudinal axis of the weld produces a bending moment, resulting in a tension force at the root of the weld, see Figure 4.9(b).*

*(3) Local eccentricity need not be taken into account if a weld is used as part of a weld group around the perimeter of a structural hollow section.*


*(a) Bending moment produces tension at the root of the weld. (b)Tensile force produces tension at the root of the weld.*

One-sided fillet welds and one-sided partial penetration welds are effective at transferring longitudinal shear forces. However, welds are poor for transferring bending moments across the throat of the weld. One-sided fillet welds and one-sided partial penetration welds introduce eccentricity in the joint that influences the development of bending moment from the application of axial force. This secondary effect significantly reduces the load carrying capacity of the weld.

One-sided fillet welds and one-sided partial penetration welds shall only be used for the transfer of longitudinal shear between connected plates, unless otherwise possible, with the exception of:

1. welds used in connections between rolled hollow sections (SHS, RHS, CHS)
2. welds used in connections between welded box sections (WB, WQ or corresponding) provided that the welds can be demonstrated to be sufficient to handle the secondary moments and forces developing as a result of the weld eccentricity
3. longitudinal welds used to connect webs and flanges in welded sections (WI, WB, WQ or corresponding). Transverse forces should be taken into account.

Two-sided welds shall be used, unless otherwise possible, for connecting plates, webs or flanges that transfer axial force and/or bending moment across welded joints. Where it is not possible to use two-sided welds, for example due to obstructions that prevent access for welding, one-sided welds may be adopted exceptionally provided that the adequacy of the weld is demonstrated taking into account secondary forces and moments that develop as a result of the eccentricity in the joint.

## 2. CALCULATION OF DESIGN RESISTANCE

The calculation of design resistance for one-sided welds is presented in the context of a T-joint where the plates are connected by a partial penetration weld with additional reinforcing fillet weld as shown in figure 2.1.

This example sets out the basic principles that are also applicable to one-sided fillet welds alone, and one-sided partial penetration butt welds alone.

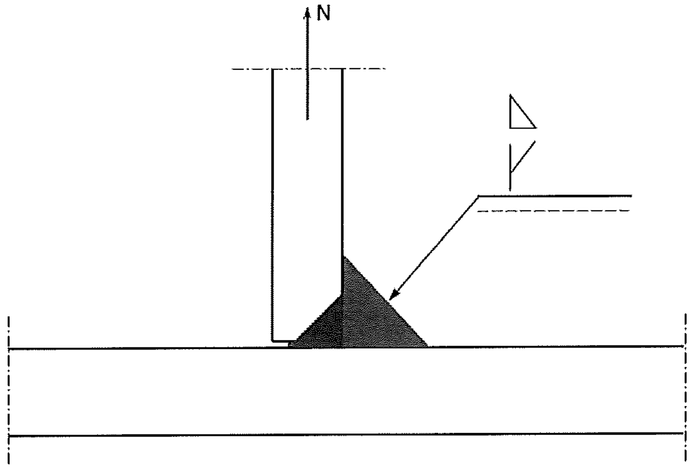



Fig. 2.1 T- joint with one-sided weld; partial penetration weld with additional reinforcing fillet weld.

EN 1993-1-8: 2005 clause 2.5(1) sets out the application rule which should be respected: "Joints should be designed on the basis of a realistic assumption of the distribution of internal forces and moments.". This includes the development of secondary forces and moments resulting from the general arrangement of the connection itself.

### 2.1 Weld Design Resistance calculated using the Directional Method

Due to the development of moment across the weld throat, the only method presented in EN1993-1-8: 2005 that is applicable for assessing the design resistance of the weld is the directional method as presented in clause 4.5.3.2, which considers in detail the combination of stress components applied to the weld throat.

EN1993-1-8: 2005 clause 4.5.3.2 presents two design checks that must be fulfilled, and that reflect the calculation of design resistance e.g. verification of design resistance in relation to the combined von Mises' stress, and verification of the design resistance in relation to the direct stress. These design checks are presented in equation (2.1). Figure 2.2 illustrates the stress components applied to the weld throat e.g. direct stress, shear stress and longitudinal shear stress.

The forces and moments applied to the weld throat are to be converted into the fundamental components of stress as presented in figure 2.2 for verification against the two design checks.

$$\sigma_w = \sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_\parallel^2)} \leq \frac{f_u}{\beta_w \gamma_{M2}} \text{ and } \sigma_\perp \leq \frac{0{,}9\, f_u}{\gamma_{M2}} \qquad (2.1)$$

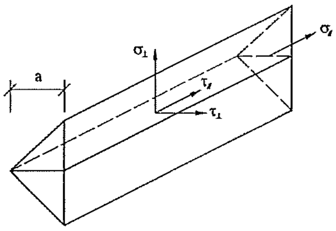



Fig. 2.2 Stress components applied to the weld throat

An explanation of the symbols applied in equation (2.1) and figure 2.2 is presented below:

a the throat thickness of the fillet weld

$\sigma_\perp$ the normal stress perpendicular to the throat

$\sigma_\parallel$ the normal stress parallel to the axis of the weld (which is always taken as 0)

$\tau_\perp$ the shear stress (in the plane of the throat) perpendicular to the axis of the weld

$\tau_\parallel$ the shear stress (in the plane of the throat) parallel to the axis of the weld

$f_u$ the nominal ultimate tensile strength of the weaker part joined

$\beta_w$ the appropriate correlation factor taken from Table 4.1 of EN 1993-1-8, (0,9 in case of S355)

$\gamma_{M2}$ the partial safety factor for material of weld

$\sigma_w$ the weld stress.

## 2.2 Identifying the Critical Weld Throat

The first step in the calculation of design resistance of the one-sided weld is to identify the critical weld throat e.g. with dimension "a". In the case of a fillet weld, this is the plane through the weld with the narrowest width.

The designer presents the required throat thickness in design documents e.g. drawings. The manufacturer may take advantage of deep penetration to achieve the required throat thickness. For the option of welding with the deep penetration welding process, the designer may specify within the execution specification production testing according to EN 1090-2 12.4.4 (and Table A.2 12.4.4).

For a fillet weld with leg length $z_2$ the critical throat is at 45 degs and has a width of $a = \frac{z_2}{\sqrt{2}}$.

For a partial penetration butt weld with penetration depth $z_1$ the critical throat is at 0 degs and has a width of a $= z_1$.

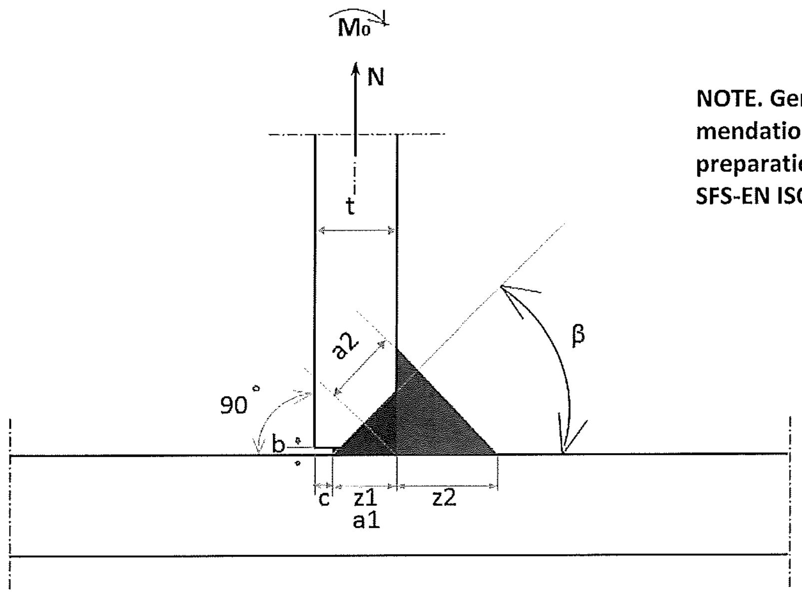
For a partial penetration butt weld with penetration depth $z_1$ that is reinforced by a fillet weld with leg length $z_2$ the critical throat is dependent upon the combination of $z_1$ and $z_2$. $z_1$ and $z_2$ are shown in figure 2.3.

If $z_2 > z_1$, as shown in figure 2.3, then the weld throat is at 45 degs and has a width a $= z_1\sqrt{2} + \frac{(z_2 - z_1)}{\sqrt{2}}$.

If $z_2 = z_1$, then the weld throat is at 45 degs and has a width a $= z_1\sqrt{2}$.

If $z_2 < z_1$, then the weld throat is at $\beta = \text{atan}(\frac{z_2}{z_1})$ and has a width a $= \sqrt{z_2^2 + z_1^2}$.

It is prudent to also verify the stress state developed across line 2-2 as shown in figure 2.4. Depending on the applied forces and developed secondary moments, the critical line may be at another angle.




NOTE. General Recommendations for joint preparation - see SFS-EN ISO 9692-1

Fig. 2.3 Weld dimension labels

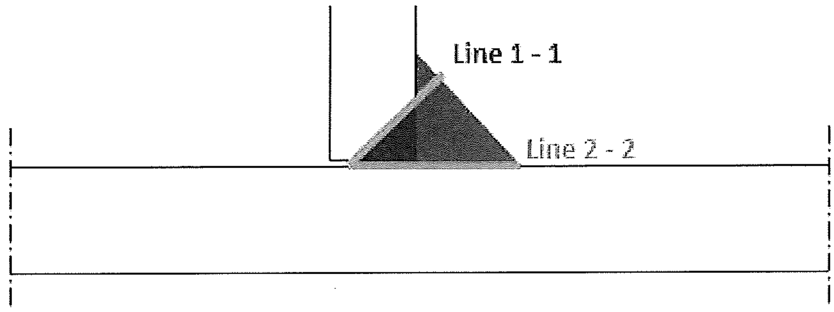



Fig. 2.4 Critical weld throat: partial penetration weld with reinforcing fillet weld (line 1-1) and other critical failure line 2-2.

## 2.3 Calculating the secondary moment due to applied axial load

Eccentricity of the load, and therefore the magnitude of the additional secondary moment, depends on the assumed failure line. The eccentricity is always measured perpendicular from the line of action of the axial load to the centre of the assumed failure line, as illustrated in figure 2.5.

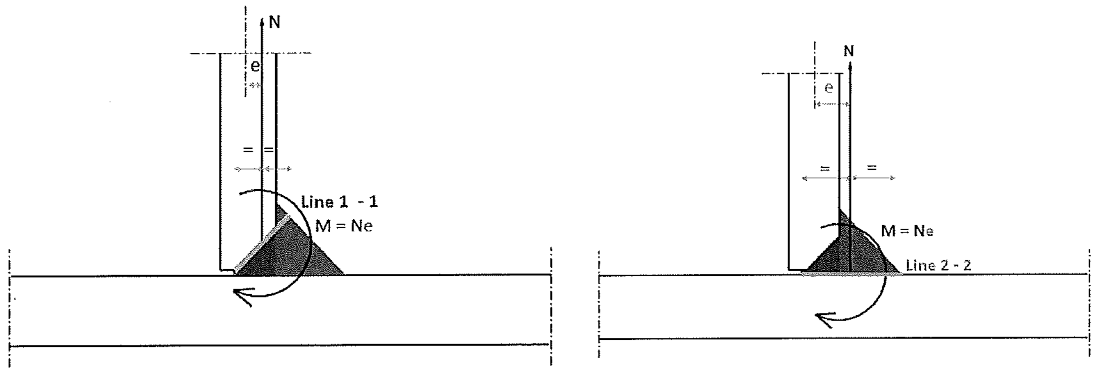



Fig. 2.5 Eccentricity for calculation of additional secondary moment

The additional secondary moment due to eccentricity of load therefore varies according to the failure line considered. The design process must identify the critical failure line, which is typically the critical weld throat.

### 2.4 Verification of weld according to direct application of design checks

#### 2.4.1 Example 1: Partial Penetration Butt Weld ($a_1$=7) + Fillet weld ($a_2$=5,7)

This example calculation illustrates the verification of the weld according to direct application of design checks eg. calculation of maximum stresses and verification against calculated limits.

Parameters used in the example calculation are shown in figure 2.6.

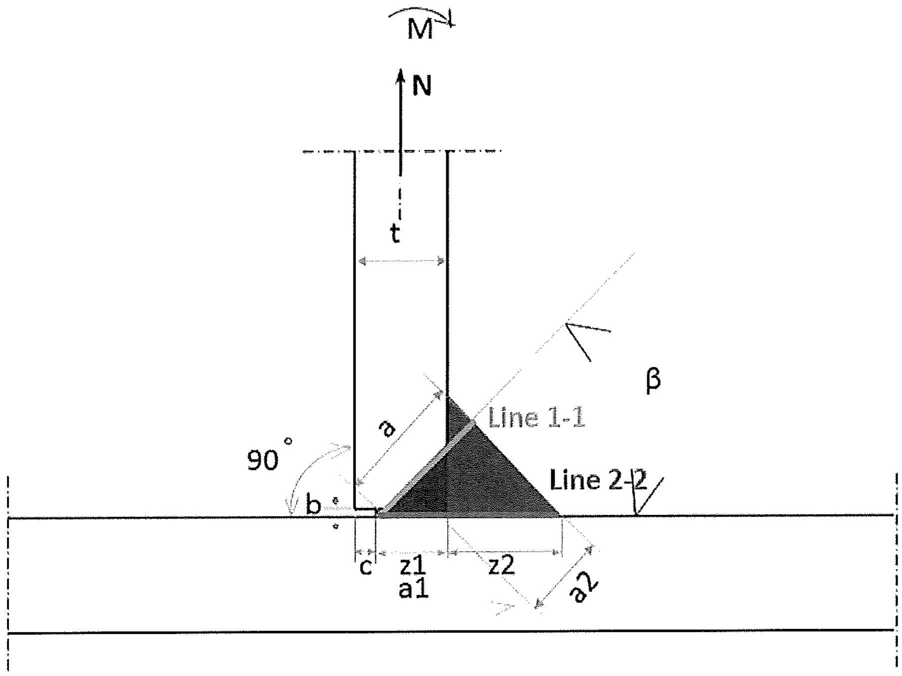



Fig. 2.6 Parameters used in example design calculation

Material properties:
Steel Grade: S355, EN 10025-2

$f_y$ = 355 N/mm$^2$, $f_u$ = 510 MPa
t = 10 mm

Weld properties:
The weld electrode is matched or over matched.
Weld dimensions:

Partial penetration butt weld $z_1$ = 7 mm
Reinforcing Fillet weld $z_2$ = 8 mm

External applied load applied at the centreline of the plate:

N = 1 000 N/mm
$M_0$ = 500 Nmm/mm

**Line 1 – 1**

Line length (weld throat):

$$L_{1-1} = z_1\sqrt{2} + \frac{(z_2-z_1)}{\sqrt{2}} = \frac{(z_1+z_2\,)}{\sqrt{2}} = 10{,}6 \text{ mm}$$

Eccentricity of applied load:

$$e_{1\text{-}1} = t - z1 + \frac{(z_1+z_2\,)}{2\sqrt{2}\sqrt{2}} - \frac{t}{2} = \frac{t}{2} - z_1 + \frac{1}{4}(z_1 + z_2) = 1{,}75 \text{ mm}$$

Additional Secondary Moment:

$M_1 = N\, e_{1\text{-}1} = 1\ 750$ Nmm/mm

Total Applied Moment to Line 1-1:

$M = M_0 + M_1 = 2\ 250$ Nmm/mm

Stresses from external applied axial force, N

$$\sigma_{\perp,1} = \frac{N}{\sqrt{2}\ L1\text{-}1} = 66{,}7 \text{ MPa}$$

$$\tau_{\perp} = \frac{N}{\sqrt{2}\ L1\text{-}1} = 66{,}7 \text{ MPa}$$

$\tau_{\parallel} = 0$ MPa

Maximum perpendicular stress from total applied moment to Line 1-1 (elastic distribution):

$\sigma_{\perp,2} = 6 \cdot M / (L_{1\text{-}1})^2 = 120{,}1$ MPa

Total maximum perpendicular stress applied to weld along line 1-1 (weld throat):
$\sigma_{\perp} = \sigma_{\perp,1} + \sigma_{\perp,2} = 186{,}8$ MPa

**Design check 1, <u>Line 1 – 1</u>:**

$\beta_w = 0{,}9,\ \ \gamma_{M2} = 1{,}25$

$$\sigma_w = \sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_\parallel^2)} \ \leq \ \frac{f_u}{\beta_w \gamma_{M2}}$$

$\sigma_w = 219{,}6$ MPa $\leq 453{,}3$ MPa. Utilisation ratio = 0,49 => ok

**Design check 2, Line 1 – 1:**

$$\sigma_{\perp} \leq \frac{0{,}9\, f_u}{\gamma_{M2}}$$

$\sigma_{\perp}$ = 186,8 MPa $\leq$ 367,2MPa. Utilisation ratio = 0,51 => ok

**Line 2 – 2**

Line length:

$L_{2\text{-}2} = z2 + z1 = 15{,}0$ mm

Eccentricity of applied load:

$$e_{2\text{-}2} = t - z1 + \frac{(z_1+z_2)}{2} - \frac{t}{2} = \frac{t}{2} + \frac{(z_2-z_1)}{2} = 5{,}50 \text{ mm}$$

Additional Secondary Moment:

$M_1 = N\, e_{2\text{-}2} = 5\,500$ Nmm/mm

Total Applied Moment to Line 2-2:

$M = M_0 + M_1 = 6\,000$ Nmm/mm

Stresses from external applied axial force, N

$\sigma_{\perp,1} = \frac{N}{L2\text{-}2} = 66{,}7$ MPa

$\tau_{\perp} = 0$ MPa

$\tau_{\parallel} = 0$ MPa

Maximum perpendicular stress from total applied moment to Line 2-2 (elastic distribution):

$\sigma_{\perp,2} = 6 \cdot M / (L_{2\text{-}2})^2 = 160{,}0$ MPa

Total maximum perpendicular stress applied to weld along line 2-2:
$\sigma_{\perp} = \sigma_{\perp,1} + \sigma_{\perp,2} = 226{,}7$ MPa

**Design check 1, Line 2 – 2:**

$\beta_w = 0{,}9,\ \gamma_{M2} = 1{,}25$

$$\sigma_w = \sqrt{\sigma_{\perp}^2 + 3(\tau_{\perp}^2 + \tau_{\parallel}^2)} \leq \frac{f_u}{\beta_w \gamma_{M2}}$$

$\sigma_w$ = 226,7 MPa $\leq$ 453,3 MPa. Utilisation ratio = 0,50 => ok

**Design check 2, Line 2 – 2:**

$$\sigma_{\perp} \leq \frac{0{,}9\, f_u}{\gamma_{M2}}$$

$\sigma_{\perp}$ = 226,7 MPa $\leq$ 367,2MPa. Utilisation ratio = 0,62 => ok

### 2.4.2 Example 2: Fillet Weld ($a_2$=12,7)

This example calculation illustrates the verification of the weld according to direct application of design checks e.g. calculation of maximum stresses and verification against calculated limits.

Parameters used in the example calculation are shown in figure 2.7.

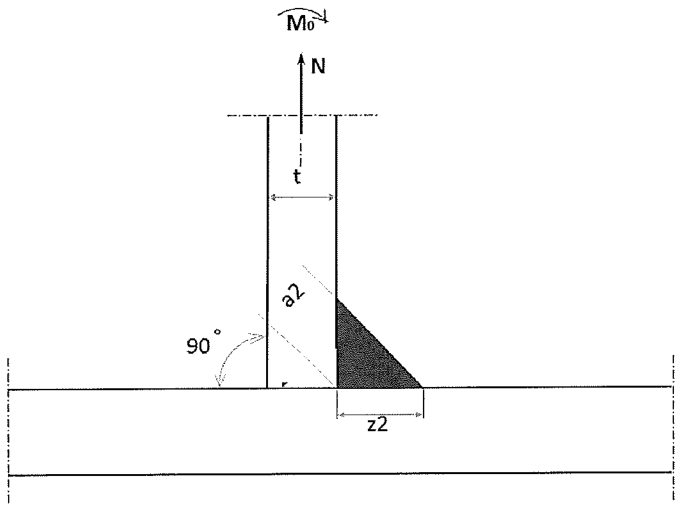



Fig. 2.7 Parameters used in example design calculation

Material properties:
Steel Grade: S355, EN 10025-2
$f_y$ = 355 N/mm$^2$, $f_u$ = 510 MPa
t = 10 mm

Weld properties:
The weld electrode is matched or over matched.
Weld dimensions:
Fillet weld z = $z_2$ = 18,0 mm

External applied load applied at the centreline of the plate:
N = 1 000 N/mm
$M_0$ = 500 Nmm/mm

**Line 1 – 1**

Line length (weld throat):

$$L_{1\text{-}1} = \frac{z}{\sqrt{2}} = 12{,}7 \text{ mm}$$

Eccentricity of applied load:

$$e_{1\text{-}1} = t + \frac{z}{2\sqrt{2}\sqrt{2}} - \frac{t}{2} = \frac{t}{2} + \frac{z}{4} = 9{,}5 \text{ mm}$$

Additional secondary moment:

$$M_1 = N\, e_{1\text{-}1} = 9\ 500 \text{ Nmm/mm}$$

Total applied moment to Line 1-1:

$$M = M_0 + M_1 = 10\ 000 \text{ Nmm/mm}$$

Stresses from external applied axial force, N

$$\sigma_{\perp,1} = \frac{N}{\sqrt{2}\ L_{1\text{-}1}} = 55{,}7 \text{ MPa}$$

$$\tau_{\perp} = \frac{N}{\sqrt{2}\ L_{1\text{-}1}} = 55{,}7 \text{ MPa}$$

$$\tau_{\parallel} = 0 \text{ MPa}$$

Maximum perpendicular stress from total applied moment to Line 1-1 (elastic distribution):

$$\sigma_{\perp,2} = 6 \cdot M / (L_{1\text{-}1})^2 = 372{,}0 \text{ MPa}$$

Total maximum perpendicular stress applied to weld along line 1-1 (weld throat):

$$\sigma_{\perp} = \sigma_{\perp,1} + \sigma_{\perp,2} = 427{,}7 \text{ MPa}$$

**Design check 1, <u>Line 1 – 1</u>:**

$\beta_w = 0{,}9$, $\gamma_{M2} = 1{,}25$

$$\sigma_w = \sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_\parallel^2)} \leq \frac{f_u}{\beta_w \gamma_{M2}}$$

$\sigma_w = 438{,}5$ MPa $\leq 453{,}3$ MPa. Utilisation ratio = 0,97 => ok

**Design check 2, <u>Line 1 – 1</u>:**

$$\sigma_\perp \leq \frac{0{,}9\, f_u}{\gamma_{M2}}$$

$\sigma_\perp$ = 427,7 MPa > 367,2MPa. Utilisation ratio = 1,17 => **NOT OK**

**Line 2 – 2**

Line length:

$L_{2\text{-}2}$ = z =18,0 mm

Eccentricity of applied load:

$$e_{2\text{-}2} = t + \frac{z}{2} - \frac{t}{2} = \frac{t}{2} + \frac{z}{2} = 14{,}0 \text{ mm}$$

Additional Secondary Moment:

$M_1 = N\, e_{2\text{-}2}$ = 14 000 Nmm/mm

Total Applied Moment to Line 2-2:

$M = M_0 + M_1$ = 14 500 Nmm/mm

Stresses from external applied axial force, N

$\sigma_{\perp,1} = \frac{N}{L2\text{-}2}$ = 55,6 MPa

$\tau_\perp$ = 0 MPa

$\tau_\parallel$ = 0 MPa

Maximum perpendicular stress from total applied moment to Line 2-2 (elastic distribution):

$\sigma_{\perp,2} = 6 \cdot M / (L_{1\text{-}1})^2$ = 268,5 MPa

Total maximum perpendicular stress applied to weld along line 2-2:
$\sigma_\perp = \sigma_{\perp,1} + \sigma_{\perp,2}$ = 324,1 MPa

**Design check 1, <u>Line 2 – 2</u>:**

$\beta_w$ = 0,9, $\gamma_{M2}$ = 1,25

$$\sigma_w = \sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_\parallel^2)} \leq \frac{f_u}{\beta_w \gamma_{M2}}$$

$\sigma_w$ = 324,1 MPa ≤ 453,3 MPa. Utilisation ratio = 0,72 => ok

**Design check 2, Line 2 – 2:**

$$\sigma_\perp \leq \frac{0{,}9\, f_u}{\gamma_{M2}}$$

$\sigma_\perp$ = 324,1 MPa $\leq$ 367,2MPa. Utilisation ratio = 0,88 => ok

**NOTE. This weld can only transfer 85% of the applied loads (see design check 2, Line 1 – 1).**

### 2.4.3 Discussion

The following figures illustrate the impact on weld volume for a variety of parameters of single-sided weld, for matching the plastic design resistance of the connected plate, but ignoring impact of weld eccentricity for simplification of this example. Figure 2.8 shows the change in volume depending on type of weld. The right hand side shows a pure single-sided fillet weld ($z_1$ = 0 mm) and the left hand side a full penetration butt weld ($z_2$ = 0 mm). The weld is sized so that the weld design resistance is equal to the plastic design resistance of the connected 10 mm thick plate, but ignoring impact of weld eccentricity for simplification of this example. The discontinuity in figure 2.8 results from a shift where the partial penetration butt weld turns into a full penetration butt weld.

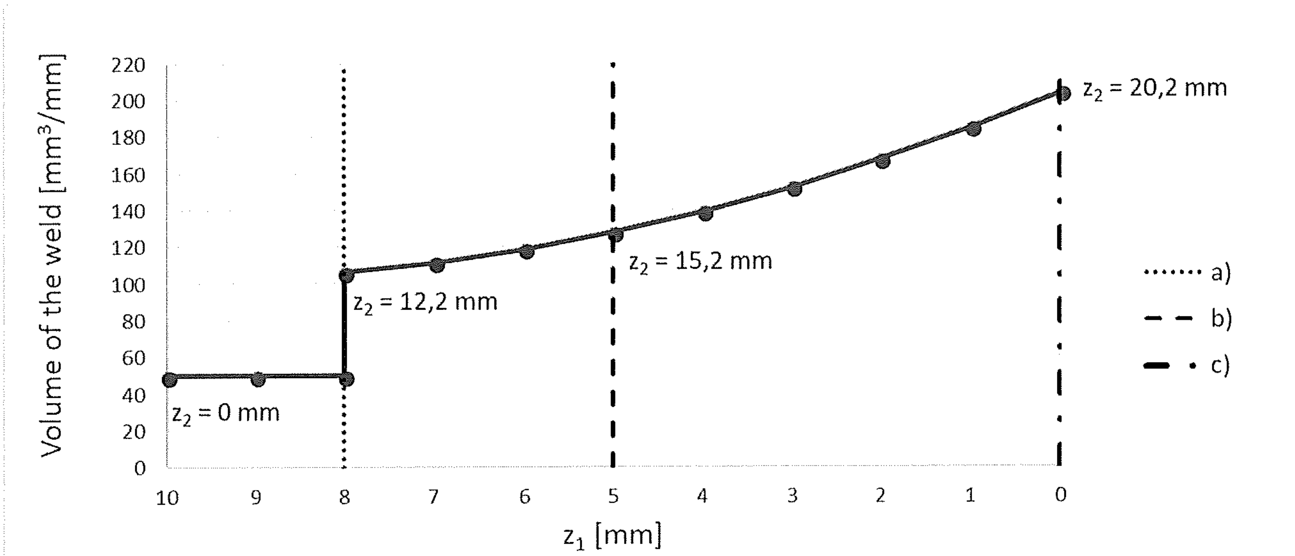



Figure 2.8 Weld volume with different values of $z_1$ and $z_2$. Eccentricity is ignored. The resistance of welds is equal to the plastic resistance $F_{w,Rd} = t\, f_y / \gamma_{M0}$ of the plate. Yield strength is 420 MPa and ultimate tensile strength is 520 MPa. The thickness of the plate is 10 mm. Sections a, b and c are shown in Figure 2.9

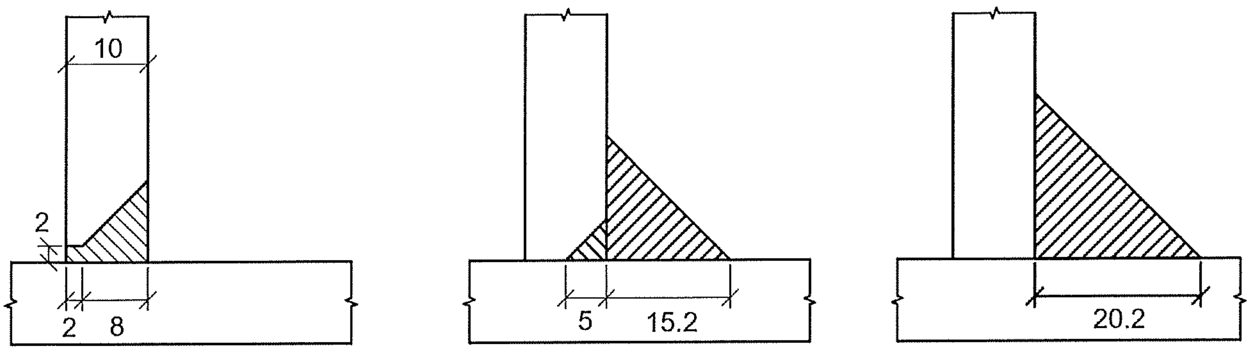



Figure 2.9 The resistances of welds are equal to the plastic resistance t $f_y / \gamma_{M0}$ of the plate. The eccentricity is neglected. Yield strength is 420 MPa and tensile strength is 520 MPa. The thickness of the plate is 10 mm. Sections a (left), b (middle) and c (right) are shown in Figure 2.8.

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Effect of bending moment on capacity of fillet weld, N. Tuominen, T. Björk, A. Ahola. Teräsrakenneyhdistys ry, Teräsrakentamisen T&K päivät, 2016, Lappeenranta

SFS-EN 1993-1-8:2005, Eurocode 3: Teräsrakenteiden suunnittelu. Osa 1.8: Liitosten mitoitus