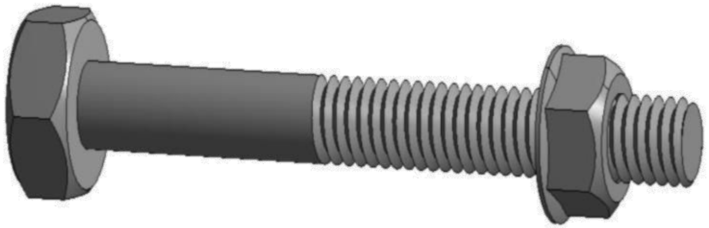
The Mechanics of Bolted Joints

Preloaded Bolted Joint Analysis – Lesson 2

Types of Bolted Joints

Bolted joints can support different load configurations.

- Two commonly used bolts are partially and fully threaded bolts.
- Choosing the wrong type of bolt can lead to joint failure.
- There are two types of joints:
  - Tension joints
  - Shear joints



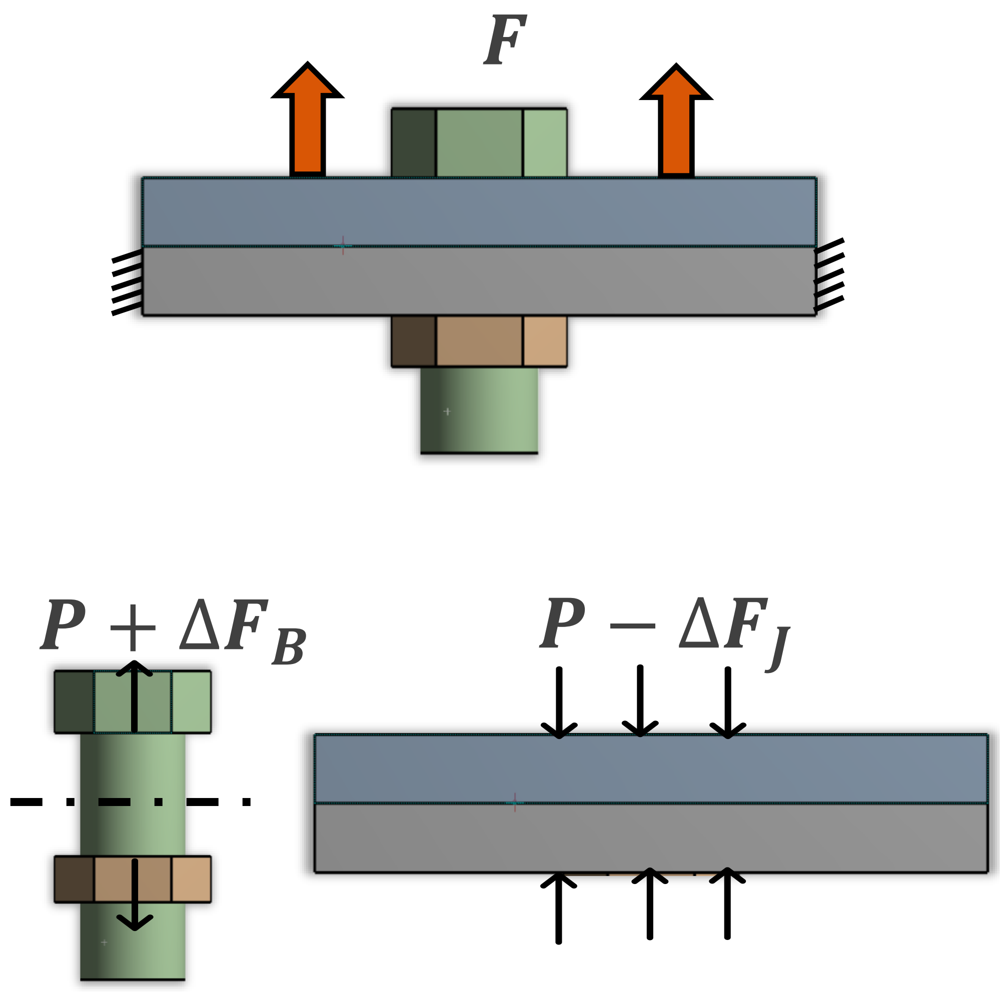
Partially Threaded Bolt

Fully Threaded Bolt

Tension Joints

In a tension joint the bolt is predominantly supporting tensile loads that pull the plates apart.

- Applied loads F act along the axis of the bolts.
- Due to external tensile loads, the forces acting through the cross-section of the bolt increase by a fraction of the total applied force, ΔF_B.
- The clamp force (which is equal to the bolt preload P) should typically be selected to ensure there is no plastic deformation of the bolt.
- A sufficiently high value of P and member (or joint) stiffness ensures that only a small portion, ΔF_B, of the external load, F, is carried by the bolts and the rest of the load, $F - \Delta F_B = \Delta F_J$, is carried by the clamped members.
- If the external load applied to the joint is large enough to overcome the initial compression in the joint achieved through the bolt preload, then the members will separate, and the entire load will be carried by the bolt, which can also greatly reduce the bolt fatigue life from repetitive loadings.
- The bolt preload P is chosen based upon the proof load of the bolt.

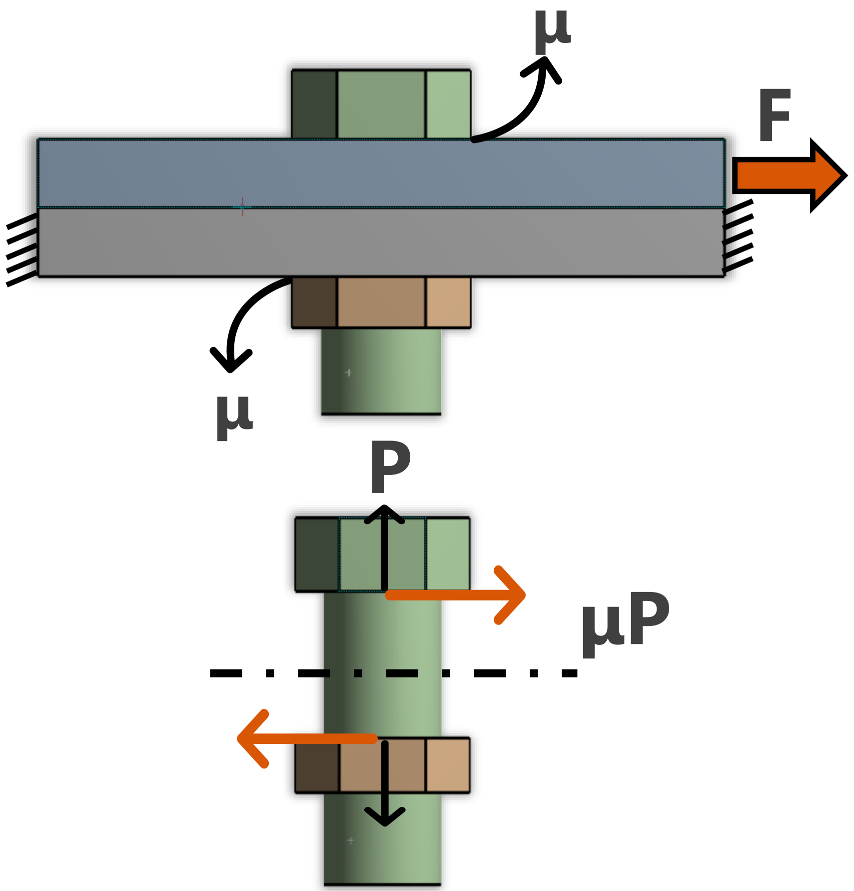


$$\Delta F_B + \Delta F_J = F$$

Shear Joints

Shear joints experience loads in a direction perpendicular to the axis of the bolt.

- Performance depends on the friction between the fastener and the component, as well as the shear strength of the bolt.
- If the frictional force due to the preload is not sufficient to counter the external load, then the component slips, which is often undesirable.
- In some cases, the bolt directly supports the external load and friction is not needed. Such loads are called bearing loads.
  - Here, preload is not important, and the shear strength of the bolt determines the strength of joint.
- Partially threaded bolts are suitable for these joints as they offer more shear resistance and better alignment.



Force Balance in Bolted Joints

- A well-designed bolted joint should establish and maintain enough initial compression in the joint so that the joint does not separate under external forces.
- To achieve this, we need to apply a sufficient preload P to the bolt such that:

$$P < \text{Proof load}$$

$$P = \text{Factor} \times \text{Proof strength} \times \text{Tensile stress area of bolt}$$

$$0.75 < \text{Factor} < 0.9\ ^{1}$$

- To determine whether P is sufficient to prevent joint separation when external force is applied, we determine the force balance in the joint using a Joint diagram

[1] - Budynas, Richard Gordon, and J. Keith Nisbett. Shigley's Mechanical Engineering Design. Eighth Edition. New York: McGraw-Hill, 2008.

Force Balance in Bolted Joints – Joint Diagram

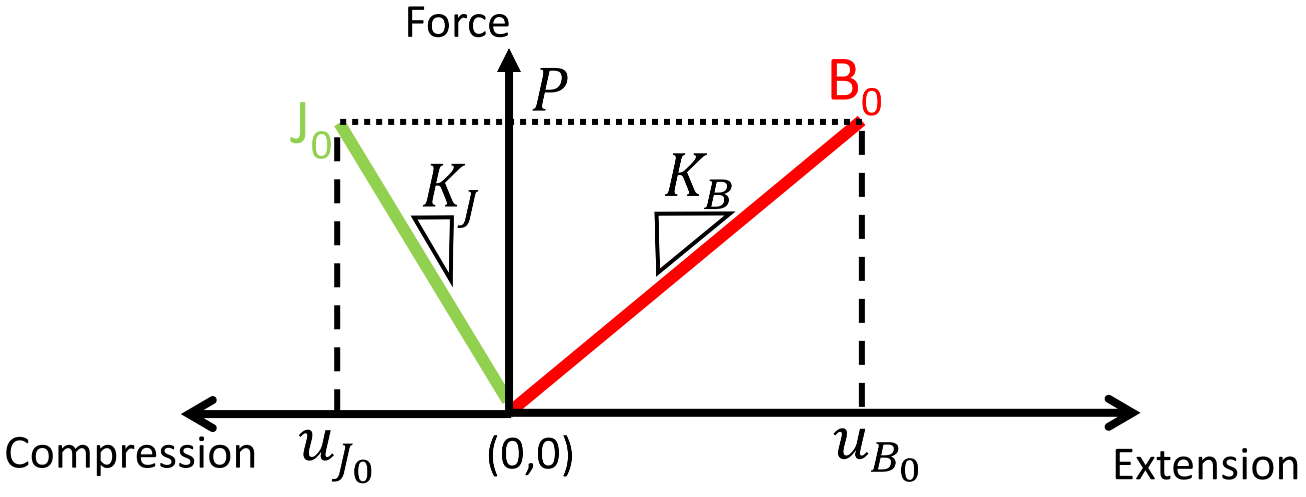
- Joint diagrams are developed to help visualize the loading in bolted joints.
- Static equilibrium dictates that the tensile force acting on the bolt is equal and opposite to the compressive clamp force on the joint.

$$F_{J_0} = F_{B_0} = P \text{ (Bolt Preload)}$$

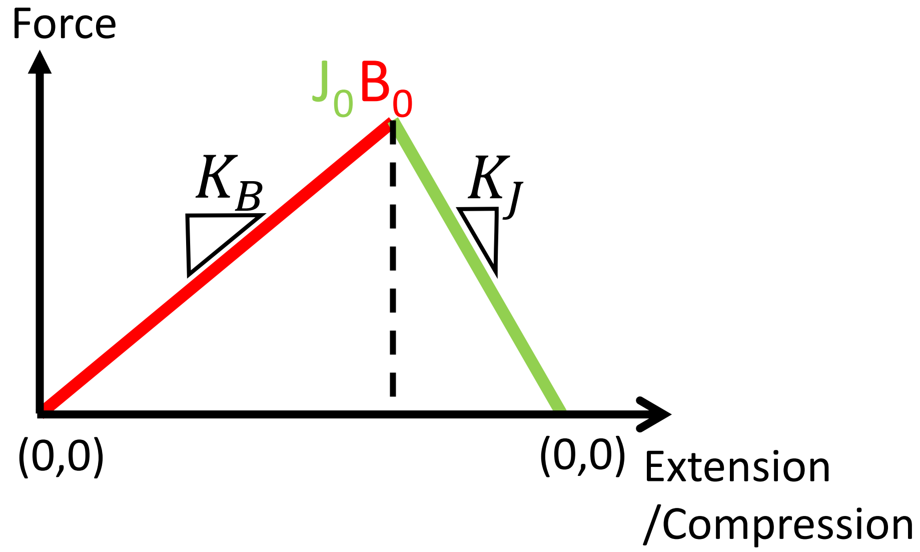
- The bolt extension and joint compression depend on their respective stiffnesses. The slopes of the two lines represent the respective stiffnesses.

$$u_{J_0} = \frac{P}{K_J} \qquad u_{B_0} = \frac{P}{K_B}$$

- The origin of the Joint compression line is moved such that points J_0 and B_0 coincide to form a triangle. This is the Joint diagram.



Joint Diagram



Force Balance in Bolted Joints – Bolt Stiffness

- Approximate bolt stiffness can be calculated as

$$K_B = \frac{A_d A_t E}{A_d l_t + A_t l_d}^{1}$$

A_t - tensile-stress area

l_t- length of threaded portion of grip

A_d - major-diameter area

l_d- length of unthreaded portion of grip

E- Young's modulus of the bolt material

1 - Budynas, Richard Gordon, and J. Keith Nisbett. Shigley's Mechanical Engineering Design. Eighth Edition. New York: McGraw-Hill, 2008.

Force Balance in Bolted Joints – Member/Joint Stiffness

- Each clamped part acts as a compressive spring. Total member or joint stiffness is calculated by considering that the compressive springs act in series.
- In presence of a soft gasket, this term dominates the formula and hence $K_J = K_{\text{Gasket}}$
- In other cases, we consider the pressure-cone developed in the clamped parts around the bolt axis.
- For $\alpha = 30°$

$$K_J = \frac{0.5774\pi E d}{ln\left[\frac{(1.155t + D - d)(D + d)}{(1.155t + D + d)(D - d)}\right]}$$ [1]

E – Young's modulus of the clamped part

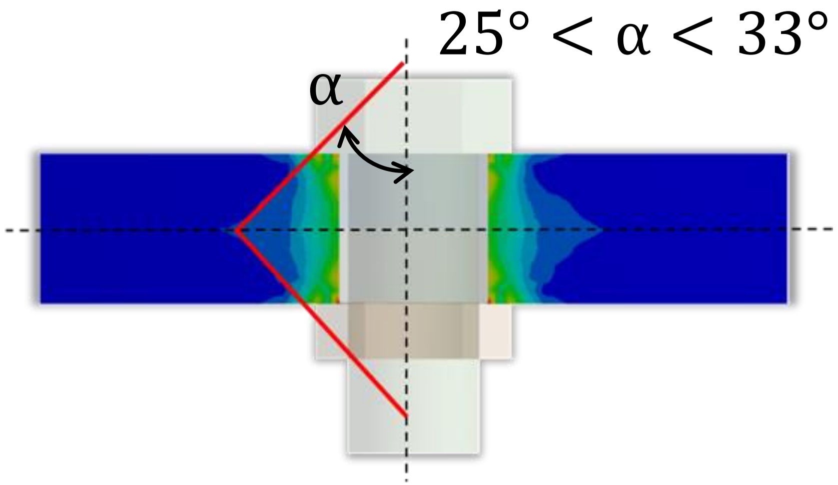
d – Major diameter of the bolt shank

D – Bolt head diameter

t – Plate thickness

When $K_{\text{Gasket}} \ll K_i$

$$\frac{1}{K_J} = \underset{\approx 0}{\cancel{\frac{1}{K_1}}} + \frac{1}{K_{\text{Gasket}}} + \underset{\approx 0}{\cancel{\frac{1}{K_2}}} \ldots$$



[1] - Budynas, Richard Gordon, and J. Keith Nisbett. Shigley's Mechanical Engineering Design. Eighth Edition. New York: McGraw-Hill, 2008.

Force Balance in Bolted Joints in presence of an external load F

- External load F reduces the clamping force on the joint by ΔF_J and increases the load on the bolt by ΔF_B such that two conditions are fulfilled:
    - External load is distributed between the bolt and the joint):

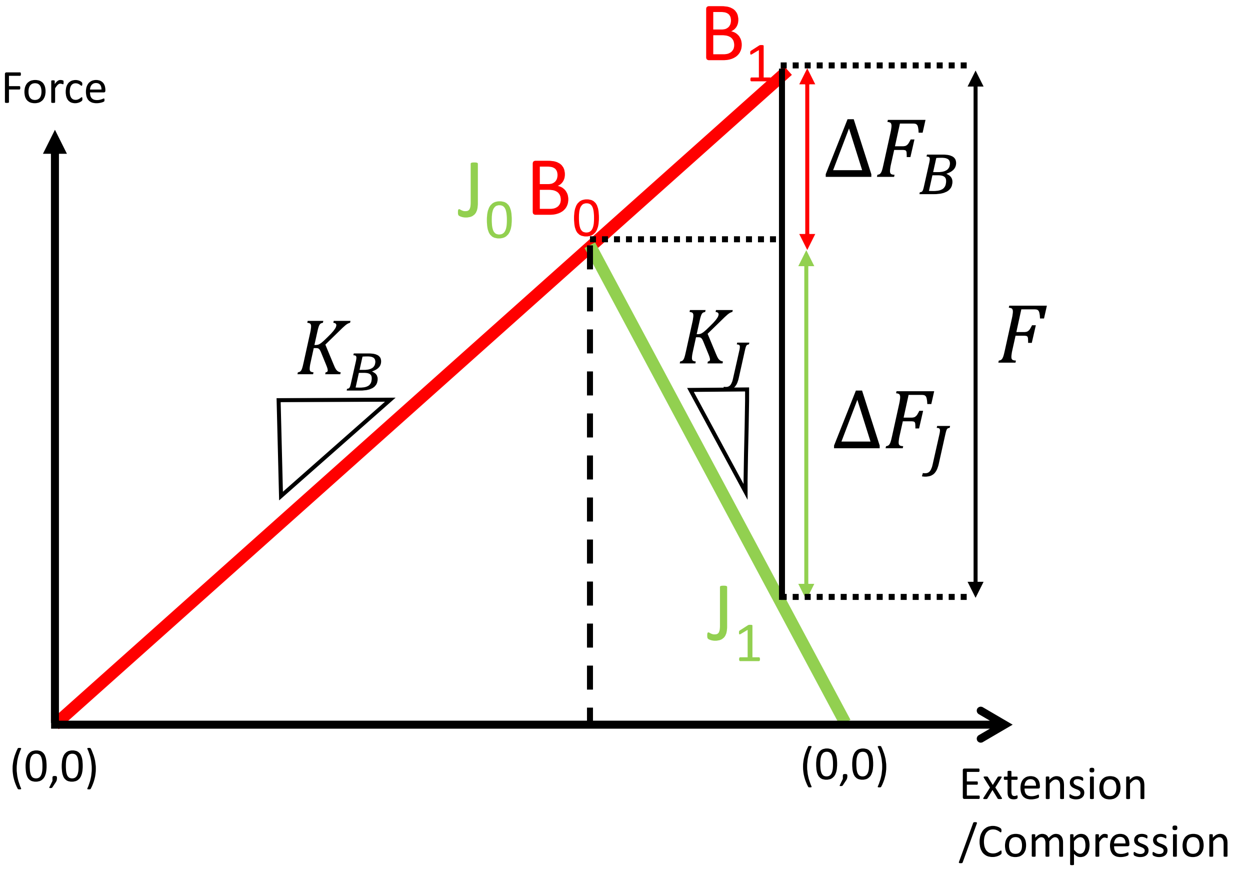
$$\Delta F_B + \Delta F_J = F$$

    - Change in deformation of the bolt and the joint due to ΔF_B and ΔF_J respectively is the same:

$$\delta_{\Delta F_B} = \delta_{\Delta F_J}$$

$$\frac{\Delta F_B}{K_B} = \frac{\Delta F_J}{K_J}$$

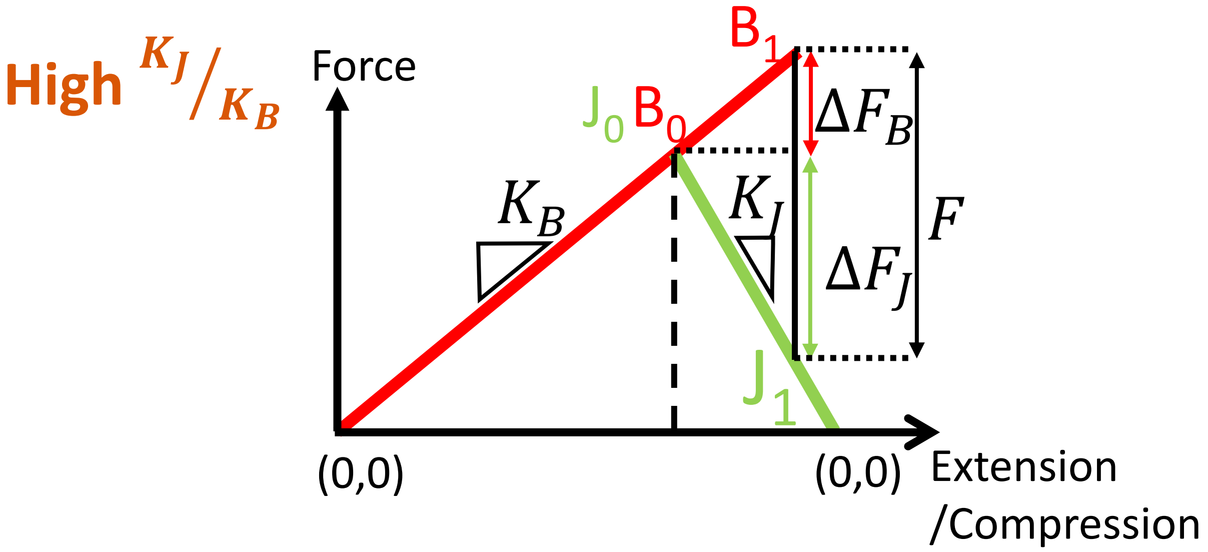
- Solving the two equations simultaneously, we get:
    - $\Delta F_B = \frac{K_B F}{(K_B + K_J)} = CF$
    - $\Delta F_J = F - \Delta F_B = (1 - C)F$

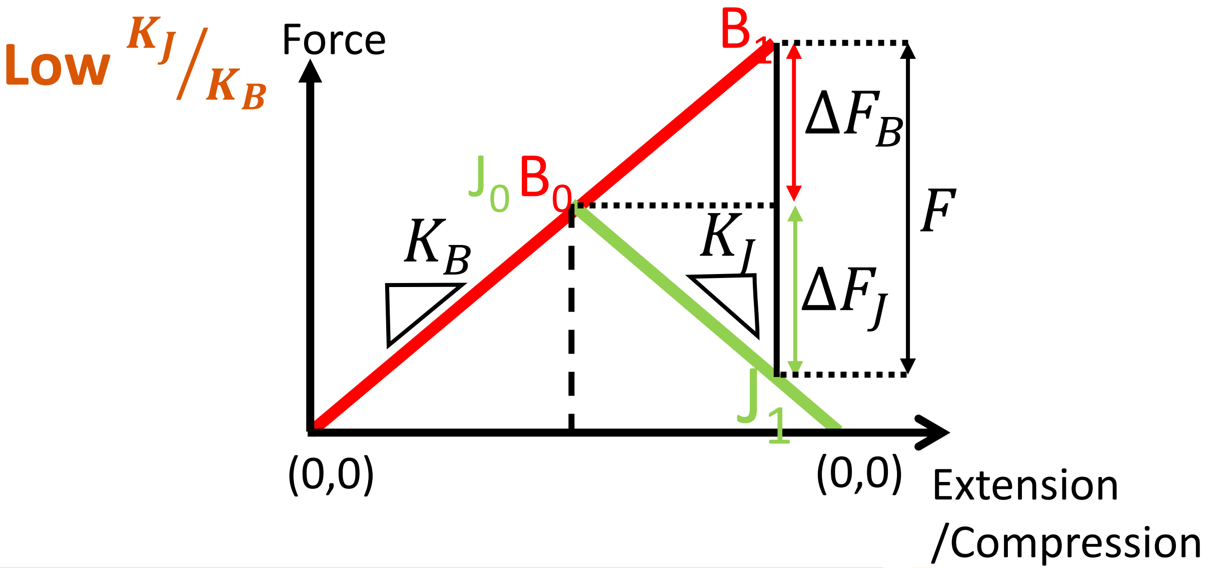


Force Balance in Bolted Joints in presence of an external load F

- ΔF_B and ΔF_J are dependent on the relative stiffness of the bolt to the joint.
  - $\Delta F_B = CF$
  - $\Delta F_J = (1 - C)F$

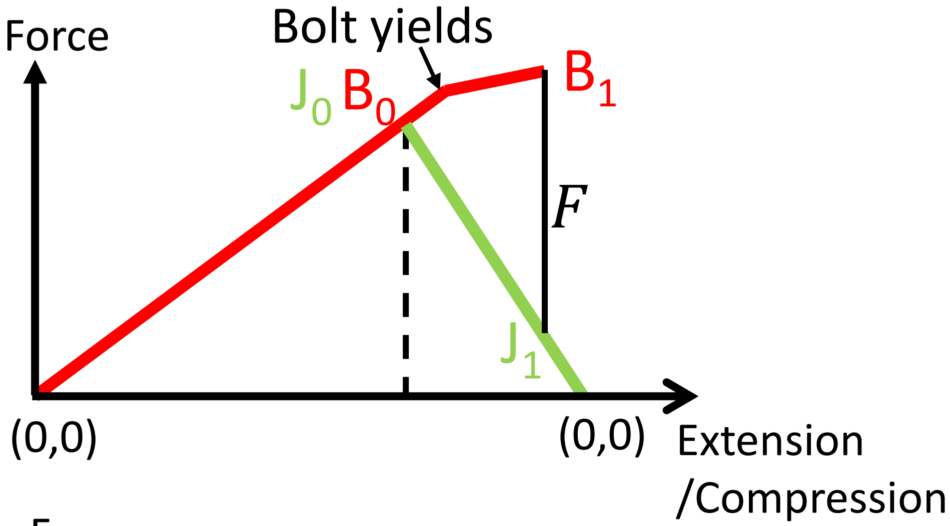
  where $C = \frac{K_B}{(K_B+K_J)} = \frac{1}{1+{}^{K_J}/_{K_B}}$
- Having a high ${}^{K_J}/_{K_B}$ ensures that majority of the external load goes into reducing the compression of the members rather than increasing the tension of the bolt.

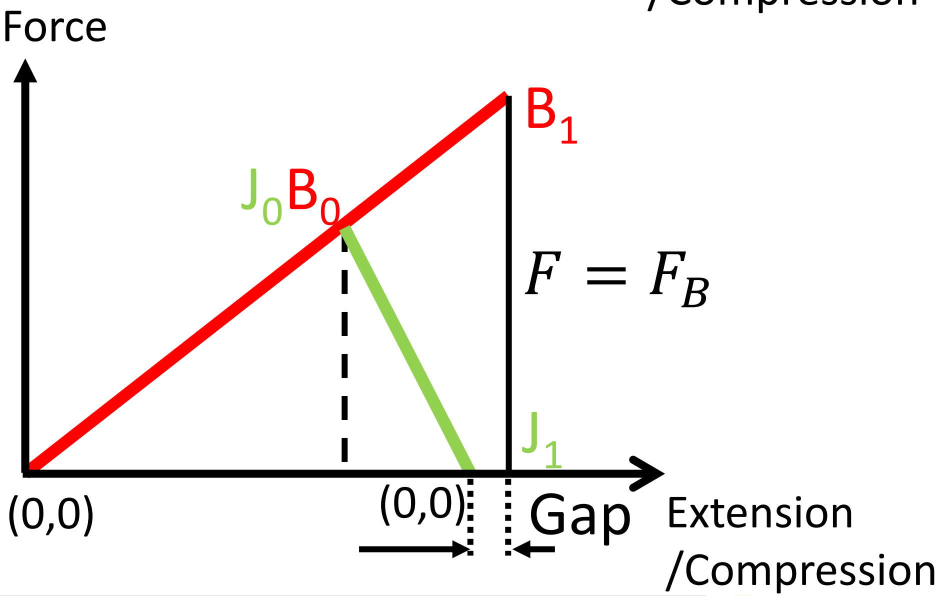




Effect of a large external force on a bolted joint

- For a large F, two situations can occur:
  - The total load acting on the bolt increases so much that it causes the bolt to yield. This will likely cause failure of the bolt.
  - The clamping force on the joint decreases so much that it reaches zero. And further increase in F will cause a gap to form between the two clamped parts and the entire external load F is now sustained by the bolt. This also leads to bolt failure.
- Hence, usually a design criteria is set such that the external forces do not cause gap formation under any circumstances.





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