CE401 DESIGN OF STEEL STRUCTURES

Course objective

- To introduce the limit state design of steel structural components subjected to bending, compression and tensile loads including connections.
- To enable design of structural components using timber

Course outcome

At the end of the course, the student should be able to:

CO 1: Apply fundamental concepts of limit state design to design bolted and welded connection.

CO 2: Analyse and design tension members.

CO 3: Design struts and built up columns along with connection subjected to axial loads.

CO 4: Design beams, plate girders and stiffeners.

CO 5: Design roof trusses and purlins.

CO 6: Design timber beams, columns and composite beam section with timber and steel.

Bolted connections

- In a steel structure, usual connection elements are cleats, gusset plates, brackets, connecting plates, etc.,
- usual connectors used are rivets, bolts, pins and welds.
- These connections must be capable of transmitting all the expected calculated design actions (loads).
- If at all a failure occurs, it should not happen at the connection points.
- There are three main connectors:
- **RIVETS, BOLTS &WELDS**

Advantages of Rivetted Connection

(a) Inspection of rivetting work is easy and involving less cost.

(b) Rivetting work requires only semi-skilled person.

(c) Less possibility of brittle fracture.

Disadvantages of Rivetting

(a) Efficiency of joint is not 100%.

(b) Fabrication of large complicated structure is very difficult.

(c) Rivetting process produces large amount of noise, due to hammering action.

(d) During the process, there may be chances of flying of rivets causing security problems for the field workers.

(e) Rivetting work is a slow process.

outdated and the new code IS 800: 2007 deals only with bolted connections (Page 73) and welded connections (Page 78).

Advantages of Bolted Connections

(a) Since there is no heating of bolt rod, this being not a hot process, there is no risk of fire to the workers.

(b) Since no hammering is involved, this process is very silent. (No Noise Pollution).

(c) When compared to rivetting, bolting process is very fast.

(d) Since there is no flying involved in the process, there is no risk or safety issues in bolting for the workers.

(e) Less number of workers are needed here hence less labour cost for contractor.

Disadvantages

(a)They sometime gets loosened when the structure is acted upon by loads having vibrating nature. This results in the reduction of strength.

(b)Since the diameter at the thread of bolt rod is less, its net area is small resulting in lesser strength or load carrying capacity in axial tension.

(c) The space between bolt rod and bolt hole sometimes will not be kept filled.

Advantages of Welded connections

(a)Joint efficiency is 100%.

(b) Fabrication in difficult structure is easy.

(c) Pure silence prevails during process (even though small sound is heard during oxy-acetelene welding when compared to rivetting.

(d) No safety precautions are needed.

(e) Welding process is much faster.

(f) Much economical.

g) Always provide rigid joints.

(h) Minimum self weight for structure.

Disadvantages

(a) Since welding is a hot process involving in non-uniform heating and cooling, structural members will be subjected to distortion resulting in more unwanted stress.

(b) Welded structures are subjected to cracks due to non-provision of expansion and contraction.

(c) Very high labour cost since skilled labour is required.

(d) Checking and verification of welding work is very difficult.

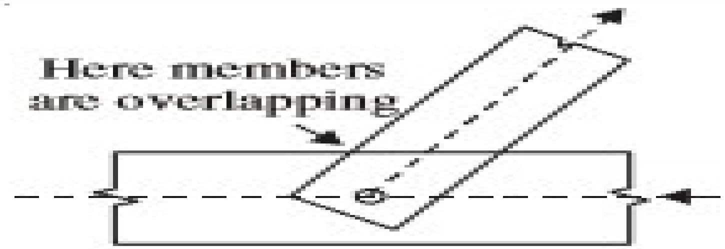
(e) Structure may be subjected to fatigue and susceptible to failure by cracking under repeated cyclic loads.

(f) Tearing of base metal plate may occur beneath the weld-known as Lamellar tearing.

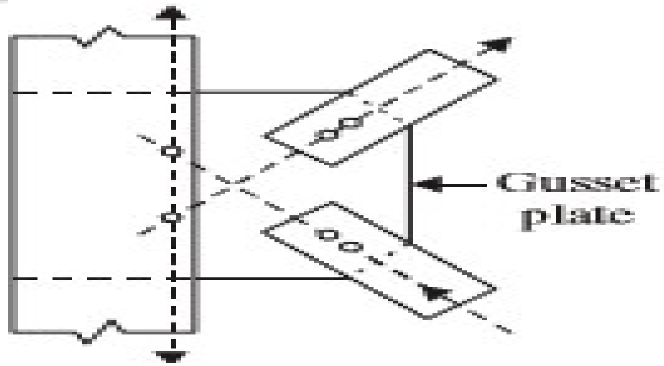
Bolted or welded connections can be classified a/c Resultant force transferred

1. Concentric 2. Eccentric and 3. Moment resisting

Concentric connection

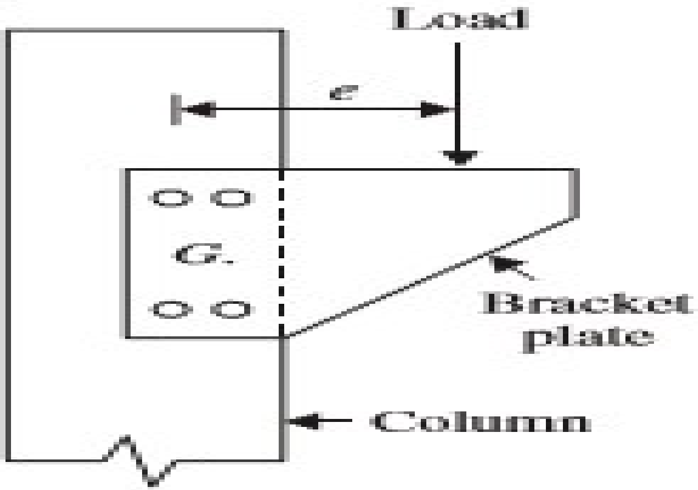


In this example only one bolt is shown. Here the members are transferring only tensile or compressive forces along their axes. In actual site conditions, overlapping of members may not be possible. So we can use gusset plate and connection is done in such a way that all the load lines will coincide and this will prevent the development of moment.



Eccentric connection (In plane)

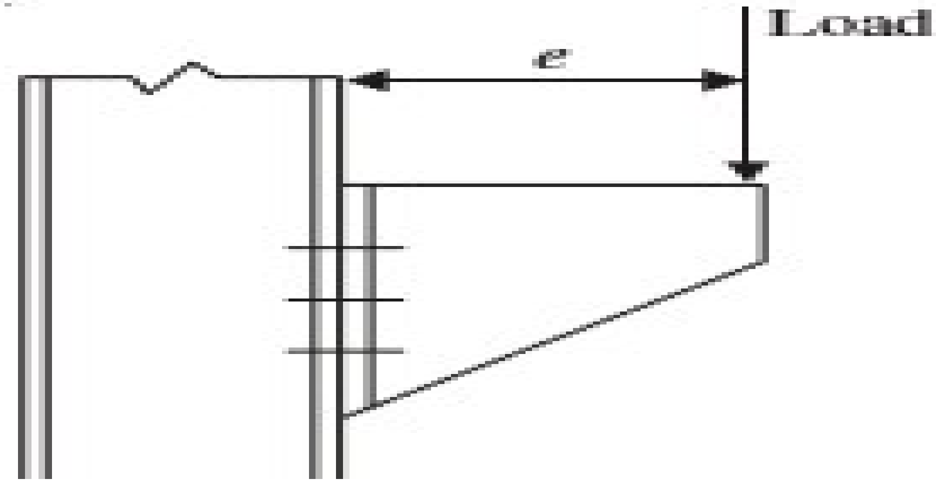
This is usually encountered in bracket connection. Here the load will be acting at an eccentric distance away from the centroid of the joint. In this case major resistance in the joint is only through shear in the bolt.



Here moment is acting in same plane as that of connection.

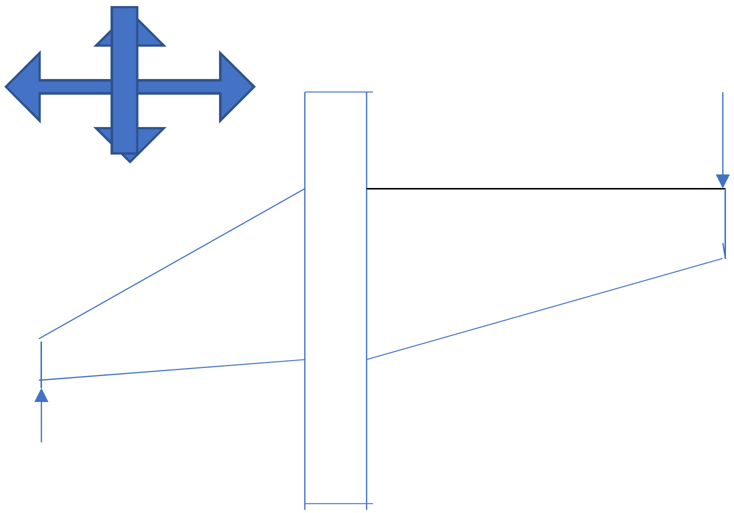
Eccentric connection (Out of plane)

This is another type of eccentric connection where the bolts are subjected to a combination of shear force and tensile force. Here moment is acting in a plane perpendicular to plane of connection.



Bolts A/c to geometry and force

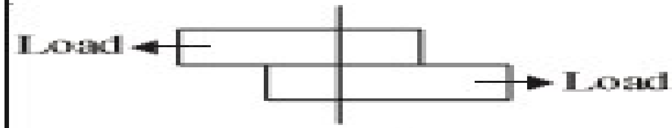
1. Shear connections
2. Tension connections and
3. Combination of 1 and 2.

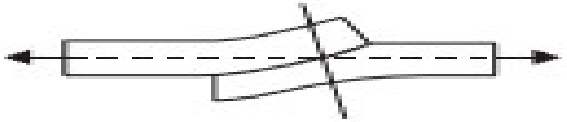


Pure moment connection

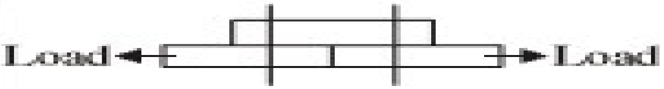
Shear connections

Here the connecting members are usually subjected to tension.
e.g., 1. Lap joint (here two plates are overlapping).

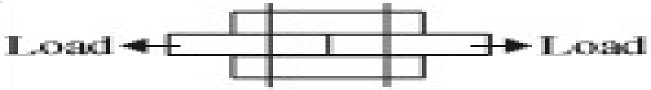




Here since forces tend to become collinear, there will be a tendency to bend.
e.g., 2. Butt joint (Here two plates butt each other)
Single cover butt joint.



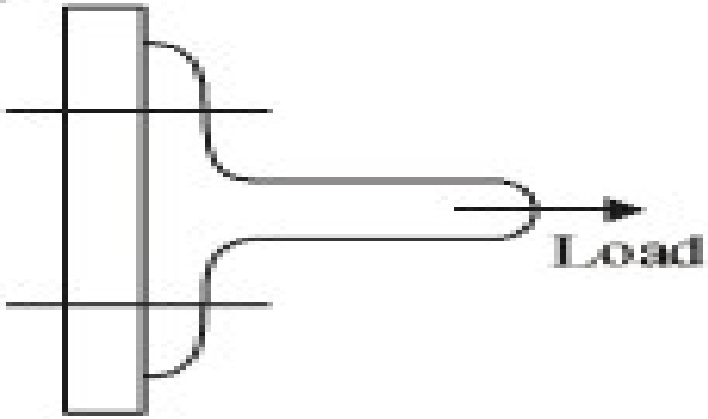
Here also joint bends since centre of cover plate becomes collinear with forces.
Double cover butt joint.



Here there is no tendency to bend.

Tension connections

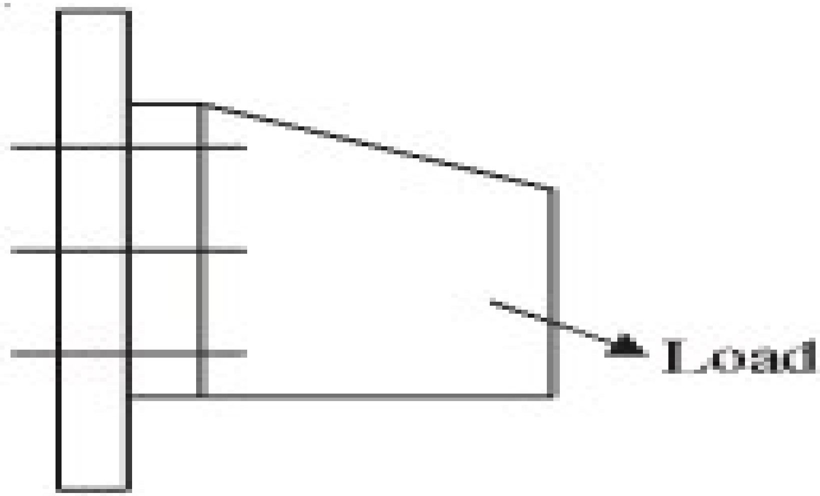
In this case load is transmitted by pure tension in the bolts example is hanger connection.



Here the connection will be subjected to prying forces) (Page 77).

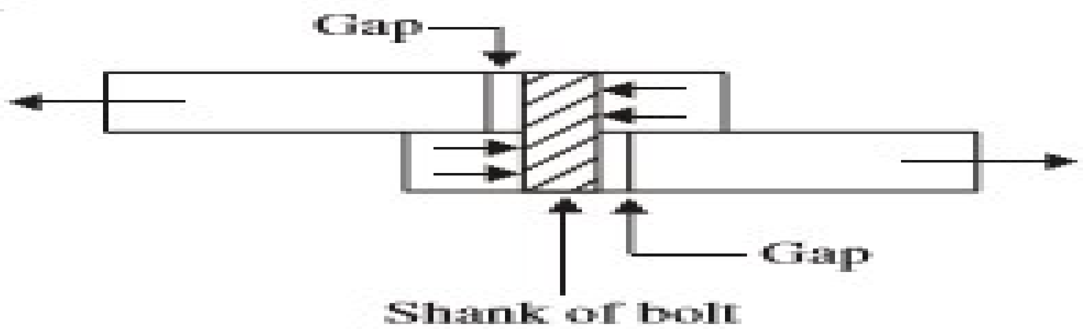
Combined connection

Here bolts are subjected to both shear and tension.



Here one has to check the safety of joint by using interaction formula. (Page 76, 77)

A/c to force transfer mechanism of bolt
a)Bearing type

Bearing type
In this type bolt surface bear against the bolt hole to transfer the force acting in the joint. If we have ordinary unfinished bolts, or unturned bolts, there will be space between plate hole and shank. So when load acts in the joint the two plates will be subjected to lateral movement resulting in the slipping of plates. This results in the contact of surface of hole with surface of shank and load is transmitted by bearing. And if load exceeds a certain limit by shearing of shank also.

But in turned and fitted bolt there is no gap and hence no slip shank fits tightly in the hole.

A/c to force transfer mechanism of bolt
b)Friction type

Friction type
In this type, force is transferred between the two plates due to clamping force created by pre-tensioning of bolts. The shank of the bolt is subjected to high tension and the joining plates are subjected to high compression. Till slip occurs, shank is in tension only. After slip has occurred, shank will be in tension, bearing and shear. This is known as post slip condition.

There are three types of bolts

Black bolt or unfinished bolt or unturned bolts	**Turned and fitted bolt**	**High strength friction grip (HSFG) bolts**
This is made of mild steel of grade 4.6. 4 means $\frac{1}{100}$th of minimum ultimate tensile strength in N/mm^2. $\frac{f_u}{100} = 4$ $f_u = 400\ N/mm^2$	In this type there will not be any gap between hole and shank. They are of grade 4.6 to 8.8.	Here grade 8.8 is used. They are used under fluctuating and fatigue load conditions. There will be tension in the bolt shank which gives rise to friction between plates. So there will not be any slip initially. Once there is slip, friction is overcome and load is transferred by

Unfinished bolts are not used under dynamic loading since they become loose

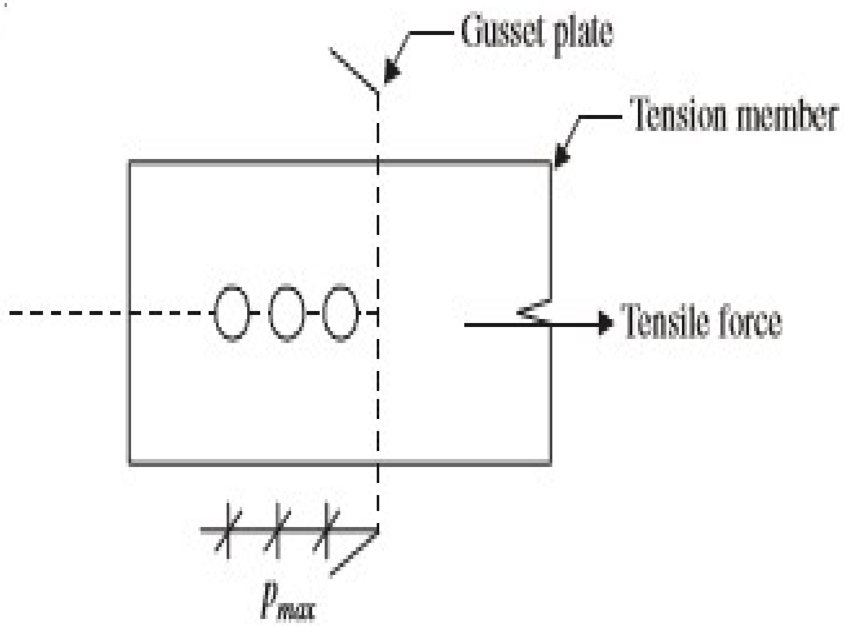
- They are also not used when there is slip
- Cost is less

HSFG BOLTS

- After slipping,load is transferred by bearing
- Under working load, resistance from bearing is not considered
- Very large holes can be used which will help in erecting
- Lack of fit issues to be considered

Bolts-Codal provisions as per IS 800:2007:p. 73 Cl. 10.1.6.

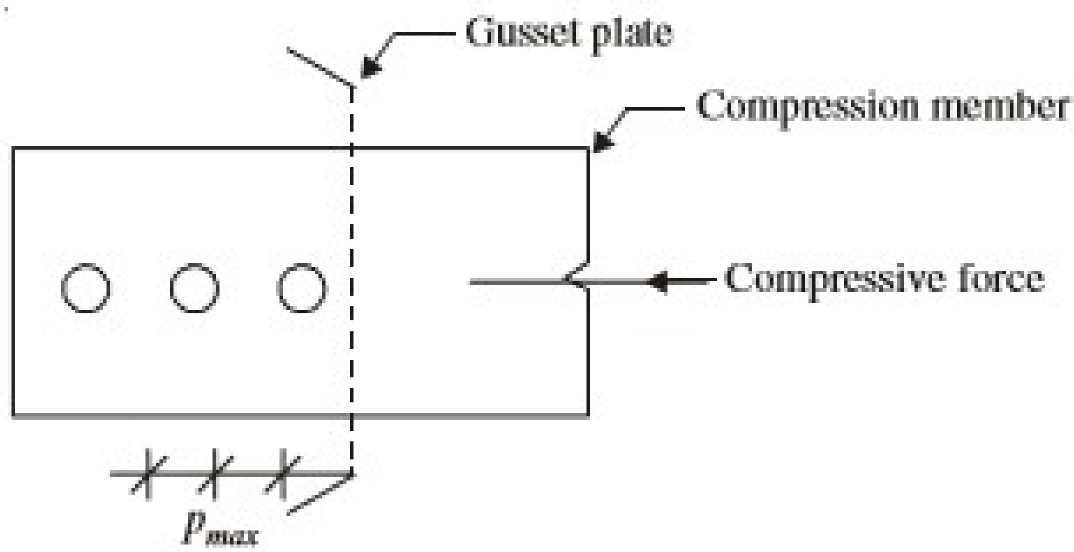
- For evaluating partial safety factor for bolted connection, use table 5 in page 30.
- The user has to choose the type of fabrications as shop or field. Location Details p73 Cl. 10.2.2
- The distance between two adjacent fasteners should be greater than 2.5 × Nominal diameter
- **$p_{minimum} > 2.5\ d$** usual d values are 16, 20, 24, 30 and 36 mm.
- This clause is intended to reduce interference and overlapping of stresses from adjacent fasteners.
- p74 Cl. 10.2.3 Maximum spacing,
- $p_{max.} < 32t$ or 300 mm whichever is less. where, t = thickness of thinner plate in mm.



Limit for max. in **tension members** is to minimize unconnected length and to prevent bending of plate in between fasteners.

p74 Cl. 10.2.3.2.

p_{max}. < 16t or 200 mm whichever is less



compression members

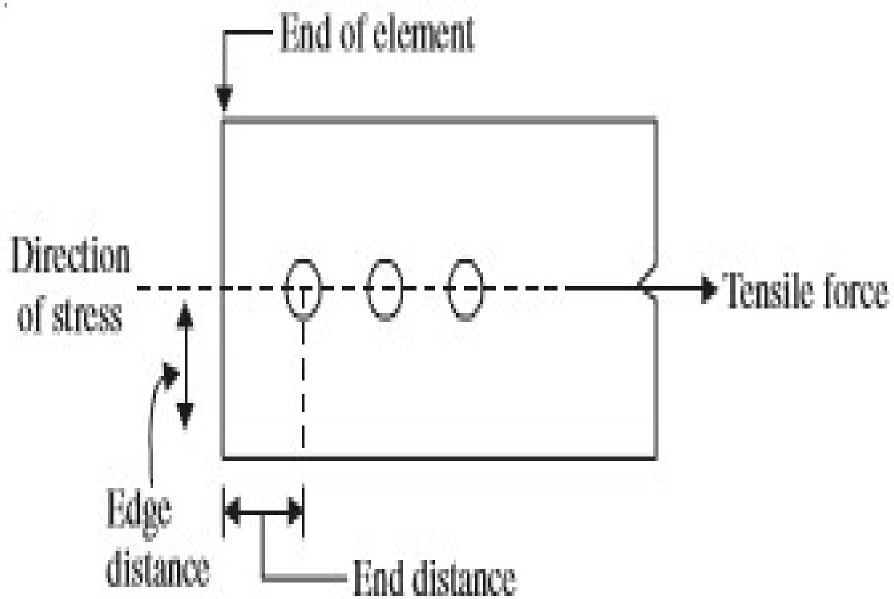
p_{max}. < 12t or 200 mm whichever is less.

t = Thickness of thinner plate.

This is to prevent buckling of unconnected part in comprn.

Cl. 10.2.4.1.

Edge &End distances



For sheared or hand—flame cut edges, minium edge and end distances >**1.7 d_0**For rolled, machine—flame cut, sawn and planed edges, this becomes **1.5 d_0 (**d_0 = hole diameter taken from p73 table 19.)

Edge distance to prevent stress concentration overlaps.

end distance is to prevent tearing of plate.

Cl.10.2.4.3. Maximum edge distance of any un-stiffened part < 12t ε

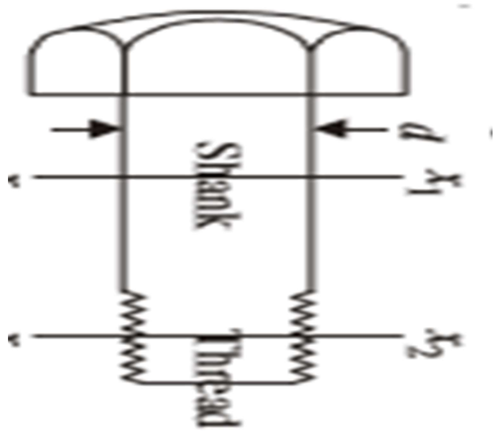
where $\varepsilon = \sqrt{\frac{250}{f_y}}$

t-thickness of thinner outer plate

Max. to prevent local buckling of unstiffened part.

Cl. 10.3. Bearing type bolts Cl 10.3.3

- (Shear capacity)Design strength of bolt, $V_{dsb} = \frac{V_{nsb}}{\gamma_{mb}}$



γ_{mb} is 1.25 (from table 5)

where, $V_{nsb} = \frac{f_u}{\sqrt{3}}(n_n A_{nb} + n_s A_{sb})$

fu = ultimate tensile strength of bolt

if 4.6 grade bolt is used then f_u = 400 N/mm^2

Suppose the shear plane is at section X_1X_1 then we consider the terms ns and Asb. where, ns = No. of shear planes without threads intercepting the shear plane Asb = Nominal plain shank area of bolt if d = Nominal diameter of the fastener

Suppose the shear plane is at section X_2X_2, n_n and A_{nb} (in this case ns = 0) where, n_n = Number of shear planes with threads intercepting the shear plane and A_{nb} = Net shear area of bolt at threads = Area corresponding to root diameter at the thread = 0.78 Asb

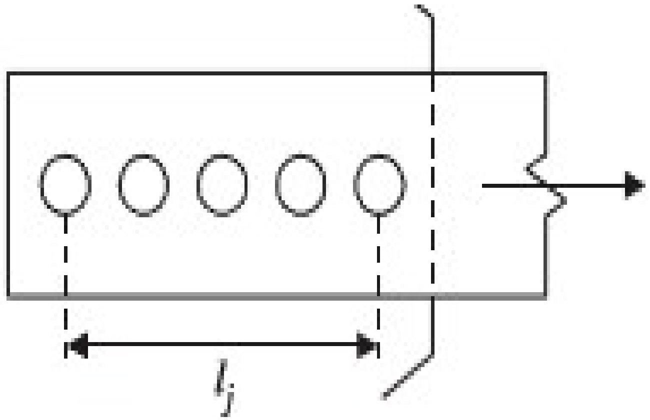
Cl.10.3.3.1 Long joints

l_j = Distance between first and last rows of bolts measured in the direction of load transfer

if lj> 15d then V_{db} is reduced by multiplying with β_{lj}

$$\beta_{lj} = 1.075 - 0.005(\frac{l_j}{d})$$

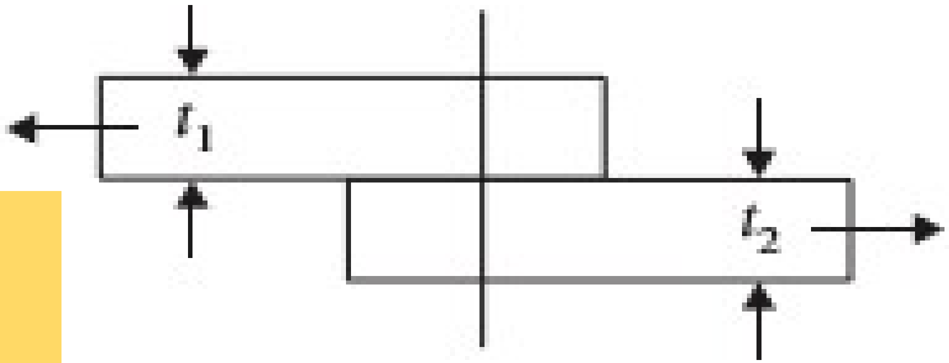
β_{lj} should be between 0.75 and 1



This provision does not apply when distribution of shear over the length of joint is uniform example as in the connection of web of a section to the flanges.

Cl.10.3.3.2 Large grip lengths

- Grip length, l_g = Total thickness of the connected plates $lg = t_1 + t_2$



when $l_g > 5d$, then V_{dsb} is reduced by multiplying with a factor β_{lg}

where, $\beta_{lg} = \frac{8d}{(3d+l_g)} = \frac{8}{\left(3+\frac{l_g}{d}\right)}$

should be < β_{lj}

l_g shall in no case greater than 8d.

Cl. 10.3.3.3 Packing plates

if $t_1 \neq t_2$ then provide a packing plate

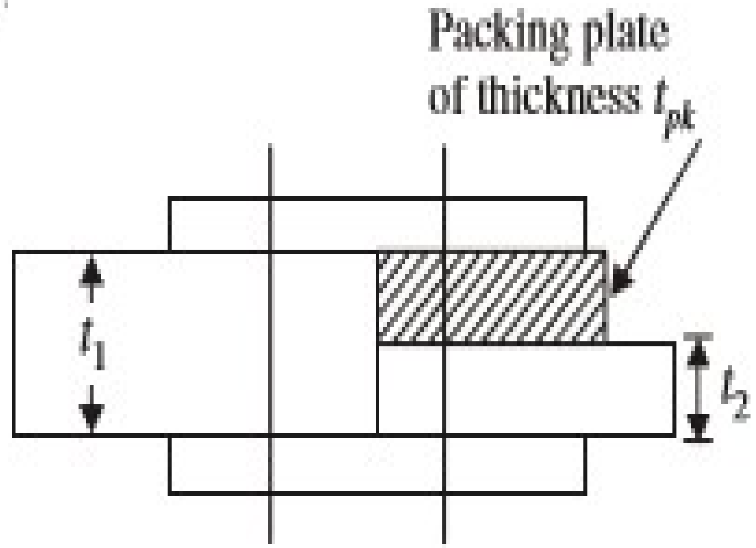
if thickness t_{pk} > 6 mm

V_{dsb} shall be reduced by multiplying by

a factor, $\beta_{pk} = (1 - 0.0125\ t_{pk})$

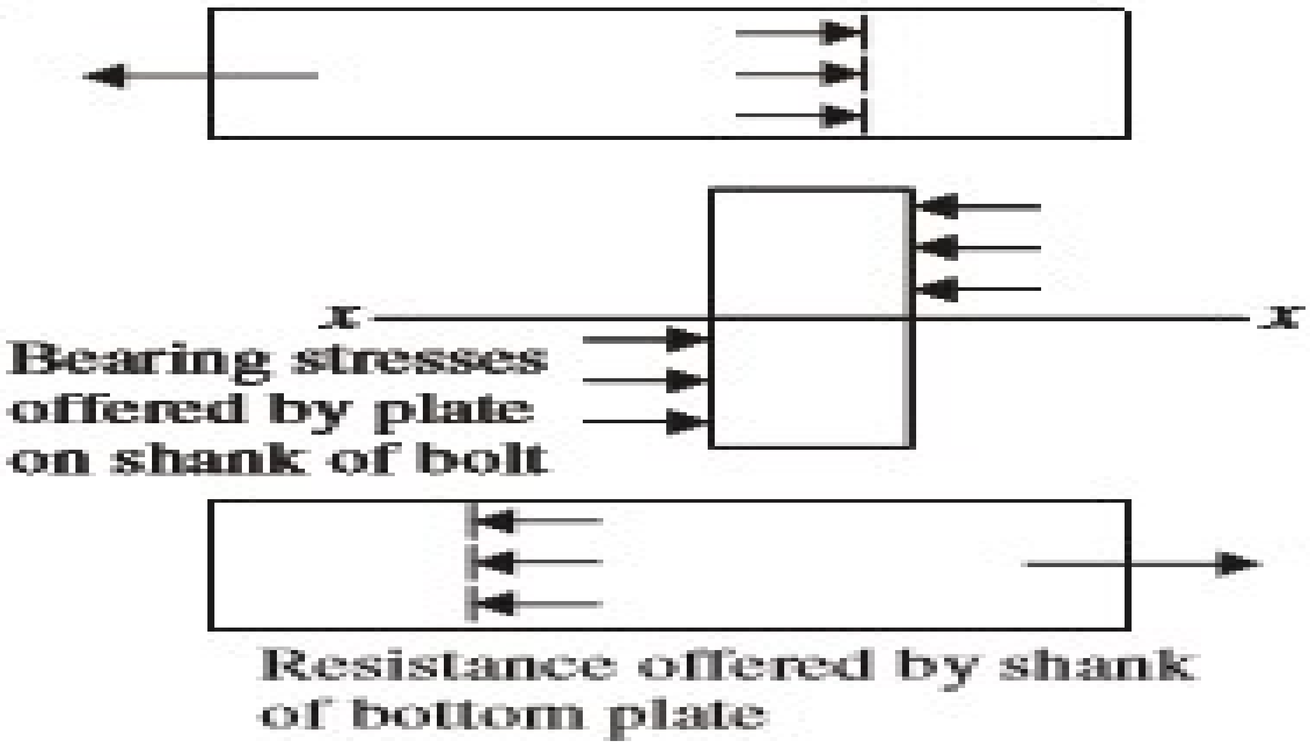
where t_{pk} is the thickness of thicker

packing in mm.

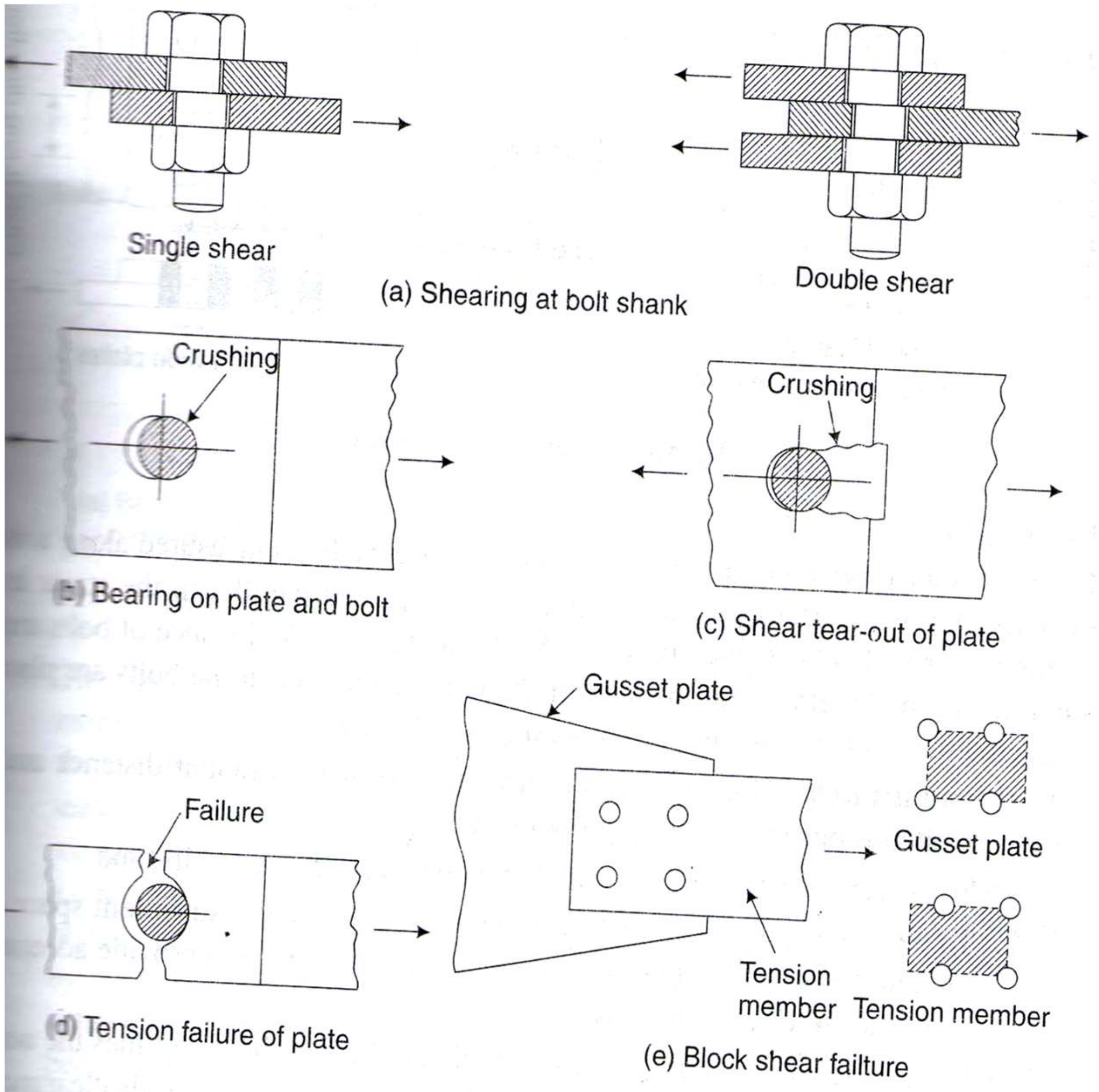


Shear Force Transfer Mechanism of Bearing Type Bolt

- When lower plate is subjected to tension, it tries to move towards right side.
- So, bearing stress gets developed between surface of hole in plate and bolt.
- In unturned bolts, due to a gap between hole and bolt, plate will slip relative to one another and then after this only bearing stress will develop.
- Critical section for shear occur either in the shank or in thread.
- If lap joint is used then there is one critical section in shear.


x
x
Bearing stresses
offered by plate
on shank of bolt
Resistance offered by shank
of bottom plate

- If we have single cover butt joint then also there will be one shear plane.
- But in double cover plate butt joint there will be two shear plane and bolts will be in double shear
- thus, V_{dsb} will be multiplied by 2.
- Failure of the joint will occur either by yielding of plate, shearing of bolt, bearing of bolt or plate or even by block shear failure.



Failure modes of bolted joints

p75 Cl. 10.3.4 Bearing Capacity of Bolt

- This will occur if plate is strong and bolt is weak. Here bearing of plate on bolt will take place.
- But if plate is weak and bolt is strong then bearing of bolt on plate will take place and hole will elongate. $V_{dpb} = \frac{V_{npb}}{\gamma_{mb}}$
- where, $V_{npb} = 2.5\ k_b\ dt\ f_u$
- f_u = smaller of ultimate tensile stress of bolt or plate

where, k_b *is smaller of*

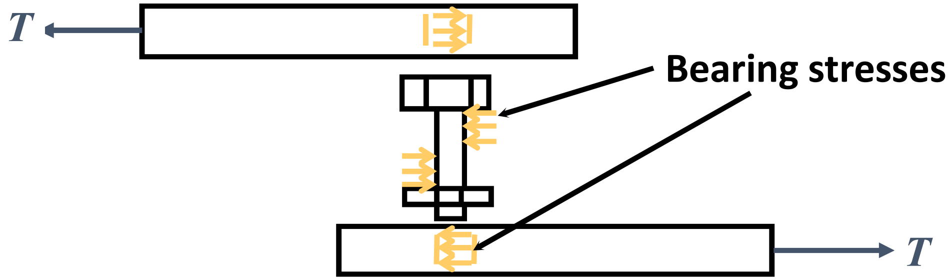
$\frac{e}{(3d_0)}$, $\frac{p}{(3d_0)} - 0.25$, $\frac{f_{ub}}{f_u}$, 1

- e,p=end and pitch distances of the fastener along bearing direction
- d_0=diameter of the hole
- f_{ub}, f_u= ultimate tensile stress of the bolt and of the plate
- d=nominal diameter of the bolt
- t=summation of the thicknesses of the connected plates experiencing bearing stress in same direction
- Or if the bolts are countersunk, thickness of plate minus half the depth of countersunking

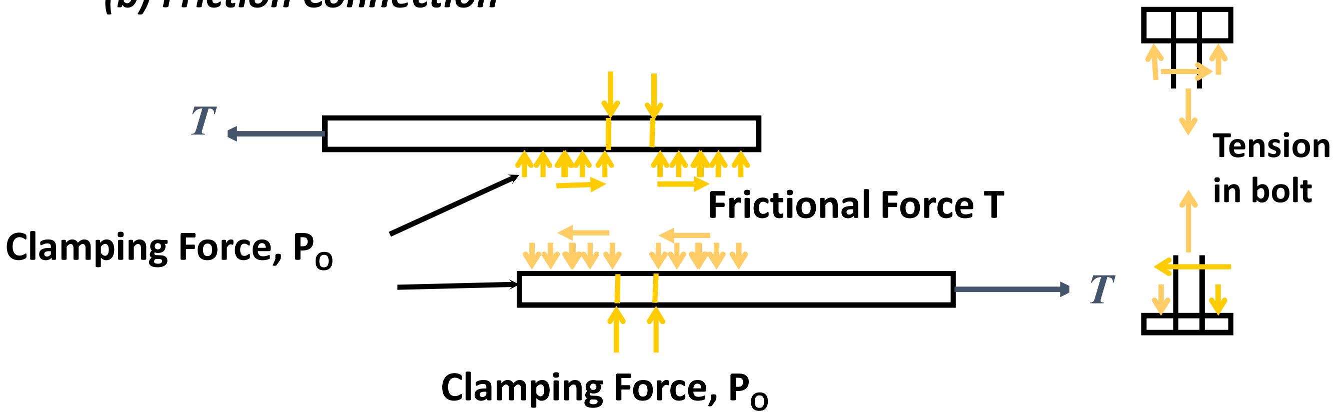
Suppose a joint has multiple bolts, due to mismatch in holes, all the bolts will not carry uniform force. When force becomes ultimate due to high bearing ductility of plates, a large amount of redistribution of force will take place and then all bolts are assumed to carry equal force.

FORCE TRANSFER MECHANISM

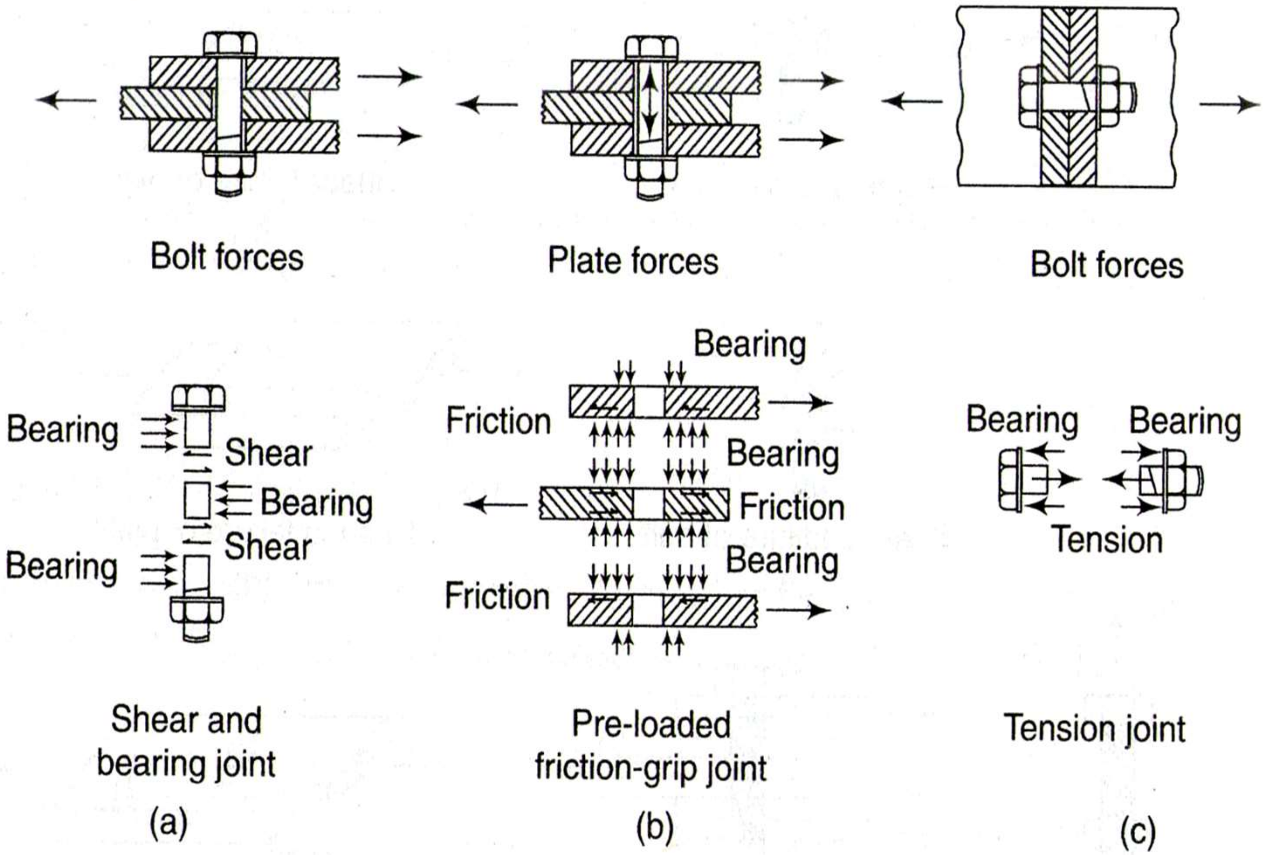
(a) Bearing Connection



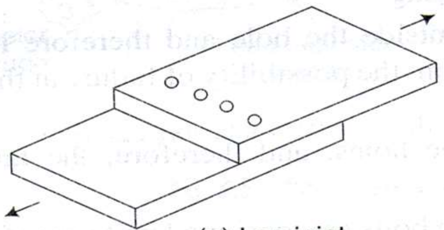
(b) Friction Connection



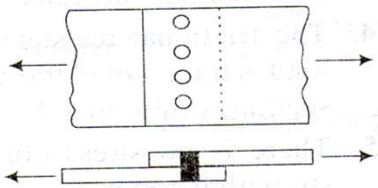
Bolt Shear Transfer – Free Body Diagram



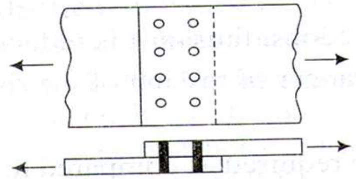
Force transmission through bolts (Trahair et al. 2001)



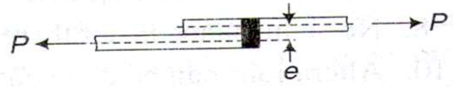
(a) Lap joint



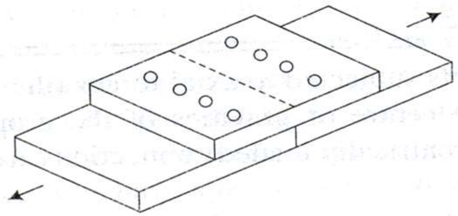
(b) Single bolted lap joint



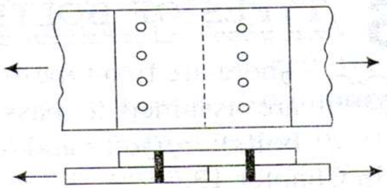
(c) Double bolted lap joint



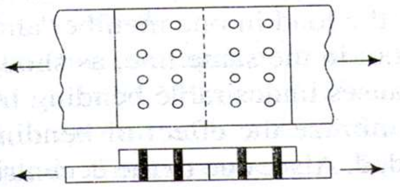
(d) Eccentricity in lap joint



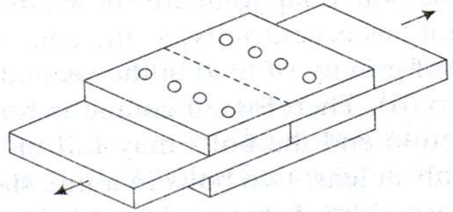
(e) Single-cover butt joint



(d) Single-cover single bolted butt joint

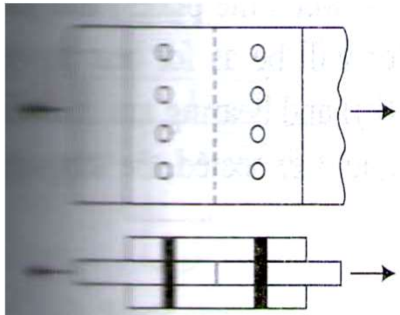


(g) Single-cover double bolted butt joint

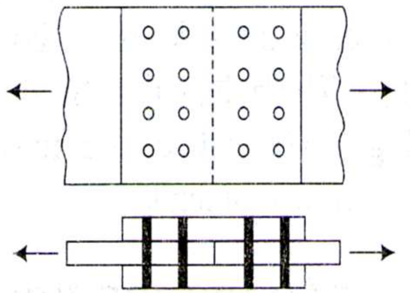


(h) Double-cover single bolted butt joint

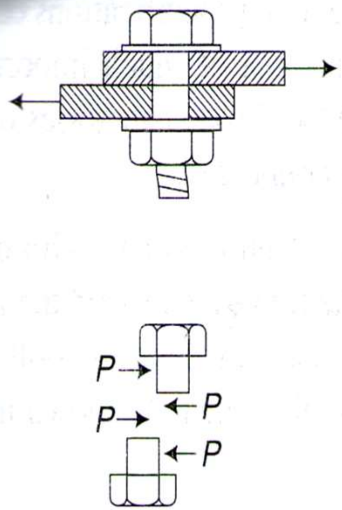
Table Cont



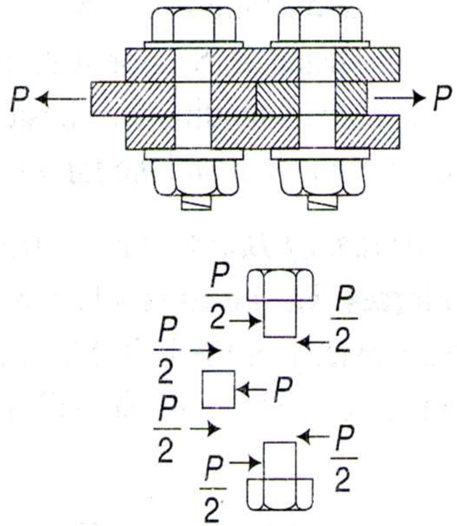
(i) Double-cover single bolted butt joint



(j) Double-cover double bolted butt joint



(k) Lap joint, bolt in single shear



(l) Butt joint, bolt in double shear

Types of bolted joints

Failure of Bolt

- Two broad categories of failure:
    - failure of the bolt and the failure of the parts being connected

- Shear Failure of Bolts: Shear stresses are generated when the plates slip due to applied forces. The maximum factored shear force in the bolt may exceed the nominal shear capacity of the bolt. Shear failure of the bolt takes place at the bolt shear plane.

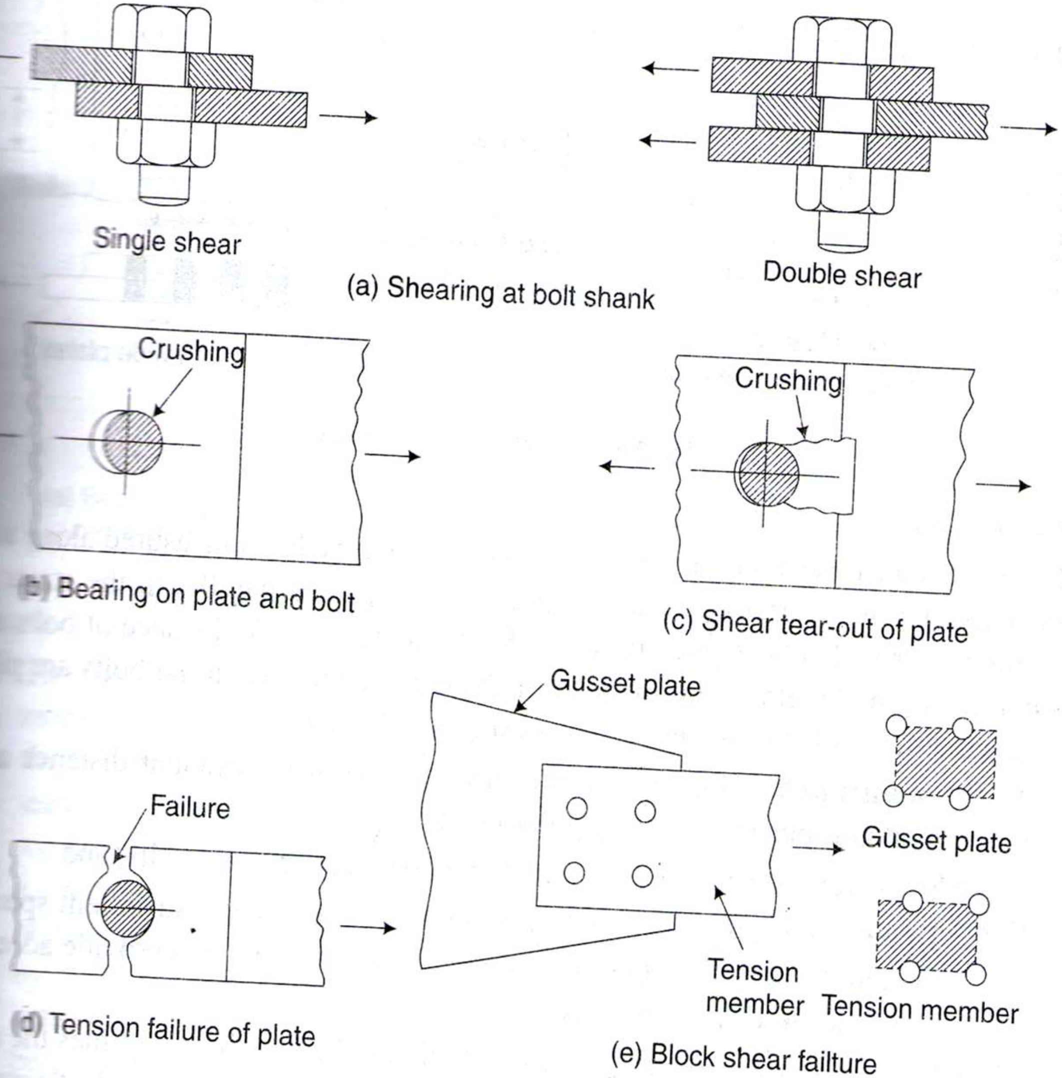
- Bearing Failure of Bolts- The bolt is crushed around half circumference. The plate may be strong in bearing and the heaviest stressed plate may press the bolt shank Bearing failure of bolts generally does not occur in practice except when plates are made of high strength steel.

- Bearing Failure of Plates - When an ordinary bolt is subjected to shear forces, the slip takes place and bolt comes in contact with the plates. The plate may get crushed, if the plate material is weaker than the bolt material.

- Tension Failure of Bolts- Bolts subjected to tension may fail at the stress area, if any of the connecting plates is sufficiently flexible additional prying forces induced in the bolts must also be considered.

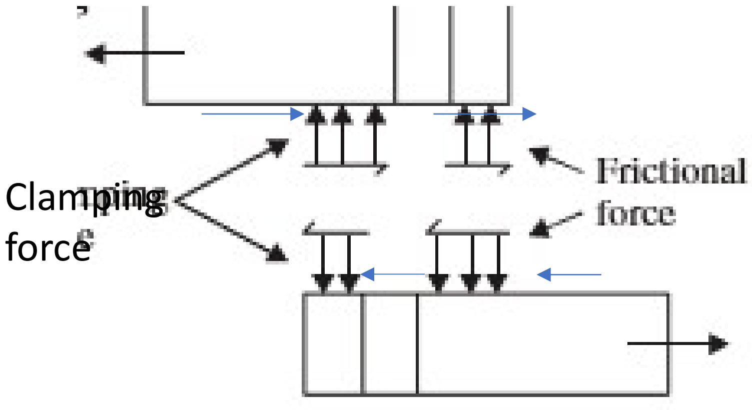
- Tension or Tearing Failure of Plates -occurs when the bolts are stronger than the plates. Tension on both the gross area and net effective area must be considered

- **Block Shear Failure**
- **Bolts** may have been placed at a lesser end-distance than required causing the plates to shear out which, however, can be checked by observing the specifications for end-distance
- May occur when a block of material within the bolted area breaks away from the remaining area. The possibility of this increases when high strength bolts are used.



Failure modes of bolted joints

p76 Cl. 10.4 Friction Grip Type Bolting



In high strength friction grip bolting, there will be initial pretension in the bolt. This results in the occurrence of clamping forces between the two connecting plates. When external force is applied, the two plates will try to slip against each other. This slipping tendency is resisted by development of frictional force between the two plates.

- Slipping is prevented till frictional force gets exceeded by external force. In this connection, relative slip is required to be avoided in service condition.
- Once plate slips, bearing stress will develop as bolt touches surface of plate.
- Beyond this stage, external load is resisted by combined action of frictional resistance and bearing resistance.
- Cl. 10.4.2 The bolt will be subjected to bearing only after slip between plates takes place. If slip is critical—(means if we are not allowing slip at any cost) then use Cl. 10.4.3. If slip is not critical then use Cl. 10.4.4.

Advantages of HSFG Bolts

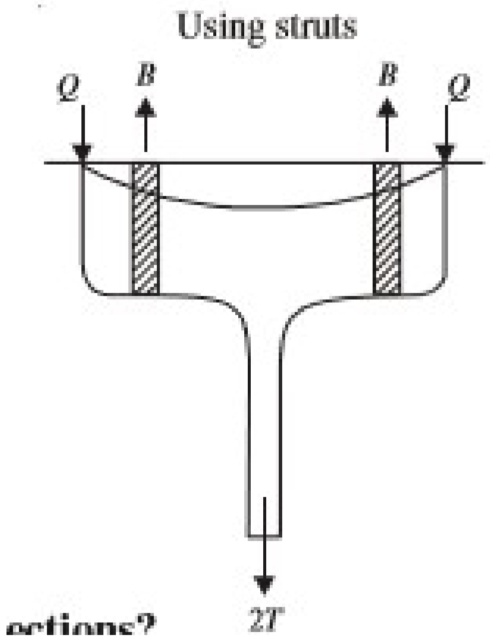
- HSFG bolts do not allow any slip between the elements connected, (especially in close tolerance holes) thus providing rigid connections.
- Due to the clamping action, load is transmitted by friction only and the bolts are not subjected to shear and bearing
- Due to the smaller number of bolts, the gusset plate sizes are reduced
- Deformation is minimized
- Since HSFG bolts under working loads do not rely on resistance from bearing, holes larger than usual can be provided to ease erection and take care of lack of fit. Thus the holes may be standard, extra large, or short/long slotted
- Noiseless fabrication, since the bolts are tightened with wrenches
- The possibility of failure at the net section under the working loads is eliminated.
- *Alterations can be done easily*

Prying Effect

- In moment resisting, beam to column connections the bolt has to transfer load by direct tension
- When plates are less stiffer, then there is a tendency for plate to get lifted up
- To counteract the bending, a force(Q) is developed at end of plate . This reaction (additional contact force) is Prying force
- Prying forces are mainly due to flexibility of connected plates (eq. in cl.10.4.7, pg.77)
- When Q is significant it should be added to tension in bolt
- If (T + Q) > Strength of bolt, then thickness of plate has to be increased.

Prying force

- Consider a Tee section connected to a plate subjected to a pull of 2 T. The flange will deform and deflect outward because of the pull in the web of Tee section. The edges of the flange tips bear against the connected piece. This gives rise to another force, Q which is known as the “Prying Force”.
- Here, Q = Prying Force
- B = Bolt Force
- 2 T = Applied Load



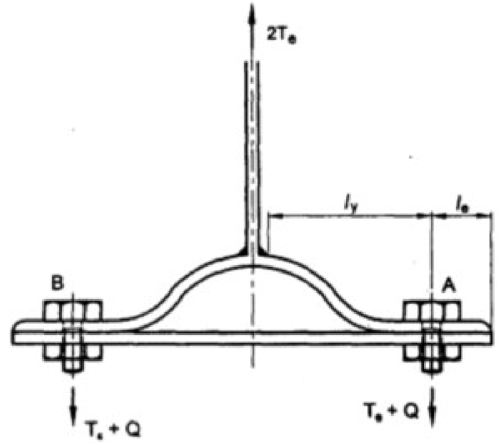
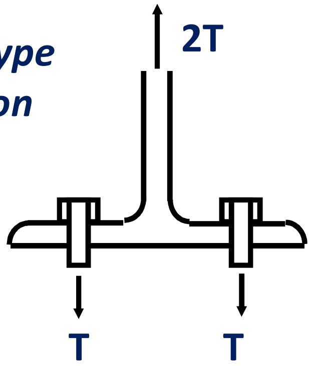


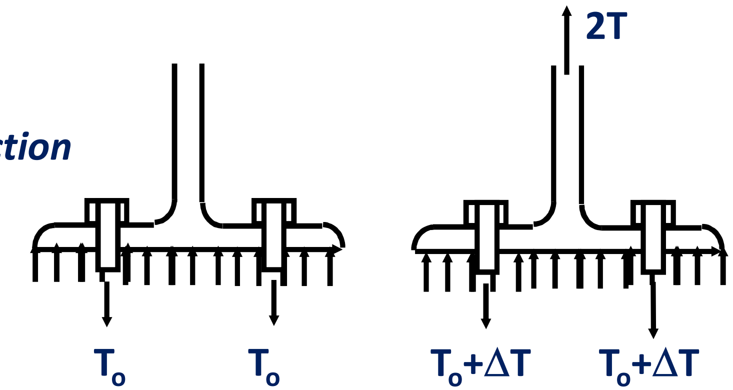
FIG. 16 COMBINED PRYING FORCE AND TENSION

BOLTS UNDER TENSION AND PRYING EFFECT

Bearing type connection



(b) HSFG Connection



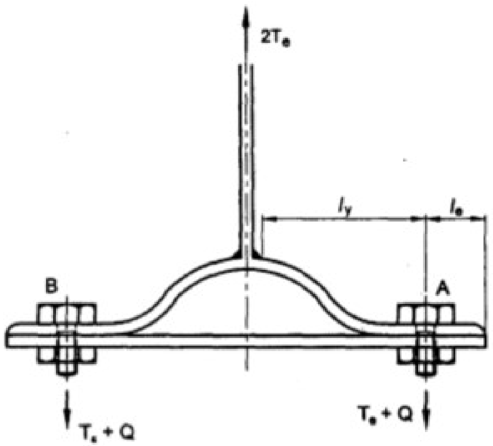
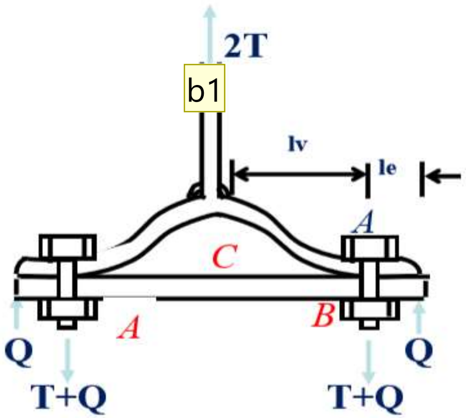


FIG. 16 COMBINED PRYING FORCE AND TENSION



(d) Prying Effect

Slide 43

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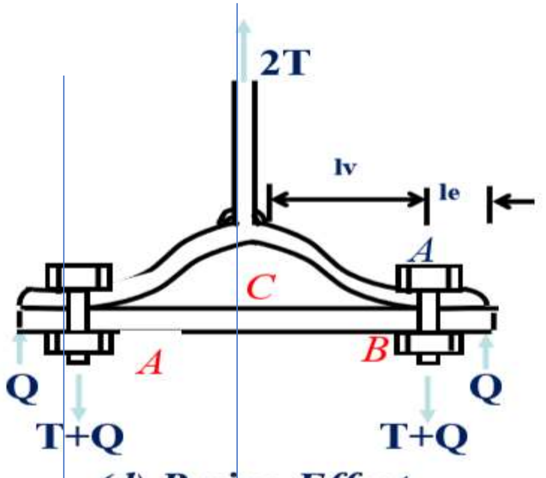
- Equation for Prying force in IS code(cl.10.4.7) is approximately
- Q = $T_e \frac{l_v}{2l_e}$(neglecting small term in brackets)
- Minimum **<u>Thickness(t) of T- flange is determined to avoid yielding of plate</u>**

(by equating the moment at the bolt centreline and at a distance lv from it to the plastic moment capacity of the plate, M_p)

- $M_A = Ql_e = T_e \frac{l_v}{2l_e} l_e = T_e \frac{l_v}{2}$
- $M_c = (Te + Q).lv - Q.(le + lv)$
- $= T_e l_v + Q l_v - Q l_e - Q l_v$

$= T_e.lv - Q.le = T_e.lv - Te.\frac{lv}{2} = Te.\frac{lv}{2}$

- $M_A = M_C = Te\frac{lv}{2} = M_p$
- Taking $M_p = \frac{fy}{1.15}\frac{wt^2}{4}$
- Minimum thickness of end plate to avoid yielding of the plate:
- $t = \sqrt{\frac{4*Mp*1.15}{w*fy}}$



(d) Prying Effect

- **Shear Lag**

➢ Plate when subjected to tension are subjected to shear deformation near edges . (Tensile stress near to zero at edges)

➢ Shear stress produced in material gradually transfer tension at edges to central axis of plate.

➢ Transfer of stresses take place in the length of member approximately equal to its width

➢ Beyond this length tensile stresses are assumed to be uniformly distributed over the whole section of plate.

➢ Transmission of tension at edges to full width by shear stress is Shear lag

- **Shear Lag…**
- If in a wide plate, tensile load is applied eccentrically, stress distribution across the width of the plate will not be uniform. The stress is transmitted from point of application of load to some other distant point by shear acting in the plane of the member. As we move further away from load, this shear reduces. This means the shear transfer will lag or becomes inefficient. Shear lag is thus the non-uniformity of stress in a plate when load is applied in an eccentric manner.
- In case of I- beam, internal transfer of force from flange to web is by shear
- In case of angles transfer of forces from on leg to other is by shear

Design strength of plate

Considering the probable failures

- Shearing of the edges- provide sufficient edge distances
- Crushing of the plate-end distance
- Rupture of plate-tear apart
- Block shear failure

- Cl.6.2 pg.32- **Design strength due to yielding of gross section**

$$T_{dg} = \frac{A_g.fy}{\gamma_{m0}}$$

where f_y= yield stress of the material

A_g = gross area of cross section

γ_{m0}= partial safety factor for failure in tension by yielding

- Cl.6.3 pg.32- Design strength due to rupture of critical section for plates

$$T_{dn} = \frac{0.9Anfu}{\gamma_{m1}}$$

where γ_{m1} = partial safety factor for failure at ultimate stress

f_u = ultimate stress of the material

A_n = net effective area of the member given by

$$An = [b - nd_h + \Sigma \frac{p_{st}^2}{4g_i}]t$$

Where

b,t= width and thickness of the plate respectively

d_h= diameter of bolt hole

g= gauge length between bolt holes

p_{si}=staggered-pitch length between line of bolt holes

n=number of bolt holes in the critical section, and

i=subscript for summation of all the inclined legs

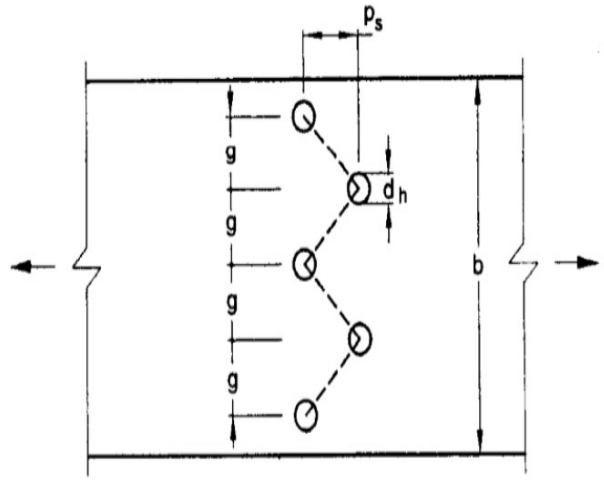


FIG. 5 PLATES WITH BOLTS HOLES IN TENSION

- Cl.6.4 pg.33- Design Strength Due to Block Shear

The block shear strength, T_{db} of connection shall be taken as the smaller of,

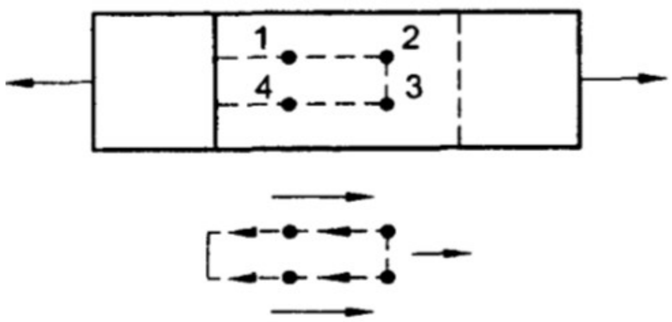
T_{db}= $[\frac{A_{vg} f_y}{\sqrt{3}\gamma_{m0}} + \frac{0.9 A tn f u}{\gamma_{ml}}]$ or

T_{db} =$[\frac{0.9Avn\ _u}{\sqrt{3}\gamma_{m1}} + \frac{A_{tg} f_y}{\gamma_{m0}}]$

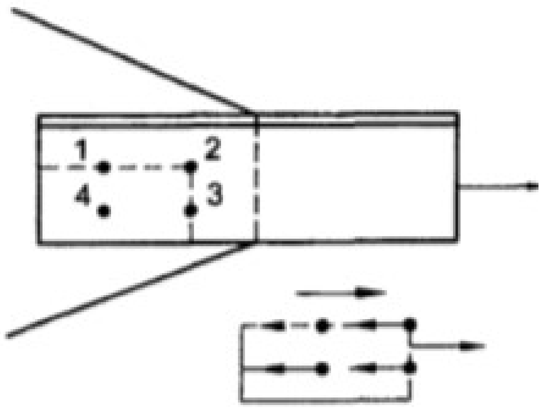
A_{vg}, A_{vn} = minimum gross and net area in shear along bolt line parallel to external force, respectively (1-2 and 3-4 as shown in Fig. 7A)

A_{tg}, A_{tn} = minimum gross and net area in tension from the bolt hole to the toe of the angle, end bolt line, perpendicular to the line of force, respectively (2-3 as shown in Fig. 7B)

f_u,f_y= ultimate and yield stress of the material, respectively.



7A Plate



7B Angle

Design strength of the plate is taken as the minimum of

T_{dg} ,T_{dn} and T_{db}