Bolted Connections

Introductions:

- Connections are always needed to connect two members.
- It is necessary to ensure functionality and compactness of structures.
- Prime role of connections is to transmit force from one component to another.
- Steel connections can be made by bolts or welds.
- Connections accounts for more than half cost of steel structure.
- Connections are designed more conservative than members because they are more complex.

Types of Bolts

- Unfinished Bolt – ordinary, common, rough or black bolts
- High strength Bolt – friction type bolts

Classifications of Bolted connections:

Based on Joint:
- Lap Joint
- Butt Joint

Based on Load transfer Mechanism:
- Shear and Bearing,
- Friction

Grade classification of Bolts:

- The grade classification of a bolt is indicative of the strength of the material of the bolt. The two grade of bolts commonly used are grade 4.6 and 8.8.
- For 4.6 grade 4 indicates that ultimate tensile strength of bolt = 4 × 100 = 400 N/mm² and 0.6 indicates that the yield strength of the bolt is 0.6 × ultimate strength = 0.6 × 400 = 240 N/mm²

<table>
<thead>
<tr>
<th>Grade of bolt</th>
<th>4.6</th>
<th>5.6</th>
<th>6.5</th>
<th>6.8</th>
<th>8.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{yb}$ (N/mm²)</td>
<td>240</td>
<td>300</td>
<td>300</td>
<td>480</td>
<td>640</td>
</tr>
<tr>
<td>$F_{ub}$ (N/mm²)</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>800</td>
<td>800</td>
</tr>
</tbody>
</table>

Properties of High Strength Friction Grip Bolts
Common Terms in Bolted Connections:

- **Gauge Line**: This is a line parallel to the direction of stress (or load) along which the bolts are placed.
- **Pitch**: It is the distance between the centres of two consecutive bolts measured along a row of bolts (Gauge Line). It is denoted by $p$.
- **Gauge Distance**: This is the perpendicular distance between adjacent gauge lines. It is denoted by $g$.
- **Edge Distance**: This is the shortest distance from the edge of the member to the extreme bolt hole centre along the Gauge line.
- **End Distance**: It is the shortest distance from the edge of the member to the extreme bolt hole centre perpendicular to the Gauge line.

**IS 800: 2007 Provisions:**

**Clearance for Holes for Fastener (Bolts)** (IS 800:2007 Clause 10.2.1, page no. 73)

- The diameter of the hole should be the nominal diameter of the bolt plus the clearance as given below:

<table>
<thead>
<tr>
<th>Nominal size of fastener, $d$ mm</th>
<th>Size of the hole = Nominal diameter of the fastener + Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard clearance in diameter and width of slot mm</td>
</tr>
<tr>
<td></td>
<td>$d$</td>
</tr>
<tr>
<td>12-14</td>
<td>$d$</td>
</tr>
<tr>
<td>16-24</td>
<td>$d$</td>
</tr>
<tr>
<td>24</td>
<td>$d$</td>
</tr>
<tr>
<td>More than 24</td>
<td>$d$</td>
</tr>
</tbody>
</table>

**Minimum pitch**: (IS 800:2007, Clause 10.2.2, page no. 73)
The distance between the centres of the bolts in the direction of stress should not be less than 2.5 times the nominal diameter of the bolt.

**Maximum pitch** (IS 800:2007, Clause 10.2.3, page no. 74)
- $32t$ or $300$ mm, whichever is less for the bolts in members including the tacking bolts. (Clause 10.2.3.1, page no. 74)
16t or 200 mm, whichever is less for the bolts in tension members, Where t is the thickness of thinner plate (Clause 10.2.3.2, page no. 74)

12t or 200 mm, whichever is less for the bolts in compression members, Where t is the thickness of thinner plate (Clause 10.2.3.2, page no. 74)

**Edge and End distance** (IS 800:2007, Clause 10.2.4.2, page no. 74)

- **Minimum edge and end distances** from the centre of any hole to the nearest edge of a plate should not be less than 1.7 times the hole diameter for sheared or hand-flame cut edges; and 1.5 times the hole diameter for rolled, machine-flame cut, sawn and planned edges

- **Maximum edge distance** from the centre of hole to the nearest edge should not exceed 12\(te\), where \(\varepsilon = \sqrt{250/f_y}\) and t is the thickness of the thinner outer plate.

**Tacking Bolts** (IS 800:2007, Clause 10.2.5.2, page no. 74)

- These are the additional bolts provided other than strength consideration.
- The maximum pitch of these bolts should be 32t or 300 mm, whichever is less, where t is the thickness of the thinner plate.
- If the members are exposed to weather, the pitch should not exceed 16 times the thickness of the outside plate or 200 mm, whichever is less.

**Strength Provisions:**

The design Strength \(V_{db}\) of bolt is lesser of

1. Design shear strength \(V_{dsb}\) of bolt, and
2. Design bearing strength \(V_{dpb}\) of bolt.

- **Shear Capacity of a Bolt** (IS 800:2007, Clause 10.3.3, page no. 75)

  The design strength of a bolt in shear \(V_{dsb}\) is given by

  \[
  V_{dsb} = V_{nsb} \frac{\gamma_{mb}}{\gamma_{mb}}
  \]

  \[
  V_{nsb} = \frac{f_u}{\sqrt{3}} \times [n_n A_{nb} + n_s A_{sb}]
  \]

  Where,
  \(V_{nsb}\) - nominal shear capacity of a bolt
  \(f_u\) = Ultimate tensile strength of the bolt material
  \(n_n\) = Number of shear planes with threads intercepting the shear plane
  \(n_s\) = Number of shear planes without threads intercepting the shear plane.
$A_{sb}$ = Nominal plain shank area of the bolt

$A_{nb}$ = Net shear area of the bolt at threads

= Area corresponding to root diameter at the thread

= $\pi \left[ d - 0.9382p \right]^2$ (I.S. 1367 part-1)

= 0.78 to 0.80 of gross area of shank (see table)

$\gamma_{mb}$ = Partial safety Factor of safety for the bolt material = 1.25 (IS 800:2007, Table 5, page no. 30)

➢ **Bearing Capacity of a Bolt** *(IS 800:2007, Clause 10.3.4, page no. 75)*

The design strength of a bolt in bearing $V_{dpb}$ is given by

$$ V_{dpb} = \frac{V_{npb}}{\gamma_{mb}} $$

Where,

$V_{npb}$ = nominal bearing strength of a bolt

$k_b$ = smallest 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_o = diameter of hole

d = nominal diameter of the bolt

t = summation of the thickness of the connected plates experiencing bearing stress in the same direction, or if the bolts are counter sunk, the thickness of the plate minus one half of the depth of counter sinking.

➢ **Tension Capacity of a Bolt** *(IS 800:2007, Clause 10.3.5, page no. 76)*

The design strength of a bolt in tension $T_{db}$

$$ T_{db} = \frac{T_{nb}}{\gamma_{mb}} $$

Where,

$T_{nb}$ = Nominal tensile capacity of the bolt, calculated as,

$f_{ub}$ = yield stress of the bolt

$A_n$ = Net tensile stress area = area at bottom of the threads, and

$A_{sh}$ = Shank area of the bolt

$\gamma_{mo}$ = Partial safety factor for resistance governed by yielding = 1.10

$\gamma_{mb}$ = Partial safety factor for material of bolt
Bolt subjected to Combined Shear and Torsion (IS 800:2007, Clause 10.3.6, page no. 76)

A bolt subjected to shear and torsion simultaneously should satisfy the condition

\[
\left( \frac{V_{sb}}{V_{db}} \right)^2 + \left( \frac{T_b}{T_{db}} \right)^2 \leq 1
\]

Where,
- \( V_{sb} \) = Factored shear force acting on the bolt
- \( V_{db} \) = Design shear capacity of the bolt
- \( T_b \) = Factored tensile force acting on the bolt
- \( T_{db} \) = Design tensile capacity of the bolt

Bolt subjected to Friction (IS 800:2007, Clause 10.4.3, page no. 76)

\[
V_{dsf} = \frac{V_{nsf}}{\gamma_{mf}}
\]

\[
V_{nsf} = \mu_f n_e K_h F_o
\]

Where,
- \( \mu_f \) = coefficient of friction (slip factor) as specified in Table 20 (\( \mu_f = 0.55 \))
- \( n_e \) = number of effective interfaces offering frictional resistance to slip
- \( K_h = 1.0 \) for fasteners in clearance holes,
  \( = 0.85 \) for fasteners in oversized and short slotted holes loaded perpendicular to the slot.
- \( \gamma_{mf} = 1.10 \) (if slip resistance is designed at service load)
  \( = 1.25 \) (if slip resistance is designed at ultimate load)
- \( F_o \) = minimum bolt tension (proof load) at installation and may be taken as \( A_{nb} f_o \)
- \( A_{nb} \) = Net shear area of the bolt at threads
- \( f_o \) = proof stress (\( = 0.70 f_{ub} \))

Load Transmission by Different Types of Bolts

Load transmitted by Black Bolt (bearing type)
Due to load the plates slip so as to come into contact with edges of the hole. The load transmission is by baring of the bolt and shear on the shank.

Load transmission by High Strength friction grip Bolt
In this case tightening the nut tension \( T \) is transmitted to the bolt to reach tensile stress equal to 0.8 to 0.9 times the yield stress.
As a consequence of this initial tension in the bolt, the two plates get tightly clamped together.

If the tensile force in the bolt is $T$, a compressive force $T$ becomes the clamping force.

Plates are prevented from slipping due to frictional resistance $F$ whose value is $\mu T$, where $\mu$ is coefficient of friction between the plate surfaces.

If pull $P$ applied to the plates is less than $\mu T$, plates do not slip at all and the load transmission from one plate to other place entirely by frictional resistance only.

**IF** the applied force $P$ exceed $\mu T$, slip between the plate occurs resulting in shearing and bearing stresses in the bolt.

<table>
<thead>
<tr>
<th>Strength</th>
<th>Black bolt or Bearing Type bolt</th>
<th>HSFG Bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Slip Resistance</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Bearing Strength</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frictional Strength</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Example: 1** Two plates 200mm × 8mm are to be connected by 16mm diameter bolts in a lap joint. Calculate the strengths for the black type (Bearing type bolts). Take 4.6 grade of bolts. Take ultimate tensile strength of plate = 410 N/mm².
Given Data: \( d = 16\text{mm} \)

\( d_o = 16 + 2 = 18 \text{ mm} \) (Table 19, Page no. 19, Page no. 73)

\( t = \text{thickness of plate} = 8 \text{ mm} \)

**Shear Strength** *(IS 800:2007, Clause 10.3.3, page no. 75)*

\[
V_{dsb} = \frac{V_{n sb}}{\gamma_{mb}}
\]

\[
V_{n sb} = \frac{f_u}{\sqrt{3}} \times \left[ n_n A_{nb} + n_s A_{sb} \right]
\]

\[
V_{dsb} = \frac{400}{\sqrt{3} \times 1.25} \times \left[ \left( 1 \times 0.78 \times \frac{\pi}{4} \times 16^2 \right) + \left( 0 \times \frac{\pi}{4} \times 16^2 \right) \right]
\]

\[
= 28.97 \text{ kN}
\]

**Bearing Capacity** *(IS 800:2007, Clause 10.3.4, page no. 75)*

\[
V_{dpb} = \frac{V_{n pb}}{\gamma_{mb}}
\]

\[
V_{n pb} = 2.5k_b \cdot df_u
\]

\[
V_{dpb} = \frac{2.5 \times 0.741 \times 16 \times 8 \times 410}{1.25}
\]
Given Data: d = 22 mm
   \(d_o = 22 + 2 = 24 \text{ mm} \) (Table 19, Page no. 19, Page no. 73)
   t = thickness of plate = 16 mm

Case 1:

- **Shear Strength** (*IS 800:2007, Clause 10.3.3, page no. 75*)

\[
V_{dsb} = \frac{V_{nsb}}{\gamma_{mb}}
\]

\[
V_{nsb} = \frac{f_u}{\sqrt{3}} \times \left[ n_nA_{nb} + n_sA_{sb} \right]
\]

\[
V_{dsb} = \frac{400}{\sqrt{3} \times 1.25} \times \left[ \left( 1 \times 0.78 \times \frac{\pi}{4} \times 22^2 \right) + \left( 0 \times \frac{\pi}{4} \times 22^2 \right) \right]
\]

\[= 54.78 \text{ kN} \]

- **Bearing Strength:** (*IS 800:2007, Clause 10.3.4, page no. 75*)

\[
V_{dpb} = \frac{V_{npb}}{\gamma_{mb}}
\]

\[
V_{npb} = 2.5K_b \, d tf_u
\]

\[
V_{dpb} = \frac{2.5 \times 0.556 \times 22 \times 16 \times 410}{1.25}
\]

\[= 160.48 \text{ kN} \]
Case 2: Single cover butt joint with 12mm cover plate

- **Shear Strength** *(IS 800:2007, Clause 10.3.3, page no. 75)*
  \[ V_{dsb} = 54.78 \]

- **Bearing Strength:** *(IS 800:2007, Clause 10.3.4, page no. 75)*
  \[ V_{dpb} = \frac{2.5 \times 0.556 \times 22 \times 12 \times 410}{1.25} = 120.36 \text{ kN} \]

Case 3: Double cover butt joint with 10mm cover plate.

- **Shear Strength** *(IS 800:2007, Clause 10.3.3, page no. 75)*
  \[ V_{dsb} = 2 \times 54.78 = 109.56 \text{ kN} \]

- **Bearing Strength:** *(IS 800:2007, Clause 10.3.4, page no. 75)*
  \[ V_{dpb} = \frac{2.5 \times 0.556 \times 22 \times 16 \times 410}{1.25} = 160.48 \text{ kN} \]

Example 3: Find the efficiency of the butt join shown in figure. Bolts are 16mm diameter of grade 4.6. Cover plates are 8mm thick.
\[ V_{dsb} = \frac{V_{nsb}}{\gamma_{mb}} \]

\[ V_{nsb} = \frac{f_u}{\sqrt{3}} \times [n_n A_{nb} + n_s A_{sb}] \]

\[ V_{dsb} = \frac{400}{\sqrt{3} \times 1.25} \times \left( \left( 2 \times 0.78 \times \frac{\pi}{4} \times 16^2 \right) + \left( 0 \times \frac{\pi}{4} \times 16^2 \right) \right) \]

\[ = 57.95 \text{ kN} \]

- **Bearing Strength:** (IS 800:2007, Clause 10.3.4, page no. 75)

\[ V_{dpb} = \frac{V_{npb}}{\gamma_{mb}} \]

\[ V_{npb} = 2.5k_b \, d f_u \]

\[ V_{dpb} = \frac{2.5 \times 0.56 \times 16 \times 12 \times 410}{1.25} \]

\[ = 88.16 \text{ kN} \]

- \( e = 30 \text{mm} \)
- \( p = 50 \text{mm} \)
- \( K_b \) is least of
  - \( e/3d_o = 30/(3 \times 18) = 0.56; \)
  - \( p/3d_o = 0.25 = [50/(3 \times 18)] - 0.25 = 0.67; \)
  - \( f_{ub}/f_u = 400/410 = 0.976; \)
  - 1
- \( t = 16 \text{mm} \)
- \( d = 12 \text{mm} \)

**Efficiency of the joint** = \[ \frac{\text{Strength of the Joint per pitch length}}{\text{Strength of solid plate per pitch length}} \] \times 100

- Strength the joint per pitch length = 57.95 kN

- **Strength of solid plate per pitch length** = \( \frac{0.9 A_{nf_u}}{\gamma_{m1}} \) (clause no. 6.3.1, page no. 32, IS 800:2007)
\[
= \frac{0.9 \times (50 - 16) \times 12 \times 410}{1.25} = 120.44 \text{ kN}
\]

\[\text{Efficiency of the joint} = \left(\frac{57.95}{120.44}\right) \times 100 = 48.11 \%
\]

**Example:** An ISA 100mm × 100mm × 10mm carries a factored tensile load of 100kN. It is to be jointed with a 12mm thick gusset plate. Design high strength bolted joint when,
(a) no slip is permitted.
(b) when slip is permitted.
Take bolt grade =8.8 with 16mm dia.

Solution:
\(f_{ub} = 800 \text{ N/mm}^2\) for 8.8 grade.

**(a) Slip critical connection:**

- **Frictional Strength** *(IS 800:2007, Clause 10.4.3, page no. 76)*

\[
V_{dsf} = \frac{V_{nsf}}{\gamma_{mf}}
\]

\[
V_{nsf} = \mu_f n_e K_h F_o
\]

Where
- \(\mu_f = \) coefficient of friction (slip factor) as specified in Table 20 \((\mu_f = 0.55)\) = 0.55
- \(n_e = \) number of effective interfaces offering frictional resistance to slip = 1
- \(K_h = \) 1.0 for fasteners in clearance holes,
- \(= 0.85 \) for fasteners in oversized and short slotted holes loaded perpendicular to the slot.
- \(\gamma_{mf} = \) 1.10 (if slip resistance is designed at service load
- \(= 1.25 \) (if slip resistance is designed at ultimate load

\[
A_{nb} = \text{Net shear area of the bolt at threads} = \left(0.78 \times \frac{2}{4} \times 16^2\right) = 157 \text{mm}^2
\]

\[f_o = \text{proof stress} ( = 0.70f_{ub}) = 0.70 \times 800 = 560 \text{ N/mm}^2
\]

\[F_o = \text{minimum bolt tension} \text{ (proof load) at installation and may be taken as } A_{nb}f_o = 560 \times 0.157 = 87.9 \text{ kN}
\]
\[ V_{dsf} = \frac{\mu f ne Kh Fo}{\gamma_{mf}} \]
\[ V_{dsf} = \frac{0.55 \times 1 \times 1 \times 87.9}{1.25} = 38.65 \text{ kN} \]

**Tension Capacity of a Bolt (IS 800:2007, Clause 10.3.5, page no. 76)**

The design strength of a bolt in tension \( T_{db} \)

\[ T_{db} = \frac{T_{nb}}{\gamma_{mb}} \]
\[ T_{nb} = 0.9 f_{ub} A_{nb} \]
\[ T_{db} = \frac{0.9 f_{ub} A_{nb}}{\gamma_{mb}} = \frac{0.9 \times 800 \times 157}{1.25} = 90.32 \text{ kN} \]

Bolt value = 38.65 kN

\[ \text{No. of bolt} = \frac{100}{38.65} \approx 3 \]

(a) Slip allowed connection:

**Shear Strength (IS 800:2007, Clause 10.3.3, page no. 75)**

\[ V_{dsb} = \frac{V_{nsb}}{\gamma_{mb}} \]
\[ V_{nsb} = \frac{f_{u}}{\sqrt{3}} \times [n_{n}A_{nb} + n_{s}A_{sb}] \]
\[ V_{dsb} = \frac{800}{\sqrt{3} \times 1.25} \times \left[ \left( 1 \times 0.78 \times \frac{\pi}{4} \times 16^2 \right) + \left( 0 \times \frac{\pi}{4} \times 16^2 \right) \right] \]
\[ = 58 \text{ kN} \]

**Bearing Strength: (IS 800:2007, Clause 10.3.4, page no. 75)**

\[ V_{dpb} = \frac{V_{npb}}{\gamma_{mb}} \]
\[ V_{npb} = 2.5k_b \, df_u \]

\[ V_{dpb} = \frac{2.5 \times 0.56 \times 16 \times 10 \times 410}{1.25} = 73.47 \, kN \]

- \( e = 30\, mm \)
- \( p = 50\, mm \)
- \( K_b \) is least of
  - \( e/3d_o = 30/(3 \times 18) = 0.56; \)
  - \( p/3d_o - 0.25 = [50/(3 \times 18)] - 0.25 = 0.67; \)
  - \( f_{ub}/f_u = 800/410 =; \)
  - \( 1 \)
- \( t = 10\, mm \)
- \( d = 16\, mm \)

Bolt value = 58 kN

\[ No. \, of \, bolt = \frac{100}{58} = 1.72 \approx 2 \]

**Example:** An I beam ISLB400@558.2 N/m is to be connected to the web of a main beam ISLB550@846.6 N/m. The factor reaction of 220 kN. Design the connection if the cleat angel size is 110 × 110 × 6 as shown in figure. Use 20mm diameter bolts.
Properties from steel table:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Notation</th>
<th>ISLB400</th>
<th>ISLB550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>h</td>
<td>400 mm</td>
<td>550 mm</td>
</tr>
<tr>
<td>Width of flange</td>
<td>b_f</td>
<td>165 mm</td>
<td>190 mm</td>
</tr>
<tr>
<td>Thickness of flange</td>
<td>t_f</td>
<td>12.5 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>Thickness of web</td>
<td>t_w</td>
<td>8 mm</td>
<td>9.9 mm</td>
</tr>
</tbody>
</table>

Connection between the angles and the web of the secondary beam:
The connecting bolts are in double shear:

➤ **Shear Strength** *(IS 800:2007, Clause 10.3.3, page no. 75)*

\[
V_{dsb} = \frac{V_{nsb}}{\gamma_{mb}}
\]

\[
V_{nsb} = \frac{f_u}{\sqrt{3}} \times \left[ n_n A_{nb} + n_s A_{sb} \right]
\]

\[
V_{dsb} = \frac{400}{\sqrt{3} \times 1.25} \times \left[ \left( 2 \times 0.78 \times \frac{\pi}{4} \times 20^2 \right) + \left( 0 \times \frac{\pi}{4} \times 16^2 \right) \right]
\]

\[
= 90.54 \text{ kN}
\]
Bearing Strength: (IS 800:2007, Clause 10.3.4, page no. 75)

\[ V_{dpb} = \frac{V_{npb}}{\gamma_{mb}} \]

\[ V_{npb} = 2.5k_b \cdot d f_u \]

\[ V_{dpb} = \frac{2.5 \times 0.606 \times 20 \times 8 \times 410}{1.25} \]

\[ = 79.51 \text{ kN} \]

- \( e = 1.5 \cdot d_o = 1.5 \times 22 = 33 \approx 40 \text{ mm} \)
- \( p = 2.5 \cdot d = 2.5 \times 20 = 50 \approx 60 \text{ mm} \)
- \( K_b \) is least of
  - \( e/3d_o = 40/(3 \times 22) = 0.606 \)
  - \( p/3d_o - 0.25 = (60/(3 \times 20)) - 0.25 = 0.659 \)
  - \( f_{ub}/f_u = 400/410 = 0.976 \)
  - 1

- \( t = 16 \text{ mm} \)
- \( d = 22 \text{ mm} \)

Bolt value = 79.51 kN

Number of bolts required = \( \frac{220}{79.51} \approx 2.78 \approx 3 \) bolts

Connection between the angles and the web of the main beam:
The connecting bolts are in single shear:

- Shear Strength (IS 800:2007, Clause 10.3.3, page no. 75)

  Design strength of the bolt in single shear = 45.27 kN

- Bearing Strength: (IS 800:2007, Clause 10.3.4, page no. 75)

  \[ V_{dpb} = \frac{V_{npb}}{\gamma_{mb}} \]

  \[ V_{npb} = 2.5k_b \cdot d f_u \]
\[ V_{dpb} = \frac{2.5 \times 0.606 \times 20 \times 9.9 \times 410}{1.25} = 98.39 \text{ kN} \]

Bolt value = 45.27 kN

Number of bolts required = \( \frac{220}{45.27} = 4.85 \cong 5 \) bolts