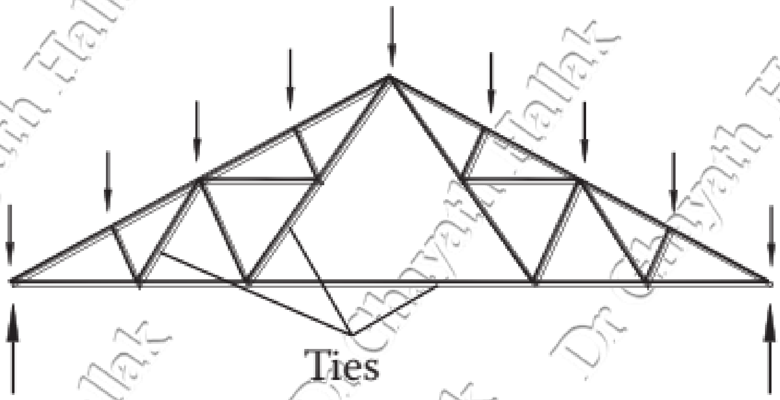
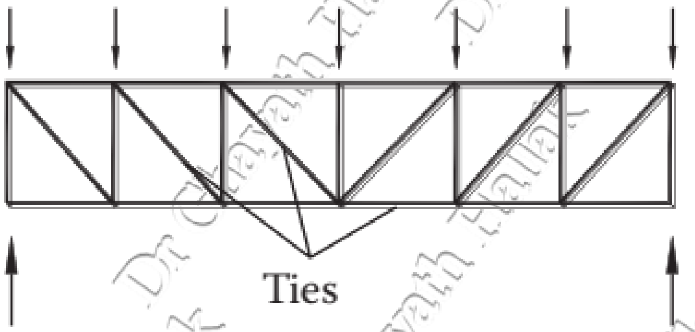
# Tension members

A tension member (or tie) transmits a direct tensile force between two points in a structure and is, theoretically, the simplest and most efficient structural element.

## Uses and types



roof truss

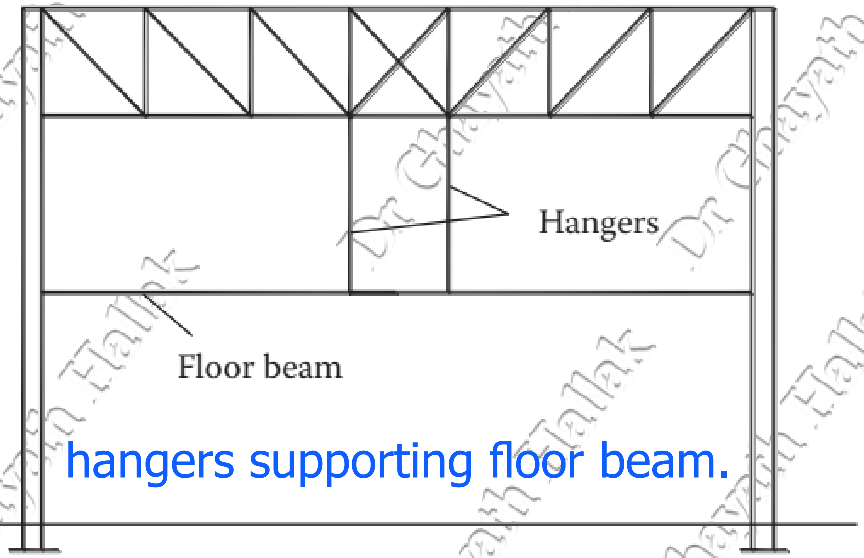


lattice girder

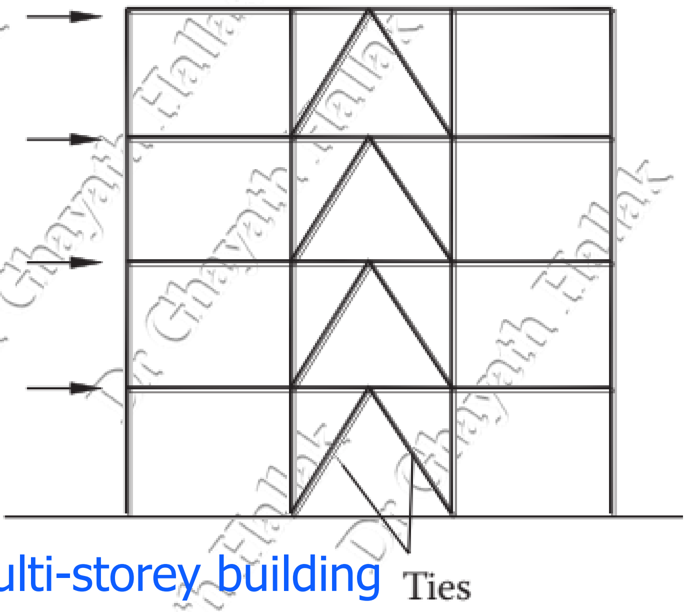
Tension members in building

# Tension members

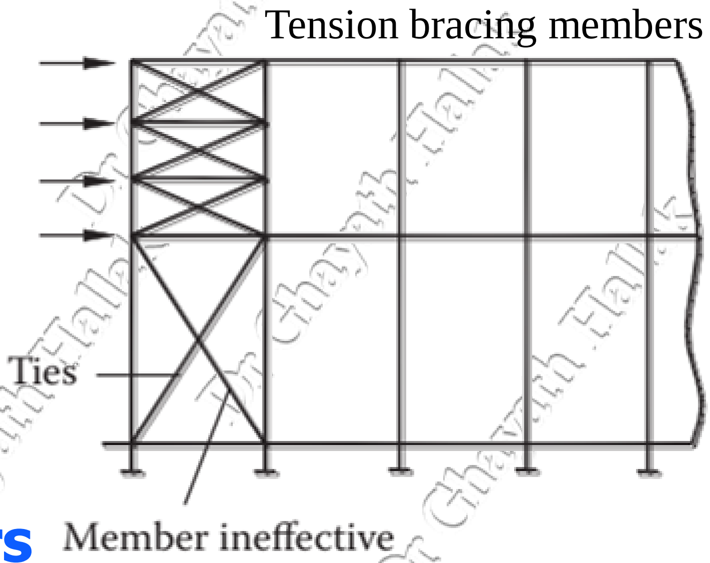
## Uses and types



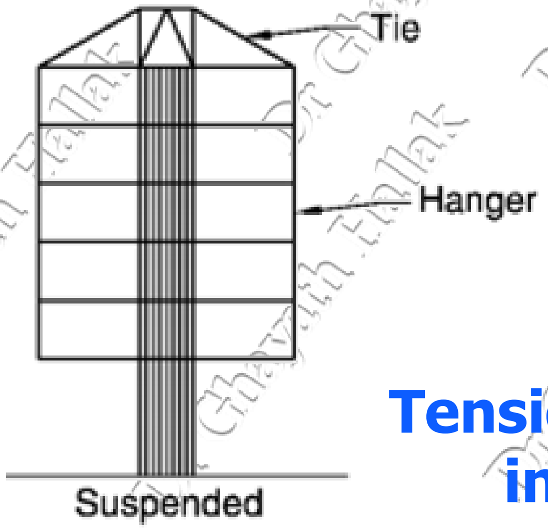
hangers supporting floor beam.



multi-storey building



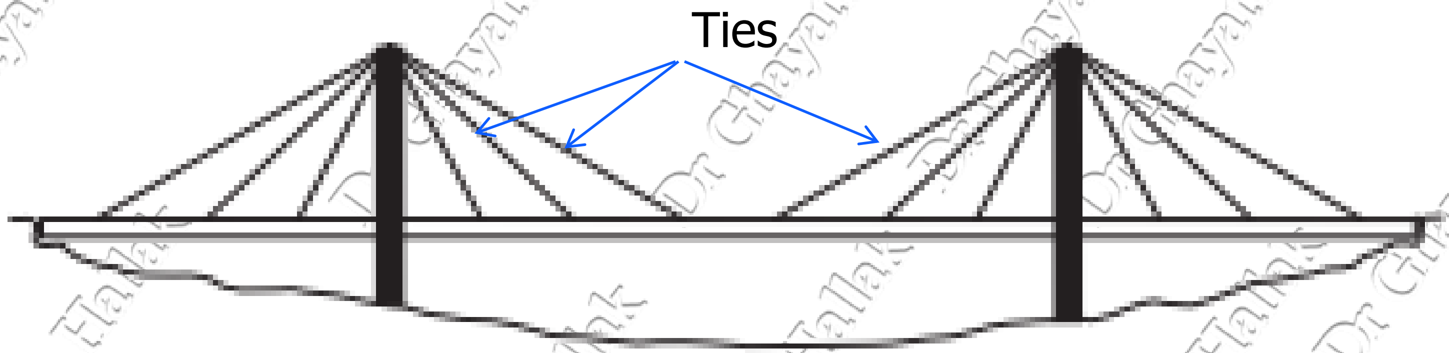
industrial building



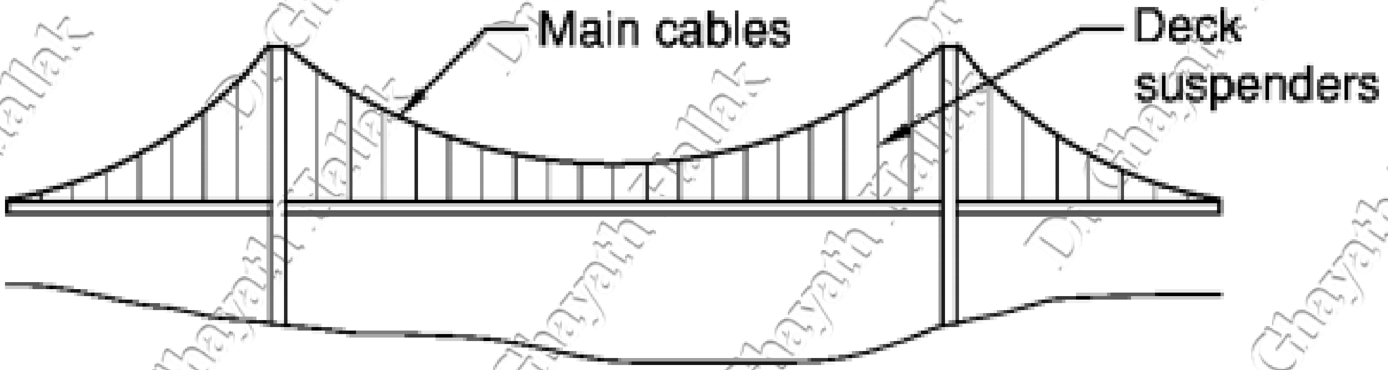
**Tension members in building**

# Tension members

## Uses and types



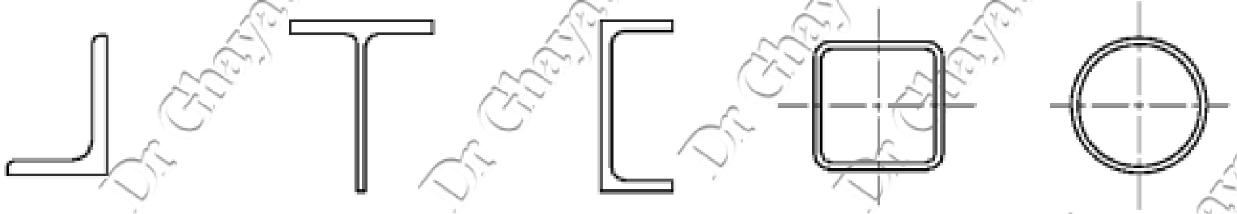
Cable stayed bridge



suspension bridge

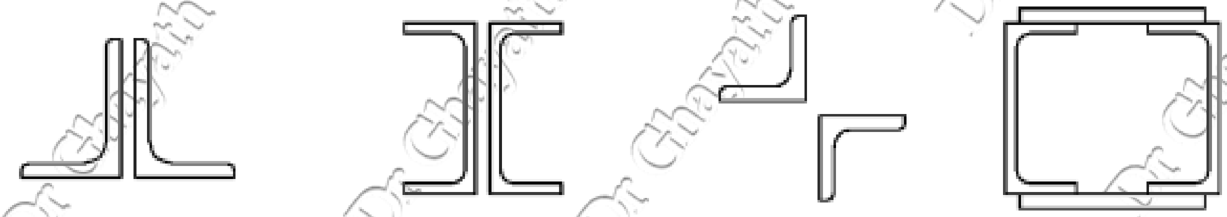
# Common types of member

1- **Open and closed single-rolled** sections such as angles, tees, channels and structural hollow sections.



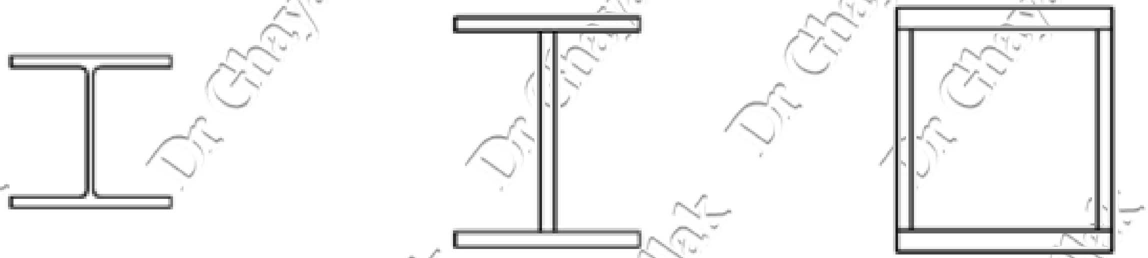
used for tension members in light trusses and lattice girders for bracing.

2- **Compound sections** consisting of double angles or channels. At least one axis of symmetry is present and so the eccentricity in the end connection can be minimised. When angles or other shapes are used in this fashion, they should be interconnected at intervals to prevent vibration, especially when moving loads are present.



# Common types of member

3- **Heavy rolled sections and heavy compound** sections of built up H- and box sections.

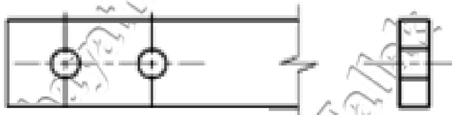


❑-The built-up sections are tied together either at intervals (batten plates) or continuously (lacing or perforated cover plates).

❑-Batten plates or lacing do serve to provide rigidity and to distribute the load among the main elements. Perforated plates can be considered as part of the tension member.

4- **Bars and flats**.

Threaded bar

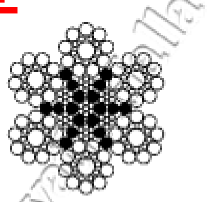


Flat

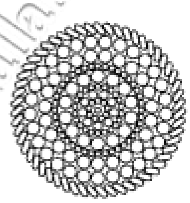
In the sizes generally used, the stiffness of these members is very low; they may sag under their own weight or that of construction workers. Their small cross-sectional dimensions also mean high slenderness values and, as a consequence, they may tend to flutter under wind loads or vibrate under moving loads

## Common types of member

5- **Ropes and cables.**



Round strand rope



Locked coil rope

## Design considerations

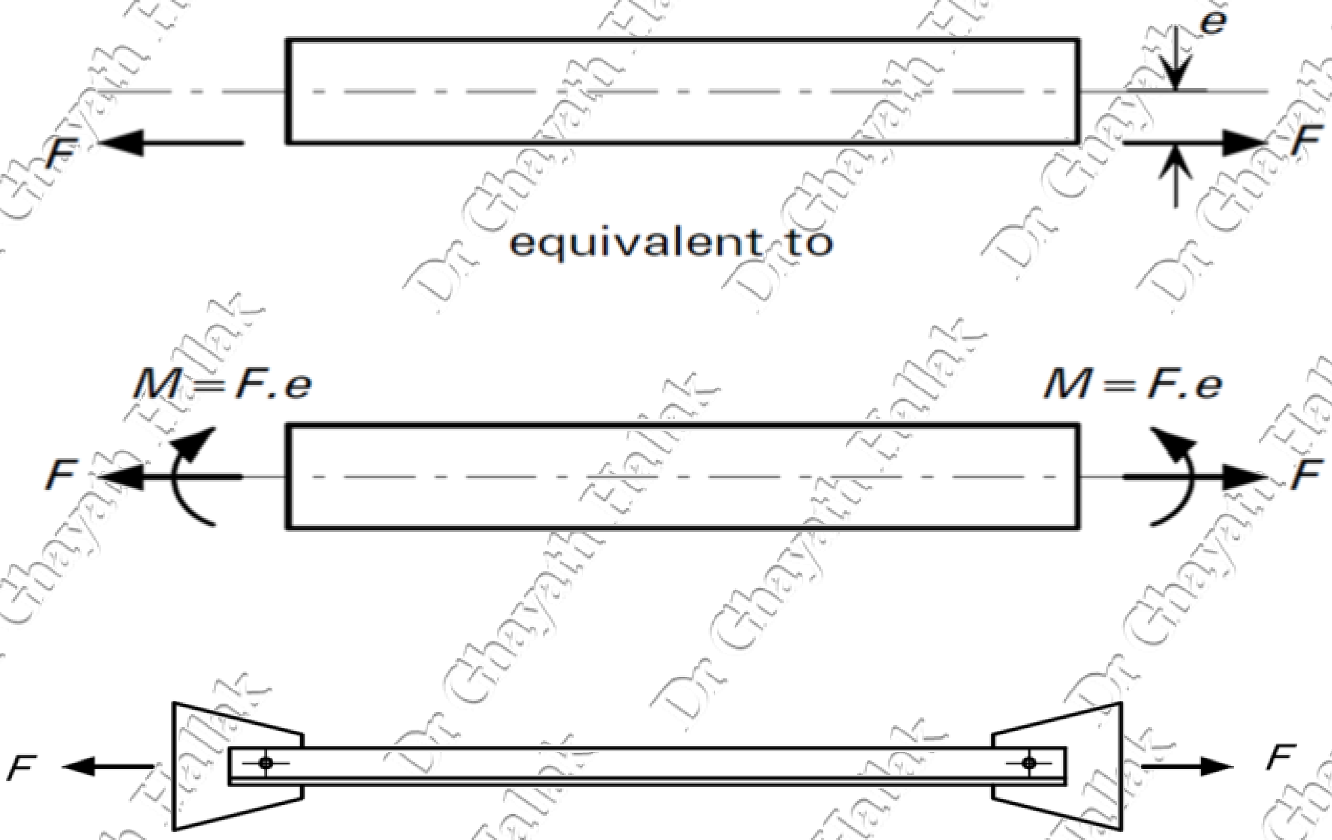
Theoretically, the tension member is the most efficient structural element, but its efficiency may be seriously affected by the following factors:

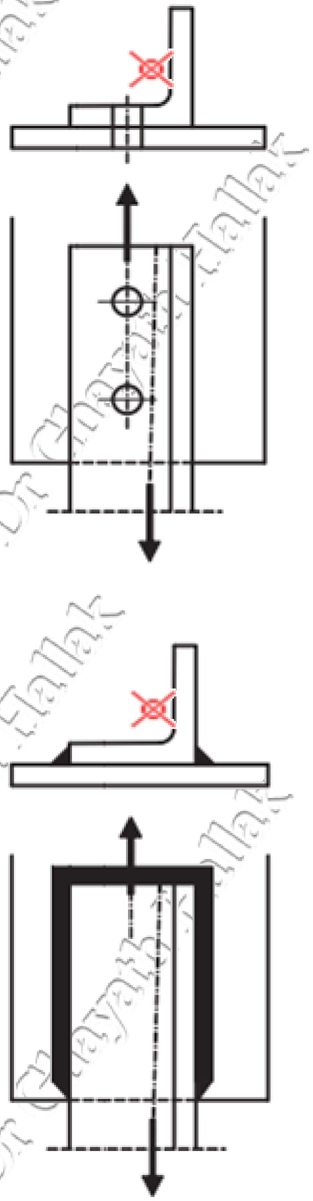
1. **The end connections**: For example, bolt holes reduce the member section.

2. **The member may be subject to reversal of load**, in which case it is liable to buckle because a tension member is more slender than a compression member.

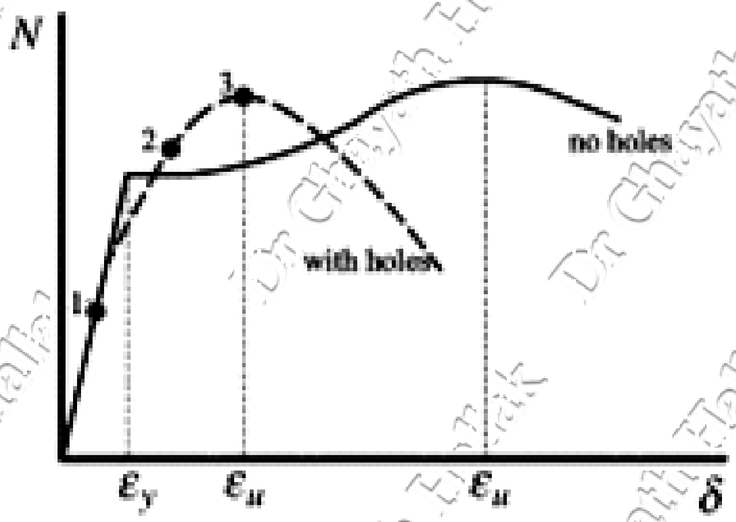
3. **Many tension members must also resist moment as well as axial load**. The moment is due to eccentricity in the end connections or to lateral load on the member.

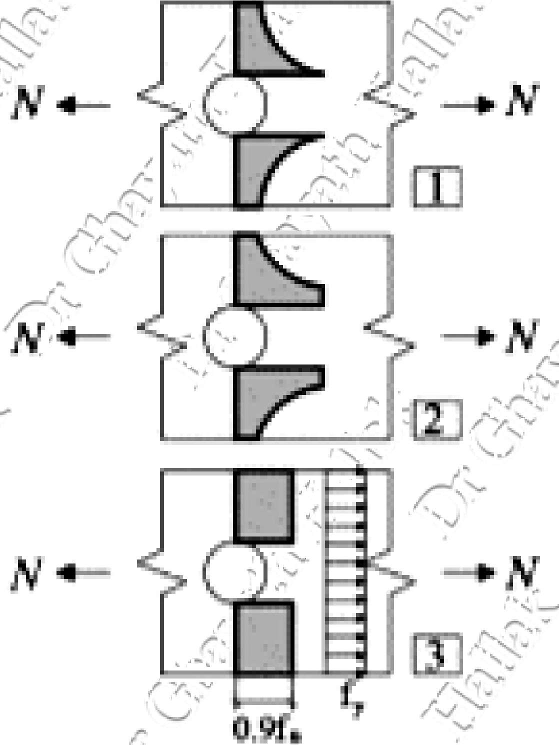
# Design considerations





# Design for axial tension





However, the global behaviour of the tension member has to be taken into account.

Imagine, for example, that the length affected by the **connection is about 5% of the total member length**; then assume that the **strain at the ultimate load of the connection is 10 times the yield strain** (Figure-----).

# Design for axial tension

When the **member reaches the yield condition**, and the **connection the failure condition**, the increases in length would be:

Connection zone:

$$\Delta L_C = \varepsilon_U L_C = 10\varepsilon_Y \times L_C = 10\varepsilon_Y \times 5\% L_{TOT} = 0.5\,\varepsilon_Y L_{TOT}$$

Member zone:

$$\Delta L_m = \varepsilon_U L_m = \varepsilon_Y \times L_m = \varepsilon_Y \times 95\% L_{TOT} = 0.95\,\varepsilon_Y L_{TOT}$$

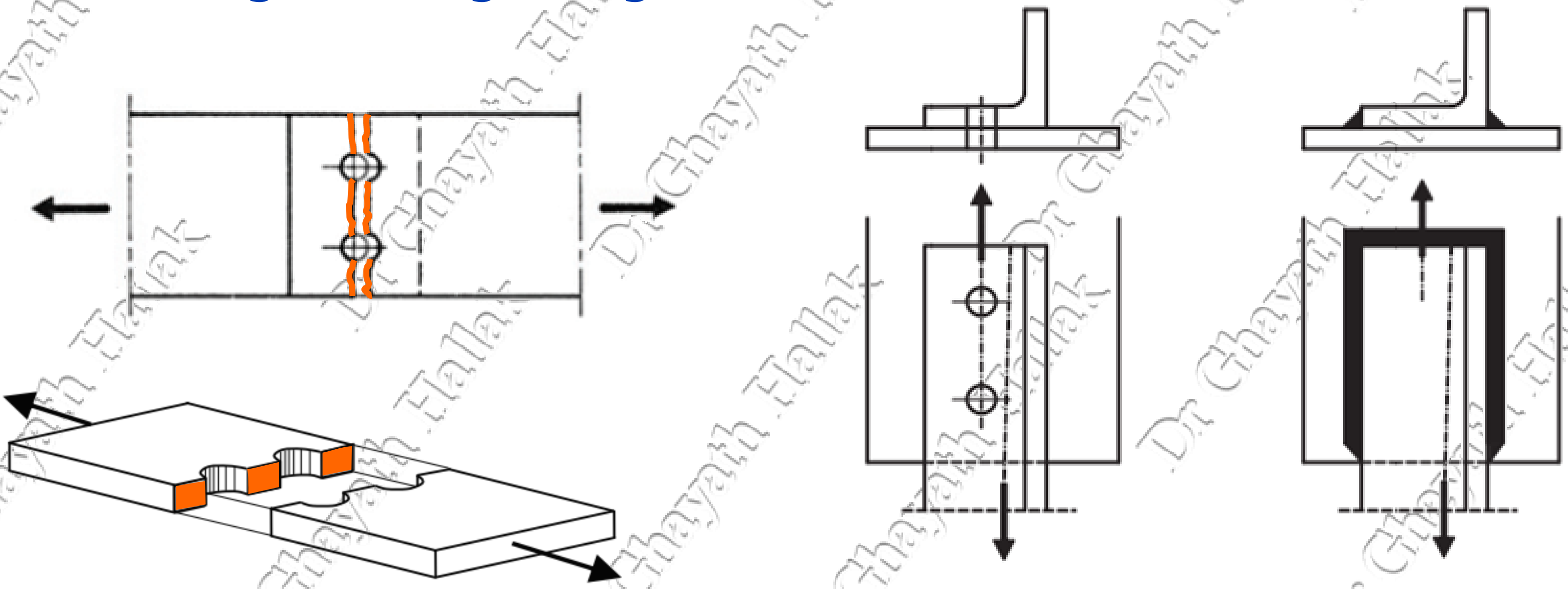
That is

$$\frac{\Delta L_C}{\Delta L_m} = \frac{0.5}{0.95} = 0.52 \approx 0.5$$

which means that the elongation within the connection zone is much smaller than that of the entire bar.

# Design for axial tension

The design of a tension member may be governed by one of the following collapse modes: i) resistance of a gross cross section far from the joints or ii) resistance of the cross section close to the joints or other discontinuities, due to the reduction of cross section, the second-order moments induced by small eccentricities or both effects ( see Fig.). Typically, the second mode is the governing design mode.



a) Collapse in the net cross section

b) Eccentric joints

# Design for axial tension

According to **BS** EN 1993-1-1: Clause 6.2.3

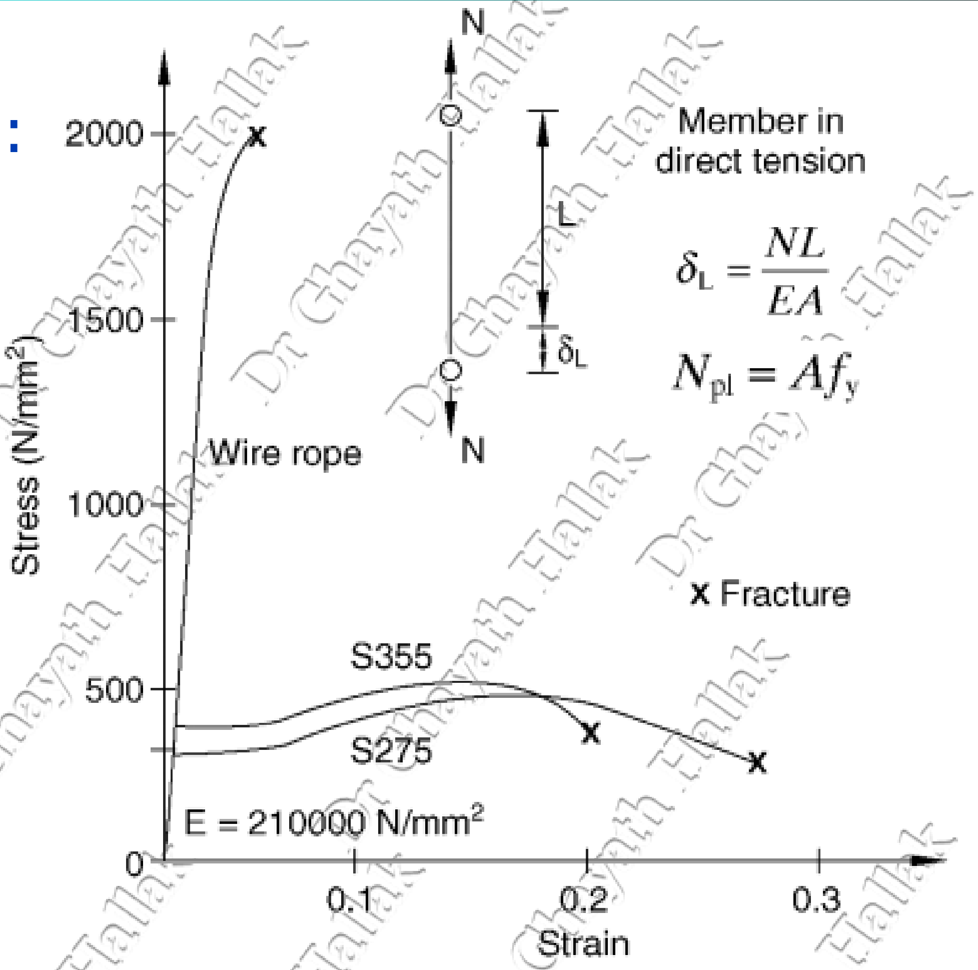
$N_{t,Rd}=\min(N_{pl,Rd}\ ,\ N_{u,Rd})$

$N_{pl,Rd}$: the yielding (plastic) resistance of the gross cross-section (to prevent excessive deformation of the member)

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

$N_{u,Rd}$ :ultimate fracture resistance of the net cross-section

$N_{u,Rd}=0.9\ A_{net}\ f_U/\gamma_{M2}$



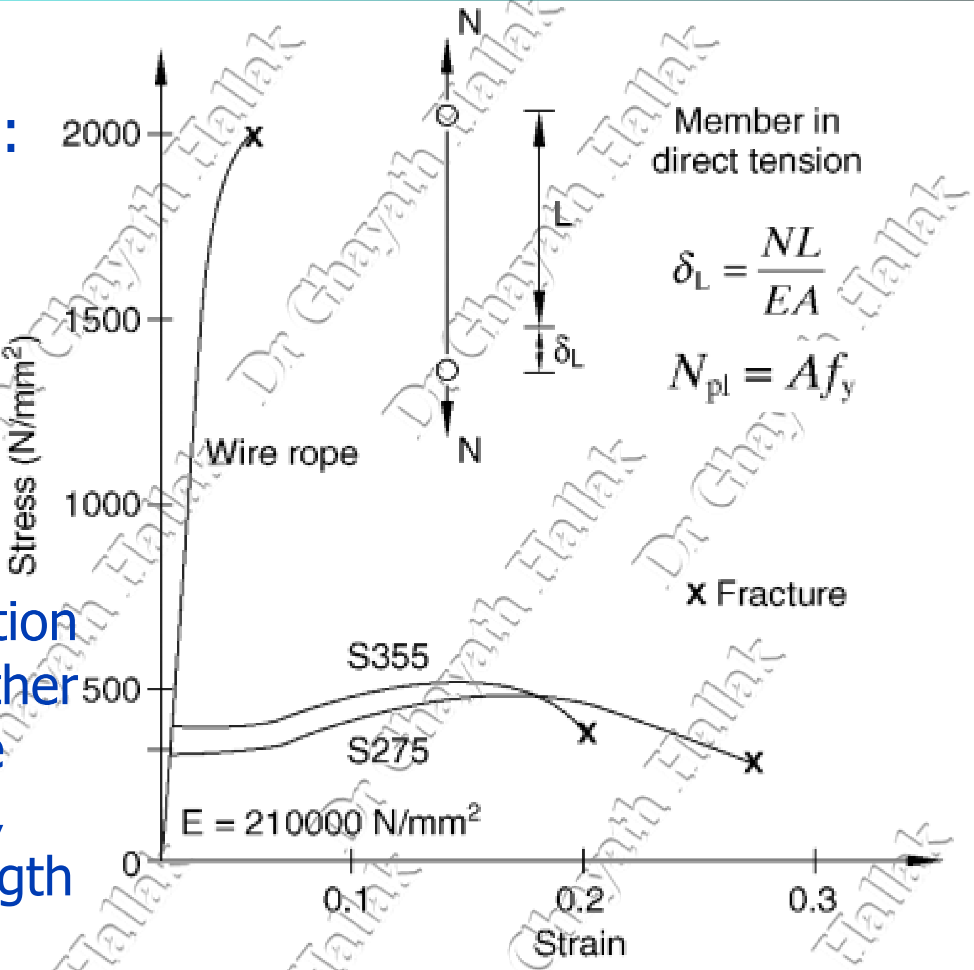
# Design for axial tension

According to **BS** EN 1993-1-1: Clause 6.2.3

$N_{t,Rd}=\min(N_{pl,Rd}\ ,\ N_{u,Rd})$

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

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



$A_{net}$ is net area of the cross-section allowing for bolt holes or other openings (defined in Clause 6.2.2.2 of BS EN 1993-1-1),

$f_u$ is the ultimate tensile strength

0.9 factor was included in the strength model following a statistical evaluation of a large number of test results for net section failure of plates.(Due to unavoidable eccentricities, stress concentrations, etc

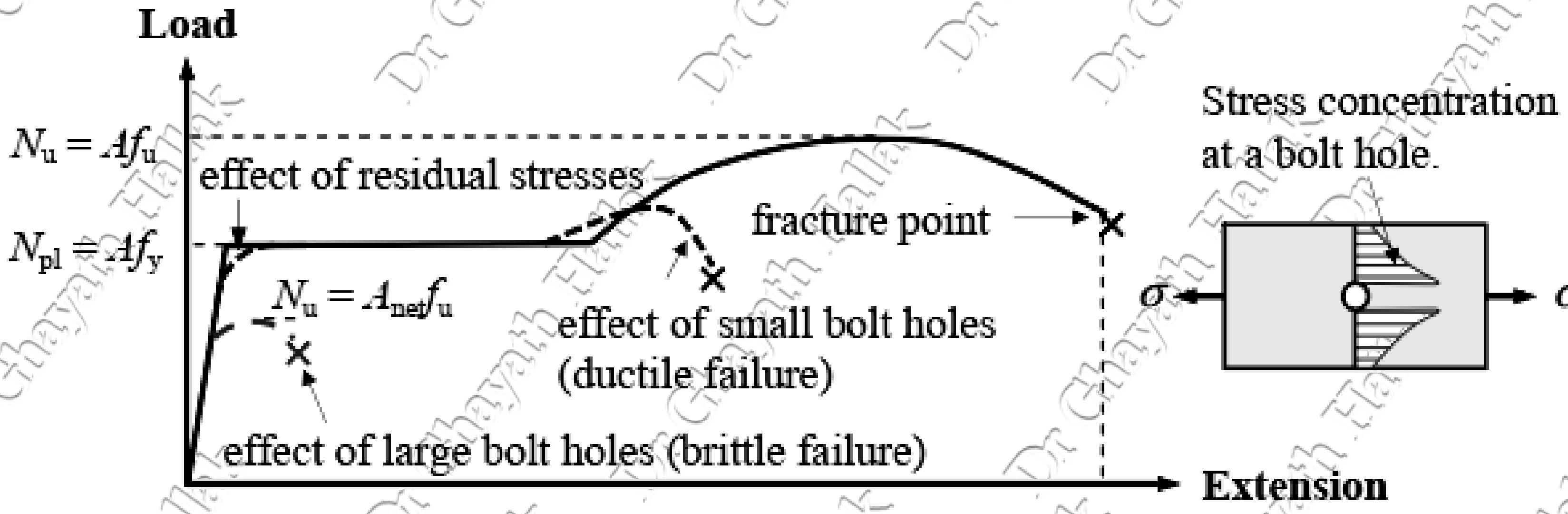
$\gamma_{M2} = 1.25$

# Design for axial tension

According to BS EN 1993-1-1: Clause 6.2.3

To ensure that the full ductile resistance is achieved before failure:

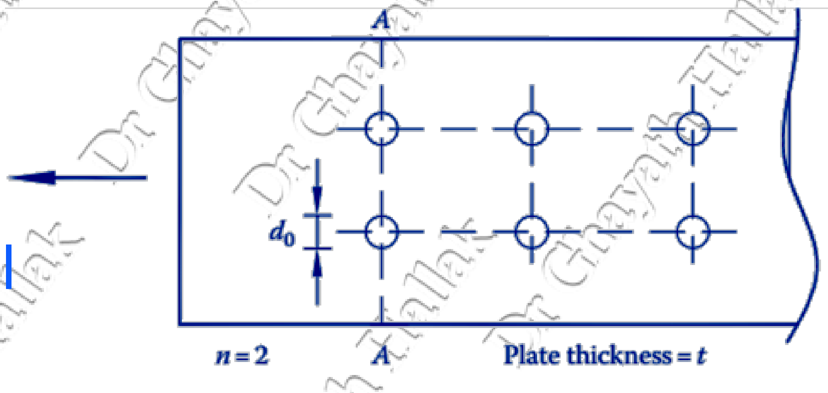
$$N_{u,Rd} > N_{pl,Rd} \rightarrow A_{net}/A > (f_y \gamma_{M2}/0.9 f_u \gamma_{M0})$$



The presence of holes in a cross-section creates stress concentrations resulting in earlier yielding around the holes. In the case of small holes, a ductile failure may still occur with the full gross area reaching the yield stress $f_y$. In the case of larger holes, failure may occur at the ultimate stress $f_u$ with fracture across the minimum cross-sectional area, i.e. $A_{net}$.

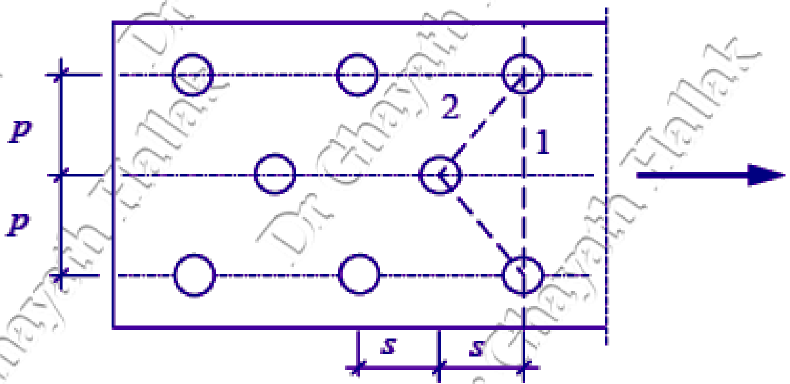
# Design for axial tension

The **net area** is defined in EN 1993-1-1: Clause 6.2.2.2 as the gross area less appropriate deductions for all holes and other openings.



$A_{net} = A - n_p\, t\, d_0 = A - 2\, t\, d_0$

In the case of **multiple fastener** holes, provided that the fastener holes are **not staggered**, the total area to be deducted for fastener holes should be the maximum sum of the sectional areas of the holes in any cross section perpendicular to the member axis (clause 6.2.2.2(3))



Where the fastener holes are **staggered**, the net area $A_{net}$ should be the minimum of:

$A - n_p\, t\, d_0$ (fracture section 1);

$A - [\, n\, t\, d_0 - t \sum( s^2/4p) \,]$ (fracture section 2)

# Design for axial tension

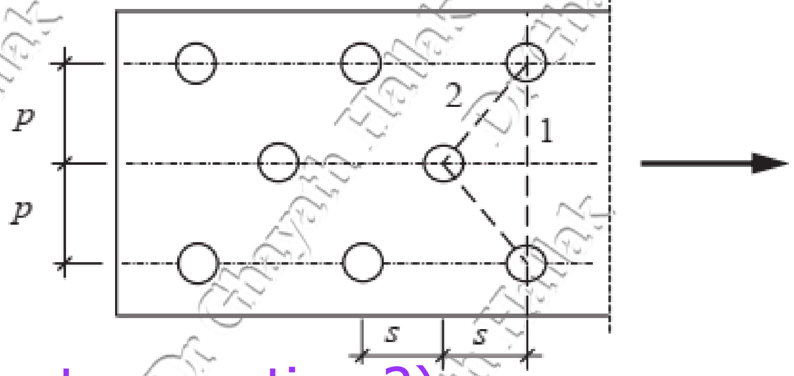
$A$ is the gross area of the section;

$n_p$ is the number of non-staggered holes in any cross section perpendicular to the member axis;

$n$ is the number of holes extending in any diagonal or zig-zag line progressively across the member or part of the member,

$t$ is the thickness;

$d_0$ is the hole diameter.



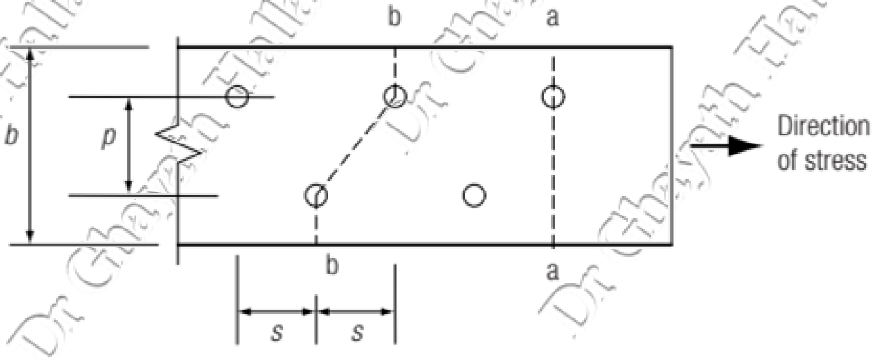
Examples

$A_{net}=Min(\,i\,,\,ii\,)$

i) $A-2\,t\,d_0$ (fracture section 1);

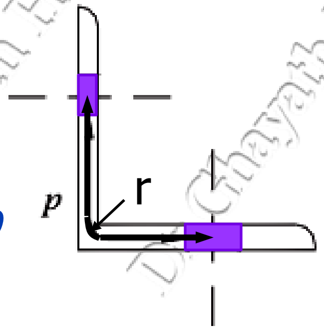
ii)$A - [3\,t\,d\,0 - t\,\text{x}2\text{x}(\,s^2/4\,p)]$ (fracture section 2)

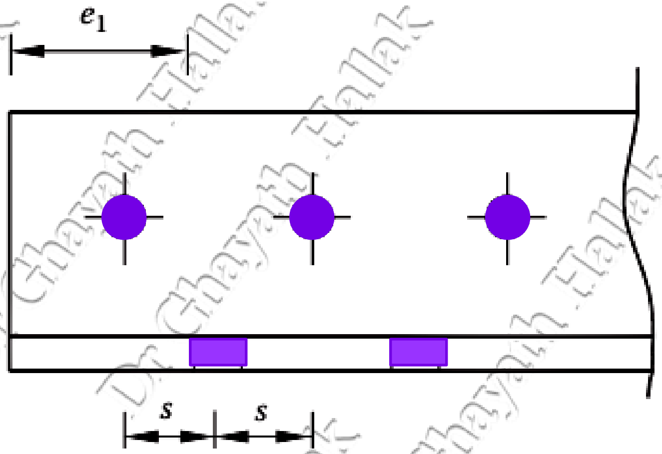
$$A_{net} = bt - \max\left(d_0 t \text{ or } t\left(2d_0 - \frac{s^2}{4p}\right)\right)$$



# Design for axial tension

For angles and other members with holes in **more than one plane, the spacing *p*** should be measured

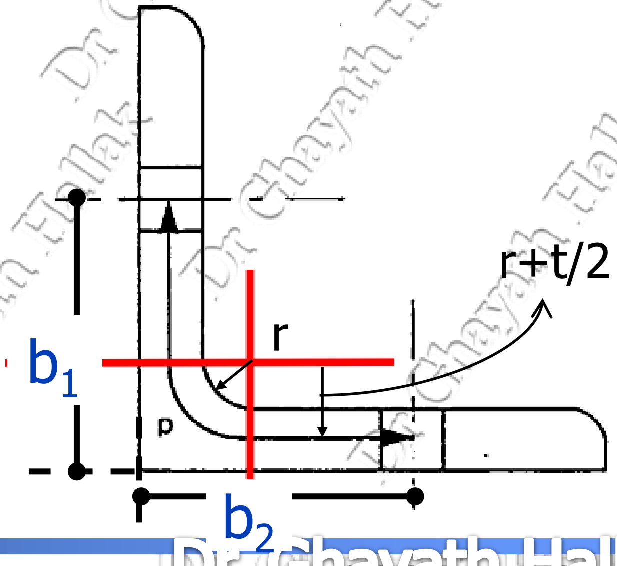




along the centre of thickness of the material as shown in the Figure. From the Figure, the spacing *p* comprises two straight portions and one curved portion of radius equal to the root radius plus half the material thickness.

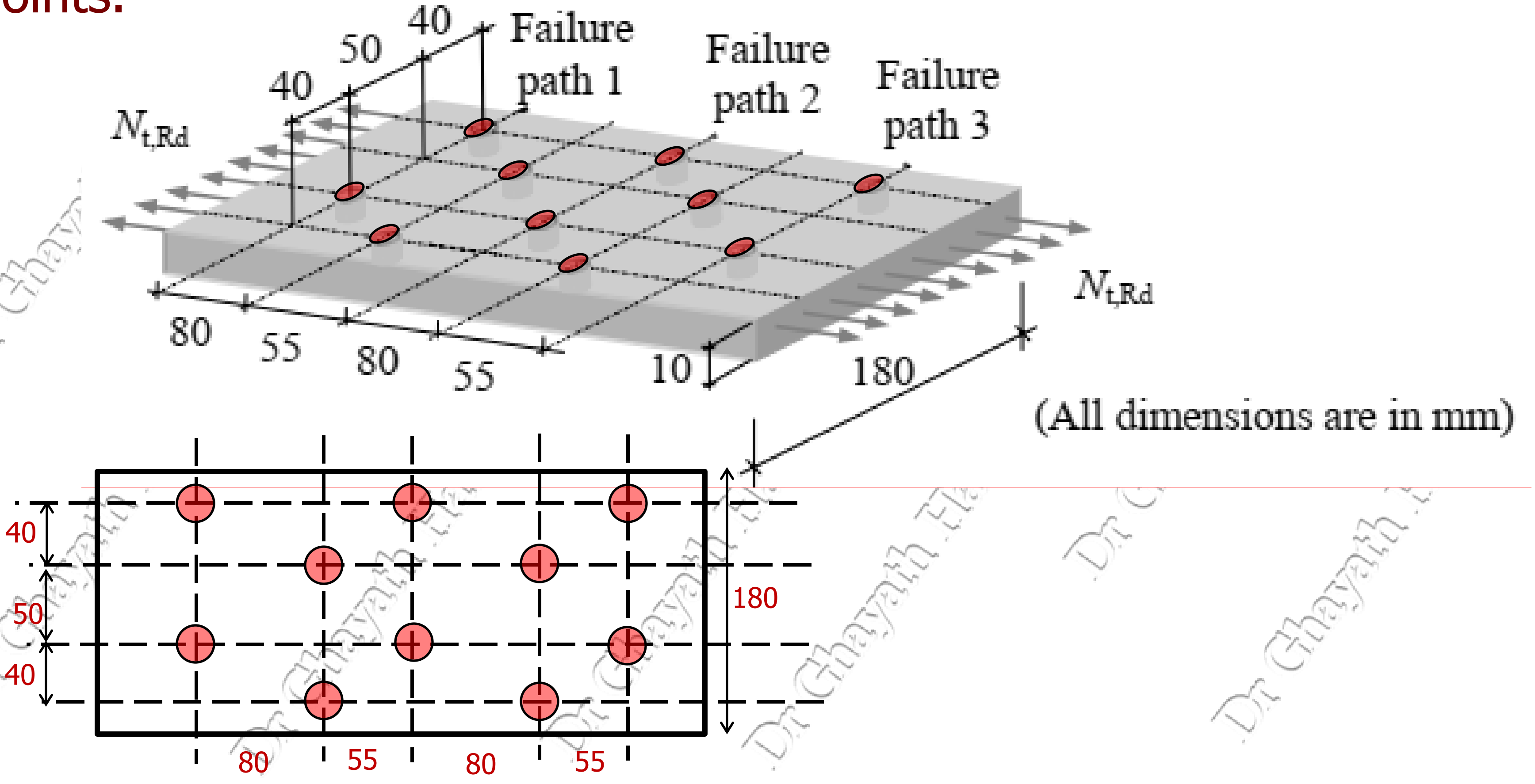
$$P=b1-(t+r)+b2-(t+r)+0.5\pi(r+t/2)$$

$$P=b1+b2-0.43\ r\ -1.215\ t$$



# Example 1

Determine the design tension resistance ($N_{t,Rd}$) of the flat plate tie member indicated in the Figure assuming M16 mm diameter non-preloaded bolts in clearance holes and S355 steel are to be used. The positioning of holes conforms to EN 1993-1-8: design of joints.



# Example 1

**Solution:**

**EN 10025-2:2004**

S355 steel: For $t \leq 16$ mm $f_y = 355$ MPa;

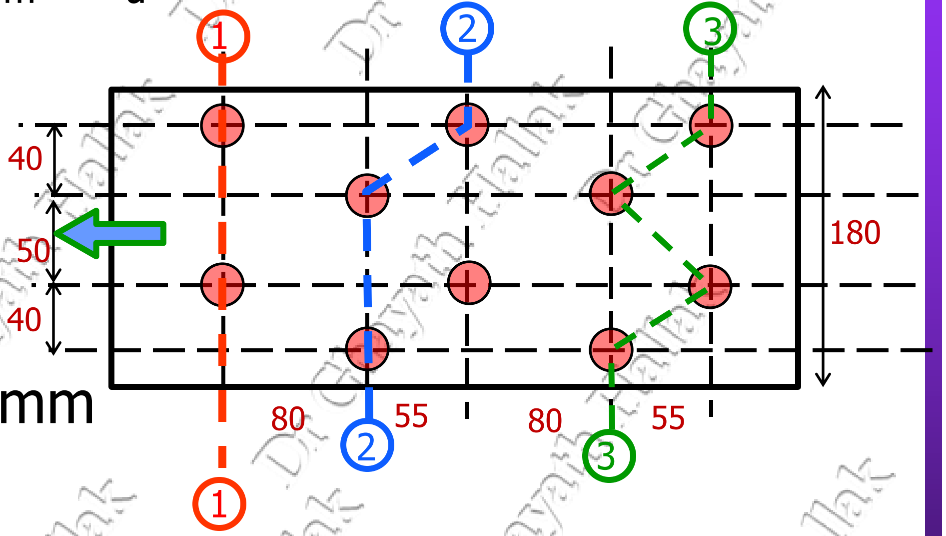
Lowest value in the range for $R_m \therefore f_u = 470$ MPa

**EN 1993-1-1: Clause 6.1**

$\gamma_{M0} = 1{,}0$ and $\gamma_{M2} = 1{,}25$

**EN 1993-1-1:2005**

Clause 6.2.2.2(4)



Assume hole diameter $d_0 = 18$ mm

Area to be deducted equals the greater of:

(i) deduction for non-staggered holes and

(ii) $t\,[n\,d_0 - \Sigma(s^2/4\,p)]$

# Example 1

**Solution:**

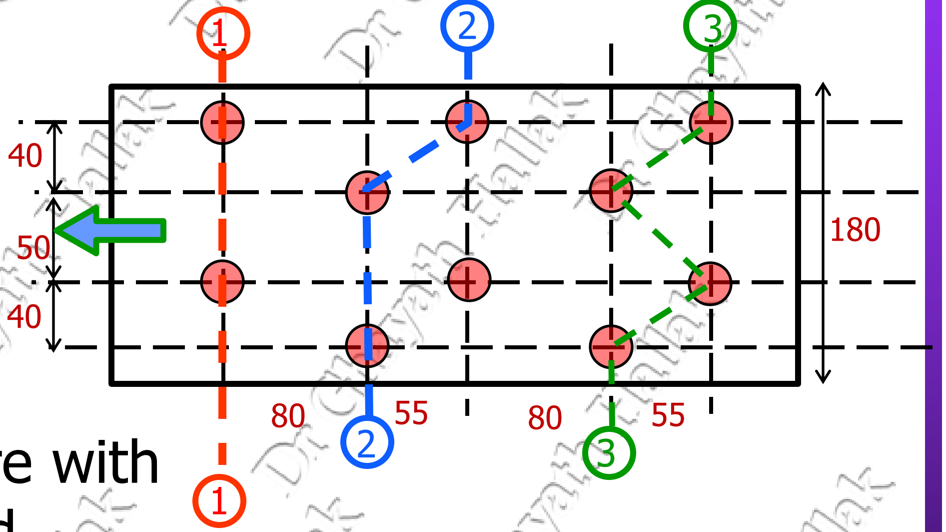
Failure Path 1: Area to be deducted = 2(18 × 10) = **360,0 mm²**

Failure Path 2: Area to be deducted= 10 ×[(3 × 18) – 55²/(4×40)] = 350,9 mm²

Failure Path 3: Area to be deducted

= 10 × [(4 × 18) – 2×55²/(4× 40) – 55²/(4 × 50)]

= 190,6mm ²



Failure Path 1 is the most severe with the highest area to be deducted = 360 mm²

The net cross-sectional area is determined as follows:

$A_{net}$ = [(180 × 10) – 360] = 1440mm²

# Example 1

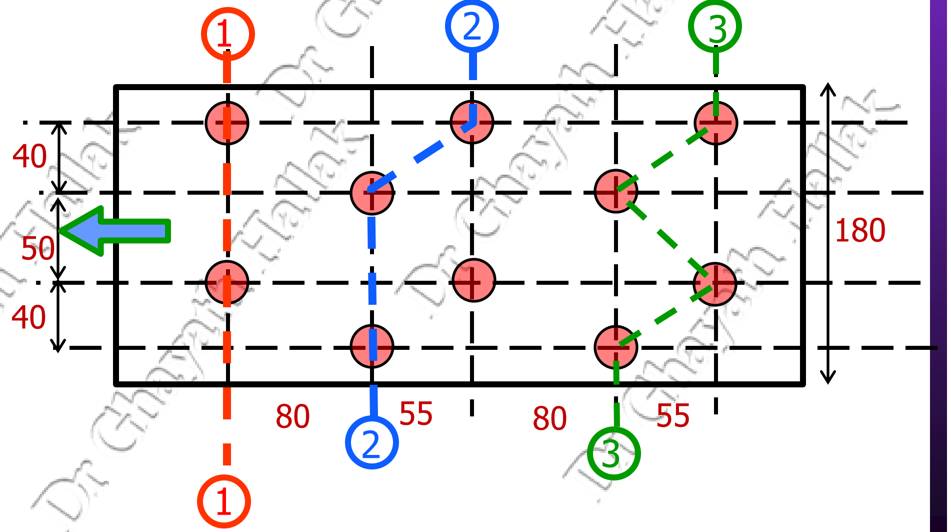
**Solution:**

$N_{t,Rd}=\min(N_{pl,Rd}\ ,\ N_{u,Rd})$

$N_{pl,Rd}=A\ f_y\ /\gamma_{M0}=1800\text{x}355/1.0=639.0\text{kN}$

$N_{u,Rd}=0.9\ A_{net}\ f_u\ /\gamma_{M2}=0.9\text{x}1440\text{x}470/1.25=487.3\text{kN}$

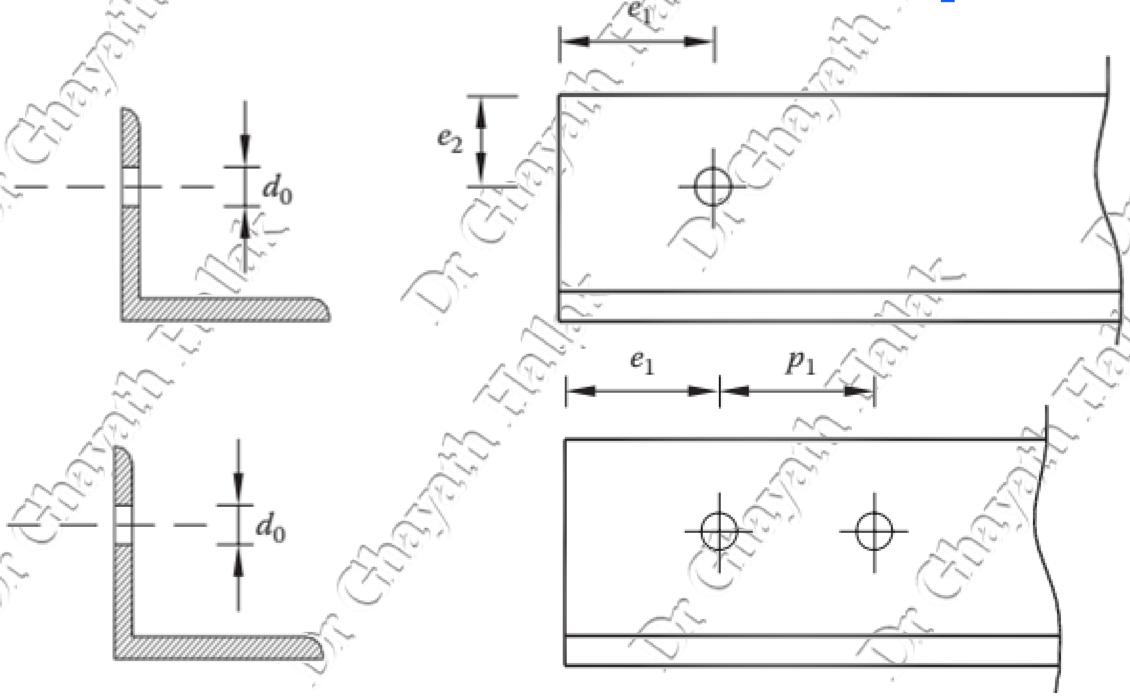
**The design tension resistance $N_{t,Rd}$ = 487.3 kN**



# Eccentricity of end connections

Clause 3.10.3 of BS EN 1993-1-8, are limited in scope and cover only **single angles** connected by a single row of bolts in one leg.

The effect of induced bending moment (due to the eccentricity of the end connections) can be approximated by reducing the cross-sectional area of the member to an effective net area, and design it as concentric load. The effective net area $A_{net,eff}$ is dependent on the number of bolts and the pitch $p_1$.

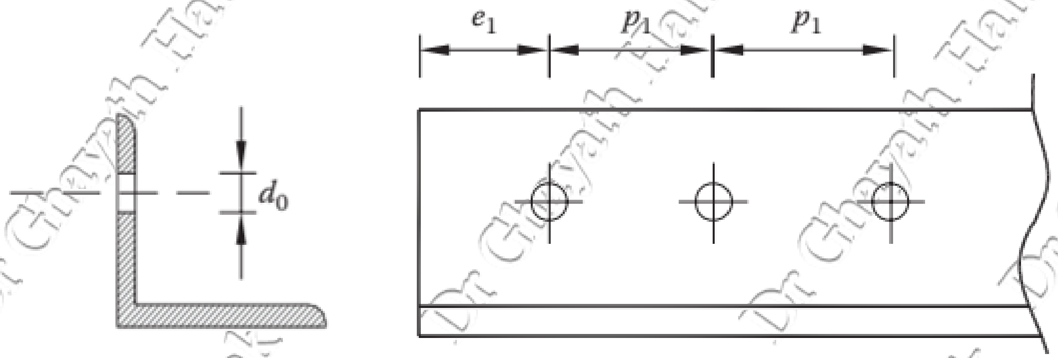


$$A_{net,eff} = 2(e_2 - 0.5d_0)t$$

$$N_{u,Rd} = A_{net,eff}\, f_u / \gamma_{M2}$$

$$A_{net,eff} = \beta 2\, A_{net}$$

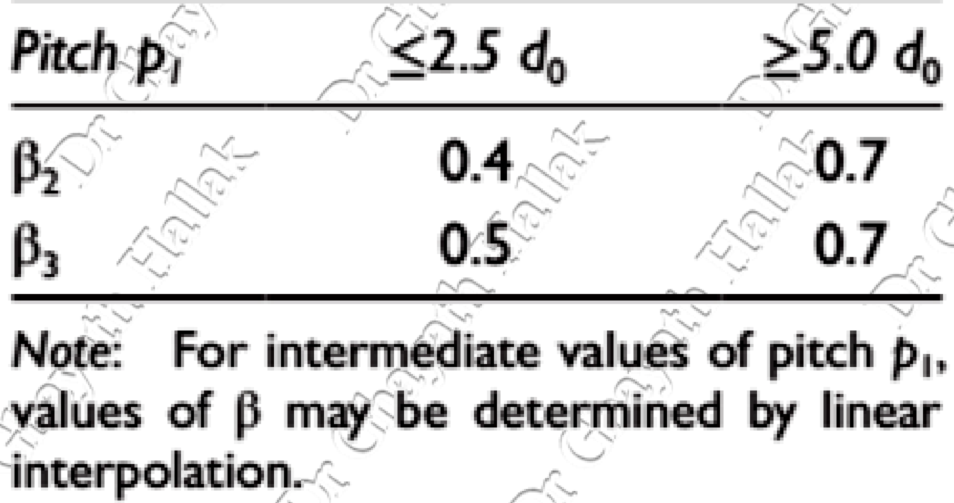
# Eccentricity of end connections



$A_{net,eff} = \beta 3\ A_{net}$

$A_{net}$ is the net area of the angle.

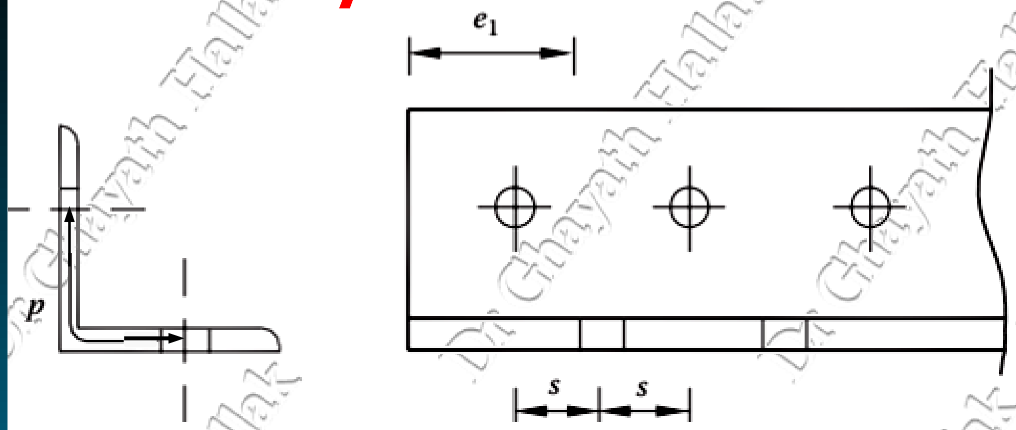
**Table 3.8: Reduction factors β 2 and β 3**



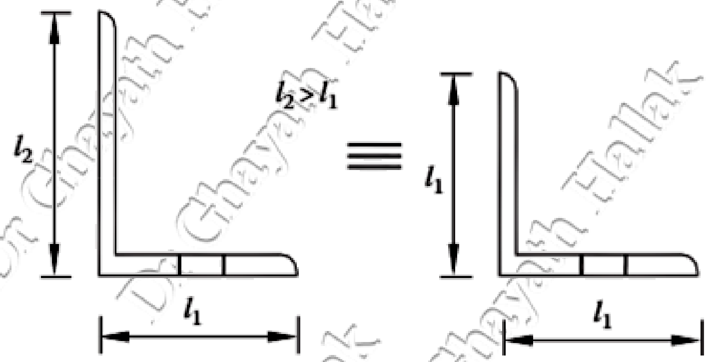
| Pitch $p_1$ | $\leq 2.5\ d_0$ | $\geq 5.0\ d_0$ |
|---|---|---|
| $\beta_2$ | 0.4 | 0.7 |
| $\beta_3$ | 0.5 | 0.7 |

*Note:* For intermediate values of pitch $p_1$, values of β may be determined by linear interpolation.

# Eccentricity of end connections

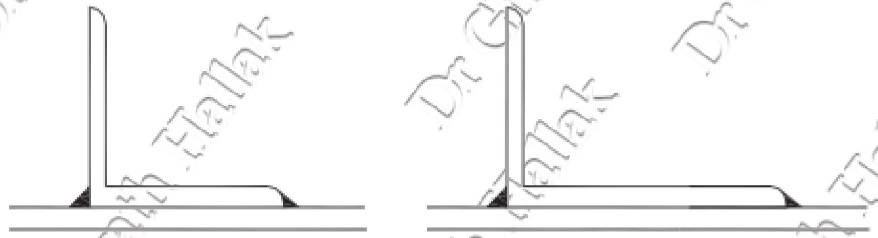


measure of spacing *p*.



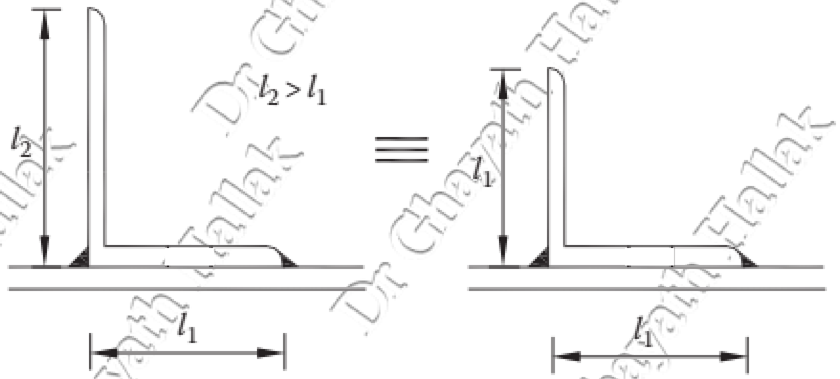
equivalent equal angle

**Net area of angle with holes**



(a) equal angle; (b) unequal angle

**Effective area = gross area**



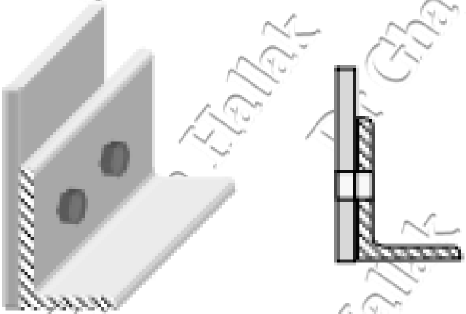
(c) effective area taken as gross area of a smaller angle.

**Effective area of welding connected angle**

# Eccentricity of end connections

## Example 2

Determine the design tension resistance ($N_{t,Rd}$) of the 100x75 x8 S275 steel, single angle tie member with the long leg connected to a gusset plate by 2/M20 diameter bolts in 22mm diameter clearance holes as indicated in the Figure.



100 x 75 x 8 single angle with the long leg connected to a gusset plate. The pitch of the bolts equals 2,5$d_0$.

**Solution:**

**EN 10025-2:2004**

S275 steel: For $t \leq 16$ mm

$f_y = 275$ MPa;

Lowest value in the range for $R_m$

$\therefore f_u = 410$ MPa

**EN 1993-1-1: Clause 6.1**

$\gamma_{M0} = 1{,}0$ and $\gamma_{M2} = 1{,}25$

**EN 1993-1-8:2005**

Table 3.8 The pitch of the bolts is 2,5$d_0$ $\therefore \beta_2 = 0{,}4$

**1/ 100 x 75 x 8 single angle S275**

**Section properties**:

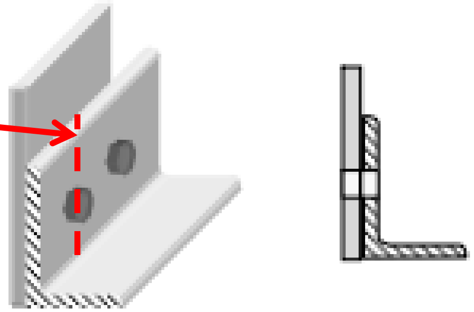
$A_g = 13{,}5$ cm$^2$ $b = 75$ mm

$h = 100$ mm $t = 8$ mm

# Eccentricity of end connections
## Example 2

$A_{eff,net}$ = β2×(gross area - deductions for 22 mm diameter bolt hole)= β2x $A_{net}$

$= 0,4 \times [1350 - (22 \times 8)] = 469,6\ \text{mm}^2$



$N_{t,Rd}=\min(N_{pl,Rd}\ ,\ N_{u,Rd})$

$N_{pl,Rd}=A\ f_y\ /\gamma_{M0}=1350x275/1.0=371.25kN$

$N_{u,Rd}=\ \beta_2\ A_{net}\ f_u\ /\gamma_{M2}=\ A_{eff,net}\ f_u\ /\gamma_{M2}=469.6x410/1.25=154.0kN$

**The design tension resistance $N_{t,Rd}$ = 154.0 kN**

failure by *block shear* will discus later

# Eccentricity of end connections (more than one bolt row and other cross sections)

## BS5950:2000: claus 3.4.3 Effective net area

$A_e = K_e A_{net} \leq A$ , $a_2 = A - a_1$

| STEEL GRADE | Ke |
|---|---|
| S275 | 1.2 |
| S355 | 1.1 |
| S460 | 1.0 |
| OTHER STEEL | $f_u / (1.2 f_y)$ |

$A_e$ effective area of the whole section

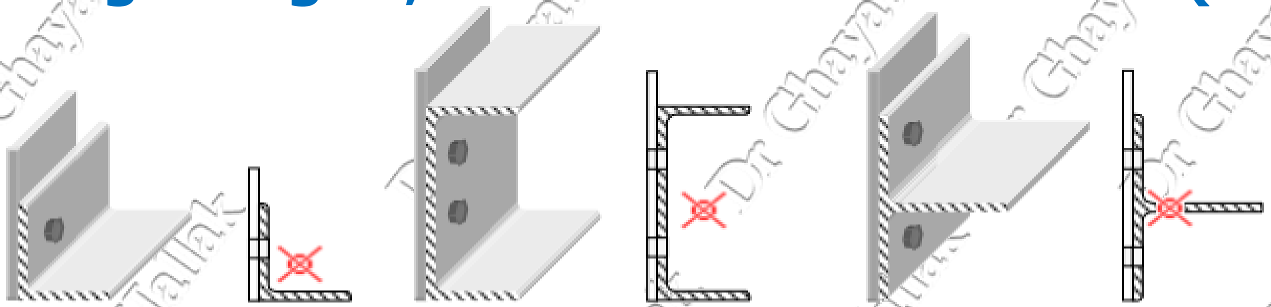
$a_1$ gross area of the connected element (with holes)

$K_e$ factor to allow for strain hardening by increasing the net area

# Eccentricity of end connections

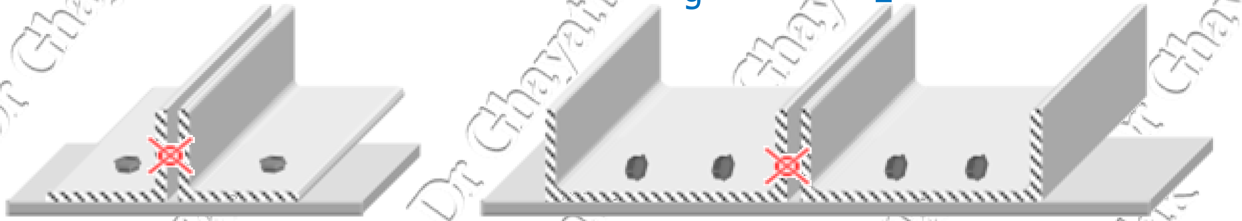
## BS5950:2000:

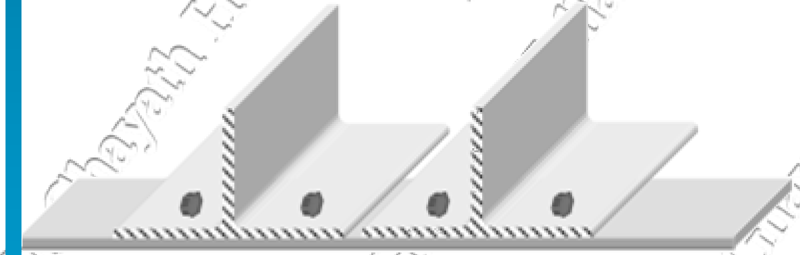
## Single Angles, Channels and T-Sections (Clause 4.6.3.1)



Reduce Effective Area = $(A_e - 0.5a_2)$ for *bolted* connections and

= $(A_g - 0.3a_2)$ for *welded* connections





$A_g$ is the gross cross-sectional area,

$a_1$ is the gross cross-sectional area of the connected element

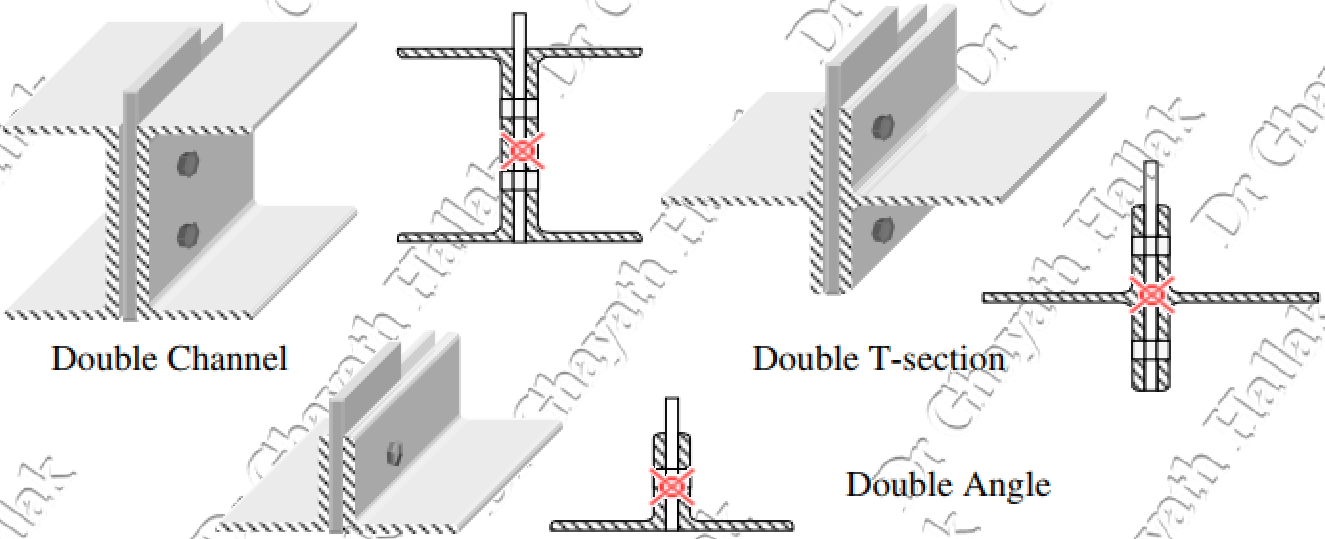
$a_2$ is equal to $(A_g - a_1)$.

$A_e$ is the sum of the effective net areas ($a_e$) of all the elements of the cross-section as defined in Clause 3.4.3 but ≤ (1.2 × Total net area $A_n$)

# Eccentricity of end connections

## BS5950:2000:

## Double Angles, Channels and T-Sections Connected, to *Both* Sides of a Gusset Plate (Clause 4.6.3.2)



Double Channel

Double T-section

Double Angle

Reduce Effective Area = ($A_e - 0.25a_2$) for *bolted* connections and
= ($A_g - 0.15a_2$) for *welded* connections

$A_g$ , $a_1$ , $a_2$ & $A_e$ are as before