Application nr. 7
(Connections)

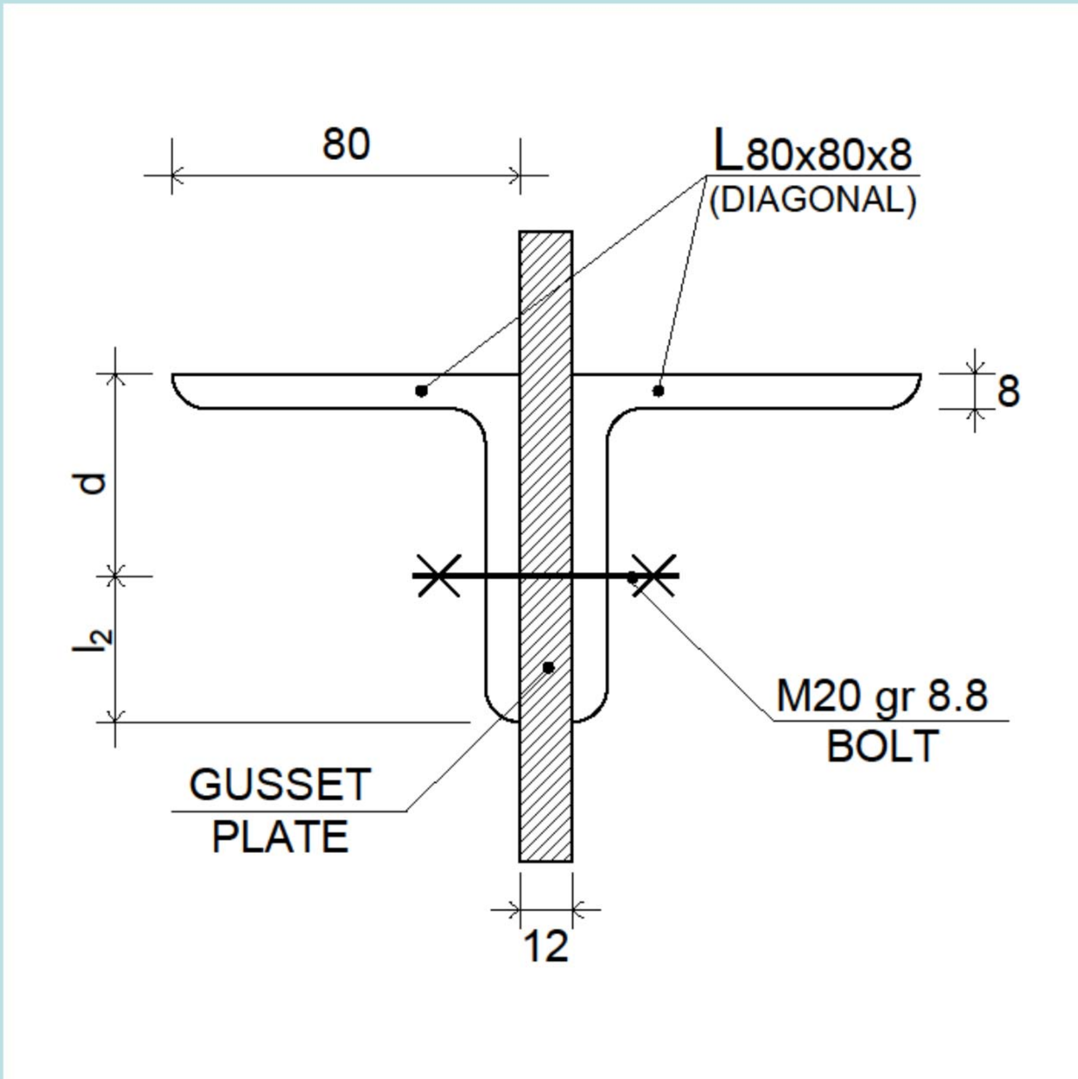
Strength of bolted connections
to EN 1993-1-8 (Eurocode 3, Part 1.8)

PART 1:
Bolted shear connection
(Category A – bearing type, to EN1993-1-8)

Structural element

- Tension diagonal made of two angle sections, with bolted end connection on gusset plate;
- This is a shear type connection category A to EN 1993-1-8 (shear connection of bearing type)

Diagonal cross-section with bolted connection:



Initial data:

- Axial load acting on diagonal: N=+46.000 daN = 460 kN
- Steel grade for angle section and gusset plate: S235
- Angle section type: L 80x80x8
- Required bolts: M20 gr.10.9
- Gusset plate thickness: t=12 mm
- Bolt nominal diameter d=20 mm =2,0 cm

Resulting data:

- For the steel in the angle section and gusset plate:

  f_y = 2350 daN/cm^2 = 235 N/mm^2

  f_u = 3700 daN/cm^2 = 370 N/mm^2

Grade indicators

- For the steel in the M20 gr.10.9 bolts:

f_{yb} =10 x 9 = 90 daN/mm^2 = 900 N/mm^2

f_{ub} =(10) x 10 =100 daN/mm^2 =1000N/mm^2

Grade indicator

a) Sizing of the bolt group

- This is a shear connection of bearing type
- The sizing should refer to:
  - The shear resistance of the bolt
  - The bearing resistance of the bolt

Shear resistance of the bolt

- Two shear planes exist in the end connection of the member
- The shear resistance of the bolt per shear plane is (non-threaded shank in shear):

$$F_{v,Rd} = \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}}$$

$$A = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot 2^2}{4} = 3{,}14\ cm^2$$

- α_V=0,5 (for grade 10.9 bolts)
- γ_{M2}=1,25

Shear resistance of the bolt:

- The shear resistance of the bolt for the two shear planes results:

$$2 \cdot F_{v,Rd} = 2 \cdot \frac{0,5 \cdot 10000 \cdot 3,14}{1,25} = 25.120\ daN$$

Bearing resistance of the bolt:

- The minimum thickness package in this case is the gusset plate, having a plate thickness of t=12 mm;
- This thickness is less than the sum of angle leg thickness:

$$2 \times t_1 = 2 \times 8{,}0 \text{ mm} = 16{,}0 \text{ mm} > t$$

The bearing resistance:

$$\begin{cases} F_{b,Rd} = \dfrac{k_1 \cdot f_u \cdot \alpha_b \cdot d \cdot t}{\gamma_{M2}} \\ \alpha_b = \min\left\{ \dfrac{f_{ub}}{f_u}; 1{,}0\ ; \alpha_d \right\} \end{cases}$$

In our application:

$$\frac{f_{ub}}{f_u} = \frac{10000}{3700} = 2{,}70 > 1{,}0$$

M20 gr.10.9 bolts are usually installed in clearance holes:

- A usual hole clearance would be of 2 mm for M20 bolts (diameter less than 24 mm)
- Consequently, the hole diameter (d_0) results:

$$d_0 = 22 \text{ mm} > d = 20 \text{ mm}$$

Calculation of the α_d value

The end distance of the bolt (i.e. distance between the last bolt of the group and end of the diagonal profile)

$e_1 = 1,5 \times d_0 = 33,0$ mm > $e_{1.min} = 1,2 d_0$

$$\begin{cases} \alpha_d = \dfrac{e_1}{3 \cdot d_0} = \dfrac{33}{3 \cdot 22} = 0,5 \\ \Rightarrow \alpha_b = 0,5 \end{cases}$$

Coefficient k_1 in the bearing resistance $F_{b,Rd}$ formula:

- The coefficient k_1 is the minimum between following values:

$$
\begin{cases}
k_1 = \min\left\{2{,}8 \cdot \dfrac{e_2}{d_0} - 1{,}7 \; ; \; 2{,}5\right\} \\
2{,}8 \cdot \dfrac{e_2}{d_0} - 1{,}7 = 2{,}8 \cdot \dfrac{1{,}5 \cdot d_0}{d_0} - 1{,}7 = 2{,}5 \\
\Rightarrow k_1 = 2{,}5
\end{cases}
$$

The bearing resistance of the gusset plate for M20 bolt results:

$$F_{b,Rd} = \frac{2{,}5 \cdot 3700 \cdot 0{,}5 \cdot 2{,}0 \cdot 1{,}2}{1{,}25} = 8880\ daN$$

Sizing of the bolt group:

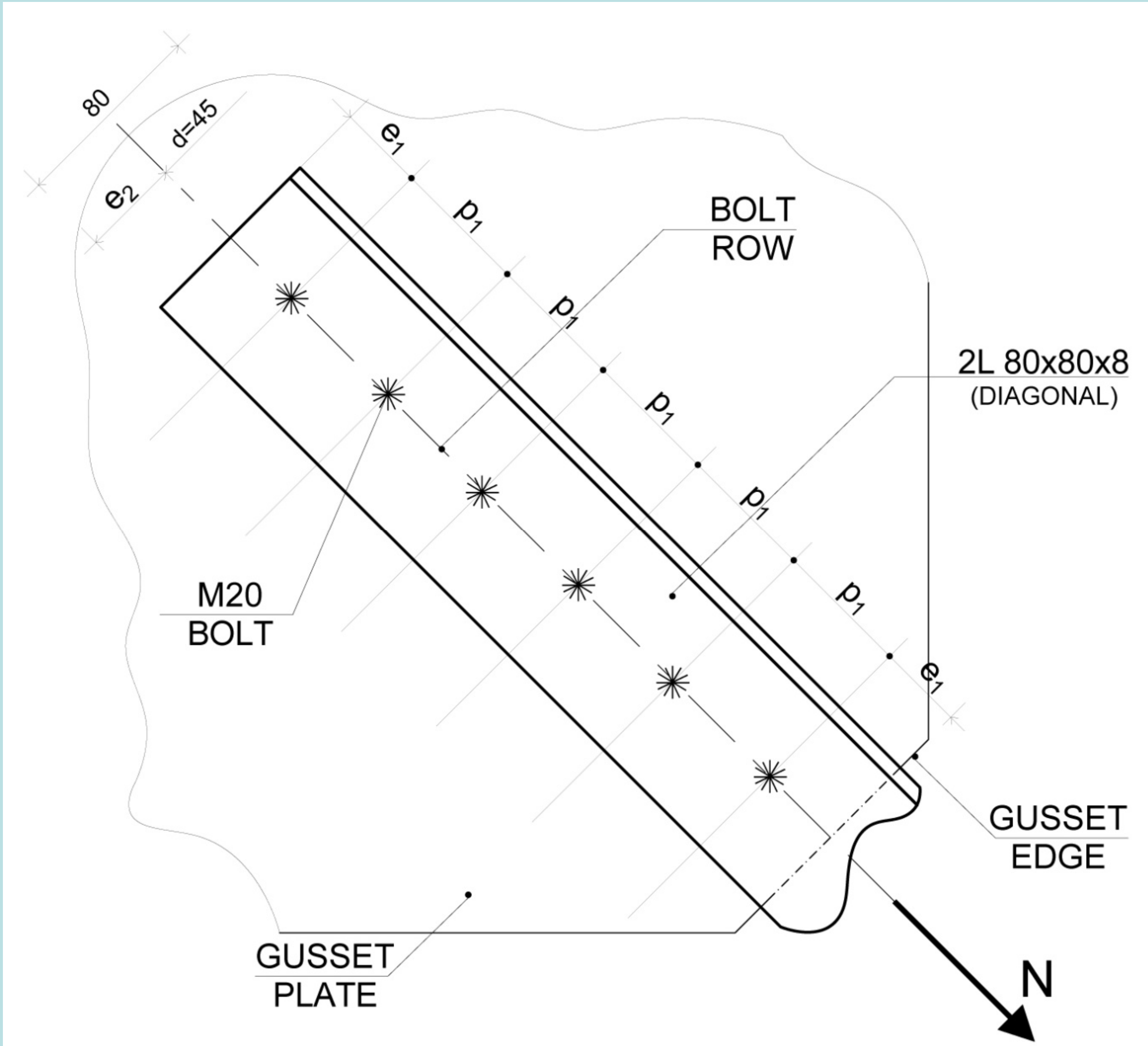
- The capacity of one bolt in the group (F_1) is the minimum between shear and bearing resistance:

$$F_1 = \min\left\{2 \cdot F_{v,Rd} \, ; F_{b,Rd}\right\} = 8880 \; daN$$

- The necessary number of bolts results as (supposing an equal distribution of the shear force):

$$n_b = \frac{N}{F_1} = \frac{46000}{8880} = 5{,}18 \cong 6{,}0 \, bolts$$

b) Bolt arrangement and checking of the bolt group resistance



In the previous drawing showing the bolted connection final geometry:

e_1 = distance between the first / last bolt of the group and gusset edge / angle end (measured parallel to axial force direction)

e_2 = distance between bolts and edge measured perpendicular to axial force direction

p_1 = distance between consecutive bolts measured parallel to axial force direction

In the first phase we know only the number of bolts (i.e. 6 bolts):

- Distances e_1,e_2, p_1 are initially unknown and have to be chosen by the designer according to the recommendations of Table 3.3 from EN1993-1-8
- For e_1,e_2,and p_1 we generally choose rounded values (i.e. multiple of 5 mm):

e_1=35 mm =1,59d_0>1,2d_0

e_2=35 mm =1,59d_0>1,2d_0

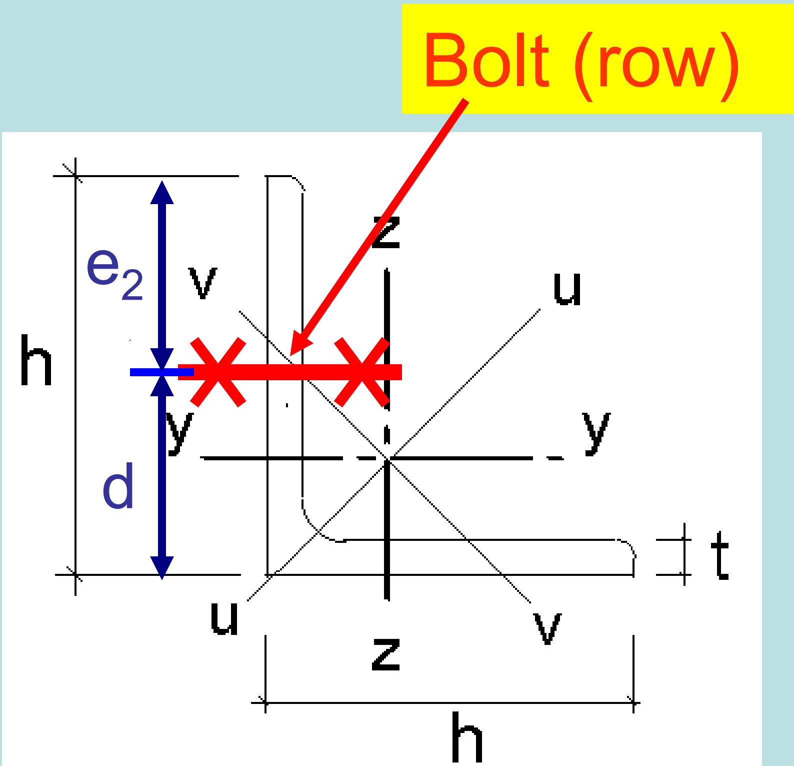
p_1=55 mm =2,50d_0>2,2d_0

- As a principle e_1,e_2,and p_1 should be chosen closer to the minimum recommended values in order to get a connection as small as possible;

- The 6 bolts resulting from the previous calculation are disposed on a single bolt row;

- The number of bolts in the row is six, i.e. the maximum permitted number in a row allowing for an equal distribution of the shear force on the connection.

Observation regarding e_2 distance:



In an angle section with the length of the leg = h, the recommended position of the bolt row (measured from the corner) is:

$d = h/2 + 5$ mm

In our case, $d=80/2 + 5 = 45$ mm

That solves also the problem for the bolt-to-edge distance, measured on perpendicular direction to the axial force N (e_2) i.e.:

$e_2 = h-d = 80 – 45 = 35$ mm

Thus $e_2 = 1{,}59d_0 > 1{,}2d_0$

Checking of the bolt group (using actual connection geometry):

- Shear resistance per bolt:

$$2 \cdot F_{v,Rd} = 25.120\, daN$$

- Bearing resistance per bolt:

$$F_{b,Rd} = \frac{k_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}}$$

$$\begin{cases} k_1 = 2{,}8 \cdot \dfrac{e_2}{d_0} - 1{,}7 = 2{,}8 \cdot \dfrac{35}{22} - 1{,}7 = 2{,}75 > 2{,}5 \\ \Rightarrow k_1 = 2{,}5 \end{cases}$$

Calculation of the (α_b) value:

$$\begin{cases} \alpha_d = \dfrac{e_1}{3 \cdot d_0} = \dfrac{35}{3 \cdot 22} = 0{,}53 \\ \dfrac{f_{ub}}{f_u} = \dfrac{10000}{3700} = 2{,}70 \\ \Rightarrow \alpha_b = \min\left\{ \alpha_d ; \dfrac{f_{ub}}{f_u} ; 1{,}0 \right\} = 0{,}53 \end{cases}$$

- Bearing resistance of the gusset plate:

$$F_{b,Rd} = \frac{2{,}5 \cdot 0{,}53 \cdot 3700 \cdot 2{,}0 \cdot 1{,}2}{1{,}25} = 9413\, daN$$

- Bolt resistance is:

$$\min\left\{2F_{v,Rd}\,; F_{b,Rd}\right\} = \min\left\{25120; 9413\right\} = 9413\, daN$$

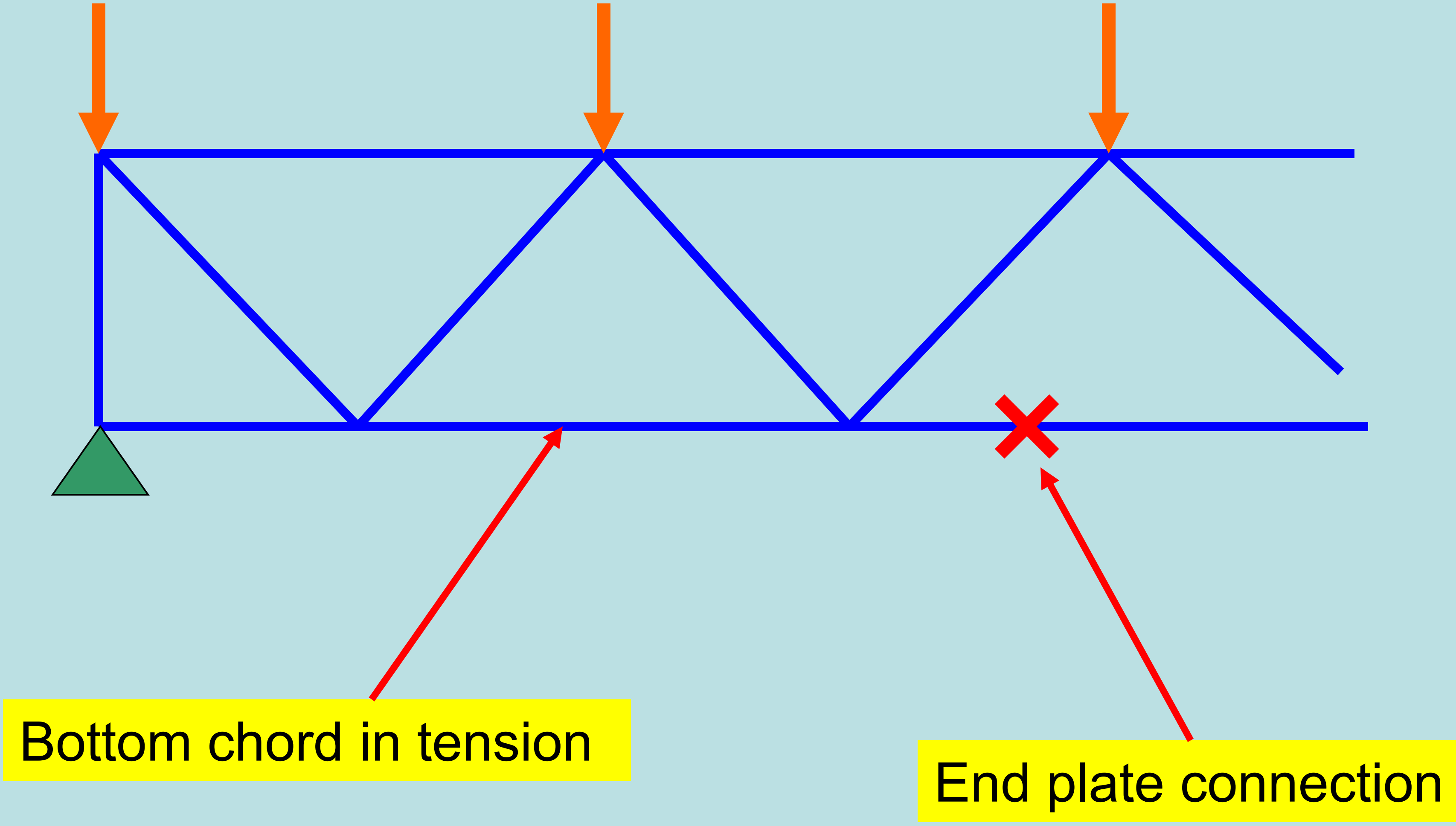
- The design shear force acting on the bolt is obtained admitting an equal (even) distribution of the axial force N on all bolts;
- This is acceptable because the code recommendation to provide a maximum number of 6 bolts per row has been respected in our example;
- Equivalently, between the first and the last bolt of the row we have the distance = 5x55mm =275 mm < 15·d = 15 x 20 mm = 300 mm

$$F_{v,Ed} = \frac{N}{6} = \frac{46000}{6} = 7.666\,daN < 9413\,daN = F_{b,Rd}$$

- Checking according to Code Table 3.2 is OK !

PART 2:
Bolted connection in tension only (end-plate splice) –Category D – non-preloaded to EN 1993-1-8

Position of the end plate splice (connection) in a lattice girder



Initial data:

- Bottom chord in tension of a lattice girder
- Bottom chord profile: circular hollow section: CHS-Φ121x8 mm
- Steel grade: S235
- Axial force N=+50.000 daN = 500 kN
- Required connection: end-plate splice
- Required bolts: M16 gr.8.8
- End plate thickness t=16 mm
- Bolt nominal diameter d=16 mm = 1,6 cm

Observation on the end plate thickness value (t=16 mm):

- As an empirical rule of good practice, for any end plate it is recommended to choose a thickness value greater-equal to the diameter of the employed bolts in the connection;
- Thus, here t = d = 16 mm !
- This is generally avoiding the prying effect in the connection (excessive deformability of the end plate)

Resulting data:

- For the required steel grade:

  $f_y = 235\ N/mm^2$

  $f_u = 370\ N/mm^2$

- For the required bolt grade:

  $f_{yb} = 8 \times 8 = 64\ daN/mm^2 = 640\ N/mm^2$

  $f_{ub} = 8 \times 10 = 80\ daN/mm^2 = 800\ N/mm^2$

Resistant area of the M16 bolt:

- For the required M16 gr.8.8 bolts, the nominal diameter is d=16 mm = 1,6 cm
- The resistant diameter of the bolt is evaluated with: d_{res} = 0,89·d=0,89·1,6 =1,424 cm
- The resistant area results:

$$A_s = A_{res} = \frac{\pi \cdot d_{res}^2}{4} = \frac{\pi \cdot 1{,}424^2}{4} = 1{,}592\,cm^2$$

Tension resistance of M16 gr.8.8 bolt according to Table 3.4:

- The tension resistance of the bolt results from the formula:

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}} = \frac{0{,}9 \cdot 8000 \cdot 1{,}592}{1{,}25} = 9170\, daN$$

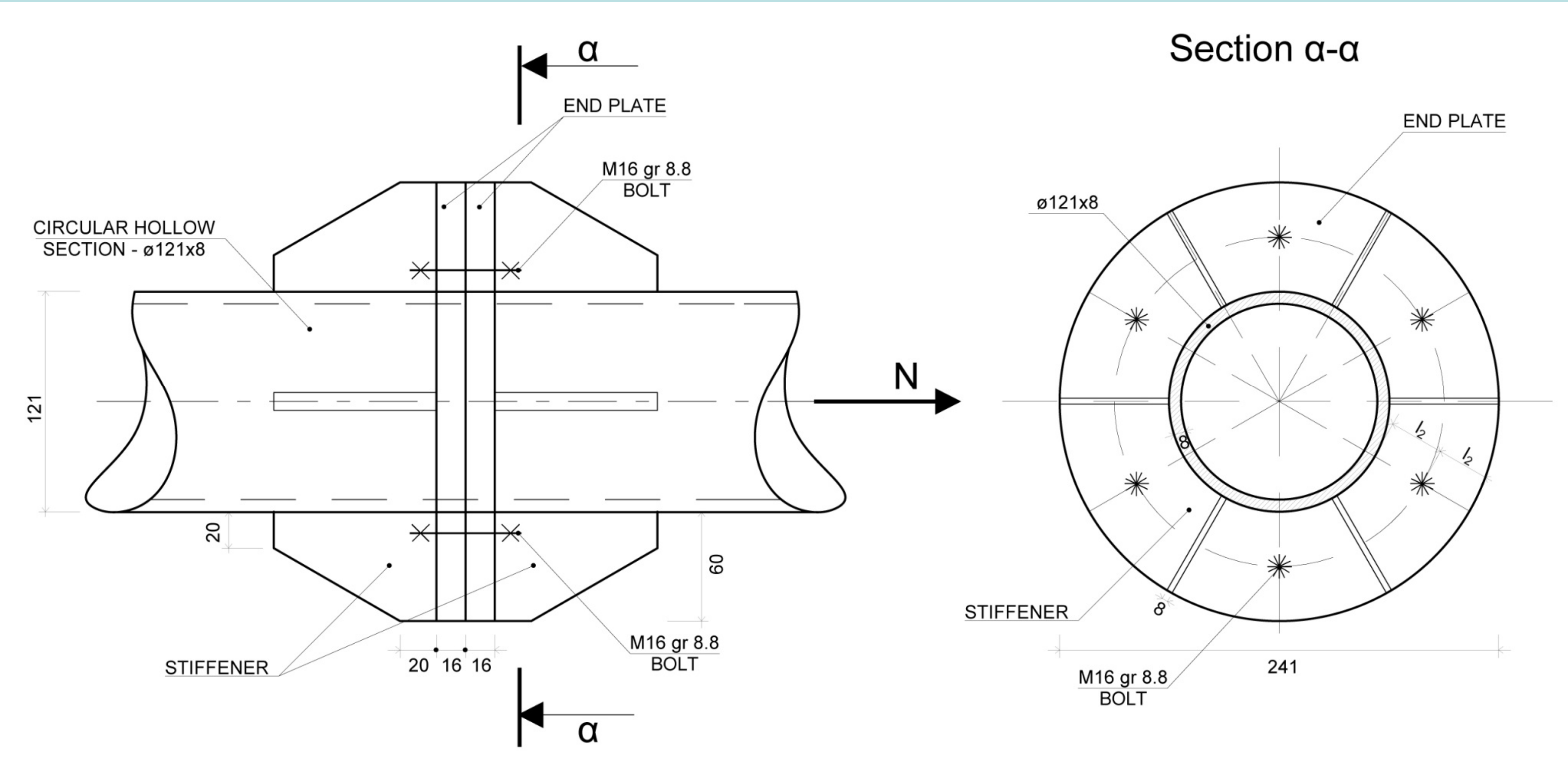
- Where A_s = tensile stress area of the bolt $=A_{res}$
- K_2 = 0,9 (to the code for regular bolts)

Sizing of the end-plate connection with bolts in tension only:

- The axial force N is equally distributed on al the bolts of the connection;
- The required number of bolts is unknown in this phase;
- The required number of M16 bolts results from the sizing procedure, i.e.:

$$n_{bolt} = \frac{N}{F_{t,Rd}} = \frac{50000}{9170} = 5{,}45 \cong 6\,bolts$$

Resulting geometry of the end-plate connection in tension:



Comment on the connection geometry (1):

- The M16 bolts are installed in clearance holes with a diameter d_0=16mm + 2mm = 18 mm

- The distances between bolt centre and the pipe wall respectively end plate edge have been taken according to Table 3.3:

  $e_1 = e_2 = 30$ mm $= 1{,}67 \cdot d_0 > 1{,}2 d_0$

Comment on the connection geometry (2):

- The provision of the stiffeners, connecting the end plate to the pipe and separating the bolts has two purposes:

  - A stronger connection between pipe and the end plate

  - Reduction of the end-plate deformability in order to eliminate prying effect (bending of the bolt shank owing to end-plate deformability)

Checking of the end-plate connection:

- The analyzed connection is a tension connection of category D (non-preloaded) according to Table 3.2
- The checking formulae to Table 3.2 are:

$$\begin{cases} F_{t,Ed} \leq F_{t,Rd} \\ F_{t,Ed} \leq B_{p,Rd} \end{cases}$$

Meaning of the terms in checking formulae:

- $F_{t,Ed}$ = design tensile force per bolt, obtained from loading;

- $F_{t,Rd}$ = tension resistance per bolt according to Table 3.4;

- $B_{p,Rd}$ = punching shear resistance (of the end plate) according to Table 3.4

Calculation of the design tensile force per bolt:

- All the six bolts are equally loaded from the tensile force N=500 kN applied on the connection (on the splice)
- The design tensile force per bolt results:

$$F_{t,Ed} = \frac{N}{6} = \frac{50000}{6} = 8333\, daN$$

- Observation: An equal distribution of the tensile force N on the bolts is assumed!

Calculation of the tension resistance of the bolt to Table 3.4:

- Previously performed, i.e.:

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}} = \frac{0,9 \cdot 8000 \cdot 1,592}{1,25} = 9170\,daN > F_{t,Ed} = 8333\,daN$$

- First condition of Table 3.4 is thus checked!

Calculation of the punching shear resistance of the end-plate

- The punching shear resistance according to Table 3.4 is referring to the end plate failure by punching under the bolt head;
- The formula is:

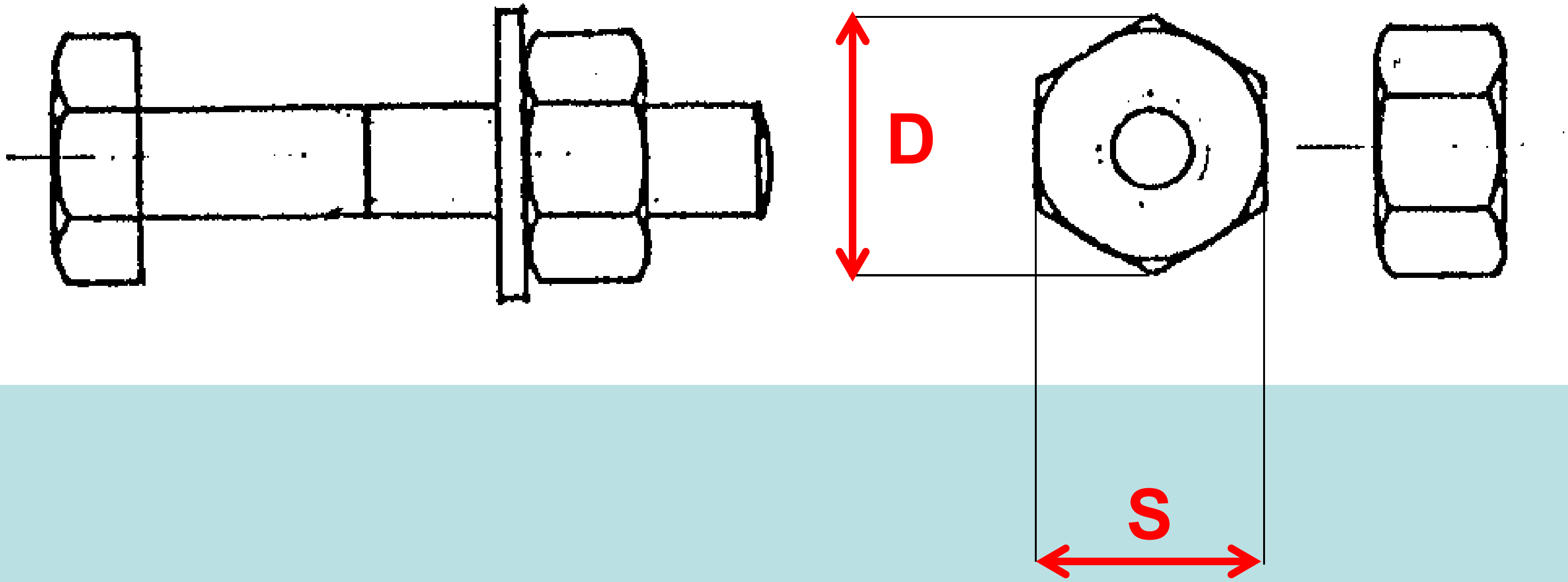
$$B_{p,Rd} = \frac{0,6 \cdot \pi \cdot d_m \cdot t_p \cdot f_u}{\gamma_{M2}}$$

- where f_u = ultimate stress of the end plate steel

Explanation of the terms in the punching resistance formula:

- d_m = the mean of the across-points (D) and across-flats (S) dimensions of the bolt head or of the nut (whichever is smaller)
- These dimensions (i.e. D and S) are usually found in the tables containing the geometric characteristics for bolts (in this case high strength bolts)
- In common practice the values are identical between bolt head and nut.

Geometry of the bolt head (nut)



Values of D and S dimensions [mm] for different types of high strength bolts:

Bolt type	M12	M16	M20	M22	M24	M27
D	24,9	30,5	36,2	40,7	46,3	52,0
S	22	27	32	36	41	46

Calculation of the d_m value:

- For the M16 gr.8.8 bolt head and nut, we get:

$$d_m = \frac{D+S}{2} = \frac{30{,}5+27}{2} = 28{,}75\,mm$$

- The value is identical either for the bolt head or for the nut.

Calculation of the punching resistance $B_{p,Rd}$ of the end plate:

- Using the end plate thickness t=16 mm, we are able now to calculate the punching resistance of the end plate under the bolt head (or nut):

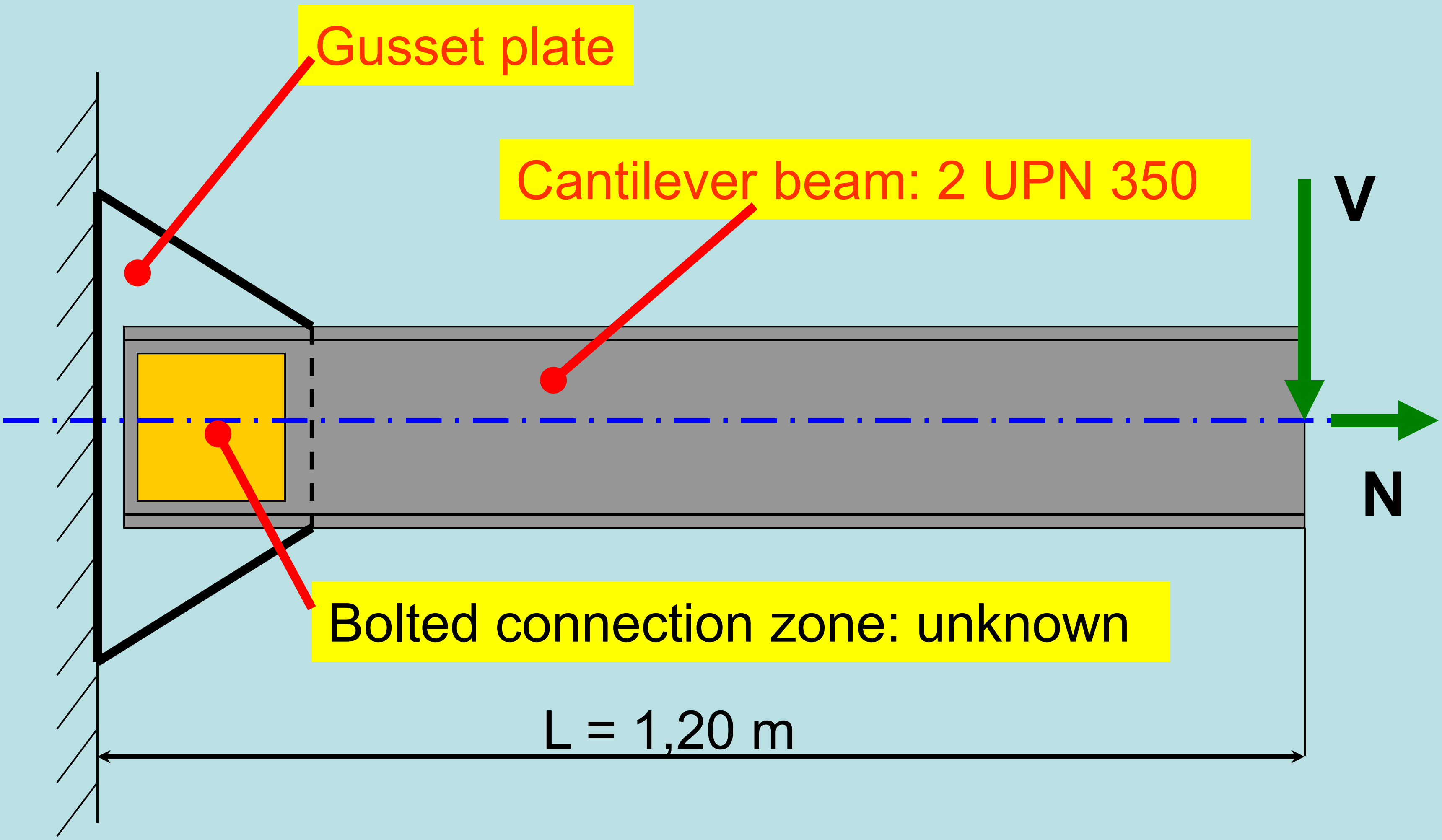
$$B_{p,Rd} = \frac{0{,}6 \cdot \pi \cdot 2{,}875 \cdot 1{,}6 \cdot 3700}{1{,}25} = 25.652\, daN > F_{t,Ed} = 8333\, daN$$

- The second condition of Table 3.4 is thus checked! This concludes the checking procedure.

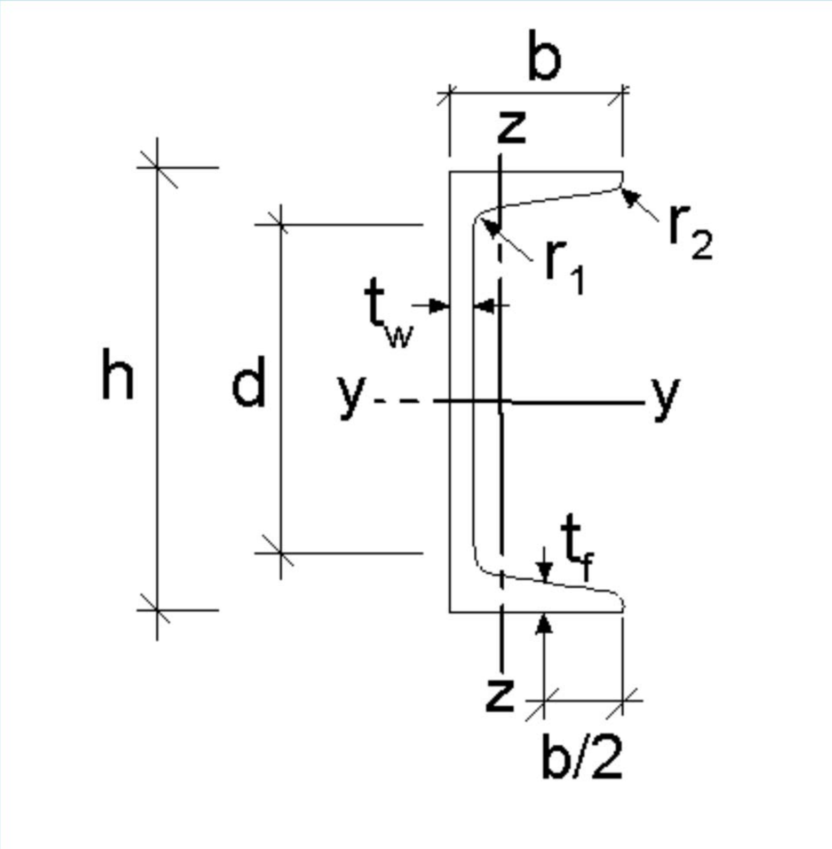
PART 3:
Shear connection under shear force and bending moment. Version 1:

Category A shear connection of bearing type

Static scheme of the connection:



A cantilever beam is required, made of two UPN 350 channel sections



Geometrical characteristics of the profile:

h = 350 mm

b = 100 mm

t_w = 14 mm

t_f = 16 mm

The problem requires the design of the cantilever beam support as a bolted connection of Category A – bearing type

- INITIAL DATA:
- V = 80 kN = 8.000 daN (shear load)
- N = 60 kN = 6.000 daN (axial load)
- Cantilever span: L=1,20 m
- Steel grade: S275
- Gusset thickness t_g = 15 mm
- Grade of the bolts = gr.5.6 (bolt diameter unknown in the initial phase)

First step: finding out the recommended diameter of the bolt

- The recommended diameter of the bolt may be found using the following empiric relation:

$$d = \sqrt{5 \cdot t_{\min}[cm]} - 0,4$$

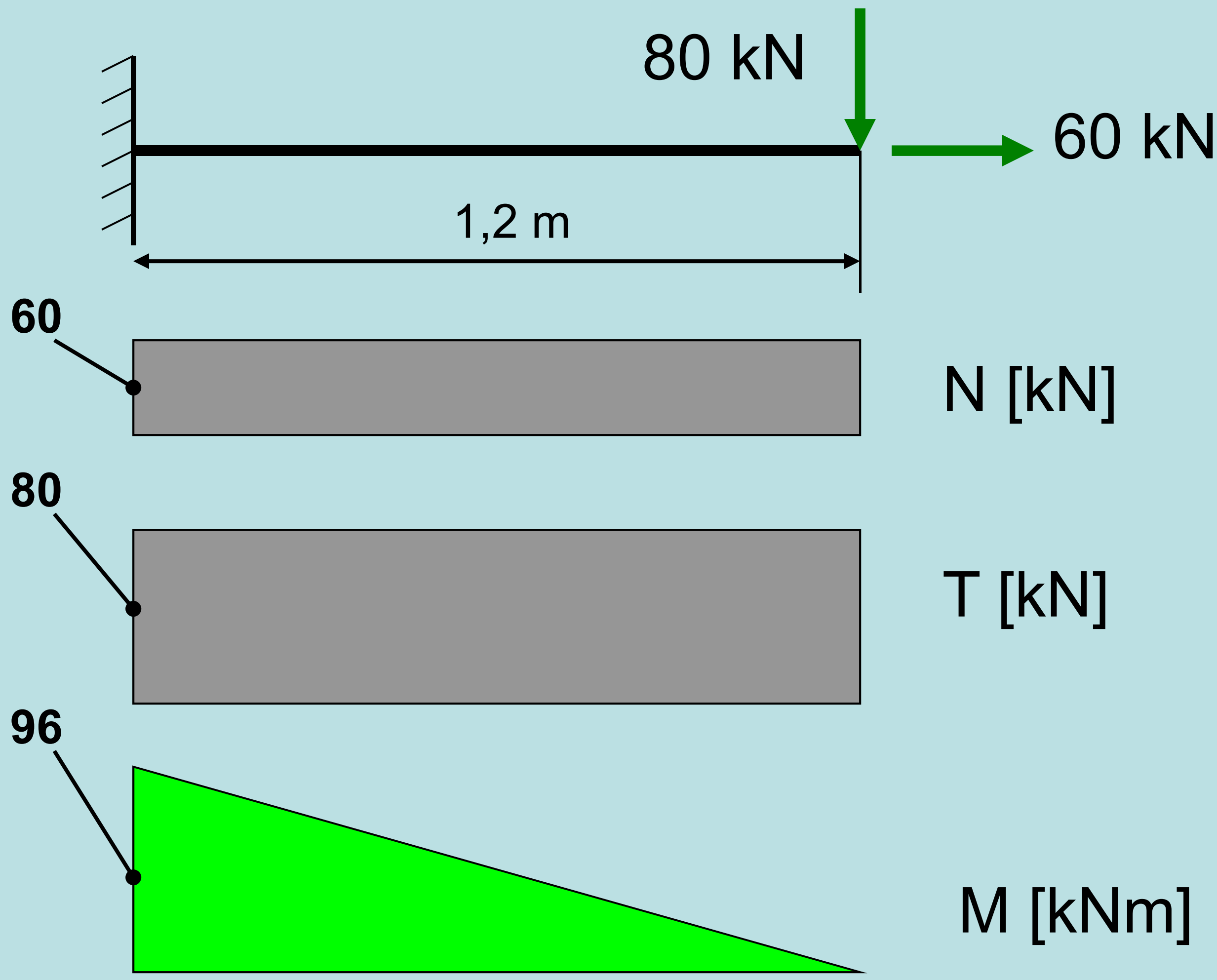
- Where t_{min}[cm] = minimum thicknes between the connected plates, in centimeters (in our case the UPN 350 web thickness =14 mm = 1,4 cm);

- Applying the empiric formula in our particular case gives:

$$d[cm] = \sqrt{5 \cdot 1{,}4} - 0{,}4 = 2{,}25\ cm \cong 22\,mm$$

- By practical reason (availability on the market) an M20 bolt is chosen for further calculation.
- Upper relation correlates the diameter of the employed bolts with the thickness of the plates in the connected package.
- This is always necessary in order to avoid bearing failure of the plates.

Internal efforts from loading on the cantilever beam:



Observation and start of design:

- In the support zone of the cantilever beam, as visible from the previous diagrams, a complex state internal efforts exists, i.e.:
  - Axial force N = 60 kN
  - Shear force T = 80 kN
  - Bending moment M = 96 kNm
- Because of this complex state of internal efforts, a <u>simple sizing calculation</u> (as in the previous examples) <u>to establish the number of bolts</u> for the connection is NOT possible!

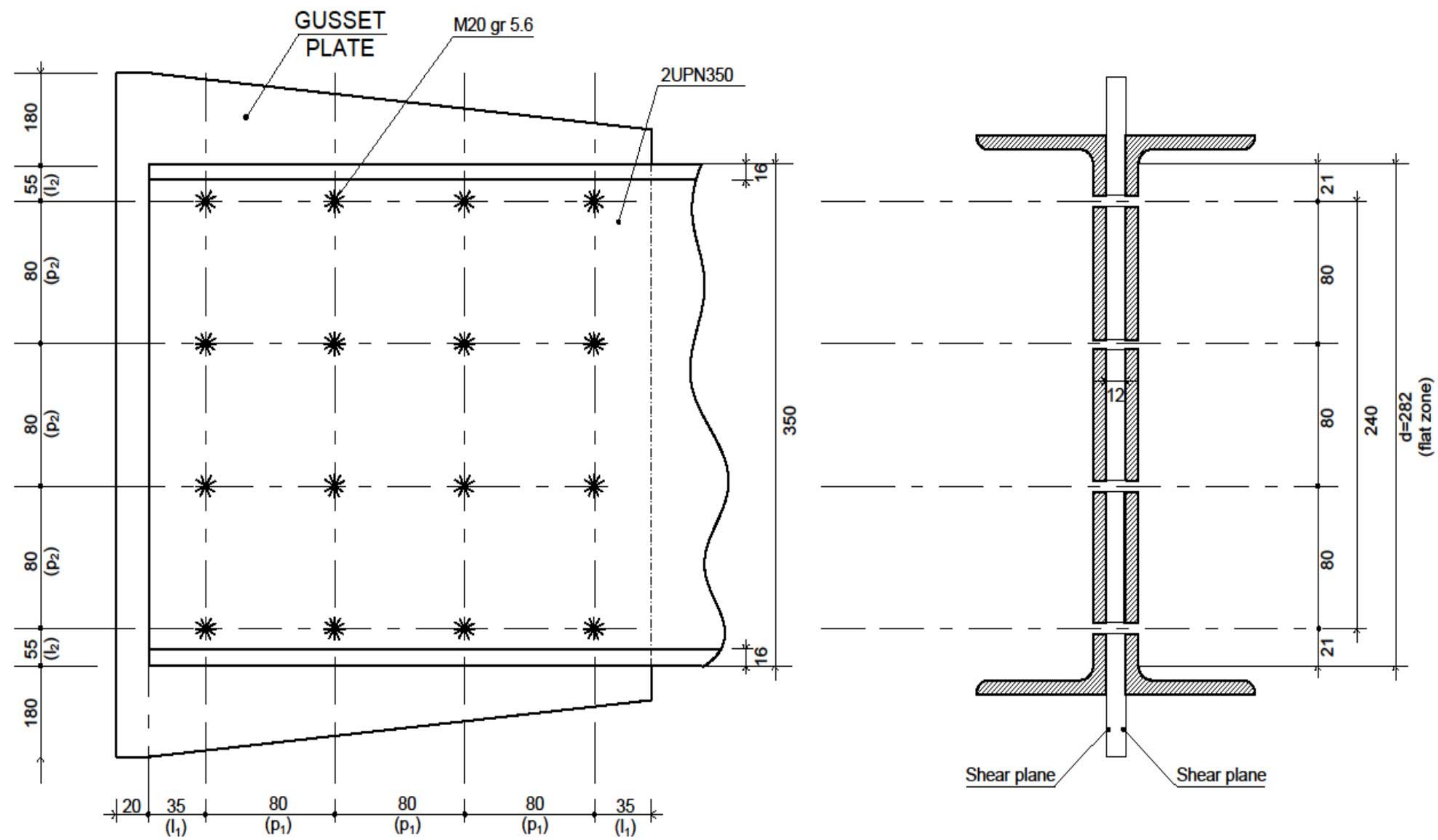
Start of the design procedure:

- To start the design procedure, the designer shall propose a number of bolts and a geometry for the connection, according to his experience.

- The proposed connection will be then checked according to the conditions for category A connection (bearing type) required in the problem.

- After calculation and conclusions, corrections will be performed on initial bolt group if necessary.

Proposed bolted connection



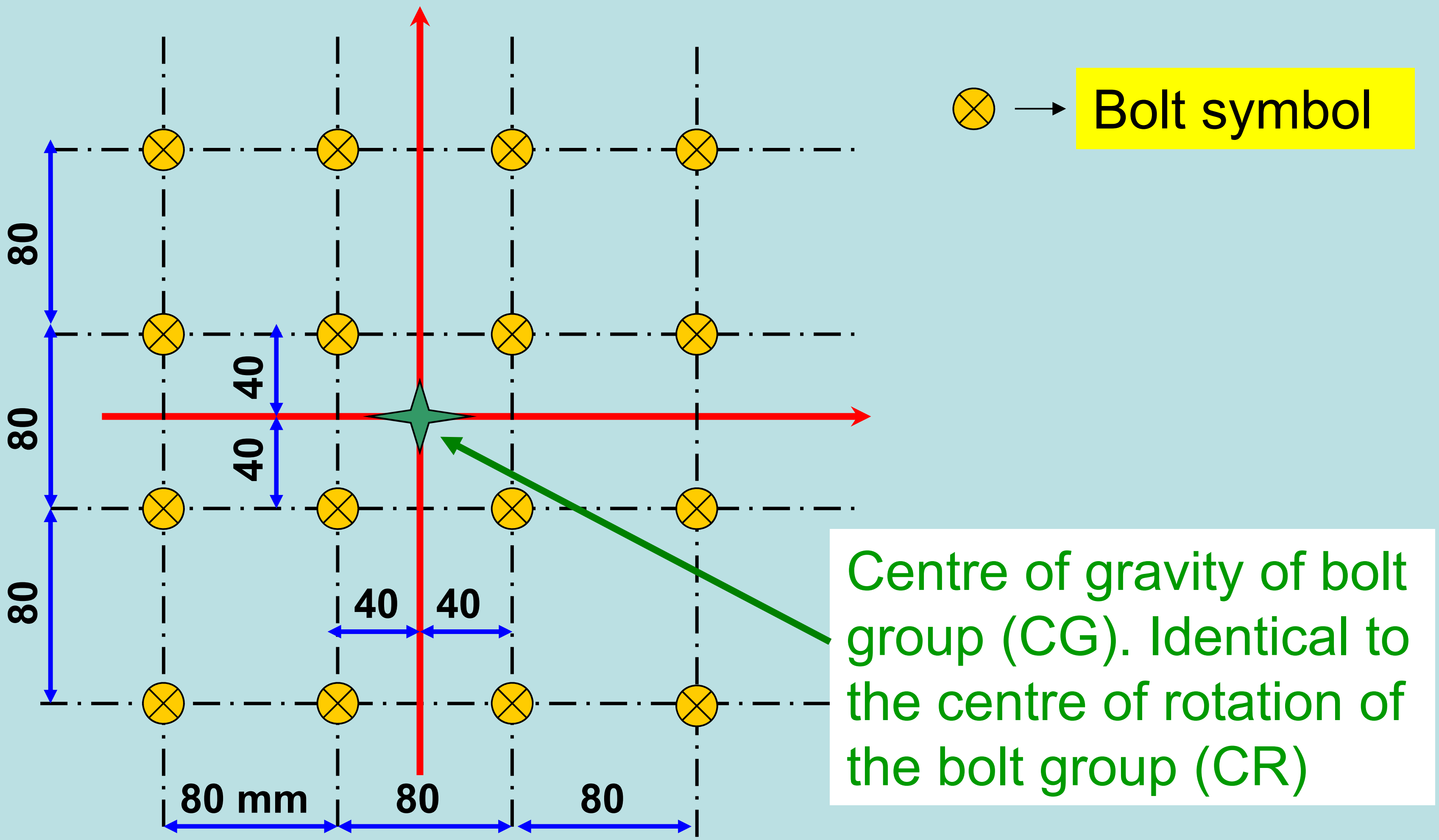
Observations concerning the geometry of the bolted connection:

- M20 bolts installed in clearance holes $\Rightarrow$ hole diameter d_0 = 22 mm;

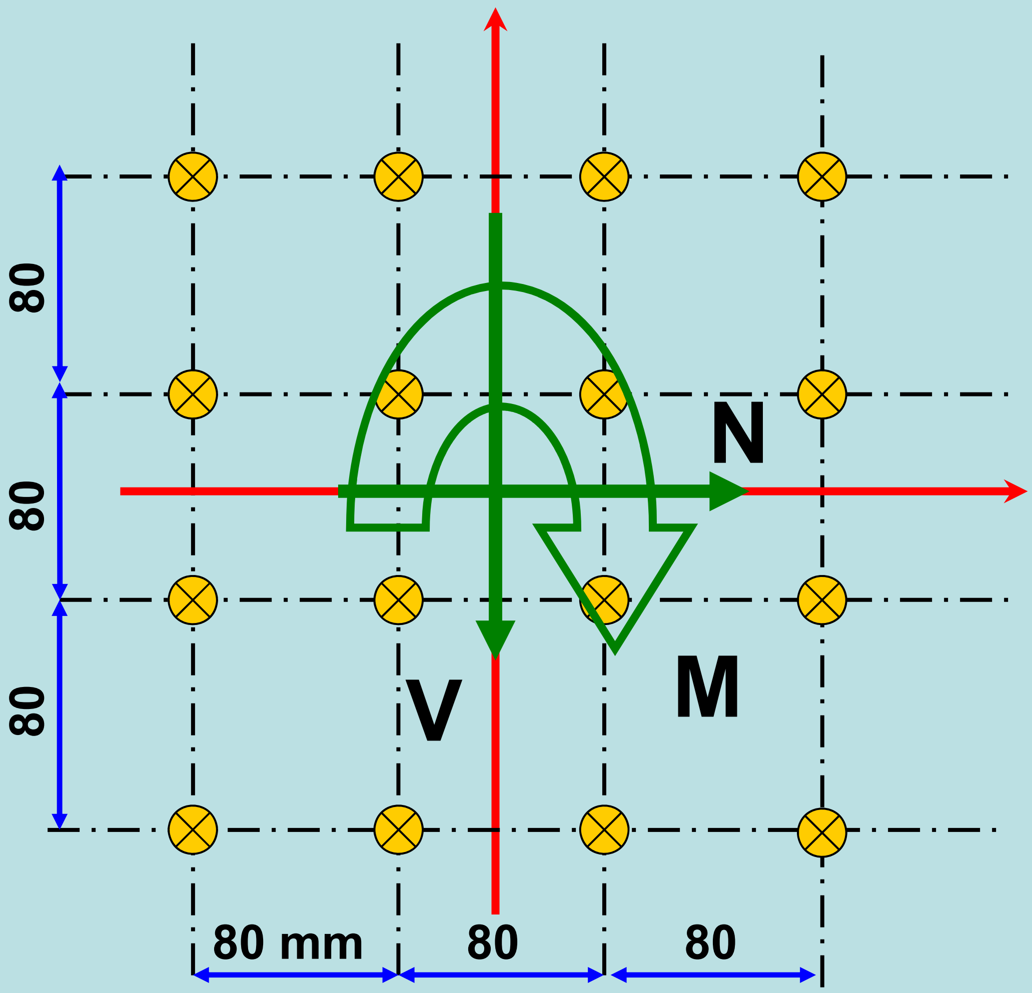
- The horizontal end distance between the two extreme bolt rows and the edge of the profile (or gusset plate) has been taken e_1 = 35 mm =1,59 d_0 > 1,2 d_0

- The vertical distance between the first and the last bolt on a row is = 3x80 mm = 240 mm < 282 mm (flat zone of channel web) !

Proposed number of bolts (=16) and geometry of the connection:



The internal efforts are acting in the centre of gravity of the connection (CG):



Distribution of internal efforts on the connection bolts (V and N):

- Since the dimensions of the connection on both directions (vertical and horizontal) are equal to 240 mm < $15d_0$ =330 mm, it is correct to admit an equal distribution on the bolts for the forces **V** and **N**;

Calculation of the design shear force per bolt produced by (N)

- Admitting an even distribution of (N) on all the 16 bolts of the group, we get:

$$T_N^x = \frac{N}{n_{bolts}} = \frac{60}{16} = 3{,}75\,kN = 375\,daN$$

- Bottom index "N" shows the provenience of the shear force per bolt (from N) and upper index "x" shows that the force vector is oriented parallel to global axis (x-x).

Calculation of the design shear force per bolt produced by (V)

- Admitting an even distribution of (V) on all the 16 bolts of the group, we get:

$$T_V^y = \frac{V}{n_{bolts}} = \frac{80}{16} = 5{,}0\,kN = 500\,daN$$

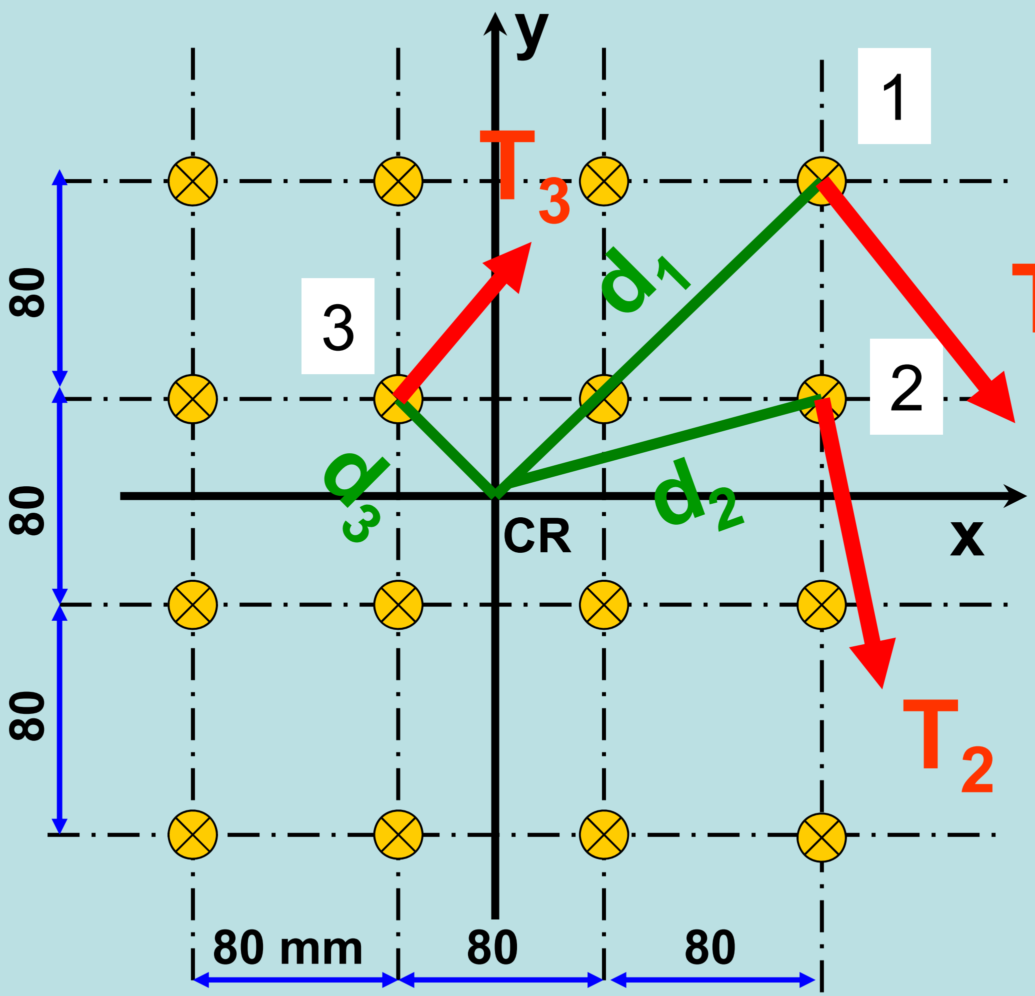
- Bottom index “V” shows the provenience of the shear force per bolt (from V) and upper index “y” shows that the force vector is oriented parallel to global axis (y-y).

Distribution of internal efforts on the connection bolts (M):

- The bending moment (M) acting in the centre of rotation of the connection (CR≡CG) will be un-equally distributed on the bolts, i.e. proportional to the distance (d_i) between each bolt (i) and point CR (see EN 1993-1-8 paragraph 3.12(1)).

- The bending moment action will produce in each point a shear force (T_i) perpendicular to the line representing the distance (d_i)-see next figure

Types of bolts depending on bolt distance to point CR≡CG



$$T_1 \perp d_1$$

$$T_2 \perp d_2$$

$$T_3 \perp d_3$$

From the point of view of the distance (d_i) to the centre of rotation, three types of bolts exist in the connection, i.e.:

- A number of 4 points of type "1" for which x_1=12 cm, y_1=12 cm (absolute values !).Distance (d_1) results

- A number of 8 points of type "2" for which x_2=4 cm, y_2=12 cm or x_2=12 cm, y_2=4 cm (absolute values!). Both these types lead to distance (d_2)

- A number of 4 points of type "3" for which x_3=4 cm, y_3=4 cm (absolute values!). Distance (d_3) results.

Using the coordinates of the three types of points (d_i) distances result:

$$\begin{cases} d_1 = \sqrt{x_1^2 + y_1^2} = \sqrt{12^2 + 12^2} = 16{,}97\,cm \\ d_2 = \sqrt{x_2^2 + y_2^2} = \sqrt{4^2 + 12^2} = \sqrt{12^2 + 4^2} = 12{,}65\,cm \\ d_3 = \sqrt{x_3^2 + y_3^2} = \sqrt{4^2 + 4^2} = 5{,}66\,cm \end{cases}$$

- As evident from upper results, $d_1 > d_2 > d_3$.

- According to the accepted unequal distribution of the shear forces T_i (produced by the moment M) proportional to (d_i), we will obtain $T_1 > T_2 > T_3$

- This means that type "1" points of the corners of the bolt group will be the most solicited. The bolt checking procedure according to EN 1993-1-8 shall be performed in these points!

Calculation of the maximum design force per fastener (T_1) produced by the bending moment (M):

- The value of T_1 results from the following equation of equilibrium:

$$M = \sum_{i=1}^{16} T_i \cdot d_i$$

- The equation shows that moment (M) is equilibrated by the sum of moments of the forces (T_i) in respect to the centre of rotation CR. The sum is extended on all the 16 bolts of the group.

- Because in our particular case we have only three types of bolts (i.e. 1,2 and 3), the equation of equilibrium becomes:

$$M = 4 \cdot T_1 \cdot d_1 + 8 \cdot T_2 \cdot d_2 + 4 \cdot T_3 \cdot d_3$$

- At the same time, the accepted hypothesis of un-even distribution of (T_i) forces produced by M, proportional with the corresponding distances (d_i) has the following mathematical expression:

$$\frac{T_{1M}}{d_1} = \frac{T_{2M}}{d_2} = \frac{T_{3M}}{d_3}$$

- This gives:

$$\begin{cases} \dfrac{T_{1M}}{d_1} = \dfrac{T_{2M}}{d_2} \Rightarrow T_{2M} = \dfrac{d_2}{d_1} \cdot T_{1M} \\ \dfrac{T_{1M}}{d_1} = \dfrac{T_{3M}}{d_3} \Rightarrow T_{3M} = \dfrac{d_3}{d_1} \cdot T_{1M} \end{cases}$$

- Thus, all the design shear forces produced by the moment M may be expressed in the equilibrium equation as a function of the maximum force in point (1), i.e. T_1

- The equilibrium equation between moments becomes:

$$M = 4 \cdot T_{1M} \cdot d_1 + 8 \cdot \left(\frac{d_2}{d_1} \cdot T_{1M} \right) \cdot d_2 + 4 \cdot \left(\frac{d_3}{d_1} \cdot T_{1M} \right) \cdot d_3$$

- Or, the equivalent form of the upper equation:

$$M = \frac{T_{1M}}{d_1} \cdot \left(4 \cdot d_1^2 + 8 \cdot d_2^2 + 4 \cdot d_3^2 \right)$$

- In this last equation, only T_{1M} is unknown: all other elements are known data of the problems

- The formula to calculate the maximum design shear force produced by the bending moment (M) becomes:

$$T_{1M} = \frac{M \cdot d_1}{4 \cdot d_1^2 + 8 \cdot d_2^2 + 4 \cdot d_3^2} = M \cdot \frac{d_1}{\sum_{1}^{n.bolts} d_i^2}$$

- Observation: The shear force vector is NOT parallel to the global axes (x-x) or (y-y). By the admitted design hypothesis, the vector has its origin in point (1) and is perpendicular to the line drawn through points CR and (1).

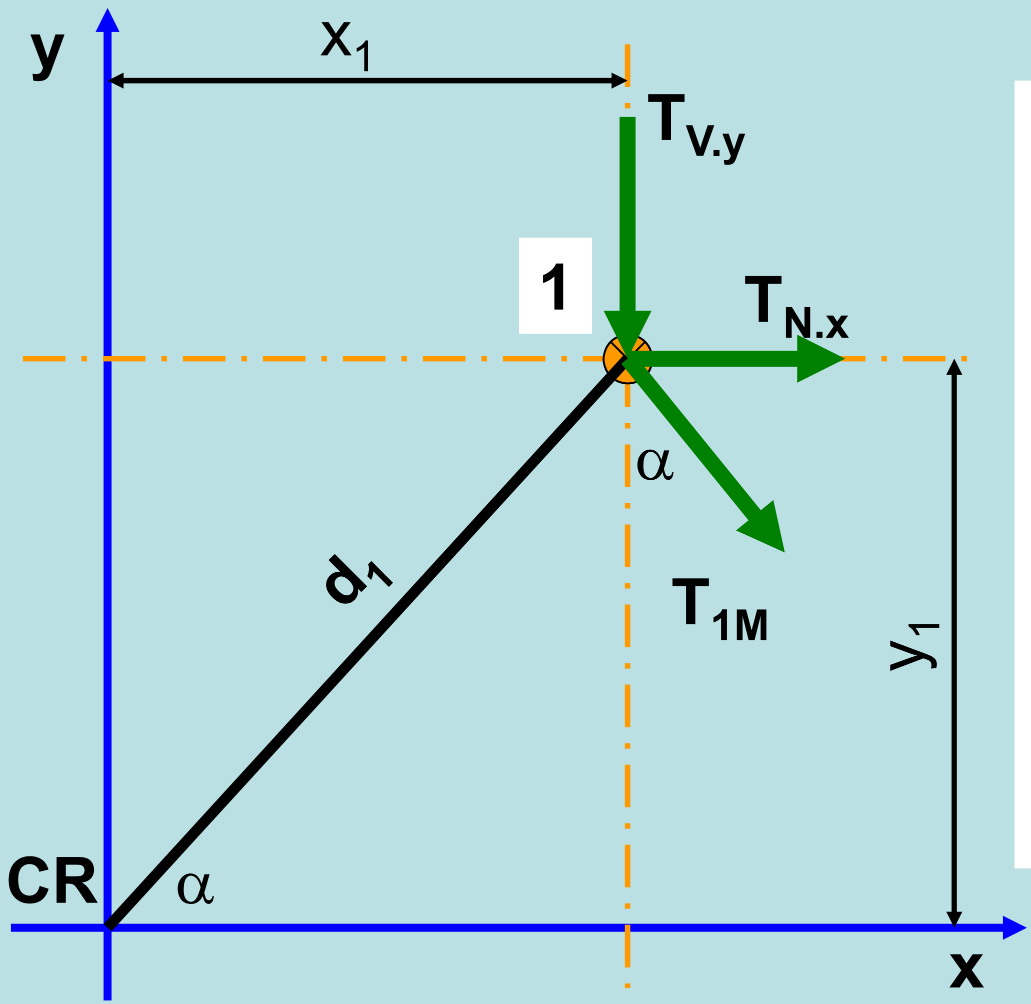
Using (M) value and previously calculated values of distances d_1, d_2, d_3 we get:

M = 96 kNm = 960000 daNcm

$$T_{1M} = \frac{960000 \cdot 16,97}{4 \cdot 16,97^2 + 8 \cdot 12,65^2 + 4 \cdot 5,66^2} = 6366\, daN$$

This is the maximum design shear force produced by moment M and acting on the most solicited bolt from the group, i.e. bolt type 1 located in the corner.

In point (1) are simultaneously acting the design shear forces produced by N, V and M:



The resultant design shear force in point 1 (the most solicited bolt of the group) is the vectorial sum between $T_{V.y}$, $T_{N.x}$ and T_{1M} vectors

In order to obtain this sum we need to calculate the projections of vector T_{1M} on the (x-x) and (y-y) axes (i.e. $T_{1M.x}$ and $T_{1M.y}$)

Calculation of T_{1M} projections using vector angle (α) to global axes:

$$tg\alpha = \frac{y_1}{x_1} \Rightarrow \alpha = arctg\left(\frac{y_1}{x_1}\right) = arctg\left(\frac{12,0}{12,0}\right) = 45^0$$

$$\begin{cases} T_{1M}^x = T_{1M} \cdot \sin 45^0 = 6363 \cdot \sin 45^0 = 4499\, daN \\ T_{1M}^y = T_{1M} \cdot \cos 45^0 = 6363 \cdot \cos 45^0 = 4499\, daN \end{cases}$$

Observation: we are here in the fortunate case when $\alpha=45^0$! In practice (α) angle may take any value, depending on the proposed geometry for the connection!

Second method to calculate the projections on the global axes for T_{1M} vector :

- By observing that, for every point (i) in the bolt group we have the relation: $d_i^2 = x_i^2 + y_i^2$

- the projections of vector T_{1M} on the global axes may be obtained using a similar procedure as before:

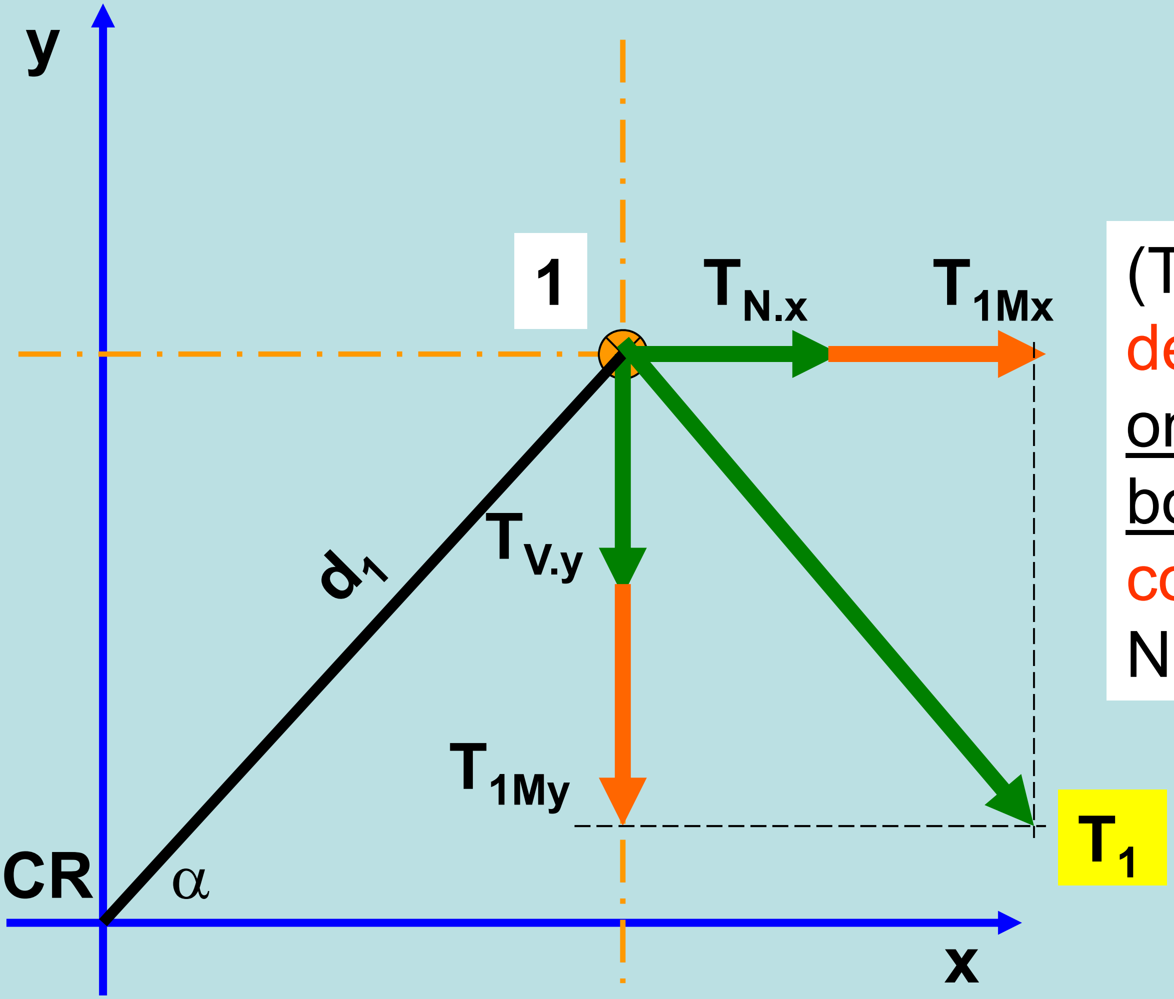
$$\begin{cases} T_{1M}^x = M \cdot \dfrac{y_1}{\sum_i \left(x_i^2 + y_i^2\right)} \\ T_{1M}^y = M \cdot \dfrac{x_1}{\sum_i \left(x_i^2 + y_i^2\right)} \end{cases}$$

Observation: Last formulae obtained are in fact an easier way to calculate T_{1M} components on the global axes, since (x_i) and (y_i) coordinates are known from the beginning from the proposed geometry of the bolt group

$$\begin{cases} T_{1M}^{x} = 960000 \cdot \dfrac{12}{4 \cdot (12^2 + 12^2) + 8 \cdot (4^2 + 12^2) + 4 \cdot (4^2 + 4^2)} = 4500\, daN \\ T_{1M}^{y} = 960000 \cdot \dfrac{12}{4 \cdot (12^2 + 12^2) + 8 \cdot (4^2 + 12^2) + 4 \cdot (4^2 + 4^2)} = 4500\, daN \end{cases}$$

The result is identical to the first method, but obtained on an easier way!

Superposition of the effects of N, V and bending moment M in point (1) is done by using the vector projections on global axes:



(T_1) is the resulting design shear force on the most solicited bolt of the group from combined effect of N, V and M

Calculation of the resulting T_1 value as a sum of vector projections:

$$T_1 = \sqrt{\left(T_N^x + T_{1M}^x\right)^2 + \left(T_V^y + T_{1M}^y\right)^2}$$

Using previously calculated values, this gives:

$$T_1 = \sqrt{(375 + 4500)^2 + (500 + 4500)^2} = 6983\,daN$$

This final value shall be compared to bolt resistances according to EN 1993-1-8.

Checking relations according to EN 1993-1-8, Table 3.2:

- For bolted connections of category A – bearing type, the following relations are prescribed for checking:

$$\begin{cases} F_{v,Ed} \leq F_{v,Rd} \\ F_{v,Ed} \leq F_{b,Rd} \end{cases}$$

- In which $F_{v,Ed} = T_1$ = design shear force acting on the most solicited bolt (i.e. bolt type 1)

In previous checking relations:

- $F_{v,Rd}$ = shear resistance of the bolt per shear plane: if several shear planes exist (as in present case, where we have n_{sh} = 2 shear planes) the resulting shear resistance per plane shall be multiplied with (n_{sh});

- $F_{b,Rd}$ = bearing resistance of the minimum thickness plate package connected by the bolt (in our case, the gusset plate which thickness is < 2 x channel web thickness)

Calculation of the bolt shear resistance:

- The shear resistance of the bolt per shear plane according to Table 3.4:

$$F_{v,Rd} = \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}}$$

- In the present case, the bolt is intersecting two shear planes, so its shear resistance becomes:

$$F_{v,Rd} = 2 \cdot \frac{\alpha_v \cdot f_{ub} \cdot A}{\gamma_{M2}}$$

In the shear resistance formula:

- α_v = 0,6 (for the studied case, where the shear planes intersect the non-threaded part of the bolt shank: this is usual for normal bolts of grades 4.6 of 5.6 or 6.6)
- A=gross area of the bolt cross-section

$$A = \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot 2^2}{4} = 3{,}14\, cm^2$$

- f_{ub} = 5 x 10 =50 daN/mm^2 = 5000 dan/cm^2 for gr.5.6 bolts

Calculation of the bolt shear resistance:

- For the two shear planes:

$$F_{v,Rd} = 2 \cdot \frac{0{,}6 \cdot 5000 \cdot 3{,}14}{1{,}25} = 15.072\, daN > F_{v,Ed} = 6983\, daN$$

First checking to Table 3.2 OK!

Calculation of the bearing resistance

- Under shear force action, the gusset plate tends to move in one direction, while the two channel sections connected by the bolt group tend to move in opposite direction.
- Gusset thickness t =15 mm (steel S275 !)
- The sum of web thickness for the channel section = $2 \cdot t_w = 2 \cdot 14$ mm = 28 mm > t
- So, the minimum thickness package is the gusset plate (to check for bearing!).

Calculation of the bearing resistance for the gusset plate:

- The bearing resistance shall be calculated according to Table 3.4:

$$F_{b,Rd} = \frac{k_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}}$$

- In which:

- f_u =ultimate strength of gusset steel (S275) =4400 daN/cm^2

- d = bolt nominal diameter =20 mm =2,0 cm

- t = gusset thickness = 15 mm = 1,5 cm

Calculation of the k_1 value in the bearing formula:

- d_0 = clearance hole diameter = 22 mm =2,2 cm

$$k_1 = \min\left\{2,8 \cdot \frac{e_2}{d_0} - 1,7\,;\, 2,5\right\}$$

- and:

$$2,8 \cdot \frac{e_2}{d_0} - 1,7 = 2,8 \cdot \frac{35}{22} - 1,7 = 2,75$$

$$\Rightarrow k_1 = \min\{2,75\,;\,2,5\} = 2,5$$

Calculation of the (α_b) value in the bearing formula:

$$\alpha_b = \min\left\{\alpha_d \,;\, \frac{f_{ub}}{f_u} \,;\, 1{,}0\right\}$$

where:

$$\begin{cases} \alpha_d = \dfrac{e_1}{3 \cdot d} = \dfrac{35}{3 \cdot 22} = 0{,}53 \\ \dfrac{f_{ub}}{f_u} = \dfrac{5000}{4400} = 1{,}136 \end{cases}$$

$$\Rightarrow \alpha_b = \min\{0{,}53 \,;\, 1{,}135 \,;\, 1{,}0\} = 0{,}53$$

Calculation of the bearing resistance and checking:

$$F_{b,Rd} = \frac{2{,}5 \cdot 0{,}53 \cdot 4400 \cdot 2{,}0 \cdot 1{,}5}{1{,}25} = 13992\,daN > F_{v,Ed} = 6983\,daN$$

Second checking to Table 3.2 OK!

Comment on the result: the design shear force value is approximately 50% of the minimum resistance which suggests a group of bolts excessively strong. Normally, the number of bolts should be diminished (for example 3 bolts instead of 4 on each vertical row) and the whole procedure repeated to obtain a more rational result.

PART 4:
Shear connection under shear force and bending moment. Version 2:

Category C shear connection –slip resistant at ultimate limit state

Initial data:

- The same cantilever beam as in Part 3 example is used, of identical materials;
- Loading is identical;
- The same proposed group of bolts is used for the shear connection, except for the type of bolts: M20 gr.10.9 preloaded
- The bolted connection will be treated as a shear connection of category C: slip resistant at ultimate limit state

Design shear force acting on the most solicited bolt:

- The design shear force acting on the most solicited bolt (type 1 in the corner of the bolt group) will be the same as before:

$$T_1 = F_{v,Ed} = 6983 \text{ daN}$$

The same hypothesis for N, V and M distributions have been applied in this case, leading to the same design shear force value.

Checking relations for the slip resistant connection according to Table 3.2:

$$\begin{cases} F_{v,Ed} \le F_{s,Rd} \\ F_{v,Ed} \le F_{b,Rd} \\ F_{v,Ed} \le N_{net,Rd} \end{cases}$$

Resistance values in checking relations:

- $F_{s,Rd}$ = design slip resistance of the preloaded bolt
- $F_{b,Rd}$ = bearing resistance of the gusset plate (as before) at ultimate limit state when the preloaded bolts loosen and friction disappears;
- $N_{net,Rd}$ = resistance of gusset to tension in the net area: this checking makes no sense here because of the non-uniform distribution of the design shear force on the bolt group.

Calculation of the design slip resistance per bolt:

According to paragraph 3.9.1(1) of EN1993-1-8, the design slip resistance formula for a preloaded bolt is:

$$\begin{cases} F_{s,Rd} = \dfrac{k_s \cdot n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} \\ F_{p,C} = 0{,}7 \cdot f_{ub} \cdot A_s \end{cases}$$

in which $F_{p,C}$ is the design preloading force of the bolt - see paragraph 3.9.1(2).

Explanation of terms in $F_{p,C}$ formula:

- Employed bolts: M20 gr.10.9

- Resulting data (from bolt grade symbol):

- f_{ub} = 10 x 10 =100 daN/mm^2 =10000 dan/cm^2
- Nominal diameter of the bolt: d=20 mm=2 cm
- Resistant diameter: d_{res}=0,89·d=1,78 cm

$$\Rightarrow A_s = \frac{\pi \cdot d_{res}^2}{4} = \frac{\pi \cdot 1{,}78^2}{4} = 2{,}487\,cm^2$$

Calculation of the design preloading force:

- The value of the design preloading force results:

$$F_{p,C} = 0{,}7 \cdot 10000 \cdot 2{,}487 = 17.409\, daN$$

- This is the value of the tension forced induced into the bolt shank by the preloading operation of the bolt (tightening).

Value of coefficients k_s,n,μ

- k_s = 1,0 (holes with standard nominal clearance - from Table 3.6)

- n = 2 (number of friction surfaces, i.e. one gusset plate between two back to back channel sections)

- μ=0,3 (slip factor for class C surface according to Table 3.7)

Calculation of the design slip resistance and checking:

$$F_{s,Rd} = \frac{1{,}0 \cdot 2 \cdot 0{,}3}{1{,}25} \cdot 17409 = 8356\,daN > F_{v,Ed} = 6983\,daN$$

First checking to Table 3.2 OK!

Comment on the obtained result: The slip resistance value is reasonably close to the design shear force, which indicates a rational proposal for the group of bolts, working as a slip resistant connection. No change of bolt geometry or other connection component is required in this case!

Calculation of the bearing resistance for the gusset plate :

- The bearing resistance shall be calculated according to Table 3.4 for a bolt with entirely threaded shank, (as high strengths bolts of gr.10.9 usually are!)

- (ultimate limit state when preloaded bolts loosen and slip occurs) :

$$F_{b,Rd} = \frac{k_1 \cdot \alpha_b \cdot f_u \cdot d_{res} \cdot t}{\gamma_{M2}}$$

Calculation of the coefficients in bearing resistance formula:

- In the previous formula:

- f_u =ultimate strength of gusset steel (S275) =4400 daN/cm^2
- d_{res}= bolt resistant diameter =0,89·20 mm =1,78 cm
- t = gusset thickness = 15 mm = 1,5 cm

Calculation of the k_1 value in the bearing formula:

- d_0 = clearance hole diameter = 22 mm =2,2 cm

$$k_1 = \min\left\{2{,}8 \cdot \frac{e_2}{d_0} - 1{,}7\,;\,2{,}5\right\}$$

- and:

$$2{,}8 \cdot \frac{e_2}{d_0} - 1{,}7 = 2{,}8 \cdot \frac{35}{22} - 1{,}7 = 2{,}75$$

$$\Rightarrow k_1 = \min\{2{,}75\,;\,2{,}5\} = 2{,}5$$

Calculation of the (α_b) value in the bearing formula:

$$\alpha_b = \min\left\{\alpha_d\,; \frac{f_{ub}}{f_u}\,; 1{,}0\right\}$$

where:

$$\begin{cases} \alpha_d = \dfrac{e_1}{3 \cdot d} = \dfrac{35}{3 \cdot 22} = 0{,}53 \\ \dfrac{f_{ub}}{f_u} = \dfrac{5000}{4400} = 1{,}136 \end{cases}$$

$$\Rightarrow \alpha_b = \min\{0{,}53\,;\,1{,}135\,;\,1{,}0\} = 0{,}53$$

Calculation of the gusset bearing resistance and checking:

$$F_{b,Rd} = \frac{2{,}5 \cdot 0{,}53 \cdot 4400 \cdot 1{,}78 \cdot 1{,}5}{1{,}25} = 12452\,daN > F_{v,Ed} = 6983\,daN$$

Second checking to Table 3.2 OK!

The third checking required in Table 3.2 of the code (resistance in the net area of the gusset plate) is NOT required in this case because of the un-equal distribution of the design shear force over the bolt group.

Consequently, this second checking concludes the procedure for the slip resistant connection.