2.72 Elements of Mechanical Design
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Elements of Mechanical Design

Lecture 10: Bolted joints
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

**Bolts 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)
Bolted Joint Components: Nut

Threads do not distribute the load evenly:
1. First thread has the shortest load path (stiffest)
2. The pitch of the bolt threads and nut threads change as they are loaded

What can be done to distribute the load better:
1. Use a softer nut material
2. Use a bolt and nut that have different pitch values to begin with
3. Use a special nut that lengthens the load path of the first thread

Bolts are used once for precision applications

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

\[
\begin{align*}
k_d &= \frac{A_d E}{l_d} \\
k_t &= \frac{A_t E}{l_t^*}
\end{align*}
\]

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

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

$$d\delta = \frac{P \ dz}{E \ A(z)}$$

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

$$k_m = \frac{\pi Ed \tan(\alpha)}{\ln \left[ \frac{(d_w - d_h + 2t \tan(\alpha))(d_w + d_h)}{(d_w + d_h + 2t \tan(\alpha))(d_w - d_h)} \right]}$$
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….
Forces in the bolt and the members

So how much does each see?

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

$$P = P_m + P_b$$

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

$$P_b = \frac{k_b}{k_m + k_b} P = P \left(1 - C\right)$$

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

$$F_b = P_b + F_i$$

$$F_m = P_m - F_i$$

What happens when joint separates?

High preload = High load capacity

$$F_b = CP + F_i$$

$$F_m = \left(1 - C\right)P - F_i$$

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Static load capacity

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

Proof load and stress
- $S_p =$ proof stress = Limiting value of $\sigma_b$ ($\sim 0.85 \sigma_y$)

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 $F_p$
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
Bolt torque and preload

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: \[ \mu_s > \mu_k \]
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.
Exercise
Group exercise

The tool holder stiffness is critical to lathe accuracy.

Calculate the stiffness of the bolted joint between your tool holder and cross slide bearing.

How does the relative stiffness of this compare with the stiffness of other parts in the load path?

- Structure
- Bearings
- Rails
- Etc…
How do you prevent bolts from coming loose?
1. Use the joint in a low vibration environment
2. Use bolts with fine threads (small pitch)
3. Use a large preload
4. Use materials with high coefficients of friction
5. Use Loctite on the threads
6. Use an adhesive between the bolt head and flange
7. Use lock washers

$F = \mu_s^* N$
Applications: Bearing Rails

Tighten bolts sequentially

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Applications: Bearing Rails

Objectives:
- Maximize stiffness
- Decrease manufacturing cost
- Maximize accuracy

Accuracy is maximized by overlapping strain cones.
Therefore, the thicker the rail, the few bolts are necessary.
But the rail becomes less stiff.

Same stiffness

Beware of bulging

High manufacturing cost

Bolt spacing should be about 4x the bolt diameter