How EXTERNAL LOADS affect BOLTED JOINTS

Forces that overcome preload can cause bolted assemblies to leak, rattle, and fail.

Understanding the structural behavior of bolted joints is paramount for good designs, and one key factor is how joints react to external loads.

In sorting out these reactions, remember that preloaded bolted joints are integral mechanical components consisting of a bolt and clamped members. Its structural properties markedly differ from those of the bolt itself.

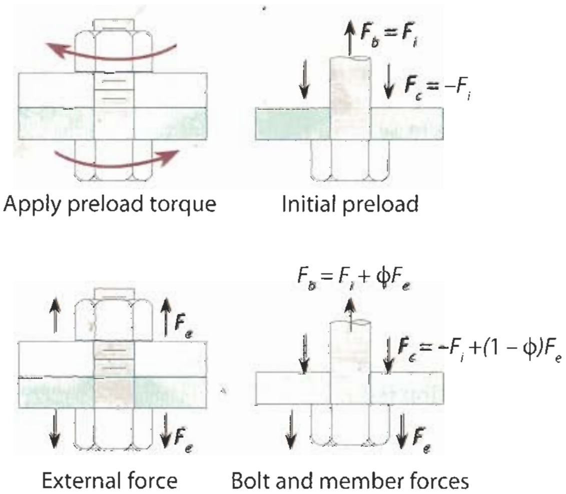
Bolt and member forces

As the accompanying loading-process diagrams depict, a bolt reacts with tension when the nut is tightened to clamp joint members. The bolt stretches and clamped members compress from their free states by δ_b and δ_c, respectively. Bolt tension and clamped-member compression equal the initial clamping (preload) force, F_i, in absolute terms. Sign convention shows positive force for tension and negative for compression:

$$F_b = k_b\delta_b = F_i, \text{ and}$$
$$F_c = k_c\delta_c = -F_i.$$

Applying an external force, F_e, to the preloaded joint elongates the bolt by x, and forces in the bolt and clamped members readjust. As long as external force is not enough to completely relieve the preload, the following relations hold:

Bolted-joint behavior under load



These images show preload and external forces on the bolt half of the joint. Similar forces act on the side of the joint held by the nut.

$$F_b(x) = F_i + k_b x,$$
$$F_c(x) = -F_i + k_c x, \text{ and}$$
$$F_b(x) + F_c(x) = F_e(x).$$

Substituting $x = F_e/(k_b + k_c)$ links forces of the bolt and clamped member directly to the external force and eliminates the need to know the displacement. If we define the bolt load-sharing ratio ϕ as:

$$\phi = k_b/(k_b + k_c), \text{ then}$$
$$F_b(x) = F_i + \phi F_e \text{ and}$$
$$F_c(x) = F_i + (1 - \phi)F_e.$$

The $F_b(x)$ equation indicates combined bolt tension is the sum of the initial tension from preload and a portion of the external load. The bolt load-sharing ratio is the fraction of external load on the bolt, with $0 < \phi < 1$. A typical ϕ value for a structural joint is about 0.2 to 0.5. For hard, thin, and wide clamped members, ϕ approaches 0. For compliant joints, such as those with a soft gasket, ϕ approaches 1.

Bolt-load-sharing ratio is an important parameter because it can be used to more-accurately calculate bolt stresses than using the sum of preload and external load.

WHAT'S THIS?
When you see a code like this, take a photo of it with your smart phone (iPhone 3G-S gives best results) and, using software from *www.neoreader.com*, you will be connected to relevant content on *machinedesign.com*

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Key points:

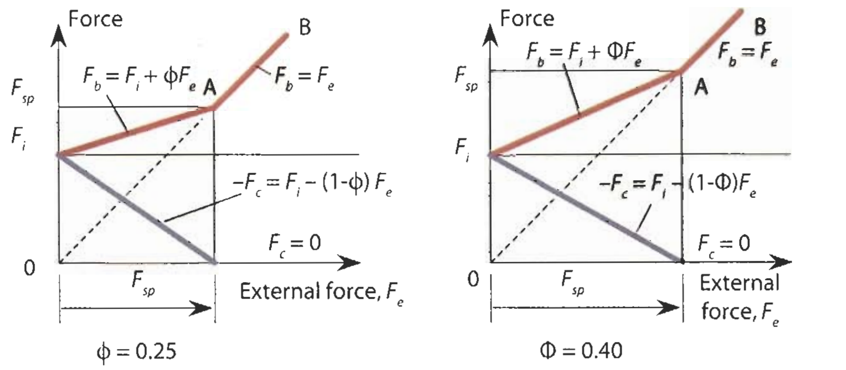
- External loads that exceed the preload can cause joints to leak and assemblies to rattle.
- Controlling separation load is critical for precision preloading on mechanisms such as bearings.

Resources:

"Structural Properties of Bolted Joints," Machine Design, Feb. 18, 2010, p. 44.

Detailed free-body diagrams of bolted joints can be found in Juvinall and Marshcek, *Fundamentals of Machine Component Design*, John Wiley & Sons, 1991

Force-sharing diagrams



The force diagrams are for load-sharing ratios of 0.25 and 0.40. Note that $-F_c$ rather than F_c is plotted to be consistent with the sign convention.

On the other hand, the $F_c(x)$ equation needs be checked to ensure clamping force is sufficient to prevent seals from leaking.

Joint separation

When external force is large enough to completely relieve preload, the bolt carries the entire external force:

$$F_b(x) = F_e(x) \text{ and}$$
$$F_c(x) = 0, \text{ for } x \geq x_{sp} = F_i/k_c.$$

External load that is just sufficient to completely relieve the preload on clamped members is the critical external load for joint separation, or separation load. Calculate it from:

$$F_{sp} = F_i/(1 - \phi).$$

The separation load ratio λ is

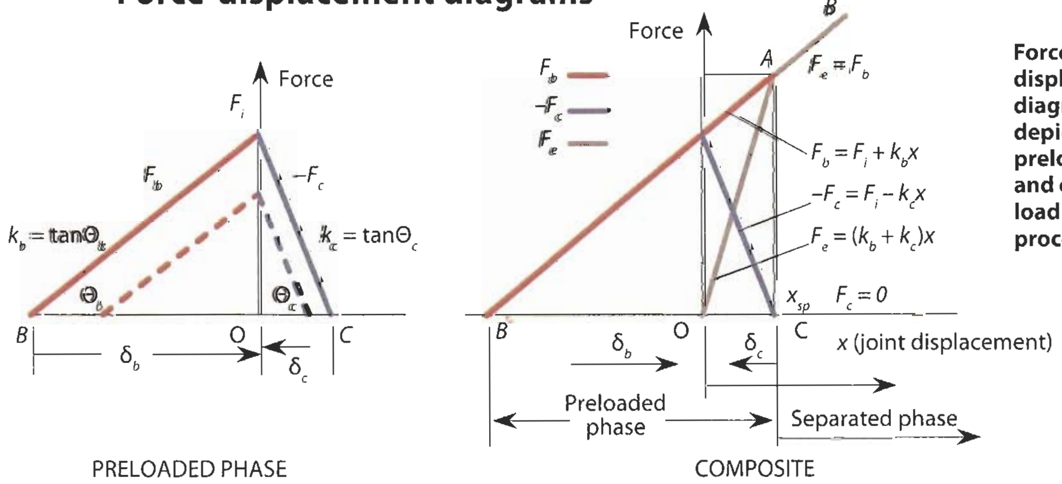
$$\lambda \equiv \frac{F_{sp}}{F_i} = \frac{1}{1-\phi} > 1.$$

Separation load is proportional to the initial preload, and the separation load ratio is a function only of ϕ.

It takes external forces larger than the initial preload to separate a joint. This is because an external load concurrently reduces clamping force while increasing bolt force. Without enough preloading, a pressure joint leaks or a mechanical assembly rattles under vibration. Rattling means rapid reversing spikelike shocks that make parts impact each other. Mechanical systems generally do not tolerate bolted-joint separation, especially for sensitive equipment or instruments in vibrating environments.

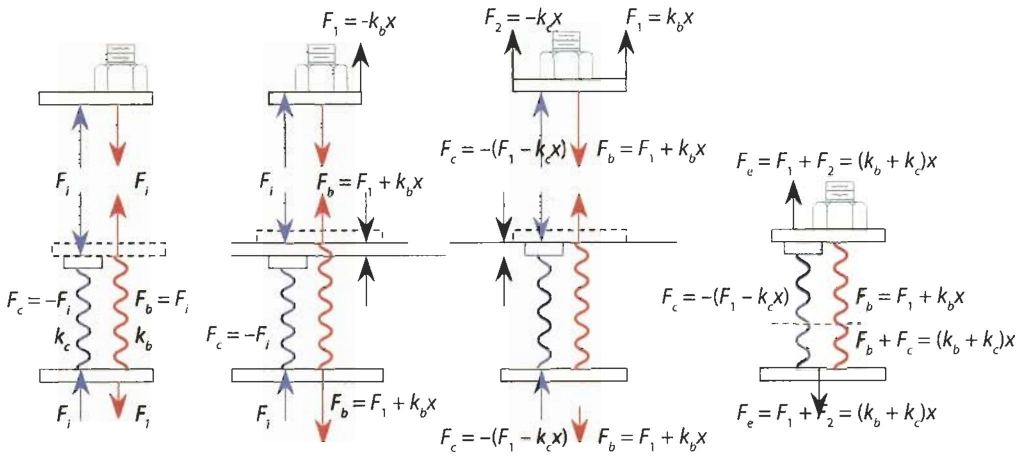
Controlling separation load is critical for precision preloading mechanisms such as bearings. These devices can-

Force-displacement diagrams



Force-displacement diagrams depict preloading and external loading processes.

How external forces affect bolted joints



This series of images shows how external forces cause changes in bolt and member forces.

Bolt and members preloaded with initial force, F_i.

Bolt elongates by x with external force, F_1, on bolt. Members stay preloaded.

Member relaxes by x, reducing compression. External force F_2 is added to compensate for weakened force F_c.

Bolt and member at displaced position share external force.

not afford to lose preload yet work best with low preloads. Unnecessarily high preloads increase friction and may overheat the bearing, or otherwise consume too much power during operation.

The bolt-load-sharing ratio affects both the combined bolt load and how well a joint stays preloaded. For instance, the accompanying load-sharing diagrams show external, bolt, and member forces for $\phi = 0.25$ and 0.4. As you can see, load sharing distinctly differs before and after joint separation.

Force-displacement diagrams depict preloading and external loading processes, as shown. For a bolted joint, bolt and member stiffnesses are fixed, as are the slopes of F_b and F_c. For a different preload F_i, both lines shift but keep the same slopes, as shown by the dashed lines.

As noted above, $x = F_e/(k_b + k_c)$. And the stiffness, k_e, of the preloaded bolted joint for external load is the sum of the bolt and clamped-member stiffnesses. Thus, under preloaded conditions:

$$k_e = F_e/x = k_b + k_c.$$

After joint separation, $Fc = 0$, the bolt bears the entire external load, and joint stiffness equals bolt stiffness, $k_e = k_b$.

The external-force paradox

Because an external pull increases bolt tension and decreases member compression at the same time, shouldn't the magnitude of the external force equal the difference of the two? If so, then joint stiffness should be the difference between the stiffnesses of the bolt and members.

The diagrams that show external force as the sum of changes in bolt and member force treat external loading as if it were a two-step process. An external load is assumed to stretch the bolt first and then relieve compression on the members.

Suppose an external force, F_e, of unknown magnitude stretches a preloaded bolted joint at the seating plane of the nut by x from preloaded conditions. It needs an external force, $F_1 = k_b x$, just to elongate the bolt beyond its preloaded condition. Because clamped members must also relax by x from their initially compressed state, the clamping force must be reduced by $F_2 = k_c x$. Because clamping force comes from the nut, an external force F_2 is required to compel the nut to relent (without rotating). F_2 is in addition to the bolt stretching force F_1. Therefore, the total external force is: $F_e = F_1 + F_2$.

The two forces take parallel routes. Force F_1 follows the path from the nut through the thread engagement and bolt rod and to the bolt head on the other end. Force F_2 travels from the seating surface of the nut through the clamped members, then reaches the bolt head. F_1 increases bolt tension, F_2, reduces member compression.

The root of the paradox is due to the deviation from the sign convention of forces. An external pull increases bolt tension and decreases member compression at the same time. Member compression is a negative force. Decreasing a negative force in absolute magnitude requires a positive force. **MD**

Nomenclature

- F_b = Bolt force
- F_c = Clamped member force
- F_e = External force
- F_i = Initial preload force
- F_{sp} = Joint-separation load
- k_b = Bolt stiffness
- k_c = Clamped-member stiffness
- k_e = Preloaded-joint stiffness for external load
- x = Bolt elongation
- x_{sp} = Clamp-separation length
- δ_b = Bolt-stretch length
- δ_c = Clamped-member compression length
- λ = Separation-load ratio
- ϕ = Load-sharing ratio