2.72 Elements of Mechanical Design

Lecture: Bolted joints

Image courtesy of Justin Lai
Bolt Basics
Bolted joint +’s and –’s

**Good:**
- Low cost?
- Able to be disassembled
- Strong
- Compatible with almost any material

**Bad:**
- Takes up a lot of space
- Micro-slip/hysteresis/damping problems
- Difficult to model and control
- Can require long fabrication and assembly time
Bolted joints: Their purpose

Bolted joints = connectors, impact many parts:

Stiffness  Vibration  Damping  Stability  Load capacity

Bolted joints are semi-permanent!

- Max benefit obtained when it is highly preloaded, i.e. near the yield point
- Threads can plastically deform/work harden
- Some elements of bolted joints are not reusable

Bolted joints are used to create assemblies that resist:

(i) Tensile loads  (ii) Moments  (iii) Shear loads

Threaded members are NOT meant to resist (i) – (iii)
Components
Anatomy of a bolted joint

- **l**
  - Grip

- **A_t**
  - Tensile stress area

- **A_d**
  - Major diameter area

- **l_t**
  - Threaded length in grip

- **l_d**
  - Unthreaded length in grip

- **d**
  - Major diameter (unthreaded)
Joint components: Clamped member

Things to consider with the clamped member:

1. Stone or lap the surface (increase stiffness)
2. Remove burs (increase joint stiffness)
3. Be sure flange surfaces are flat so bolt does not bend
Bolted joint components: Bolt

Rolled Threads

NEVER in shear or bending

- Stress concentrations at the root of the teeth
- Fatigue crack propagation!
- Exception: Shoulder bolts

Cut Threads

Keep threads clean & lubed to minimize losses

- ~50% power to bolt head friction
- ~40% power to thread friction
- ~10% power to deforming the bolt and flange

Steel is most common
Bolted joint components: Washers

Purpose of Washers:

- Spacer
- Distribute load in clamped member
- Reduce head-member wear
- Lower coefficient of friction/losses
- Lock bolt into the joint (lock washer)
- Increase preload resolution (wave washer)
Threads plastically deform → Bolts are used once for precision applications
Stiffness
While preloading joint, are the flange & bolt “springs” in parallel or in series?

**Series:**
- Same Forces
- Different Displacements (stretches)

**Parallel:**
- Same Displacements (stretches)
- Different Forces

\[
\frac{F_{\text{preload}}}{K_{\text{flange}}} = \text{Flange Compression}
\]

\[
\frac{F_{\text{preload}}}{K_{\text{Bolt}}} = \text{Bolt Stretch}
\]
Preloaded joint modeled as series spring

Need to find equivalent bolt and member stiffness
Bolt stiffness

Shoulder bolt/cap screw consists of two different parts

- Threaded
- Unthreaded

Each has different

- Cross sectional area
- Axial stiffness

The load passes through both

- They act in series
- This is a series spring calculation

\[ k_b = \left( \frac{1}{k_t} + \frac{1}{k_d} \right)^{-1} = \frac{k_t k_d}{k_t + k_d} \]

The effective threaded grip length, \( l_t^* \), used in the stiffness calc is the sum of the threaded grip length plus three threads.

\[ k_d = \frac{A_d E}{l_d} \]

\[ k_t = \frac{A_t E}{l_t^*} \]
Member stiffness

Pressure cone exists in the member materials and bolt head

The clamping area at the member interfaces depends upon

- Washer diameter, \( d_w \)
- Half-apex angle, \( \alpha \)
- Bore clearance, \( d_h \)

Stiffness calculation by integration through the depth of the member

\[
A(z) = \pi \left[ \left( z \tan(\alpha) + \frac{d_w}{2} \right)^2 - \frac{d_h^2}{2} \right]
\]

\[
d\delta = \frac{P \, dz}{E \, A(z)}
\]

\[
k_m = \frac{\pi E d \tan(\alpha)}{\ln \left[ \frac{\left( d_w - d_h + 2t \tan(\alpha) \right) \left( d_w + d_h \right)}{\left( d_w + d_h + 2t \tan(\alpha) \right) \left( d_w - d_h \right)} \right]}
\]
Loading
Tensile loads in bolted joints

- $F_i$: Preload
- $P$: External tensile load
- $P_{b}$: Portion of $P$ taken by bolt
- $P_{m}$: Portion of $P$ taken by members
- $C$: Fraction of $P$ carried by bolt
- $1-C$: Fraction of $P$ carried by members
Forces in the bolt and the members

When loaded with a tensile force

- Most of the force is taken by the members
- Very little (<15%) of the force is taken by the bolt
- For most, this is counter intuitive…. 

\[
\begin{align*}
P & \quad (\text{b}) \\
\text{km} & \quad (\text{m}) \\
\text{kb} & \quad (\text{b})
\end{align*}
\]
Forces in the bolt and the members

So how much does each see?

- $P_m = \text{Portion of } P \text{ taken by members}$
- $P_b = \text{Portion of } P \text{ taken by bolt}$

$P = P_m + P_b$

$$P_b = \frac{k_b}{k_m + k_b} P = P \ C$$

$$P_m = P \ (1 - C)$$

$$\delta = \frac{P_b}{k_b} = \frac{P_m}{k_m}$$

$$F_b = P_b + F_i$$

$$F_m = P_m - F_i$$

High preload = High load capacity

$$F_b = CP + F_i$$

$$F_m = (1 - C)P - F_i$$

What happens when joint separates?
Static load capacity

Typically the bolt fails first, why?
- It is the least expensive
- It is the most easily replaced

Proof load and stress
- \( S_p = \text{proof stress} = \text{Limiting value of } \sigma_b \approx 0.85 \sigma_y \)

Load factor (like a factor of safety)
- \( n > 1 \) ensures \( \sigma_b < S_p \)

How high should the pre-load be?
- Non-permanent: Some suggest \( 0.75 F_p \)
- Permanent: Some suggest \( 0.90 F_p \)

\[
\sigma_b = \frac{CP}{A_t} + \frac{F_i}{A_t}
\]

\[
C \frac{n \cdot P}{A_t} + \frac{F_i}{A_t} = S_p
\]

\[
n = \frac{S_p A_t - F_i}{C P}
\]
Shear resistance

When joint is in shear

- Friction between the members takes the load, not the bolt
- Coefficient of friction and preload are the important properties
- Dowel pins or shoulder bolts should be used to resist shear

\[ P = \mu_s F_i \]
Torque,
friction,
preload
Threaded mechanisms: Geometry

\[ \text{Force}_{\text{exert}} \]

\[ s \]

\[ x \]

\[ \theta \]

Lead
How to measure

- Via stretch = but impractical
- Via strain = expensive built-in bolt sensor
- Via torque = not “ultra-repeatable” but easy and most often used

Relationship between Torque and Stretch?

\[ E_{\text{Torque}} = E_{\text{friction}} + E_{\text{stretch}} \]

How much do you torque the bolt when tightening?

- Too little = weak, compliant joint
- Too much = bolt may break or the joint may bulge
- Usually torque the bolt until Proof Load is reached

Continuous tightening is important: \( \mu_s > \mu_k \)
Threaded mechanisms: Modeling

From energy balance for our control volume:

\[ \Sigma E_{in} = \left[ \Sigma E_{out} \right] + \Sigma E_{stored} \quad \rightarrow \quad E_{applied} = \left[ E_{exert} + E_{loss} \right] + E_{bolt} + E_{member} \]

Energy in via work by applied Torque:

\[ E_{applied} = \int_{\theta_{initial}}^{\theta_{final}} T_{applied}(\theta) \cdot d\theta \]

Energy out via work done by exerted Force:

\[ E_{exert} = \int_{\chi_{initial}}^{\chi_{final}} F_{exert}(\chi) \cdot d\chi \]

Energy loss due to friction Torque:

\[ E_{loss} = \int_{\theta_{initial}}^{\theta_{final}} T_{friction}(\dot{\theta}) \cdot d\dot{\theta} \]

Energy stored in stretched "cylinder":

\[ E_{bolt} = \int_{0}^{\delta_{b}} F_{bolt} \cdot d\delta_{b} \]

Energy stored in member:

\[ E_{member} = \int_{0}^{\delta_{m}} F_{member} \cdot d\delta_{m} \]

From geometry: \( x = \left( \frac{\Delta \theta}{2\pi} \right) \text{lead} \)
Best practices
Best practices

Threads should be at least 1.5 D deep for bolt to reliably hold a load.
Wave washers can reduce tightening sensitivity to achieve desired preload.

Applications: Gasket / roller bearings