Design of Tension Members
Members that carry pure tension, generally referred to as ties, are relatively simple to design. Load carrying capacity of tension members is essentially governed by:

- Distribution of the residual stresses due to the manufacturing process.
- Connection details of the element ends.

### 1.1 Resistance of cross-section

Members in tension subjected to the design axial force $N_{Ed}$ must satisfy the following condition at every section, in accordance with European provisions:

$$N_{Ed} \leq N_{t,Rd}$$

The design tension resistance $N_{t,Rd}$ of a cross-section is given by Clause 6.2.3(2) of BS EN 1993-1-1 as the smaller of:

a) The design plastic resistance of the gross cross-section

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}}$$

b) The design ultimate resistance of the net cross-section at holes for fasteners

$$N_{u,Rd} = \frac{0.9 A_{net} f_u}{\gamma_{M2}}$$

Where: $\gamma_{M0} = 1.00$ ; $\gamma_{M2} = 1.25$

It should be noted that term $N_{pl,Rd}$ is associated with ductile failure due to the attainment of the yield strength, while $N_{u,Rd}$ is related to a brittle failure in the connection section (governed by the attainment of the ultimate strength). In case of seismic loads, the well-established capacity design approach requires a ductile behavior of member under tension ($N_{u,Rd} > N_{pl,Rd}$), which could be guaranteed if:

$$A_{net} \geq \frac{f_y}{f_u} \cdot \frac{\gamma_{M2}}{\gamma_{M0}} \cdot \frac{A}{0.9}$$

### 1.2 Resistance of angles connected by one leg

When a single angle is used, reference has to be made to the criterion reported in EN 1993-1-8: a single angle in tension connected by a single row of bolts in one leg may be treated as concentrically loaded over an effective net section for which the design ultimate resistance $N_{u,Rd}$ has to be determined as:

$$N_{u,Rd} = \frac{2.0(s_2-0.5d_o)f_u}{\gamma_{M2}}$$  \hspace{1cm} \text{(For 1 bolt)}

$$N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}}$$  \hspace{1cm} \text{(For 2 bolts)}

$$N_{u,Rd} = \frac{\beta_3 A_{net} f_u}{\gamma_{M2}}$$  \hspace{1cm} \text{(For 3 bolts or more)}
Figure 1: Single angle connected by one leg via (a) one bolt, (b) two bolts and (c) three bolts.

Reduction factors $\beta$ for angles connected via a single leg.

<table>
<thead>
<tr>
<th>Pitch $p_1$</th>
<th>$\leq 2.5 \ d_0$</th>
<th>$\geq 5 \ d_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two bolts</td>
<td>$\beta_2 = 0.4$</td>
<td>$\beta_2 = 0.7$</td>
</tr>
<tr>
<td>Three bolts or more</td>
<td>$\beta_3 = 0.5$</td>
<td>$\beta_3 = 0.7$</td>
</tr>
</tbody>
</table>

For an intermediate value of $p_1$ the value of $\beta$ may be determined by linear interpolation.

**Note:**

A common detail is an angle connected by one leg using one or more rows of bolts as shown in Figure 4.2. Unfortunately, BS EN 1993-1-8 does not give any guidance for calculating the resistance of angles connected in this way.

Figure 2: Angle connected by one leg with two bolt rows
The European connections committee, ECCS TC10, has considered this detail and suggested that the following expression may be used for calculating the design resistance of the section:

\[ N_{u,Rd} = \frac{2.0(e_2 + p_2 - 1.5d_0)\tau f_u}{\gamma_{M2}} \]

1.3 Tension Member Design Steps Summary

![Flow chart for the design of tension members.](image-url)
1.4 Nominal values of yield strength $f_y$ and ultimate tensile strength $f_u$ for hot rolled structural steel

<table>
<thead>
<tr>
<th>Table 3.1: Nominal values of yield strength $f_y$ and ultimate tensile strength $f_u$ for hot rolled structural steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard and steel grade</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>EN 10025-2</td>
</tr>
<tr>
<td>S 235</td>
</tr>
<tr>
<td>S 275</td>
</tr>
<tr>
<td>S 355</td>
</tr>
<tr>
<td>S 450</td>
</tr>
<tr>
<td>EN 10025-3</td>
</tr>
<tr>
<td>S 275 N/NL</td>
</tr>
<tr>
<td>S 355 N/NL</td>
</tr>
<tr>
<td>S 420 N/NL</td>
</tr>
<tr>
<td>S 460 N/NL</td>
</tr>
<tr>
<td>EN 10025-4</td>
</tr>
<tr>
<td>S 275 M/ML</td>
</tr>
<tr>
<td>S 355 M/ML</td>
</tr>
<tr>
<td>S 420 M/ML</td>
</tr>
<tr>
<td>S 460 M/ML</td>
</tr>
<tr>
<td>EN 10025-5</td>
</tr>
<tr>
<td>S 235 W</td>
</tr>
<tr>
<td>S 355 W</td>
</tr>
<tr>
<td>EN 10025-6</td>
</tr>
<tr>
<td>S 460 Q/QL/QL1</td>
</tr>
</tbody>
</table>

1.5 Net area of a cross section, $A_{net}$

The total area to be deducted should be taken as the greater of:

$$A_{net} = A - ntd_o + t \sum \frac{s^2}{4p}$$

where:

- $A$ is the gross area of the section
- $n$ is the number of holes extending in any zig-zag line
- $t$ is the thickness of the plate.
- $d_o$ is the hole diameter.
- $s$ is the staggered pitch of the two consecutive holes.
- $p$ is the spacing of the centers of the same two holes measured perpendicular to the member axis.
1.6 Solved Problems

Problem (1)

Determine the net area of the unequal angle 200 × 150 × 15 connected with three staggered bolts \((d_o = 15 mm)\) \(A_g = 50.5 \text{ cm}^2\)

**Solution:**

\[ A_{net} = A - \sum d_o \cdot t + t \sum \frac{s^2}{4p} \]

Fracture line (1):

\[ A_{net,1} = 50.5 \times 10^2 - 1 \times (15 \times 15) = 48.25 \times 10^2 \text{ mm}^2 \]

Fracture line (2):

\[ A_{net,2} = 50.5 \times 10^2 - 2 \times (15 \times 15) + 15 \times \frac{60^2}{4 \times 45} = 49.00 \times 10^2 \text{ mm}^2 \]

Fracture line (3):

\[ A_{net,3} = 50.5 \times 10^2 - 3 \times (15 \times 15) + 15 \times \frac{60^2}{4 \times 45} + 15 \times \frac{60^2}{4 \times 40} = 50.125 \times 10^2 \text{ mm}^2 \]

*choose min. \(A_{net} \rightarrow A_{net,1} = 48.25 \times 10^2 \text{ mm}^2*
Problem (2)

Both flanges of a universal column section member have 22 mm diameter holes arranged as shown in Figure (1). If the gross area of the section is $201 \times 10^2 \text{mm}^2$ and the flange thickness is 25 mm.

1- Determine the net area $A_{net}$ of the member which is effective in tension.
2- Determine the tension resistance of the tension member using steel S355.

**Solution:**

$$A_{net} = A - \sum d \cdot t + t \sum s^2$$

Fracture line (1):

$$A_{net,1} = 201 \times 10^2 - 2 \times 2 \times (22 \times 25) = 179 \times 10^2 \text{mm}^2$$

Fracture line (2):

$$A_{net,2} = 201 \times 10^2 - 2 \times 4 \times (22 \times 25) + 2 \times 2 \times 25 \times \frac{30^2}{4 \times 60} = 160.75 \times 10^2 \text{mm}^2$$

choose min. $A_{net} \rightarrow A_{net,2} = 160.75 \times 10^2 \text{mm}^2$

$$t_f = 25 \text{mm}, f_y = 345 \text{N/mm}^2, f_u = 490 \text{N/mm}^2.$$  

$$N_{pl,Rd} = \frac{A f_y}{Y_{M0}} = \frac{201 \times 10^2 \times 345}{1.0} \times 10^{-3} = 6934.5 \text{KN}$$

$$N_{u,Rd} = \frac{0.9 A_{net} f_u}{Y_{M2}} = \frac{0.9 \times 160.75 \times 10^2 \times 490}{1.25} \times 10^{-3} = 5671.26 \text{KN}$$

$$N_{t,Rd} = 5671.26 \text{KN} \text{ (the lesser of } N_{pl,Rd} \text{ and } N_{u,Rd}).$$
Problem (3).

A UB 610 x 229 x 125 tension member of S355 steel is connected through both flanges by 20 mm bolts (in 22 mm diameter bolt holes) in four lines, two in each flange as shown in Figure (2). Check the member for a design tension force of $N_{t,Ed} = 4000$ KN.

Solution:

$t_f = 19.6 \text{ mm}, f_y = 345 \text{ N/mm}^2, f_u = 490 \text{ N/mm}^2, A = 159 \text{ cm}^2.$

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} = \frac{159 \times 10^2 \times 345}{1.0} \times 10^{-3} = 5485.5 \text{ KN}$$

$A_{net} = 159 \times 10^2 - 4 \times (22 \times 19.6) = 14175.2 \text{ mm}^2$

$$N_{u,Rd} = \frac{0.9 A_{net} f_u}{\gamma_{M2}} = \frac{0.9 \times 14175.2 \times 490}{1.25} \times 10^{-3} = 5001 \text{ KN}$$

$N_{t,Rd} = 5001 \text{ KN (the lesser of } N_{pl,Rd} \text{ and } N_{u,Rd} \text{)} > 4000 \text{ KN}.$

So, the member is satisfactory.

Problem (4).

Verify, according to the EC3 Code, the strength of a single equal leg angle L 120 x 10 mm in tension connected on one side via one line of two M16 (d=16mm) bolts in standard holes ($d_o=17\text{mm}$) as shown in Figure (3), (dimensions in millimeters). Bolts connect only one side of the angle to a gusset plate. The angle is subjected to a design axial load $N_{t,Ed}$ of 350 KN.

Solution:

$f_y = 235 \text{ N/mm}^2, f_u = 360 \text{ N/mm}^2, A = 23.2 \text{ cm}^2.$

$$N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} = \frac{23.2 \times 10^2 \times 235}{1.0} \times 10^{-3} = 545.2 \text{ KN}$$
Design of Tension Members

\[ N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}} \]

\( p_1 = 70 \text{ mm} \rightarrow 2.5d_c = 42.5 \text{ mm} \& 5d_c = 85\text{mm} \rightarrow \)

\( 42.5 < 70 < 85 \rightarrow \) linear interpolation between 0.4\&0.7

\( \rightarrow \beta_2 = 0.594 \)

\( A_{net} = 23.2 \times 10^2 - (17 \times 10) = 2150 \text{ mm}^2 \)

\[ N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}} = \frac{0.594 \times 2150 \times 360}{1.25} \times 10^{-3} = 367.80 \text{ KN}. \]

\( N_{t,Rd} = 367.80 \text{ KN (the lesser of } N_{pl,Rd} \text{ and } N_{u,Rd}) > 350 \text{ KN}. \)

So, the member is satisfactory.

**Problem (5).**

Design unequal angle connected from the long leg loaded with an axial factored tensile force 580 \text{ KN} using steel grade S355 connected using:

(a) Welded \hspace{1cm} (b) Two bolts \((d_o = 15\text{mm})\)

**Solution:**

(a) Welded

\[ N_{Ed} \leq N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} \rightarrow \]

\( \gamma_{M0} = 1.0 \) , \( f_y = 355 \text{ N/mm}^2 \)

\[ 580 = \frac{A \times 355 \times 10^3}{1.0} \rightarrow A = 1.63 \times 10^{-3} \text{ m}^2 = 16.33 \text{ cm}^2 \]

Use angle \( 100 \times 75 \times 10 \rightarrow A_y = 16.6 \text{ cm}^2 \)

(b) Two bolts \((d_o = 15\text{mm})\)

\[ N_{Ed} \leq N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} \rightarrow \gamma_{M0} = 1.0 \) , \( f_y = 355 \text{ N/mm}^2 \)

\[ 580 = \frac{A \times 355 \times 10^3}{1.0} \rightarrow A = 1.63 \times 10^{-3} \text{ m}^2 = 16.33 \text{ cm}^2 \]

Use angle \( 100 \times 75 \times 10 \rightarrow A_y = 16.6 \text{ cm}^2 \)

\[ N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}} \rightarrow \gamma_{M2} = 1.25 \) , \( f_u = 470 \text{ N/mm}^2 \)

\( A_{net} = 16.6 \times 10^2 - 1 \times (10 \times 15) = 15.10 \times 10^2 \text{ mm}^2 \)
\( p_1 = 100 \text{ mm} \rightarrow 2.5d_e = 37.5 \text{ mm} \) & \( 5d_e = 75 \text{ mm} \) \( \rightarrow \beta_2 = 0.7 \)

\[
N_{u,Rd} = \frac{0.7 \times 15.1 \times 10^2 \times 470 \times 10^{-3}}{1.25} = 397.43 \text{ KN} < 580 \text{ KN Not Ok.}
\]

Try angle \( 150 \times 75 \times 12 \rightarrow A_g = 25.7 \text{ cm}^2 \)

\[
N_{pl,Rd} = \frac{25.7 \times 10^2 \times 355 \times 10^{-3}}{1.0} = 912.35 \text{ KN} > 580 \text{ KN Ok.}
\]

\[
A_{net} = 25.7 \times 10^2 - 1 \times (12 \times 15) = 23.9 \times 10^2 \text{ mm}^2
\]

\[
N_{u,Rd} = \frac{0.7 \times 23.9 \times 10^2 \times 470 \times 10^{-3}}{1.25} = 629.04 \text{ KN} > 580 \text{ KN Ok.}
\]

So, angle \( 150 \times 75 \times 12 \) is satisfactory.

### Problem (6).

Design check of an equal angle \( 150 \times 150 \times 10 \) for an axial factored tensile force 300 KN using steel grade S275 connected using: \( (d_o = 22 \text{ mm}) \)

(a) Welded \hspace{1cm} (b) One bolt \hspace{1cm} (c) Two bolts \hspace{1cm} (d) Three bolts

#### Solution:

\( f_y = 275 \text{ N/mm}^2 \), \( f_u = 430 \text{ N/mm}^2 \), \( A = 29.3 \text{ cm}^2 \)

(a) Welded

\[
N_{pl,Rd} = \frac{A f_y}{\gamma_{M0}} = \frac{29.3 \times 10^2 \times 275 \times 10^{-3}}{1.0} = 805.75 \text{ KN} > 300 \text{ KN Ok.}
\]

(b) One bolt

\[
N_{u,Rd} = \frac{2.0(e_2 - 0.5d_o) f_u}{\gamma_{M2}} = \frac{2(50 - 0.5 \times 22) \times 10 \times 430 \times 10^{-3}}{1.25} = 268.32 \text{ KN}
\]

\(< 300 \text{ KN Not Ok.} \)

Try increase thickness or distance \( e_2 \)

(c) Two bolts

\[
A_{net} = 29.3 \times 10^2 - (22 \times 10) = 27.10 \times 10^2 \text{ mm}^2
\]

\[
p_1 = 30 \text{ mm} \rightarrow 2.5d_e = 55 \text{ mm} \) \( & \) \( 5d_e = 110 \text{ mm} \) \( \rightarrow \beta_2 = 0.4 \)

\[
N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}} = \frac{0.4 \times 27.10 \times 10^2 \times 430 \times 10^{-3}}{1.25} = 372.9 \text{ KN} > 300 \text{ KN Ok}
\]
(d) Three bolts

\[ A_{\text{net}} = 29.3 \times 10^2 - (22 \times 10) = 27.10 \times 10^2 \text{ mm}^2 \]

\[ p_1 = 30 \text{ mm} \rightarrow 2.5d_v = 55 \text{ mm} & 5d_v = 110 \text{ mm} \rightarrow \]

\[ \beta_3 = 0.5 \]

\[ N_{u,Rd} = \frac{\beta_3 A_{\text{net}} f_u}{\gamma M_2} = \frac{0.5 \times 27.10 \times 10^2 \times 430 \times 10^{-3}}{1.25} = 466.1 \text{ KN} > 300 \text{ KN Ok} \]

Note/ by increse the number of bolts the design capacity increse too.

**Problem (7).**

Design unequal angle connected from the short leg loaded with an axial factored tensile force 580 KN using steel grade S355 connected using:

(a) Welded  
(b) Two bolts \((d_o = 15\text{mm})\)

**Solution:**

(a) Welded

\[ N_{Ed} \leq N_{pl,Rd} = \frac{A f_y}{\gamma M_0} \rightarrow \]

\[ \gamma M_0 = 1.0 \ , \ f_y = 355 \text{ N/mm}^2 \]

\[ 580 = \frac{A \times 355 \times 10^3}{1.0} \rightarrow A = 1.63 \times 10^{-3} \text{ m}^2 = 16.33 \text{ cm}^2 \]

Use angle \(100 \times 75 \times 10 \rightarrow A_g = 16.6 \text{ cm}^2\)

(b) Two bolts \((d_o = 15\text{mm})\)

\[ N_{Ed} \leq N_{pl,Rd} = \frac{A f_y}{\gamma M_0} \rightarrow \gamma M_0 = 1.0 \ , \ f_y = 355 \text{ N/mm}^2 \]

\[ 580 = \frac{A \times 355 \times 10^3}{1.0} \rightarrow A = 1.63 \times 10^{-3} \text{ m}^2 = 16.33 \text{ cm}^2 \]

Use angle \(100 \times 75 \times 10 \rightarrow A_g = 16.6 \text{ cm}^2 \text{ connected from short leg} \)

\[ A_e = A_g \text{ for } 75 \times 75 \times 10 \rightarrow \text{Not available} \]

*Use* \(A_e = A_g = 19.2 \text{ cm}^2 \text{ for angle } 100 \times 100 \times 10 \)

We will actually use angle \(200 \times 100 \times 10 \rightarrow A_g = 29.2 \text{ cm}^2 \)

\[ A_{\text{net}} = 19.2 \times 10^2 - 1 \times (10 \times 15) = 17.70 \times 10^2 \text{ mm}^2 \]


\[ N_{u,Rd} = \frac{\beta_2 A_{\text{net}} f_u}{\gamma_{M2}} \rightarrow \gamma_{M2} = 1.25 , \quad f_u = 470 \text{N/mm}^2 \]

\[ p_1 = 100 \text{mm} \rightarrow 2.5d_\phi = 37.5 \text{mm} \& 5d_\phi = 75\text{mm} \rightarrow \beta_2 = 0.7 \]

\[ N_{u,Rd} = \frac{0.7 \times 17.7 \times 10^2 \times 470 \times 10^{-3}}{1.25} = 465.86 \text{KN} < 580 \text{KN Not Ok.} \]

Try angle 200 $\times$ 100 $\times$ 15 $\rightarrow A_g = 43 \text{cm}^2$

*Use* \( A_e = A_g = 28 \text{cm}^2 \) for angle 100 $\times$ 100 $\times$ 15

\[ A_{\text{net}} = 28 \times 10^2 - 1 \times (10 \times 15) = 26.5 \times 10^2 \text{mm}^2 \]

\[ N_{u,Rd} = \frac{0.7 \times 26.5 \times 10^2 \times 470 \times 10^{-3}}{1.25} = 697.48 \text{KN} > 580 \text{KN Ok.} \]

\[ N_{p,l,Rd} = \frac{A f_y}{\gamma_{M0}} = \frac{43 \times 10^2 \times 355 \times 10^{-3}}{1.0} = 1526.5 \text{KN} > 580 \text{KN Ok.} \]

So, angle 200 $\times$ 100 $\times$ 15 connected from the short leg is satisfactory.

Notice that connect from the short leg makes the design not economic.
1.7 Extra Problems

Problem (1)

The tension member shown in the following figure channel $200 \times 90 \times 30$ of steel grade S275 connected from the web using bolts $d_o = 18 \text{ mm}$ compute $A_{net}$.

Problem (2)

The tension member shown in the following figure universal beam $457 \times 152 \times 82$ of steel grade S355 connected from the web using bolts $d_o = 16 \text{ mm}$ compute $A_{net}$. 
**Problem (3)**

A plate 200 mm width and 10 mm thickness connected with six bolts $d_o = 20 \text{ mm}$ as shown in the following figure using steel grade S355. **Check If the member is safe and Determine tensile strength of the tension member.**

![Diagram of plate with bolts](image)

**Problem (4)**

A channel $100 \times 50 \times 10$ is connected with bolts in each flange as shown in the following figure. Using steel grade S235. **Check If the member is safe and Determine tensile strength of the tension member.**

![Diagram of channel with bolts](image)
**Problem (5)**

Design a Tee shape cut from universal beam connected from the flange using three bolts in two lines as shown in the following figure loaded with an axial factored tensile force 300 KN using steel grade S275 (neglect the eccentricity).

![Diagram of Tee shape beam with three bolts](image)

**Problem (6)**

Design a hot finished square hollow section loaded with an axial factored tensile force 200 KN using steel grade S235. The ends will be connected by welding completely around the section.