Application nr. 6
(Connections)

Strength of welded connections to EN 1993-1-8 (Eurocode 3, Part 1.8)

PART 1:
Design of a fillet weld connection in shear

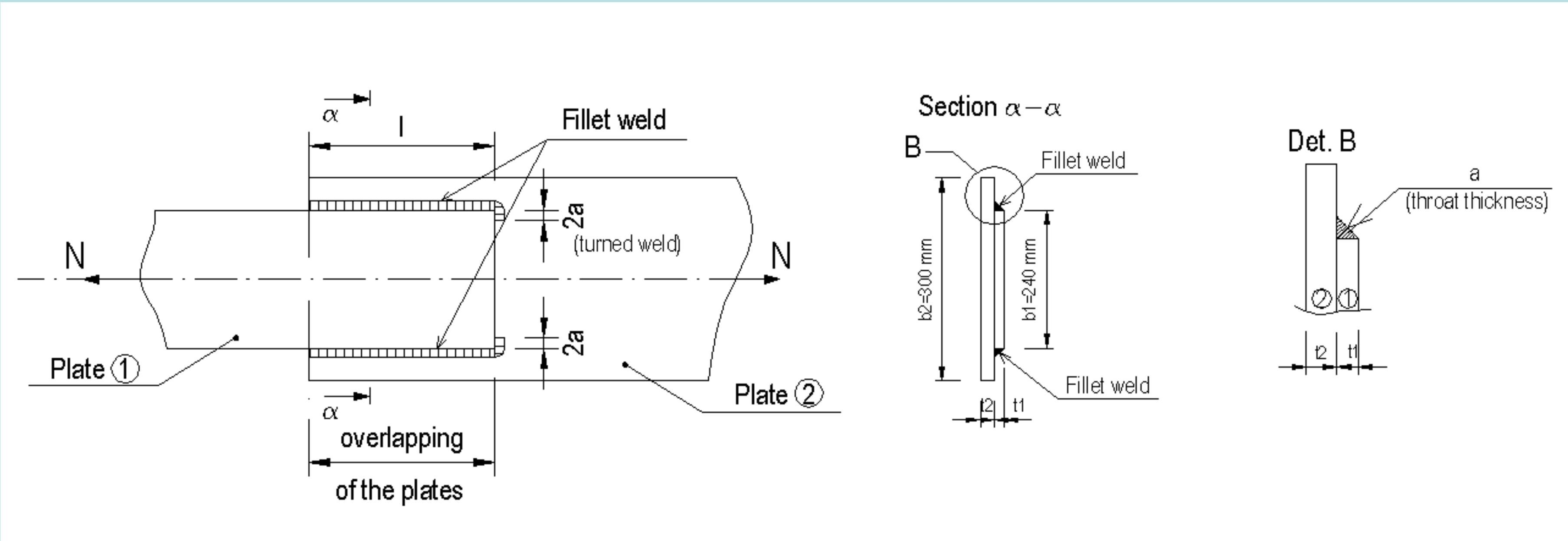
Initial data of the problem:

- Given two overlapping plates with the following dimensions:
- Plate 1: width = b_1=240 mm;
  thickness=t_1=15 mm
- Plate 2: width = b_2 = 300 mm;
  thickness = t_2 = 12 mm

Steel grade of the plates: S235

An overlapping welded connection is required between plates under axial force N = 720 kN

Geometry of the proposed connection and loading:



Comment on problem required result:

- Two fillet welds are required, connecting Plate 1 to Plate 2 (see previous drawing) and resisting the axial force N;
- A shear effect is produced between the two plates which tend to move in opposite directions under the effect of axial load;
- The unknown elements in this phase (to be found out as a result) are the weld effective length (l) and throat thickness (a) for the fillet weld.

Design resistance of the fillet weld: simplified method of EN 1993-1-8

- According to the code, the design resistance of a fillet weld may be assumed to be adequate if, at every point along its length, the resultant of all the forces per unit length transmitted by the weld, satisfy the following criterion:

$$F_{w,Ed} \leq F_{w,Rd}$$

In the previous formula:

- $F_{w,Ed}$ = is the design value of the weld force per unit length (from load action);
- $F_{w,Rd}$ = is the design weld resistance per unit length;

a) Sizing of the weld (finding weld length and weld throat thickness):

- The following equation of equilibrium is used (from eq.4.2):

$$F_{w,Ed}^{Total} = F_{w,Rd}^{Total}$$

- Where, in our case:

$$F_{w,Ed}^{Total} = N = 720\,kN$$

(total weld force)

Weld resistance:

- According to the simplified code method (ch. 4.5.3.3), the weld resistance is given by the formula:

$$F_{w,Rd}^{Total} = \left(f_{vw.d} \cdot a \cdot l \right) \cdot 2$$

Number of welds in our case

- and ($f_{vw.d}$) is the design strength of the weld

Design strength of the weld (eq. 4.4):

$$f_{vw.d} = \frac{\left(f_u / \sqrt{3} \right)}{\beta_w \cdot \gamma_{M2}}$$

with:

f_u = 340 N/mm^2 (ultimate strength for S235 steel of the plates)

β_w = 0,8 (correction factor for fillet welds, table 4.1)

γ_{M2} = 1,25

Previous formula gives:

$$f_{vw.d} = \frac{340}{0,8 \cdot 1,25 \cdot \sqrt{3}} = 196.3\ N/mm^2$$

In the weld resistance formula:

- (a) = throat thickness of the weld;
- (l) = effective length of the weld

- These two elements are both unknown.

- They appear simultaneously in a single equation, which normally makes impossible any solution!

This is a typical engineer problem!

- The solution is obtained by imposing one of this two unknown values, based on the previous experience of the designer

- Usually we impose the (a) value, i.e. the throat thickness of the weld;
- As required by the code , this value should be: $a > 3,0$ mm

Imposing (a) value and calculation of the weld resistance:

- Let's impose: a = 5,0 mm
- In this case, using previously determined data, we get:

$$F_{w,Rd}^{Total} = (196.3 \cdot 5 \cdot l) \cdot 2$$

A [mm]

- And consequently:

$$720000 = 196.3 \cdot l \Rightarrow l = \frac{720000}{196.3} = 367\, mm$$

Comment on the obtained result:

- As the code does not prescribe a superior limit for the weld effective length, we will adopt the following value as actual value of the length:

$$l_{act} = 370 \text{ mm}$$

- As required by the code, the effective length value should be larger than the prescribed minimum limit:

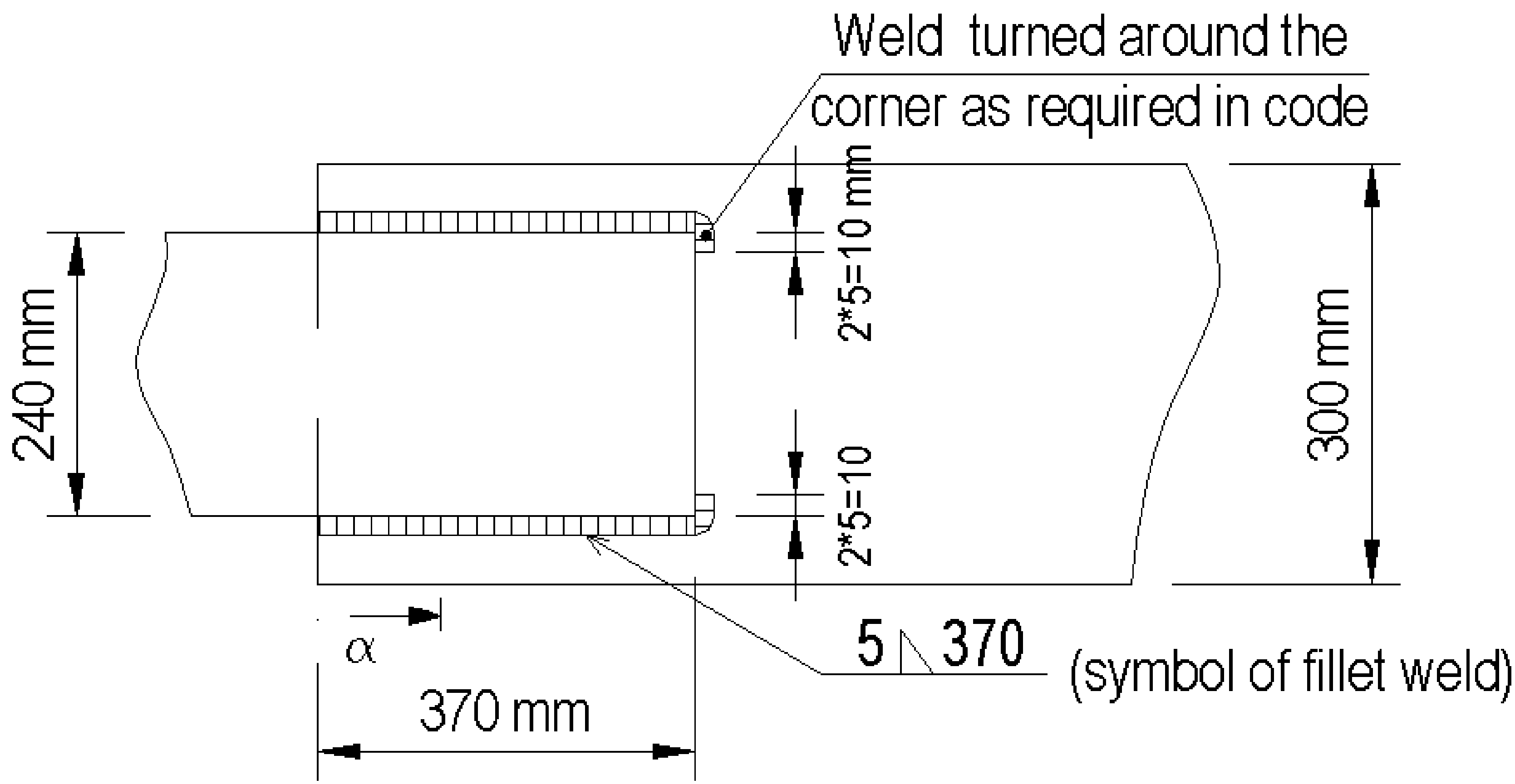
$$l_{act} > l_{min} = 30 \text{ mm } (l_{min} = 6a = 30 \text{ mm})$$

OK !

b) Checking of the weld:

- The obtained welding has now the geometry (dimensions) presented in the next figure

Geometry of the fillet weld (to be shown on technical drawing):



Comment on the weld symbol:

- The weld symbol for a fillet weld includes:

  - an arrow showing the weld seam position on the connection drawing;

  - number “5” which indicates the weld throat thickness in [mm]

  - a triangle indicating a single side fillet weld (type of weld)

  - number “370” indicating the length of the fillet weld in [mm]

- The design throat area of the weld:

$$A_w = \Sigma a \cdot l = 2 \cdot 5 \cdot 370 = 3700\, mm^2$$

- The design value of the weld force per unit length becomes:

$$F_{w,Ed} = \frac{N}{A_w} = \frac{720000}{3700} = 194.6\, N / mm^2$$

- The design resistance per unit length of the weld:

$$F_{w,Rd} = 1963 \text{ daN/cm}^2 \text{ (calculated before)}$$

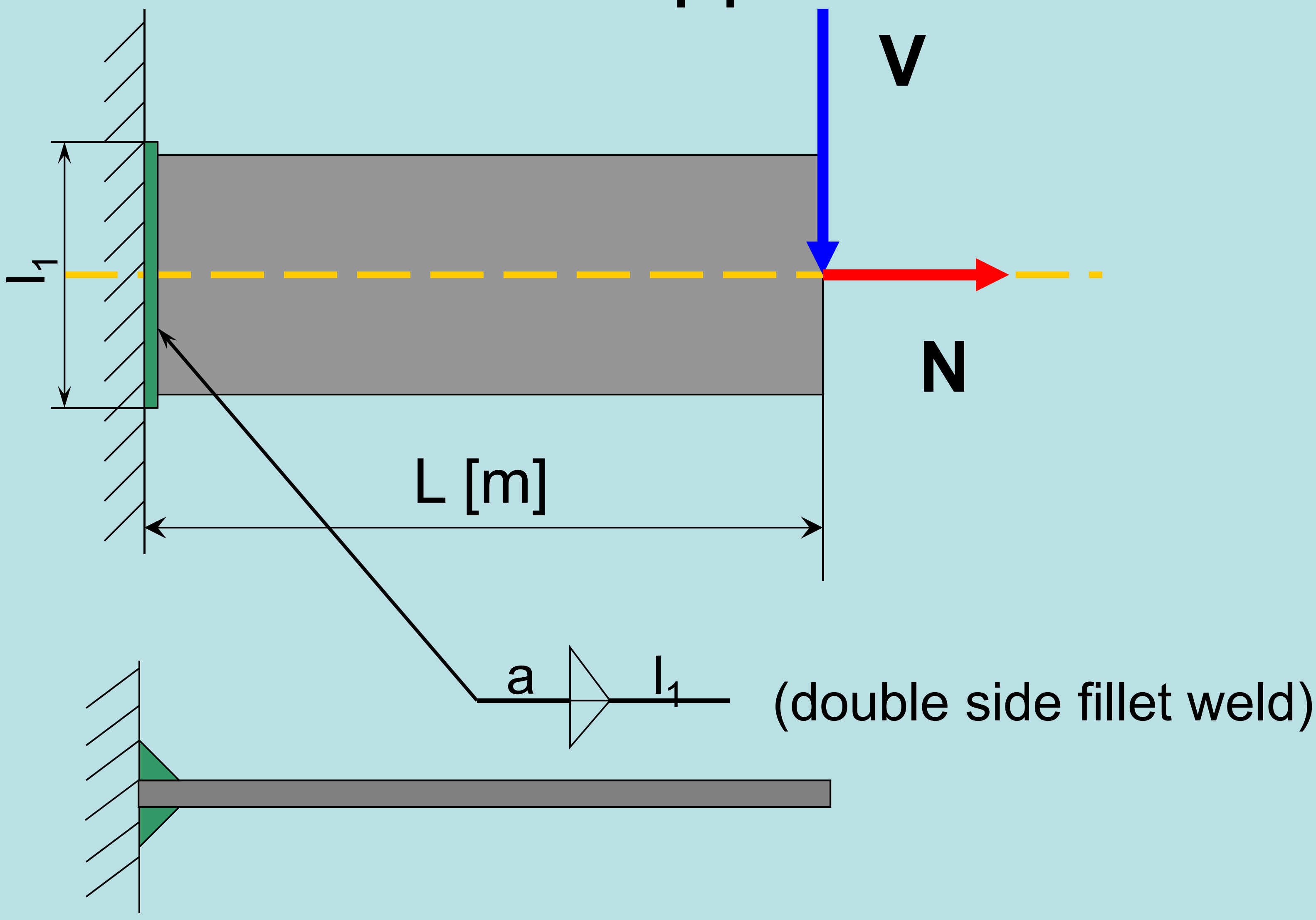
Obviously:

$$F_{w,Ed} < F_{w,Rd}$$

This concludes the checking procedure.

PART 2:
Design of a fillet weld connection in bending and shear (using directional method, ch.4.5.3.2)

Cantilever plate under shear and axial force applied at its end



Initial data:

- Cantilever span: L=1,2 m
- Loading at cantilever end:
- V = 150 kN
- N = 100 kN
- Steel grade (of the plate): S355
- Plate cross-section = 20 X 500 mm
- Welded connection using a double side fillet weld

Required:

- Checking of the fillet weld connection under bending and shear for a weld throat thickness:

  a = 10 mm

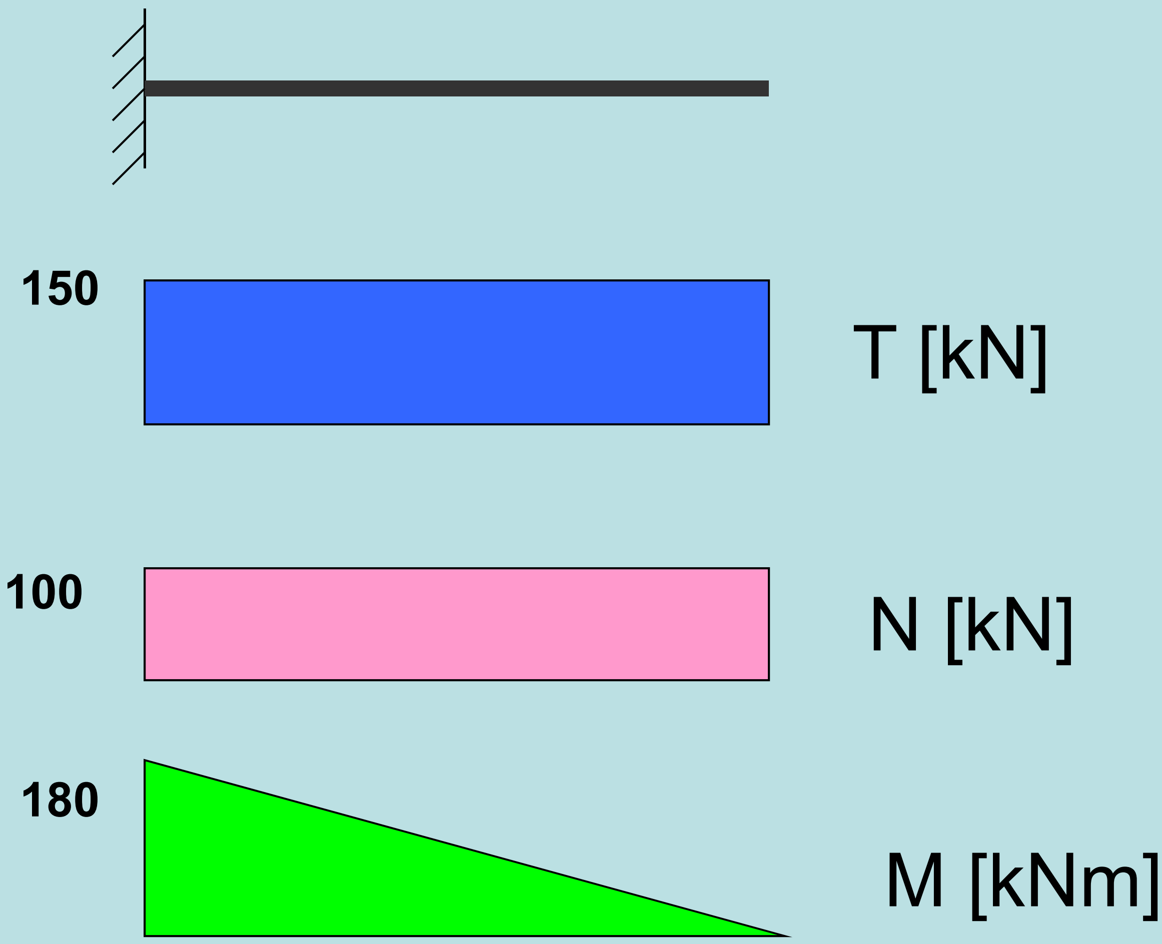
- Two such fillet welds are used to connect the cantilever onto the support

- (Effective length of the weld: l_1 = 500 mm)

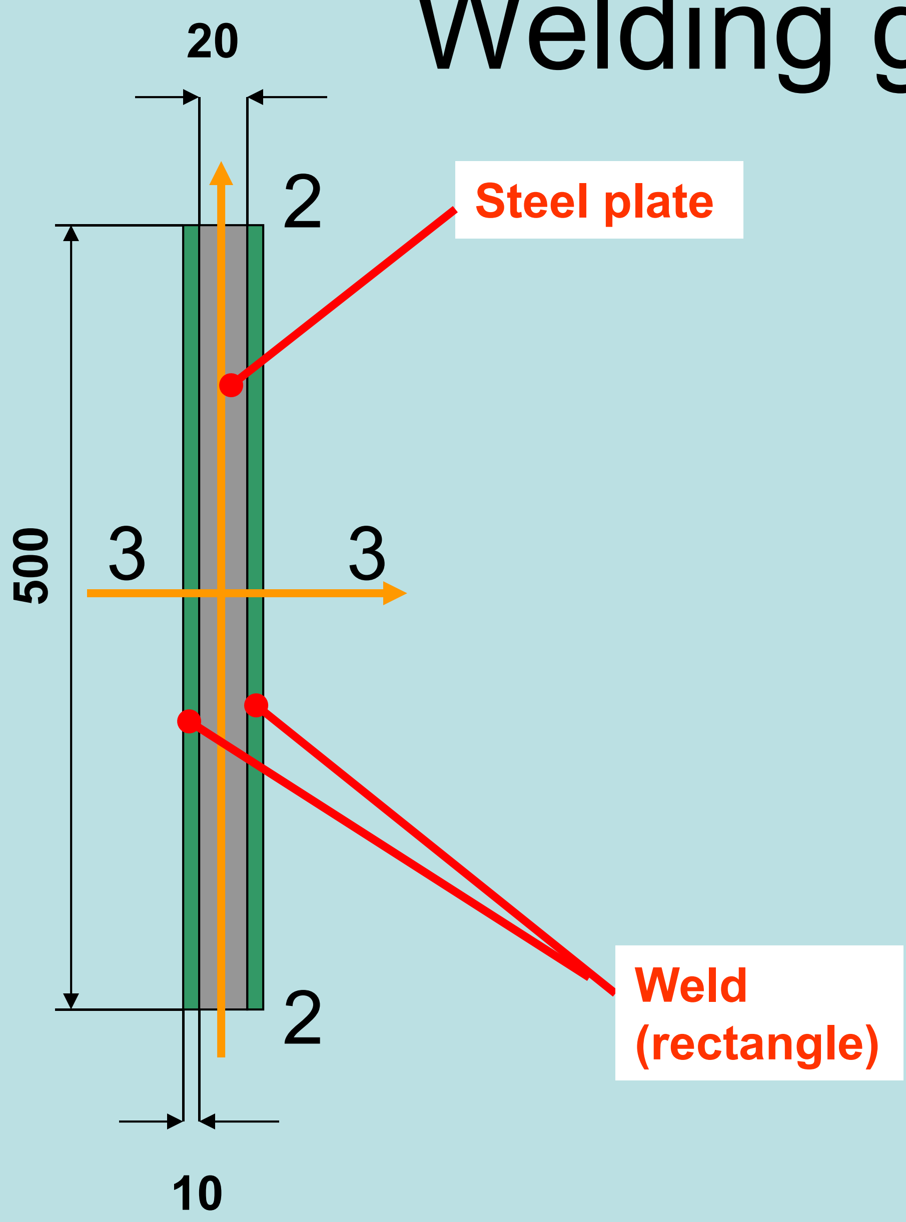
Resulting data:

- For S355 steel:
- $f_y = 355\ N/mm^2$
- $f_u = 520\ N/mm^2$

Diagrams of internal efforts:



Welding geometry:



Geometrical characteristics of the fillet weld (two 1,0 x 50,0 rectangles):

Weld area:

$$A_w = 2 \cdot 10 \cdot 500 = 10000 \text{ mm}^2$$

Section modulus of the two weld rectangles (fillet weld):

$$W_3 = (10 \times 500^2 / 6) \times 2 = 833000 \text{ mm}^3$$

Correspondence between internal efforts and weld stresses:

- The resistance of the weld has to be checked under a complex state of internal efforts (N,T,M) generating different types of stresses, i.e.

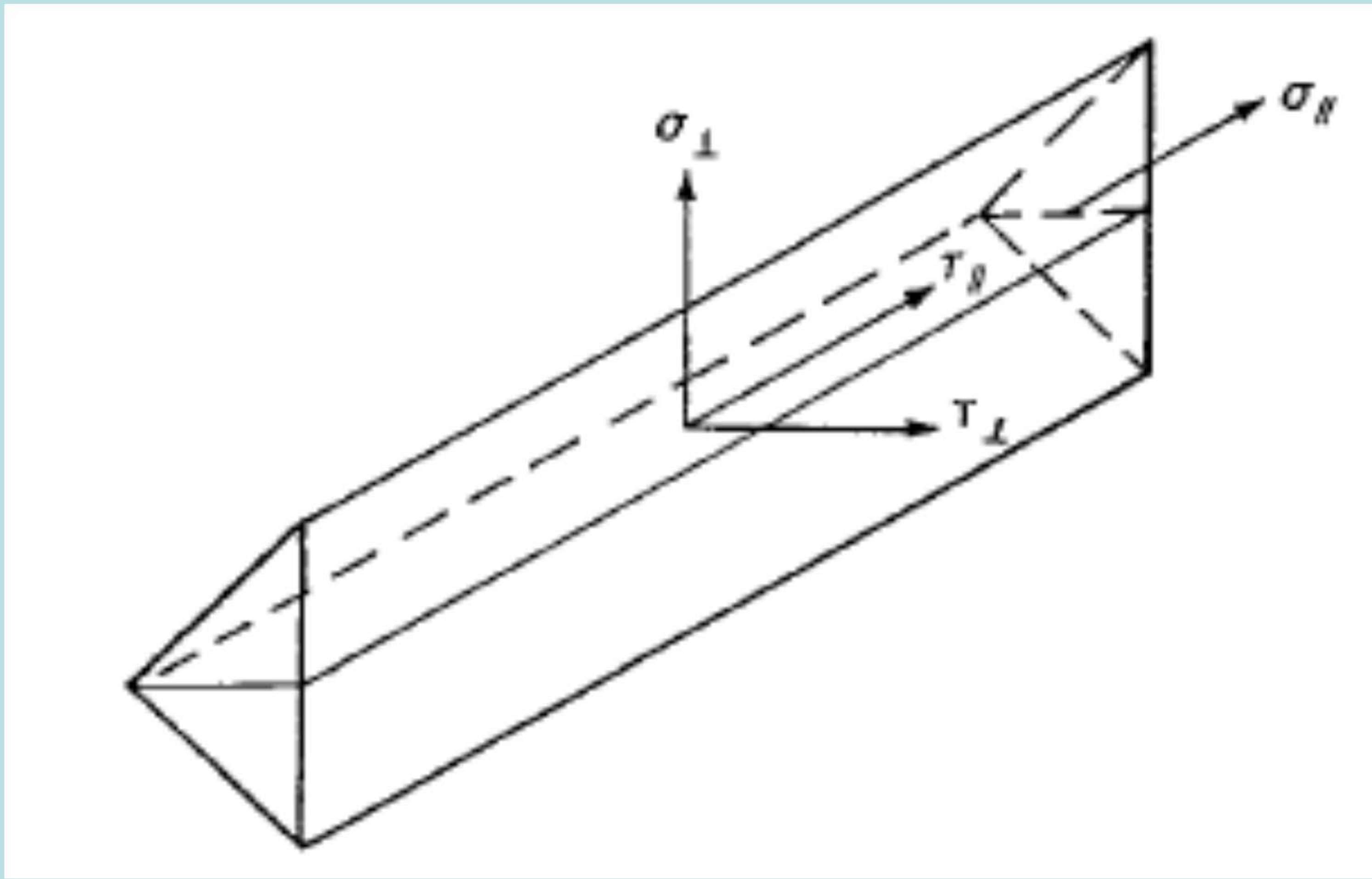
  N = generating ($\sigma_{\perp}^{N}$);

  T = generating (τ_{II});

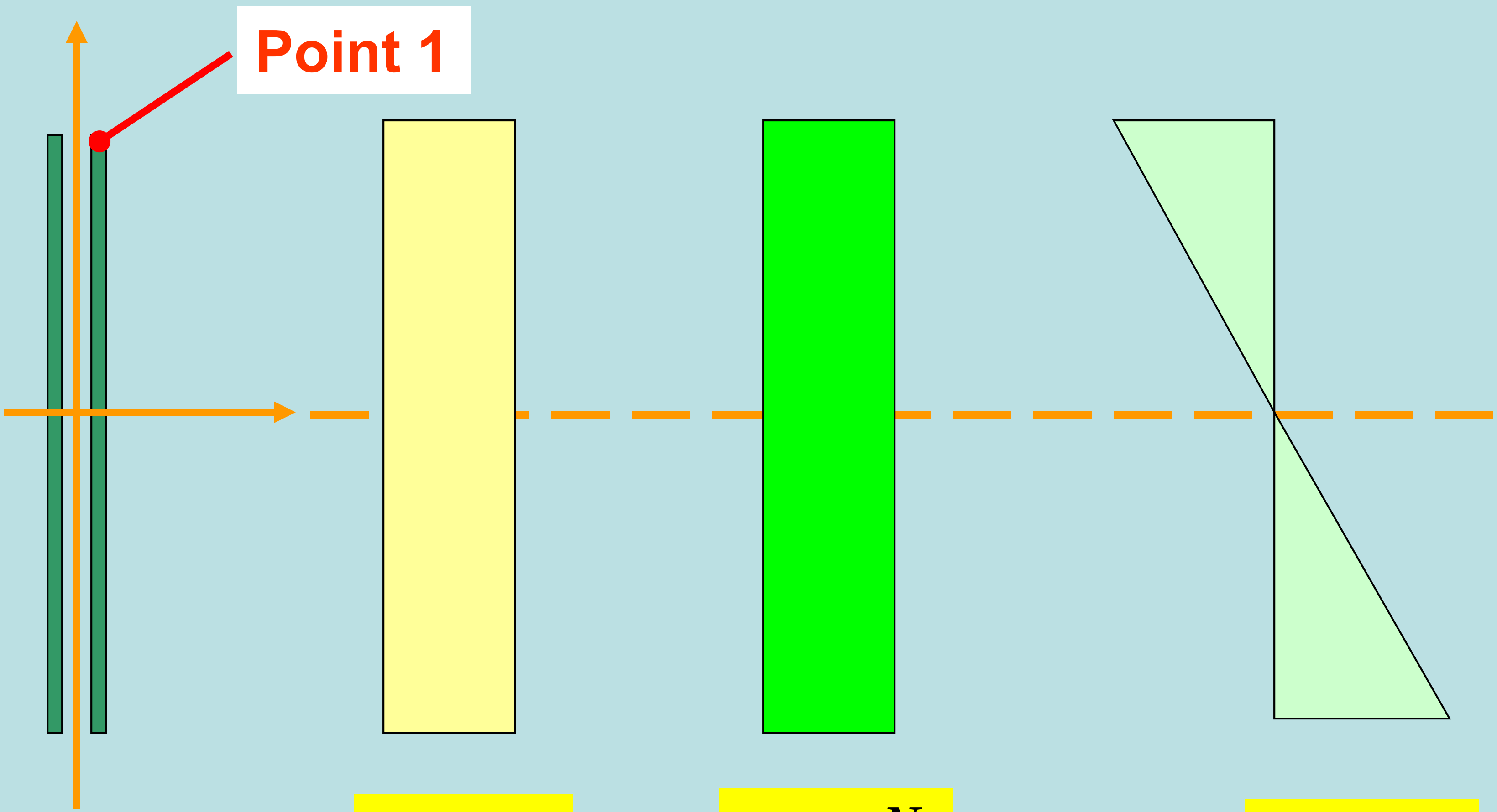
  M = generating ($\sigma_{\perp}^{M}$): variable;

Observation: $\tau_{\perp} = 0$!

Weld 3D state of stress in the code (fig. 4.5):



Stress diagrams on fillet weld:



$$\tau_{II} = \frac{V}{A_w}$$

$$\sigma_{\perp}^{N} = \frac{N}{A_w}$$

$$\sigma_{\perp}^{M} = \frac{M}{W_3}$$

Checking =performed in point 1 using the following stresses:

($\tau_{\perp}$=0 !) = in the weld plan, perpendicular to weld and constant all over the height

(τ_{II}) = in the weld plan, parallel to the weld and constant all over the height

($\sigma_{\perp}$) = perpendicular to welding plan and variable all over the height (maximum value in point 1)

Calculation of stress values:

$$\begin{cases} \tau_{II} = \dfrac{V}{A_w} = \dfrac{12000}{100,0} = 120\ daN/cm^2 \\ \sigma_{\perp}^{N} = \dfrac{N}{A_w} = \dfrac{10000}{100,0} = 100\ daN/cm \\ \sigma_{\perp}^{M} = \dfrac{M}{W_3} = \dfrac{1800000}{833} = 2161\ daN/cm^2 \\ \Rightarrow \sigma_{\perp} = 100 + 2161 = 2261\ daN/cm^2 \end{cases}$$

Checking formula for the fillet weld, according to EN 1993-1-8 (eq. 4.1):

$$\begin{cases} \left[\sigma_{\perp}^{2} + 3 \cdot \left(\tau_{\perp}^{2} + \tau_{II}^{2}\right)\right]^{0,5} \leq \dfrac{f_u}{\beta_w \cdot \gamma_{M2}} \\ \sigma_{\perp} \leq \dfrac{f_u}{\gamma_{M2}} \end{cases}$$

Where β_w= 0,9 (correlation factor from Table 4.1)

Application of the checking relations:

$$\left[2261^2 + 3\cdot\left(0^2 + 120^2\right)\right]^{0,5} = 2271\,daN/cm^2 < \frac{5200}{0,9\cdot 1,25} = 4622\,daN/cm^2$$

Checking OK !

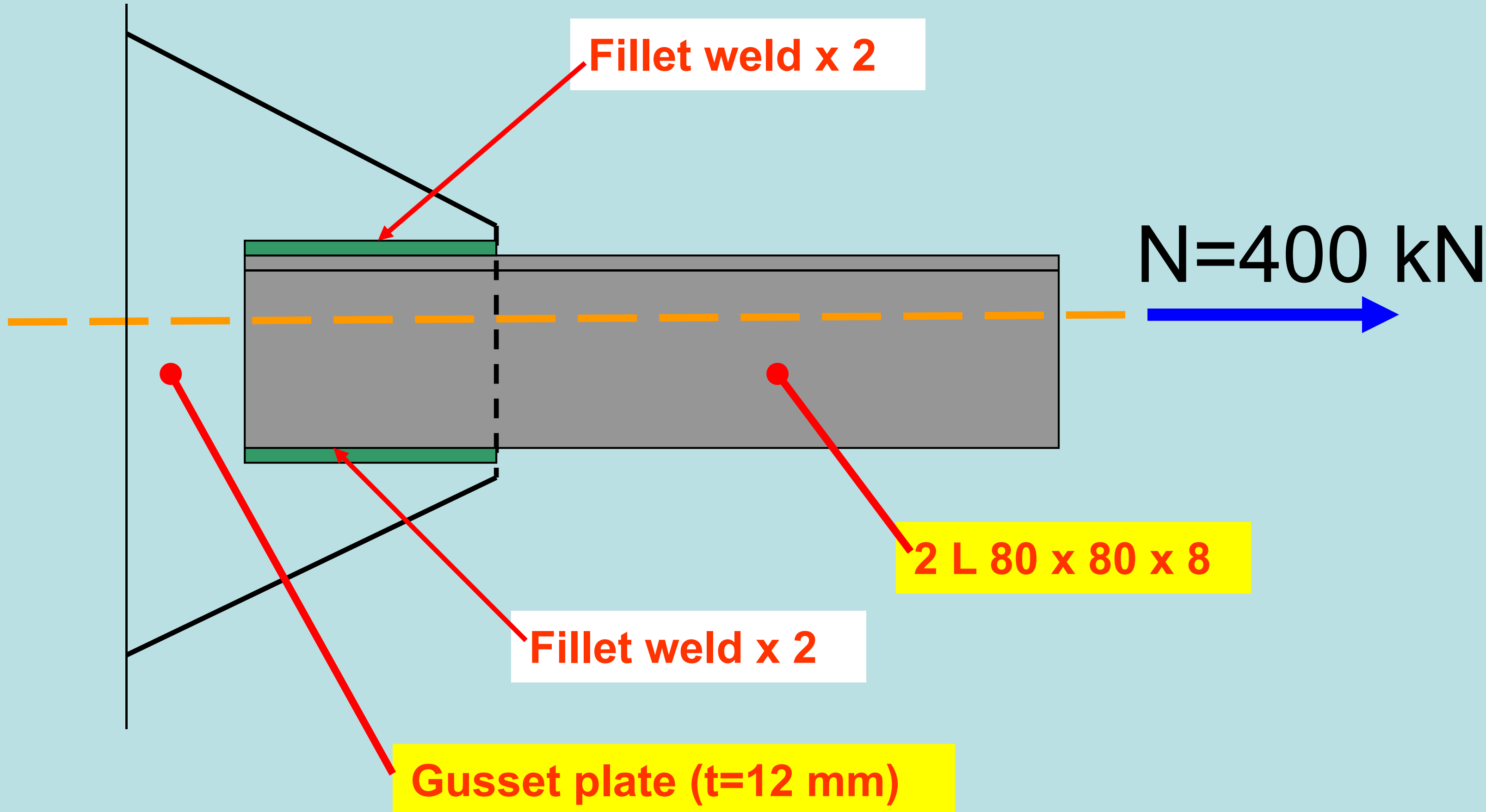
$$2261 < \frac{5200}{1,25} = 4160\,daN/cm^2$$

Checking OK !

Conclusion: Fillet weld too strong! Diminishing weld throat thickness to 6…8 mm would be recommendable (beneficial for welding procedure)!

PART 3:
Design of the fillet weld connection for a double angle section

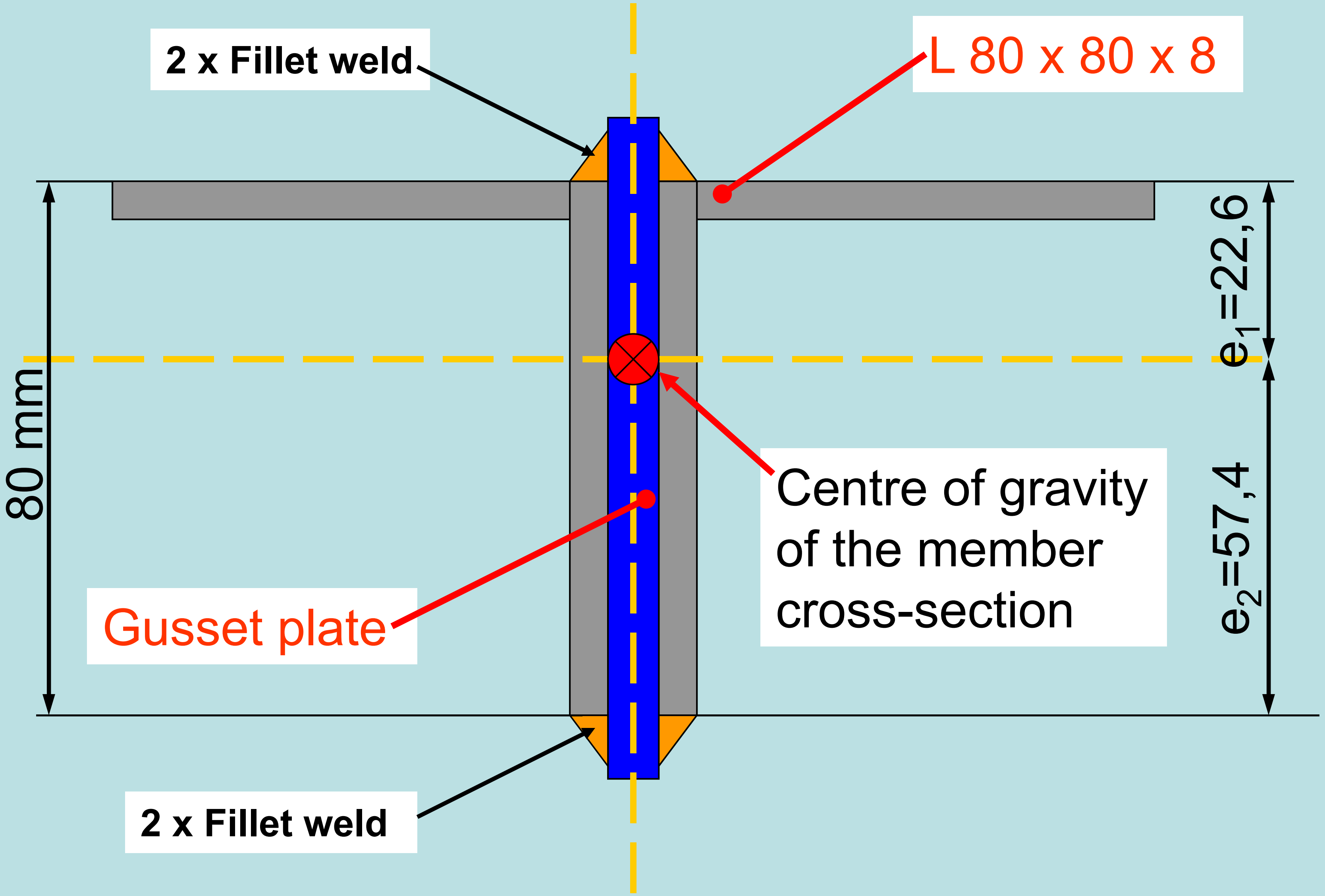
Geometry and initial data:



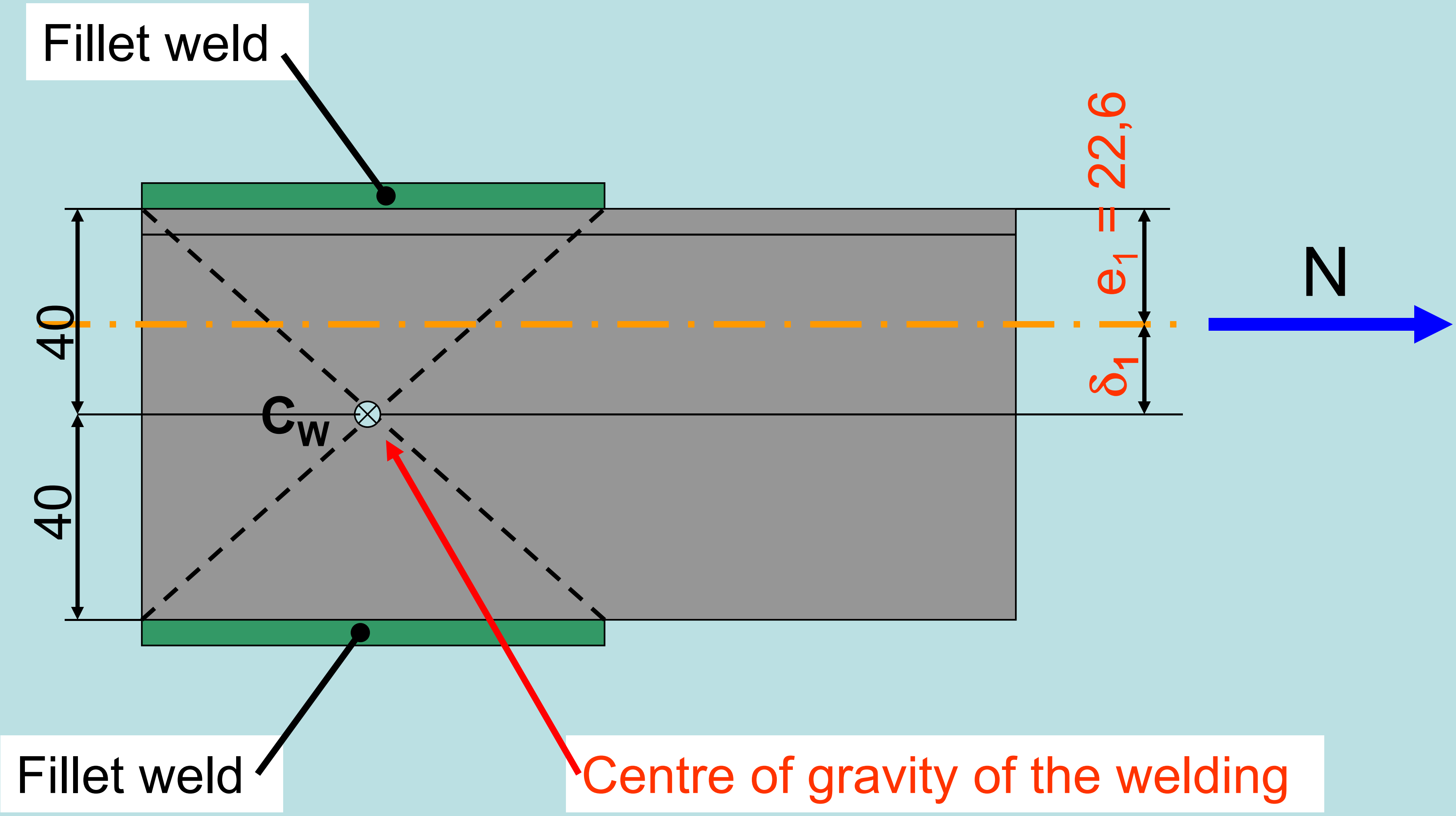
Initial data:

- Member cross section = 2 L 80x80x8
- Angle leg b = 80 mm
- Steel grade: S235
- Gusset thickness: t=12 mm
- Axial force on member: N = 300 kN
- f_y = 235 N/mm^2
- f_u = 370 N/mm^2

Member cross-section geometry:



Effect of weld eccentricity:



Explanation of eccentricity:

- The axial force N is acting at the level of the centre of gravity of the member (i.e. at distance e_1=22,6 mm from angle corner)

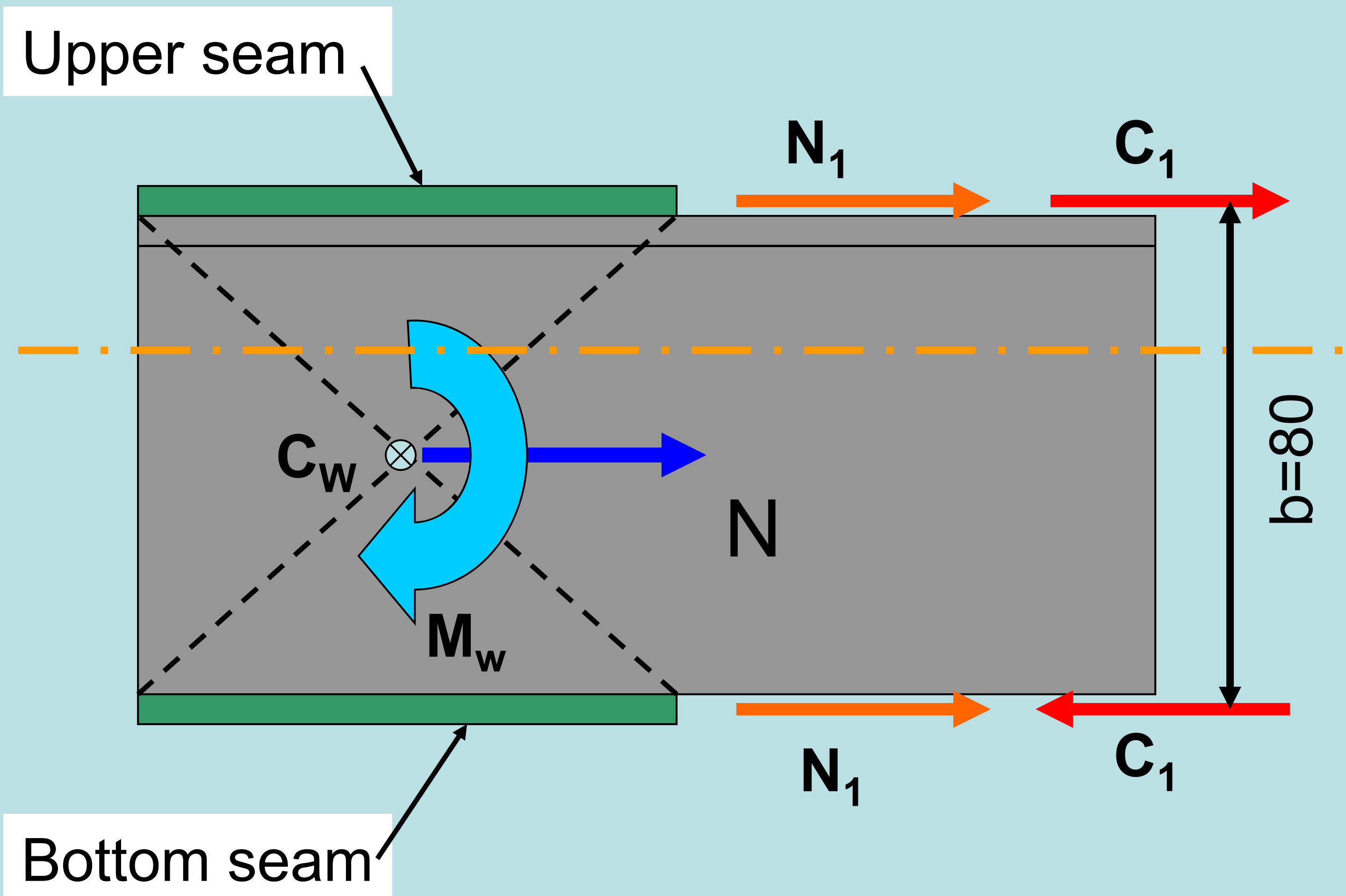
- If a symmetric welding is used (the bottom and the upper fillet weld are identical) then the centre of gravity of the welding, will be located at angle leg mid height (40 mm from angle corner).

Eccentricity (2):

- The distance δ_1=40mm-22,6mm between the centre of gravity of the welding and the direction of the force is called "eccentricity"
- The force N is an eccentric force with respect to the centre of gravity of the welding;
- Because of this eccentricity, a supplementary bending moment (M_w) appears in the plan of the welding, i.e.

$$M_w = N \cdot \delta_1$$

Reduction of the force N in the centre of gravity of the welding C_w



Distribution of the shear forces on the weld seams

- The axial force N and the bending moment M_w generate shear forces into the weld seams:

- The axial force N is equally distributed on both seams, i.e. $N_1 = N/2$;

- The bending moment generates a couple of forces: $M_w = C_1 \cdot b \Rightarrow C_1 = M_w/b$

The maximum shear effect appears in the upper seam:

- In the upper seam both components (N_1 and C_1) have the same sense: their resultant (F_R) is maximum:

$$F_R = N_1 + C_1 = \frac{N}{2} + \frac{N \cdot \delta_1}{b}$$

- In the bottom seam the components are opposite and the shear force is lower!

Simplified method to check the resistance of the upper weld:

- Checking relation:

$$F_{w,Ed} \leq F_{w,Rd}$$

in which:

$F_{w,Ed}$ = design value of the weld force per unit length

$F_{w,Rd}$ = design weld resistance per unit length

Weld dimensions are imposed:

- Weld throat thickness:

  $a = 5$ mm > a_{min}=3mm

- Weld length:

  $l_1 = 120$ mm

Calculation of the weld force per unit length:

$$\begin{cases} F_R = \dfrac{300}{2} + \dfrac{300 \cdot (40 - 22,6)}{80} = 215\,kN = 215000\,N \\ F_{w,ED} = \dfrac{F_R}{2 \cdot l_1} = \dfrac{215000}{2 \cdot 120} = 895,8\,N/mm \end{cases}$$

Calculation of the design shear strength of the weld:

$$\begin{cases} F_{w,Rd} = f_{vw.d} \cdot a \\ f_{vw.d} = \dfrac{f_u}{\sqrt{3} \cdot \beta_w \cdot \gamma_{M2}} \end{cases}$$

Where:

a= 5 mm =weld throat thickness (imposed)

β_w = 0,8 (from Table 4.1 of the code, for S235 steel)

γ_{M2} = 1,25

Calculation (2):

$$\begin{cases} f_{vw.d} = \dfrac{370}{\sqrt{3} \cdot 0{,}8 \cdot 1{,}25} = 213{,}6\, N/mm^2 \\ F_{w,Rd} = a \cdot f_{vw.d} = 5 \cdot 213{,}6 = 1068\, N/mm > F_{w,ED} \end{cases}$$

Checking OK

OBSERVATION: If the relation does not check as required, the dimensions of the weld should be increased (higher value for the weld throat thickness "a" or higher value for the seam length "l_1"). The procedure is repeated until checking OK.

SECOND METHOD

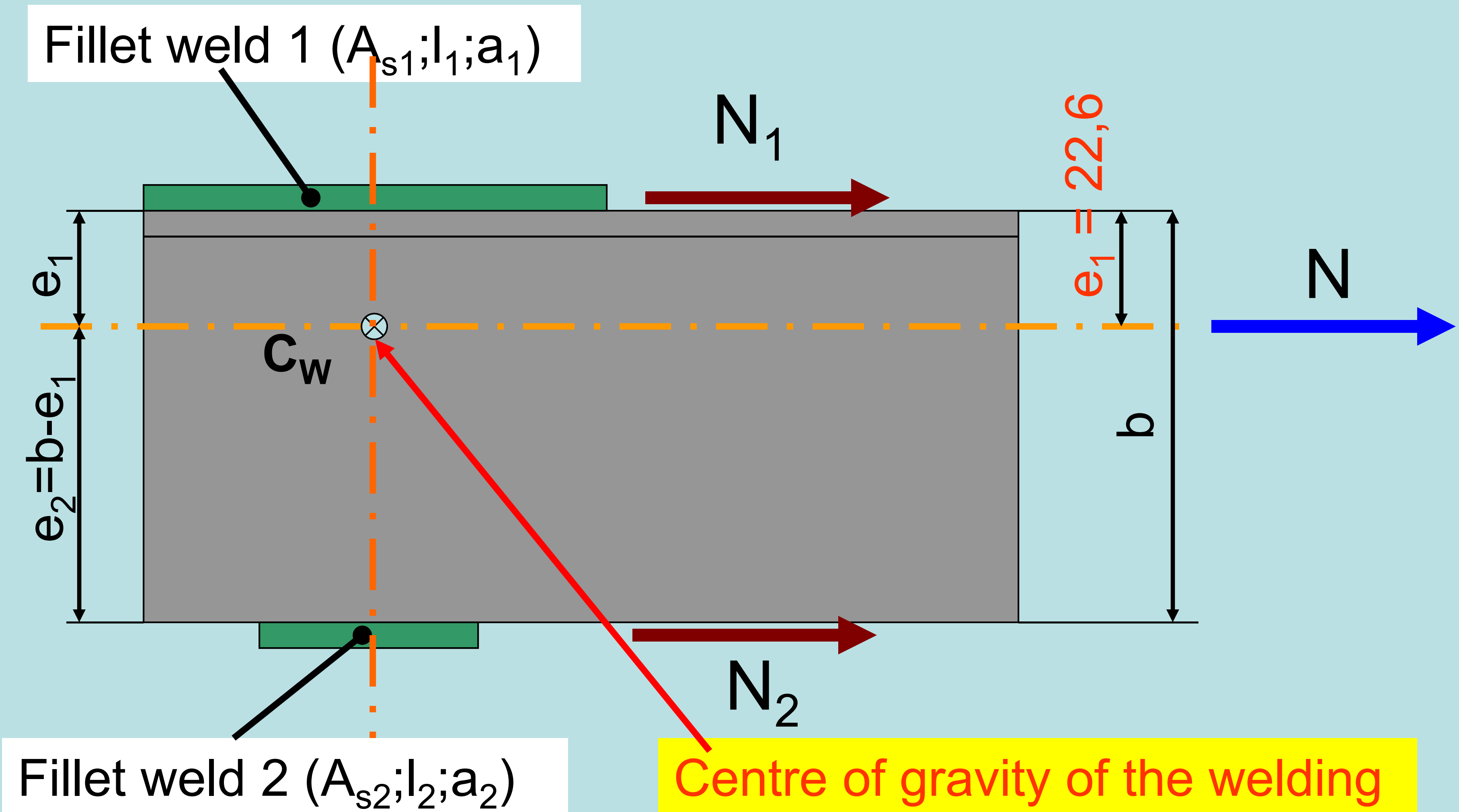
to connect the angle section member to the gusset plate:

(Improved system which avoids the eccentricity of axial force N)

How to avoid N eccentricity towards the centre of gravity of the weld?

- The centre of gravity of the weld should be moved upwards and located on member longitudinal axis (thus $\delta_1 = 0$!)
- The longitudinal axis of the member passes through the centre of gravity of the 2L80x80x8 section;
- Unequal weld seams are used to that purpose (the upper weld seam larger than the bottom weld seam)

Unequal weld connection:



Condition for the two unequal welds to have the centre of gravity on member axis:

- The static moment of the welds with respect to member axis should be identical (equal):
- Static moment of weld 1: $S_{w1}=A_{s1} \times e_1$
- Static moment of weld 2: $S_{w2}=A_{s2} \times e_2$

CONDITION: $S_{w1} = S_{w2}$

Notations:

- In previous drawing and relations:

- A_{s1}; A_{s2} = areas of the unequal welding
- l_1; l_2 =effective lengths of unequal welding
- a_1; a_2 =weld throat thickness of each welding

Total area of the weld (A_s):

- If the axial force N is acting centrically, no bending moment occurs in the connection ($M_w = 0$);
- Under axial force (N) only, a simple sizing of the weld is possible: i.e. calculation of the overall area of the welding (A_s)

- To calculate the overall area of the weld (A_s), the following equation of equilibrium is used:

$$N = A_s \cdot f_{vw.d} \Rightarrow A_s = \frac{N}{f_{vw.d}}$$

- Where:

$$f_{vw.d} = \frac{f_u}{\sqrt{3} \cdot \beta_w \cdot \gamma_{M2}} = \frac{370}{\sqrt{3} \cdot 0,8 \cdot 1,25} = 213,6\, N / mm^2$$

- The overall (total) area of the weld results:

$$A_s = \frac{N}{f_{vw.d}} = \frac{300000}{213,6} = 1404\, mm^2$$

- This is the sum of unequal areas for the upper and bottom welds:

$$A_s = A_{s1} + A_{s2}$$

However, the problem is not yet solved !

- The final purpose of the designer is to find the effective length (l) and the throat thickness (a) for each of the two unequal fillet welds;

- Therefore, the unknown elements in this stage of the problem are:

  - l_1 and a_1 for weld 1 (and A_{s1}=2x l_1 x a_1);
  - l_2 and a_2 for weld 2 (and A_{s2}=2x l_2 x a_2);.

To find the unknown dimensions, we will use the previously established relations, as a system of equations:

$$\begin{cases} A_{s1} \cdot e_1 = A_{s2} \cdot e_2 \\ A_{s1} + A_{s2} = A_s \end{cases}$$

Equal static moments

Overall area of welding

In upper system, A_{s1} and A_{s2} are the unknown

By solving the system, the unknown values of area result:

$$\begin{cases} A_{s1} = A_s \cdot \dfrac{e_2}{e_1 + e_2} = A_s \cdot \dfrac{b - e_1}{b} \\ A_{s1} = A_s \cdot \dfrac{e_1}{e_1 + e_2} = A_s \cdot \dfrac{e_1}{b} \end{cases}$$

In which “b” is the length of angle leg and “e_1” is the distance from angle corner to angle centre of gravity. Both these values are known (found in profile tables for angle section)!

In our particular case:

$$\begin{cases} A_{s1} = 1404 \cdot \dfrac{80 - 22{,}6}{80} = 1007\, mm^2 \\ A_{s2} = 1404 \cdot \dfrac{22{,}6}{80} = 397\, mm^2 \end{cases}$$

To find weld unknown dimensions, we write:

$$\begin{cases} A_{s1} = 1007 = 2 \cdot l_1 \cdot a_1 \\ A_{s2} = 397 = 2 \cdot l_2 \cdot a_2 \end{cases}$$

Again, this is a typical engineer problem: two equations and four unknown!

- To solve the problem, the values of the throat thickness a_1 and a_2 are imposed
- It is also recommended that $a_1=a_2+1mm$ (in order to avoid excessive length l_1 of upper weld seam)
- Imposing: $a_2=4mm$ > $a_{min}=3mm$, then a_1 results: $a_1=4mm+1mm = 5\ mm$

The unknown effective length for the unequal welding result:

$$\begin{cases} A_{s1} = 1007 = 2 \cdot l_1 \cdot 5 \Rightarrow l_1 = 100\,mm \\ A_{s2} = 397 = 2 \cdot l_2 \cdot 4 \Rightarrow l_2 = 50\,mm \end{cases}$$

Checking of the code minimum length condition for each weld:

$l_1 > 6 \cdot a_1 = 6 \times 5{,}0 = 30$ mm;

$l_2 > 6 \cdot a_2 = 6 \times 4{,}0 = 24$ mm; $l_2 > 30$ mm

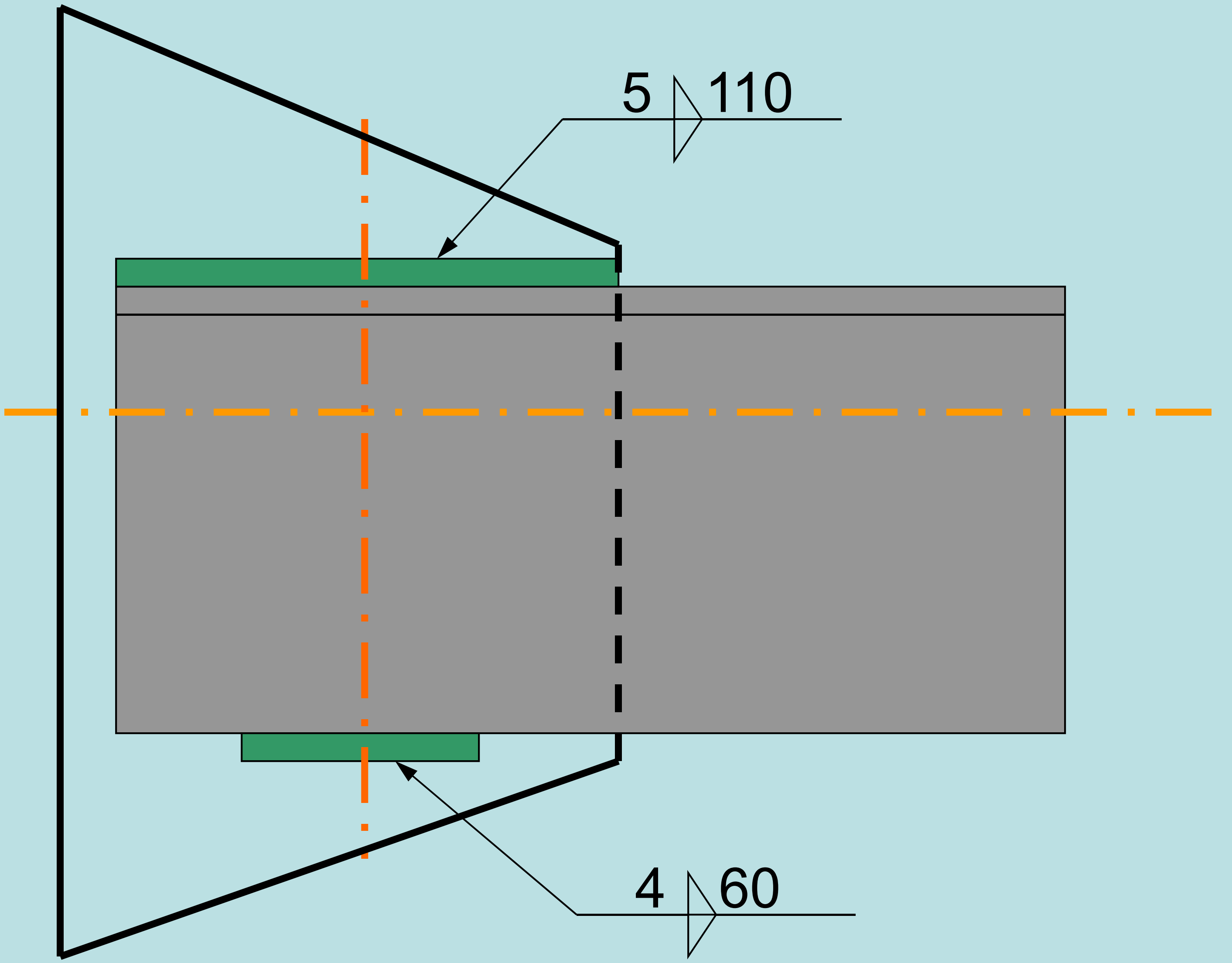
The real length of the welding:

- The real length of the welding (written on the weld symbol on the technical drawings of the project) should include the end returns of the weld seam:
- $l_{1R}=l_1+2\cdot a_1$ (rounding to an increased value multiple of 5 mm!)
- $l_{2R}=l_2+2\cdot a_2$ (rounding to an increased value multiple of 5 mm!)

In our particular case:

- $l_{R1} = l_1 + 2 \cdot a_1 = 100 + 2 \cdot 5 = 110$ mm
- $l_{R2} = l_2 + 2 \cdot a_2 = 50 + 2 \cdot 4 = 58$ mm $\cong 60$ mm

Symbols for the welding:



Final checking of the unequal welding:

- The axial force N is distributed in unequal parts to each welding, using the same principle (in fact proportional to the area of each weld):

$$\begin{cases} N_1 = N \cdot \dfrac{b - e_1}{b} = 300000 \cdot \dfrac{80 - 22{,}6}{80} = 215250\, N \\ N_2 = N \cdot \dfrac{e_1}{b} = 300000 \cdot \dfrac{22{,}6}{80} = 84750\, N \end{cases}$$

To check the welding the simplified procedure will be used:

- Checking relation:

$$F_{w,Ed} \leq F_{w,Rd}$$

in which:

$$\begin{cases} F_{w,Ed1} = \dfrac{N_1}{2 \cdot l_1} = \dfrac{215250}{2 \cdot 100} = 1076\ N/mm \\ F_{w,Ed2} = \dfrac{N_2}{2 \cdot l_2} = \dfrac{84750}{2 \cdot 50} = 848\ N/mm \end{cases}$$

The design weld resistance per unit length:

$$\begin{cases} F_{w,Rd1} = a_1 \cdot f_{vw.d} = 5{,}0 \cdot 213{,}6 = 1068\, N/mm \cong F_{w.ED1} \\ F_{w,Rd2} = a_2 \cdot f_{vw.d} = 4{,}0 \cdot 213{,}6 = 854{,}4\, N/mm > F_{w.ED2} \end{cases}$$

Checking OK !