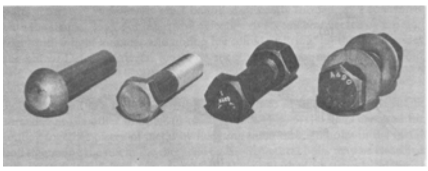
CE 388 – FUNDAMENTALS OF STEEL DESIGN

CHAPTER 6: FASTENED CONNECTIONS

Introduction

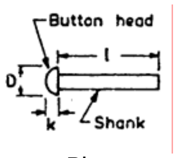
- The purpose of fasteners is to transmit the stresses from a structural member to another so that members acts as a whole (a single member)
- The most essential fasteners used in steel structures are ***rivets*** and ***bolts***



Fasteners in steel structures (rivets and bolts)

Rivets

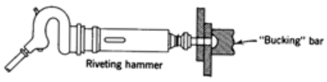
- For many years, rivets were accepted method for connecting the members of steel structures.
- Today, the use of rivets is quite limited and replaced by welding and high-strength bolting
- A usual rivet consists of a *cylindirical steel shank* with *a rounded head* (button head) on one end



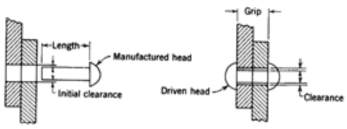
Rivet

Rivets

- A rivet is installed using a riveted hammer in *hot-driven* and *cold-driven* forms
- In hot-driven form
  - A rivet is heated first and inserted in the hole
  - A head is formed on the other end by the riveting hammer, which is operated by a compressed air
  - A hot driven rivet swells under hammer load and fills the hole completely



Riveting hammer



Installation of a rivet

Rivets

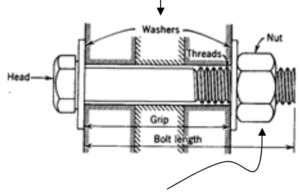
- As the rivet colds, it tends to shrink both lengthwise and diametrically
- The tendency of the rivet to shrink in length is largely prevented by the plates, thus producing tension in the shank of the rivet and compression between the plates

- In cold-driven form
  - Rivets are driven at room temperature and require large pressures to form the head and complete the process
    - Positive aspects: Cold driving increases the strength of the rivet and eliminates the need for heating
    - Negative aspects: the process is limited by equipment required and inconvenience of using it in the field

Bolts

- Bolts are short pieces of round steel bars generally with a hexagonal head at one end and a threaded portion at the other.
- There are several types of bolts, some of which are
  - unfinished bolts
  - turned bolts
  - high-strength bolts

Provide a better distribution of pressure and keep the threases part outside the grip



secure the bolt in place

A typical bolt assembly

Bolts

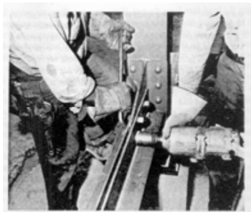
- Unfinished bolts:
  - Generally come with square heads and nuts
  - Have relatively large tolerance in shank and thread dimensions, hence their allowable stresses are considerably small
  - Primarily used in light structures subjected to static loads and for secondary members
- Turned bolts:
  - They are made of 4D steel for St37 structures and 5D steel for St52 structures
  - Their yield stresses are 4.6 t/cm^2 for 4D steel and 5.6 t/cm^2 for 5D steel

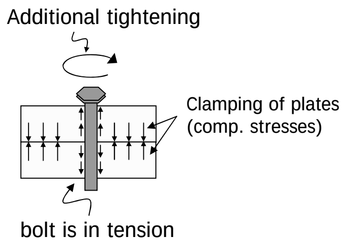
Bolts

- High-strength bolts:
  - They are made of 10K and sometimes 8G steel
  - They have tensile strength several times those of ordinary bolts, between 8-12 t/cm^2
  - Today they are the most popular method for connecting steel members in the field as well as in the shop
  - They can be used for all types of structures, from small buildings to monumental bridges

Pretensioning of High-Strength Bolts

- A high-strength bolt can be pretensioned
- The pretensioning is generated by tightening a bolt additionally once it is installed properly
- As a result of tightening, the plates are clamped tightly and they exert an opposite force on the bolt. Hence, plates are subjected to compressive stresses, whereas the bolt is subjected to tension (pretension or initial tension)

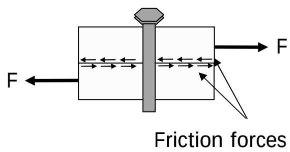




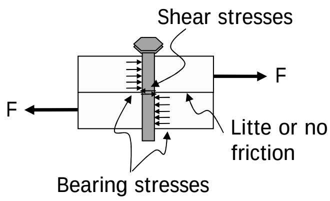
Pretensioning of a bolt

Pretensioning of High-Strength Bolts

- The bolts can be tightened in such a manner that the tension induced is equal to or greater than 70% of the specified minimum tensile strength of steel
- The advantages of pretensioning:
  - The load is transmitted from one plane to another by friction between plates (bolts are not subjected to any bearing or shearing stresses)
  - Have no slip between the plates
  - Have high fatique strength
  - Nuts are prevented from loosening



A pretensioned bolt



A regular bolt

Rivets vs. High-Strength Bolts

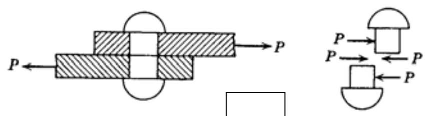
- High strength bolts exhibit the following advantages as compared to rivets:
  - Smaller and relatively less skilled crews are involved
  - Inspection procedures are easier
  - Fewer bolts are required to provide the same strength
  - Noise in bolting is very little
  - No fire hazard and/or danger are present from tossing of hot rivets
  - The bolted joints have a higher fatique strength
  - Bolts can be removed easily wherever structures are disassambled

Types of Fastened Connections

- Fastened connections may be classified
  - According to mode of load transmission
    - Shear connections
    - Tension connections
  - According to nature and location of load with respect to fastener groups
    - Direct load connections
    - Eccentric load connections
    - Pure torque connections
    - Shear and moment connections

Classification As to Mode of Load Transmission

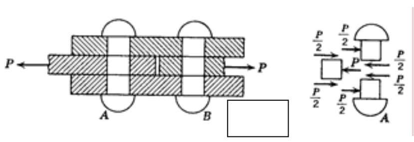
- In shear type connections,
  - The load is transmitted by the action of bearing between the plate and fastener with shear stresses induced in the fasteners
  - They may be arranged in different forms
    - Lap-joint: the load is tranmissted by shear only in one section



Lap-joint

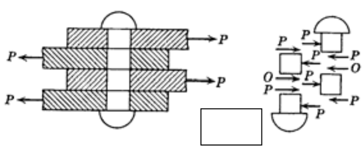
Classification As to Mode of Load Transmission

- Butt-joint: three members are connected and fasteners are subjected to double shear



Butt-joint

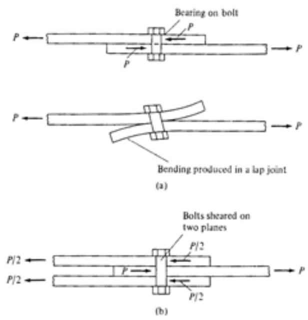
- Multiple-shear joint: the load on fastener is transmitted by shear in more than two planes



Multiple shear-joint

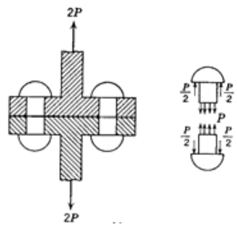
Classification As to Mode of Load Transmission

- The butt joint is more desirable than a lap joint for the following reasons:
  a) the shearing force in each plane in butt joint is one half of that in a lap joint
  b) In lap joint, there is an eccentricity of the load which causes bending in the connection. In butt joint, this is reduced or even eliminated

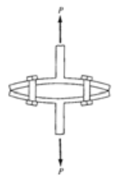


Classification As to Mode of Load Transmission

- In tension type connections,
  - The fasteners are in tension
  - Two problems associated with these connections are that
    - Fasteners heads might be pulled off
    - Prying action can take place in the connection
  - Bolts should be used instead of rivets

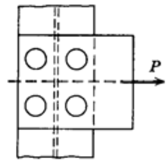


Tension-type connection

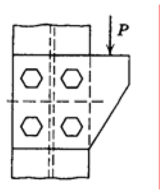

Prying action

Classification As to Nature and Location of Load

- Direct Load Connection:
  - The resultant load passes through the centroid of the fastener cross-sectional areas (shear force due to P only)
- Eccentric Load Connection:
  - The resultant load does not pass through the centroid of the fastener cross-sectional areas (shear force due to P and torque both)



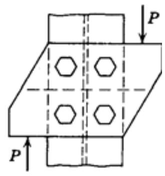
Direct load connection



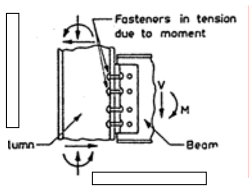
Eccentric load connection

Classification As to Nature and Location of Load

- Pure Torque Connection:
  - The load transmitted consists of pure torque (shear due to torque only)
- Shear and Moment Connection:
  - In a usual beam-column connection, there is a shear and moment at the joint
  - The fasteners are subjected to both shear and tension due to moment transmitted



Pure Torque connection



Shear and moment connection

Allowable Stresses for Fasteners

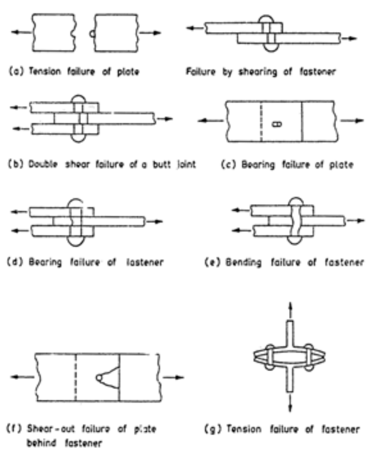
- The allowable stresses for rivets and bolts under shear, bearing and tension are given in Table 12 in TS648

Load Condition		Rivets		Turned Bolts		Black Bolts	
		EY	EIY	EY	EIY	EY	EIY
Shear τ_{em}	kgf/cm^2	1400	1600	1400	1600	1120	1260
	N/mm^2	137	157	137	157	110	124
Bearing σ_{ez}	kgf/cm^2	2800	3200	2800	3200	2400	2700
	N/mm^2	275	314	275	314	235	265
Tensile $\sigma_{çem}$	kgf/cm^2	400	540	1120	1120	1120	1120
	N/mm^2	47	53	110	110	110	110

- Particularly note that
  - $\tau_{em} = 1/2\sigma_{ez}$
  - The allowable tension stress for rivets is quite low

Modes of Failures in Fastened Connections

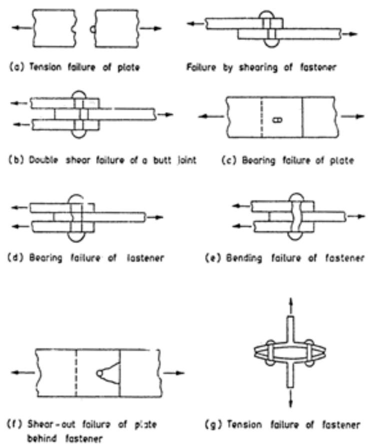
- Failures modes in fastened connections:
  - Tension failure of the plate
  - Shear failure across one or more cross-sections of the fastener
  - Bearing failure of the plate
  - Bearing failure of the fastener
  - Bending failure of the fastener
  - Shear-out failure of the plate
  - Tension failure of the fastener



Modes of failures

Modes of Failures in Fastened Connections

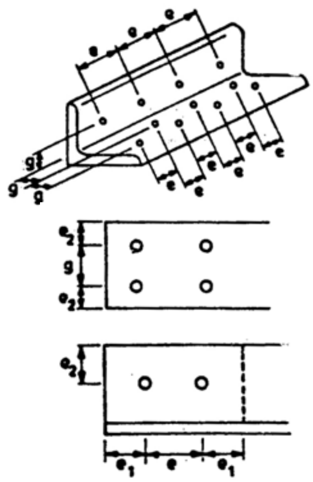
- Normally minimum edge distance prevents shear-out failure
- Tension failure is prevented by using net cross-sectional area in design of tension member
- Hence, in design of fastener only shear, bearing and tensile stresses should be checked



Modes of failures

Fastener Spacings

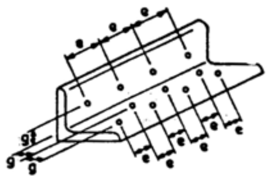
- Minimum and maximum spacings are often prescribed in specifications
- Notations:
  - d_1: fastener hole diameter
  - t_{min}: minimum plate thickness
  - e (pitch): center-to-center distance of fasteners in longitudinal axis
  - g (gage): center-to center distance of fasteners normal to the long. axis (in Turkish practice, g = 3.0-3.5d_1)
  - e_1: edge distance in long. axis
  - e_2: edge distance normal to long. axis



Notational Convention

Fastener Spacings

- Minimum spacing (min e):
  - to permit efficient installation
  - to prevent tension failures of fastened plates
- Maximum spacing (max e):
  - to avoid local buckling of parts of the plates between the fasteners



Notational Convention

- Minimum edge distance spacing (min e_1 or e_2):
  - to prevent danger of a fastener tearing through the metal
- Maximum edge distance spacing (max e_1 or e_2):
  - to prevent development of openings between plates being connected

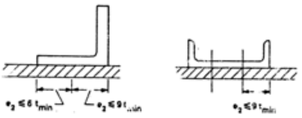
Fastener Spacings

- According to TS648:
  - Minimum and maximum spacings for load carrying fasteners are

Table VI.2 Minimum and Maximum Spacing for Load Carrying Fasteners

Spacing	Minimum Spacing	Maximum Spacing
e	$3d_1$	$8d_1$ or $15t_{min}$
e_1	$2d_1$	$3d_1$ or $6t_{min}$
e_2	$1{,}5d_1$	$3d_1$ or $6t_{min}$

  - For the stiffened edge max e_2 can be taken as



  - For fasteners not carrying loads (stitch fasteners), only maximum spacings are important

Table VI.3 Maximum Spacing for Stitch Fasteners Used in Buildings According to TS648

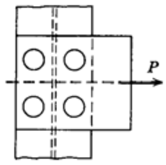
Spacing	Compression Members	Tension Members
e	$8d_1$ or $15t_{min}$	$12d_1$ or $25t_{min}$
e_1	$3d_1$ or $6t_{min}$	$3d_1$ or $6t_{min}$
e_2	$3d_1$ or $6t_{min}$	$3d_1$ or $6t_{min}$

Design of Fastened Connections

- Design procedures for various types of connections will be discussed
- Topics to be covered in this section are
  - Direct shear connectors
  - Eccentric load connections
  - Methods of instantaneous center of rotation
  - Combined shear and tension

Direct Load (Shear) Connections

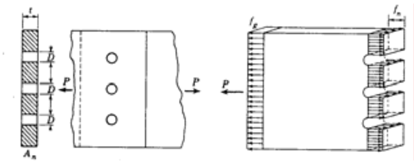
- When the line of action coincides with the center of gravity, the connection is said to be in direct shear
- The followings have to be checked:
  - Tension failure of the plate
  - Shear failure of the fastener
  - Bearing failure of the fastener
  - Bearing failure of the plate



Direct shear connection

Direct Load (Shear) Connections

- Tension stress in the plate:



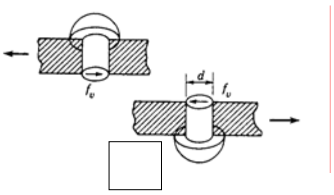
computed tension stress → $\sigma_t = \dfrac{P}{A_n}$

load acting on the connection: P

net section of the area of the plate: A_n ⇒ $A_n = \underbrace{A_g}_{\text{gross area of plate}} - \underbrace{\sum Dt}_{\text{deductions for the bolt or rivet holes}}$

Direct Load (Shear) Connections

- Shear stress in the fastener:

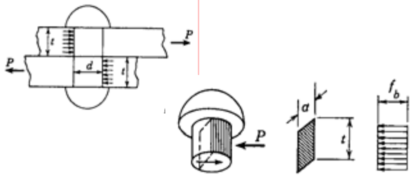


computed shear stress → $\tau = \dfrac{P}{A_s}$

load acting on the connection: P

total shearing area ($A_s = \sum(\pi d^2/4)$)

- Bearing stress in the fastener:



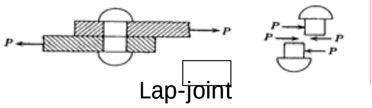
computed bearing stress → $\sigma_b = \dfrac{P}{A_b}$

load acting on the connection: P

total projected bearing area ($A_b = \sum dt$)

Direct Load (Shear) Connections

- To have equal strength in shear and bearing



Lap-joint

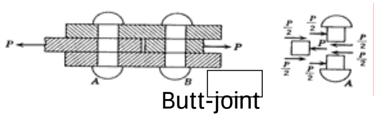
$$P_{all} = n\left(\frac{\pi d^2}{4}\right) x\, \boxed{\tau_{em}} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

$$P_{all} = n(dt_{\min})\, x\, \sigma_{ez} \longleftarrow \sigma_{ez}=2\tau_{em}$$

$$= n(dt_{\min})\, x\, (2\tau_{em}) \quad \ldots\ldots\ldots\ldots\ldots(2)$$

(1) = (2)

$$d = \frac{8}{\pi} t_{\min} = 2.55 t_{\min}$$



Butt-joint

$$P_{all} = n\left(2x\frac{\pi d^2}{4}\right) x\, \tau_{em} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

$$P_{all} = n(dt_{\min})\, x\, \sigma_{ez} \longleftarrow \sigma_{ez}=2\tau_{em}$$

$$= n(dt_{\min})\, x\, (2\tau_{em}) \quad \ldots\ldots\ldots\ldots\ldots..(4)$$

(3) = (4)

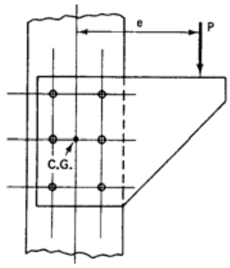
$$d = \frac{4}{\pi} t_{\min} = 1.275 t_{\min}$$

Direct Load (Shear) Connections

Example Problems

Eccentric Load Connections

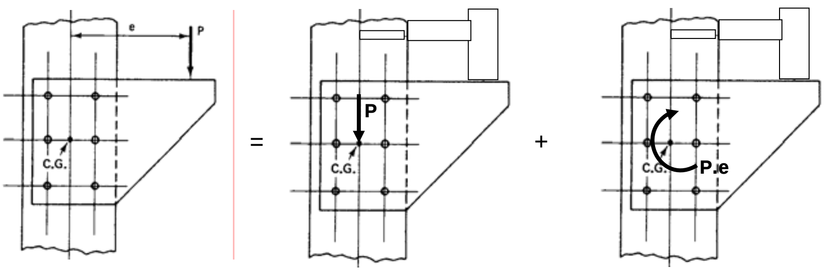
- When bolt groups are loaded by some external load that does not pass through the center of gravity of fastener shear area, the connection is said to be eccentric load connection
- Consider a force P which has an eccentricity e from the center of gravity of the bolt group



Eccentric load connection

Eccentric Load Connections

- The eccentric force can be decomposed into a concentric load passing through the center of gravity plus a torsional moment equal to P.e



Eccentric load Concentric load Torsional moment

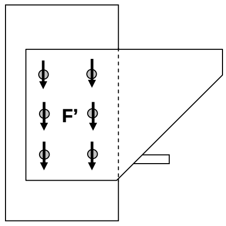
Eccentric Load Connections

- The force transmitted to each bolt can be obtained using the principle of superposition
- Concentric load:
  - P is carried by a bolt in proportion to its cross-sectional area

Shear force carried by a bolt → $\vec{F}_i' = \frac{PA_i}{\sum A_i}$ ← Cross-sectional area of i-th bolt

  - If the force P has components along x and y axes,

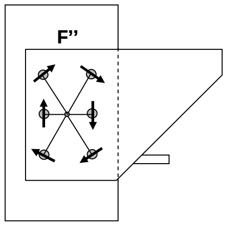
$$F_{ix}' = \frac{P_x A_i}{\sum A_i} \quad \text{and} \quad F_{iy}' = \frac{P_y A_i}{\sum A_i}$$



Shear force in bolts due to concentric load

Eccentric Load Connections

- Torsional moment:
  - The shear force (F'') in a bolt due to torsion is normal to the radious drawn from c.g. to the bolt
  - This force can be determined by applying the classical torsional stress formula



Shear force in bolts due to torsional moment

$$\tau = \frac{M_T r_i}{J_0}$$

shear stress in a bolt → τ; torsional moment → M_T; radial distance between center of gravity and a bolt → r_i; polar moment of inertia of bolts group → J_0

Eccentric Load Connections

- Polar moment of inertia (J) of bolts group

$$J_0 = \sum A_i r_i^2 \quad \text{..........................(1)}$$

- Noting that $r_i^2 = x_i^2 + y_i^2$

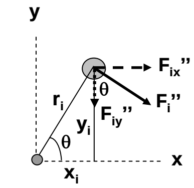
$$J_0 = \sum A_i (x_i^2 + y_i^2) \quad \text{...................(2)}$$

- Inserting (2) into torsion formula

$$\tau = \frac{M_T r_i}{\sum A_i (x_i^2 + y_i^2)} \quad \text{....................(3)}$$

- Shear force in a bolt due to torsion (F_i''):

$$\vec{F}_i'' = A_i . \tau = \frac{A_i M_T r_i}{\sum A_i (x_i^2 + y_i^2)} \quad \text{.............(4)}$$



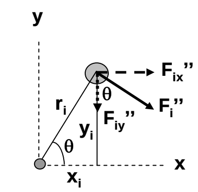
Torsional shear force in a bolt

Eccentric Load Connections

- The x and y components of F_i''

$$F_{ix}'' = F_i''.Sin\theta = \frac{A_i M_T r_i}{\sum A_i (x_i^2 + y_i^2)} . \left(\frac{y_i}{r_i} \right) = \frac{A_i M_T y_i}{\sum A_i (x_i^2 + y_i^2)}$$

$$F_{iy}'' = F_i''.Cos\theta = \frac{A_i M_T r_i}{\sum A_i (x_i^2 + y_i^2)} . \left(\frac{x_i}{r_i} \right) = \frac{A_i M_T x_i}{\sum A_i (x_i^2 + y_i^2)}$$

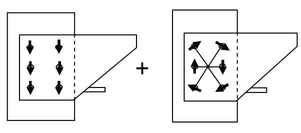


Torsional shear force in a bolt

- Total shear force

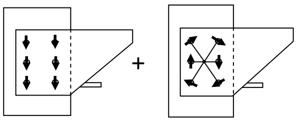
$$F_{ix} = F_{ix}' \pm F_{ix}'' = \frac{P_x A_i}{\sum A_i} \pm \frac{A_i M_T y_i}{\sum A_i (x_i^2 + y_i^2)}$$

$$F_{iy} = F_{iy}' \pm F_{iy}'' = \frac{P_y A_i}{\sum A_i} \pm \frac{A_i M_T x_i}{\sum A_i (x_i^2 + y_i^2)}$$



Eccentric Load Connections

- Total shear force (if the fasteners have all the same area):



  - Vector formulation

$$\vec{F}_i = \vec{F}_i' + \vec{F}_i'' = \overrightarrow{\left(\frac{P}{n}\right)} + \underbrace{\overrightarrow{\left(\frac{M_T r_i}{\sum (x_i^2 + y_i^2)}\right)}}_{J = \sum r_i^2} = \overrightarrow{\left(\frac{P}{n}\right)} + \overrightarrow{\left(\frac{M_T r_i}{J}\right)}$$

  - Scalar formulations

$$F_{ix} = F_{ix}' \pm F_{ix}'' = \frac{P_x}{n} \pm \frac{M_T y_i}{\sum (x_i^2 + y_i^2)} = \frac{P_x}{n} \pm \frac{M_T y_i}{J}$$

$$F_{iy} = F_{iy}' \pm F_{iy}'' = \frac{P_y}{n} \pm \frac{M_T x_i}{\sum (x_i^2 + y_i^2)} = \frac{P_y}{n} \pm \frac{M_T x_i}{J}$$

Eccentric Load Connections

Example Problem

Method of Instantenous Center of Rotation

- For eccentrically loaded connections, the location of most heavily loaded fastener (called critical fastener) is located farthest from the center of gravity
  - For simple connections, the critical fastener can be located by inspection
  - For more complicated connections, the method of instantenous center of rotation can be used
- Instantenous center of rotation (ICR) is defined as the point on the connection where shear stress is zero

Method of Instantenous Center of Rotation

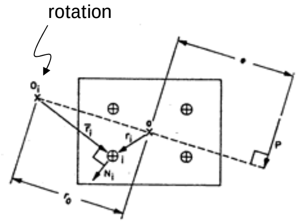
- If all the fasteners have the same cross-sect. area, resulting shear force in a bolt

$$F_i = \frac{P}{n} + \frac{P.e.r_i}{\sum r_i^2}$$

- At $r = r_0$, $F_i = 0$

$$\frac{P}{n} + \frac{P.e.r_o}{\sum r_i^2} = 0 \Rightarrow r_o = -\frac{\sum r_i^2}{e.n}$$

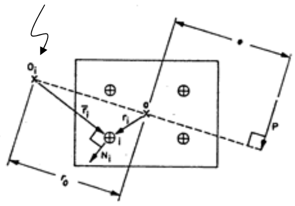
  - The negative sign indicates that ICR must be on the opposite side of load P
  - The shear force caused by concentric load is directed (↓)



Instantenous center of rotation

Method of Instantenous Center of Rotation

- Then, to have zero shear, the shear force caused by torsion must be directed in the opposite sense (↑)
- The shear force caused by torsion is directed (↑) only on the opposite side of the load
- Also note that since the shear force due to torsion is normal to the radious drawn from center of gravity, ICR must lie on a line perpendicular to the line of application of the load P



Instantenous center of rotation

Method of Instantenous Center of Rotation

- ICR can be thought of a point where only rotation takes place without any translation. It is the center of rotation
- The torsional moment (M_T) at ICR:

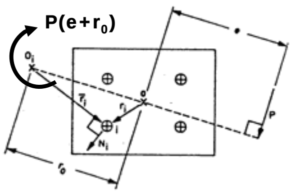
$$M_T = P(e + r_0)$$

Use positive value

- The magnitude of shear force in any bolt is obtained from torsion formula measured from ICR

$$F_i = \frac{M_T \bar{r}_i}{\sum \bar{r}_i^2} = \frac{P(e+r_o)\bar{r}_i}{\sum \bar{r}_i^2}$$

radial distance measured from ICR



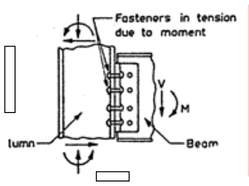
Instantenous center of rotation

Method of Instantenous Center of Rotation

Example Problem

Combined Shear and Tension

- When eccentrically applies loads lies outside the plane of connection, the fasteners are subjected to a combination of shear and tension
- It is customary to consider the combined effect through the interaction diagram



Shear and moment connection

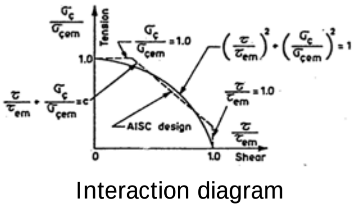
computed shear stress

computed tensile stress

$$\left(\frac{\tau}{\tau_{em}}\right)^2 + \left(\frac{\sigma_ç}{\sigma_{çem}}\right)^2 \leq 1.0$$

allowable shear stress

allowable tension stress



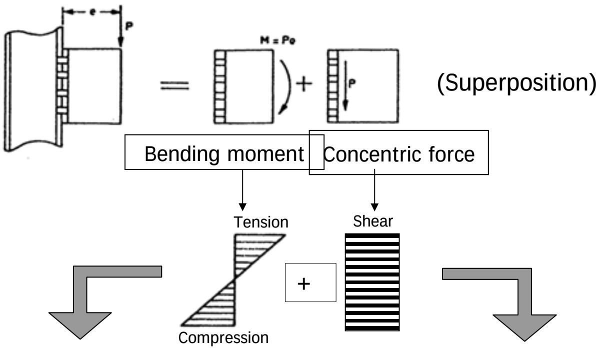
Interaction diagram

Combined Shear and Tension

- To compute tension forces in the fasteners, two different approaches can be used:
  - Neglecting initial tensions in the fasteners
    - (unfinished or turned bolts)
  - Considering initial tensions in the fasteners
    - (high-strength bolts)

Combined Shear and Tension

- Neglecting initial tensions in the fasteners:

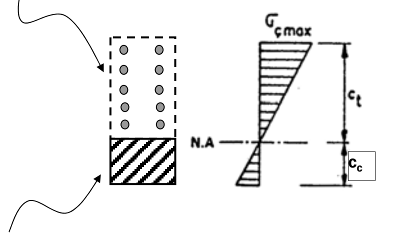


- Hence, stress distribution varies linearly over the cross-section in accordance with flexural formula
- The bending moment tends to separate the bracket from the column at the top and press it against the column at the bottom
- The fasteners are subjected to identical and uniform shear stresses

Combined Shear and Tension

- How is the moment transmitted?

Above the neutral axis (no contact between connection plate and column) – moment is transmitted by tension in the fasteners



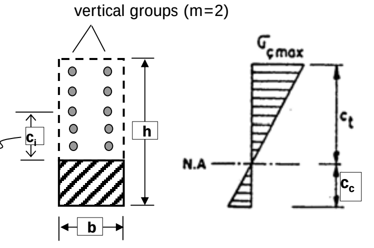
Below the neutral axis (full contact between connection plate and column) – moment is tranmistted by bearing surface

Combined Shear and Tension

- Tension stress in a bolt (accurate analysis)

m : number of fastener vertical groups (m=2)

distance between a bolt row and neutral axis

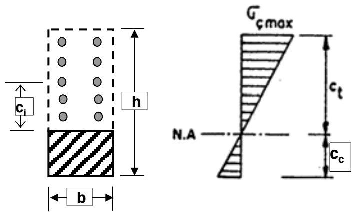


- Neutral axis must pass through the centroid. Equating the moments of effective areas above and below the neutral axis,

$$\frac{1}{2}c_c^2.b = m.A.\sum c_i = m.A(c_1 + c_2 + ...)$$

Shear area of a single fastener

Combined Shear and Tension



- The tensile stress in a fastener row group,

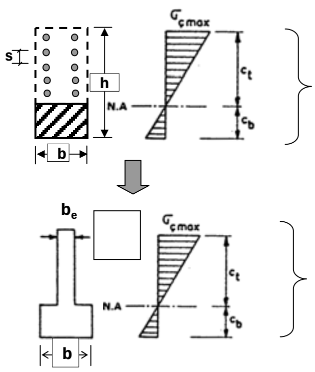
Tensile stress in a fastener row group located c_i distance above N.A. $\longrightarrow$ $\sigma_ç = \dfrac{Mc_i}{I}$

Moment of inertia wrt to N.A

$$I = \frac{1}{3}bc_c^3 + m.A\sum c_i^2$$

Combined Shear and Tension

- Tension stress in a bolt (approximate analysis)
  - An equivalent rectangular area for fasteners in tension zone



Area of a single fastener

Total area of fastener in tension zone $\longrightarrow$ $A_f = \underbrace{Am}\frac{c_t}{s}$ ...... (1)

Area of fasteners in each horizontal row

number of horizontal row

$A_f = c_t.b_e$ .... (2)

The fastener area in tension can be replaced by an equivalent rectangle of width b_e

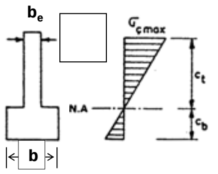
Combined Shear and Tension

- Equating (1) = (2):

$$b_e = Am/s$$

- Neutral axis must pass through the centroid of the equivalent section. Equating the moments of effective areas above and below the neutral axis,

$$\frac{1}{2}b_e c_t^2 = \frac{1}{2}bc_c^2 \quad \Rightarrow \quad \frac{c_t}{c_c} = \sqrt{\frac{b_e}{b}} = \sqrt{\frac{Am}{sb}}$$



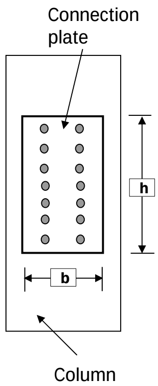
- The tensile stress in the top fastener is

$$\sigma_ç = \frac{Mc_t}{I} \qquad I = \frac{1}{3}\left(b_e c_t^3 + bc_c^3\right)$$

Combined Shear and Tension

- Considering initial tensions in the fasteners:
  - If each bolt is given a pretension force P_1, the initial tensile stress in a bolt (σ_{ini}) is

Initial tensile stress in a bolt → $\sigma'_ç = \dfrac{P_1}{A_{s1}}$ ← Pretension force in a bolt; ← Area of a single fastener



  - Due to pretention force given to bolts, the connection plate is clamped to the column resulting in an initial bearing (compressive) stress on the plate.

Combined Shear and Tension

- This stress (σ_o) is assumed to be uniform over the plate area and can be computed from

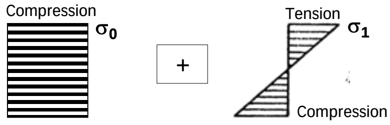
Pretension force in a bolt

Number of fasteners

Initial bearing stress

$$\sigma_0 = \frac{P_1 . n}{\underbrace{b . h}_{\text{Plate area}}}$$

- The normal stresses in connection plate:



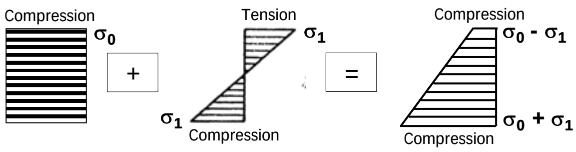
Initial normal stress in connection plate due to pretension of fasteners

Normal stress in connection plate due to bending moment

$$\sigma_1 = \frac{My}{I} = \frac{M(h/2)}{\frac{1}{12}bh^3} = \frac{6M}{bh^2}$$

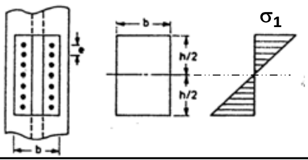
Combined Shear and Tension

- If $\sigma_o > \sigma_1$,



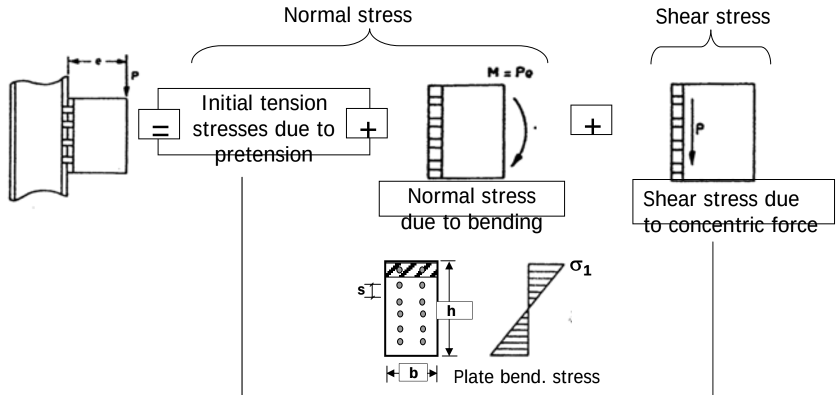
Resulting normal stress

- the connection plate remains in complete contact with the column. Hence the neutral axis occurs at the mid-point of the plate



Combined Shear and Tension

- The stress in a bolt:



$$F_{eff} = \sigma_1 . b . s$$

$$\sigma'_ç = \frac{P_1}{A_{s1}} \qquad \sigma''_ç = \frac{F_{eff}}{mA_{s1}} = \frac{6Ms}{h^2 mA_{s1}} \qquad \tau = \frac{P}{nA_{s1}}$$

Fastened Connections

Example Problems