2.72 Elements of Mechanical Design
Spring 2009

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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

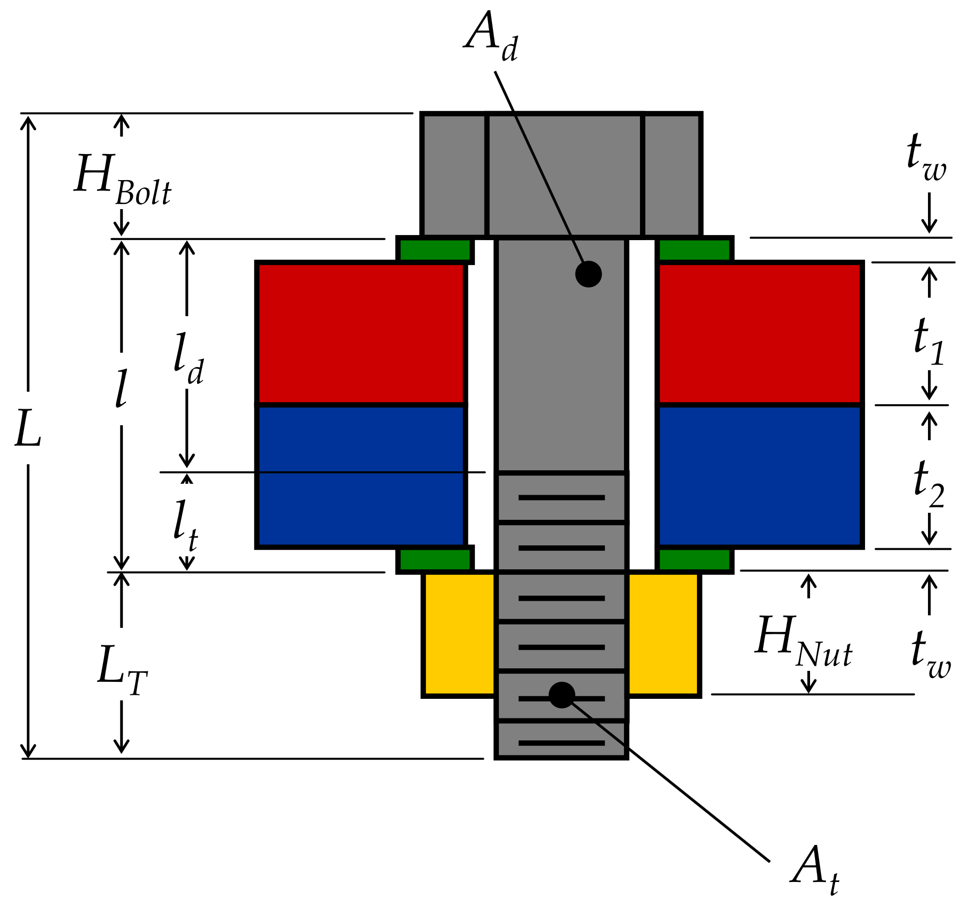
- Threaded length in grip

l_d

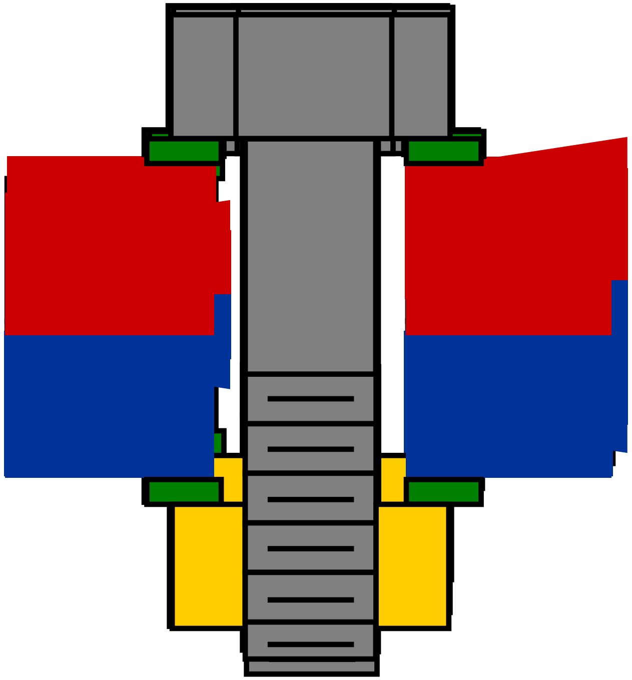
- Unthreaded length in grip

d

- Major diameter (unthreaded)

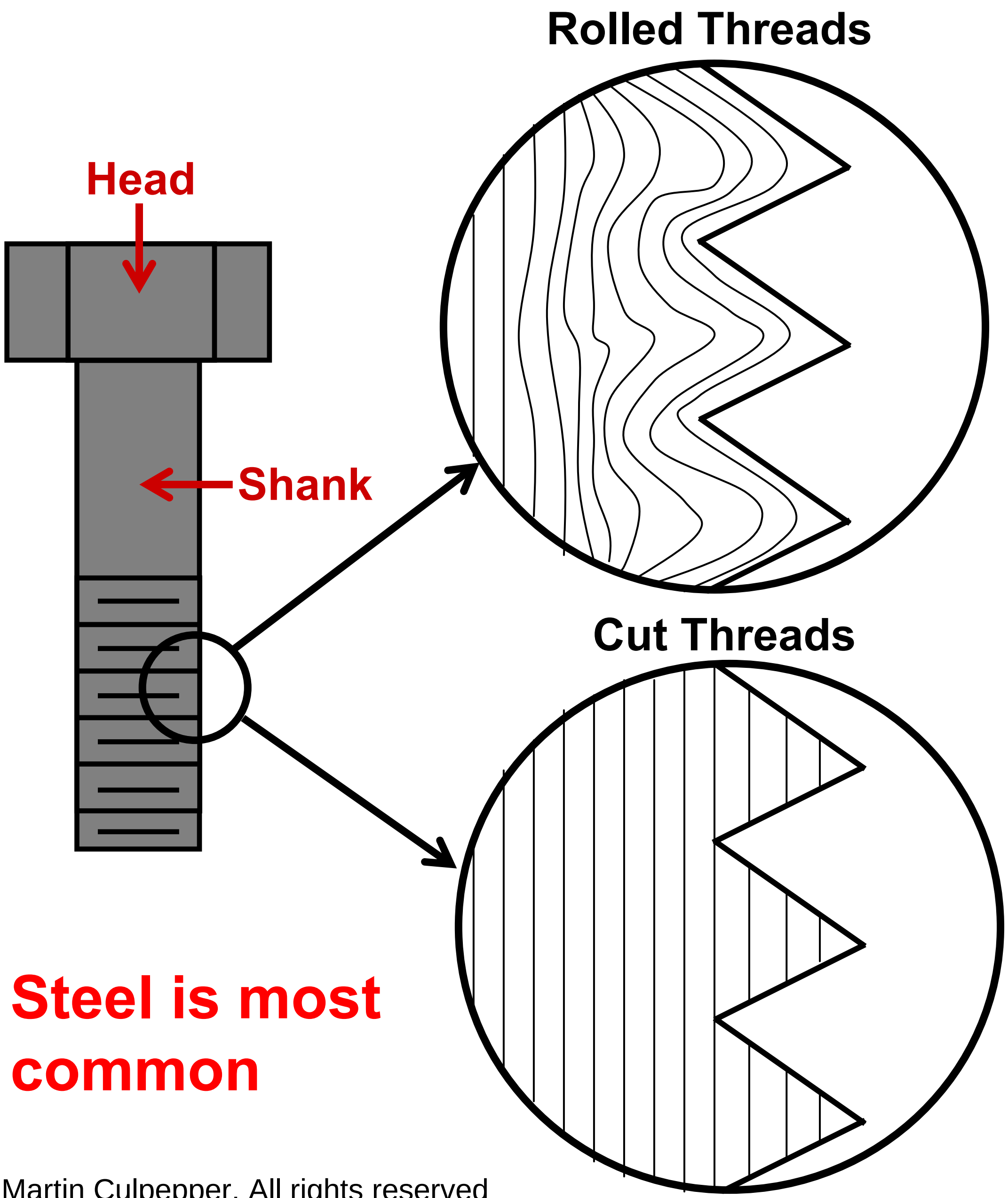


Joint components: Clamped member



Things to consider with the clamped member:

Bolted joint components: Bolt



Steel is most common

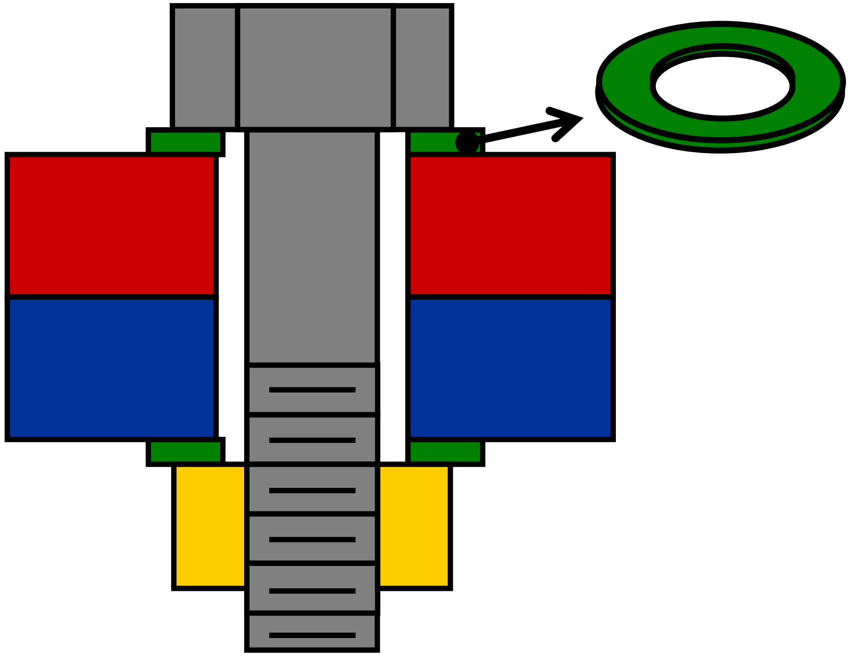
NEVER in shear or bending

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

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

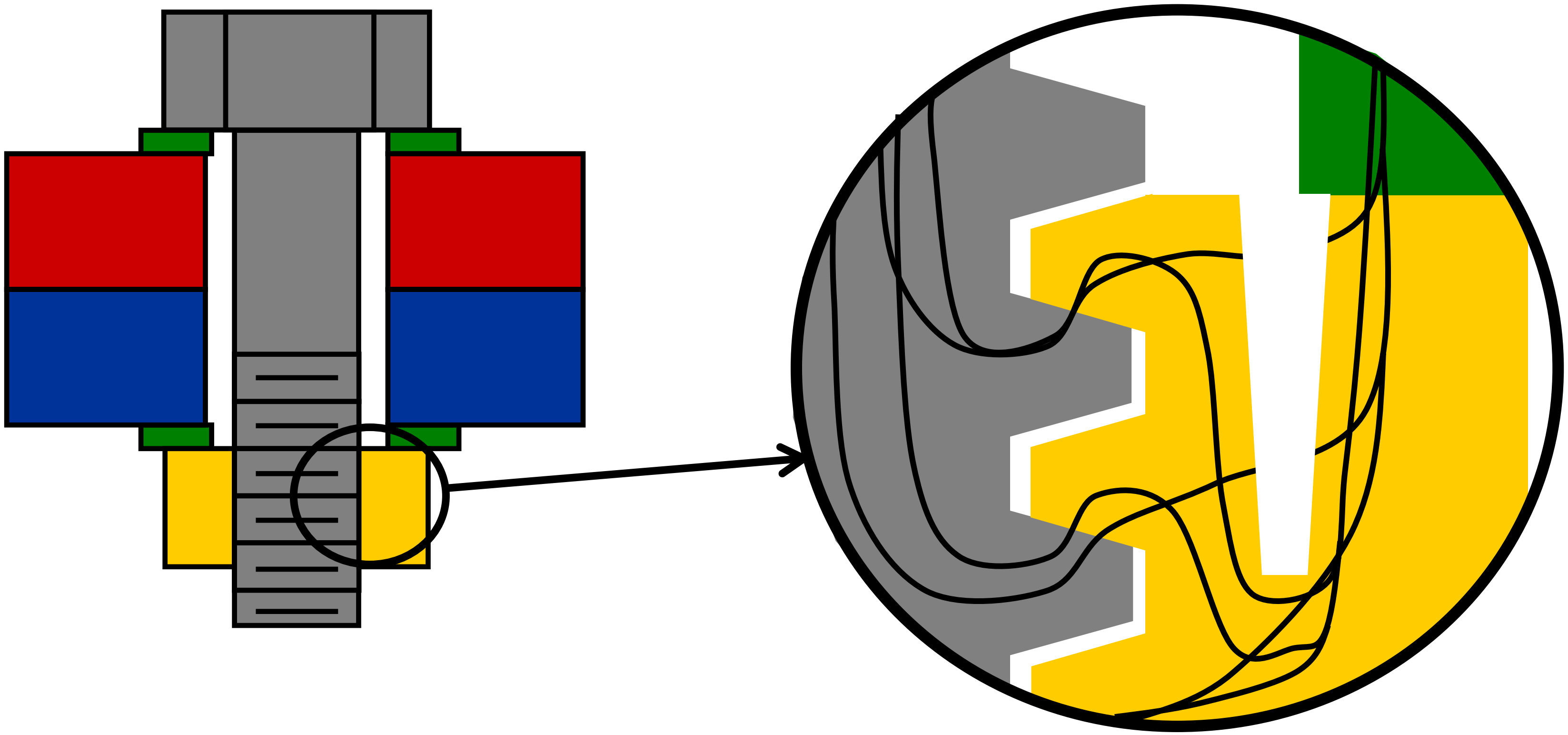
Bolted joint components: Washers



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

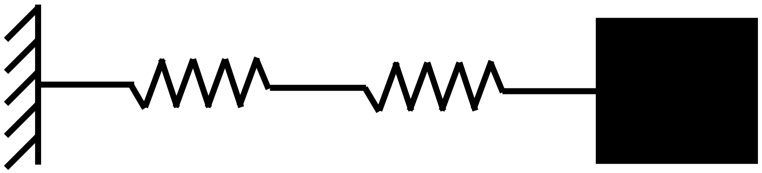


Threads plastically deform ⟶ Bolts are used once for precision applications

Stiffness

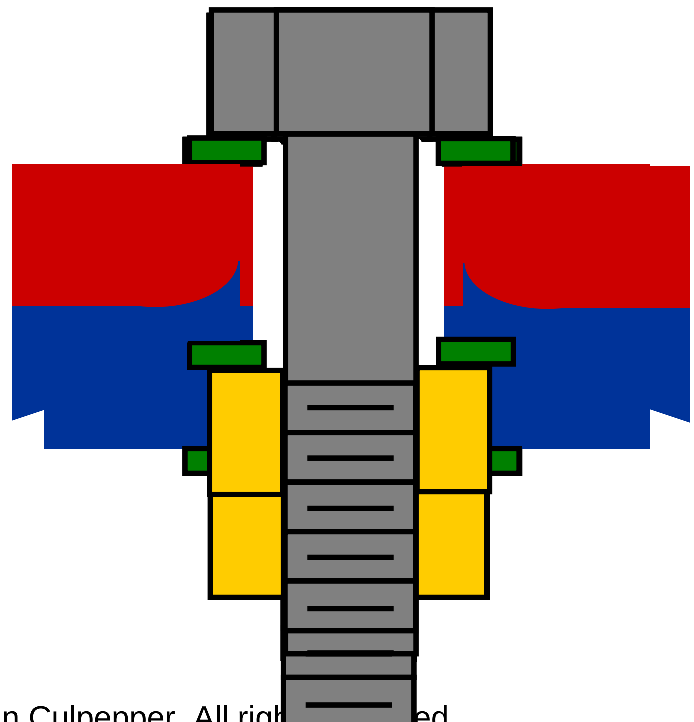
Preload

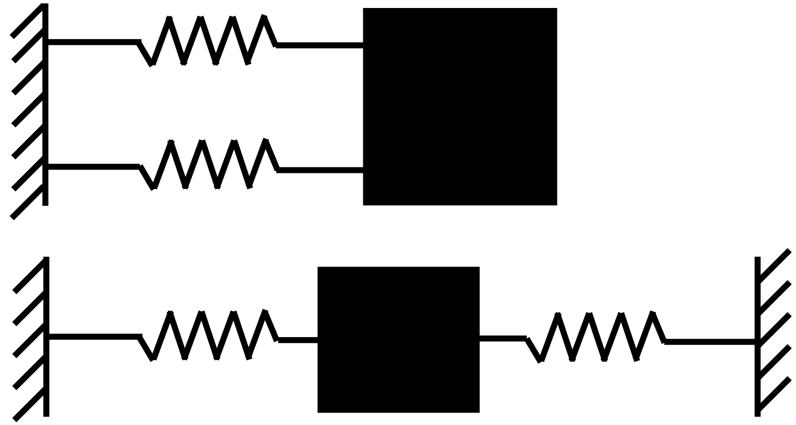
While preloading joint, are the flange & bolt "springs" in parallel or in series?



Series:

- Same Forces
- Different Displacements (stretches)





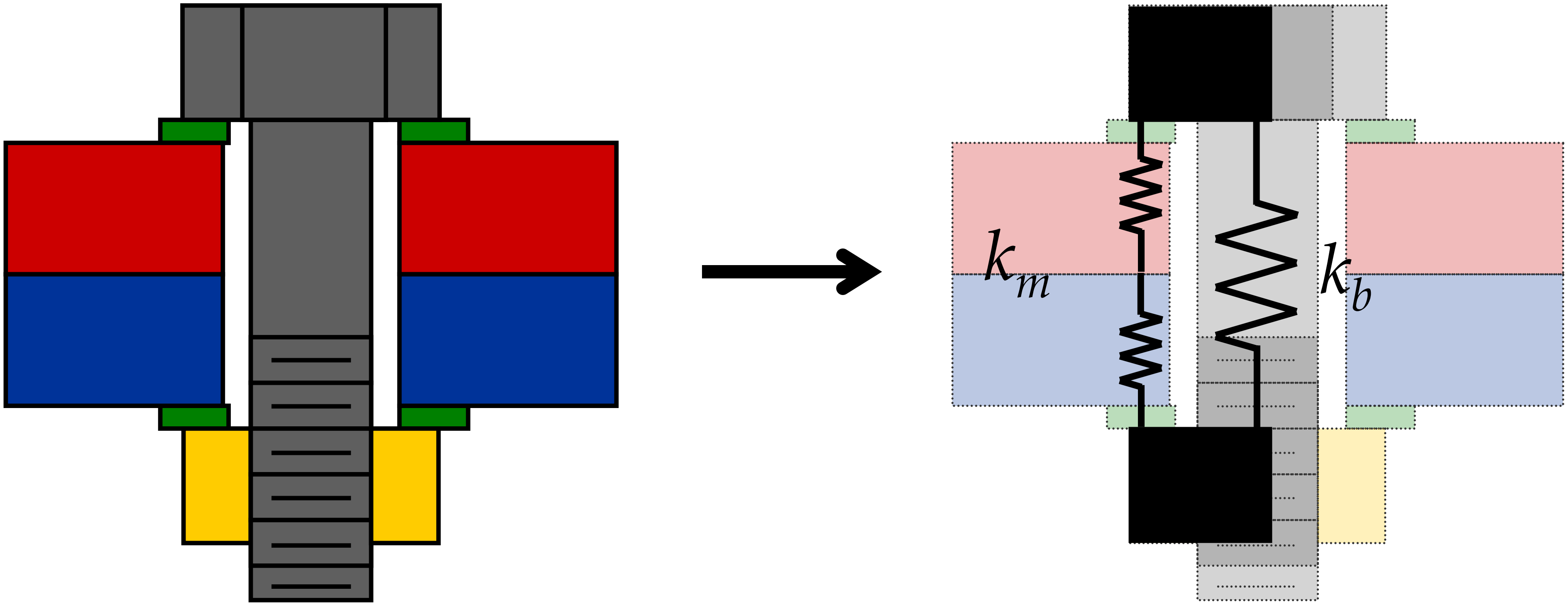
Parallel:

- Same Displacements (stretches)
- Different Forces

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

$$\frac{F_{preload}}{K_{Bolt}} = \text{Bolt Stretch}$$

Preloaded joint modeled as series spring

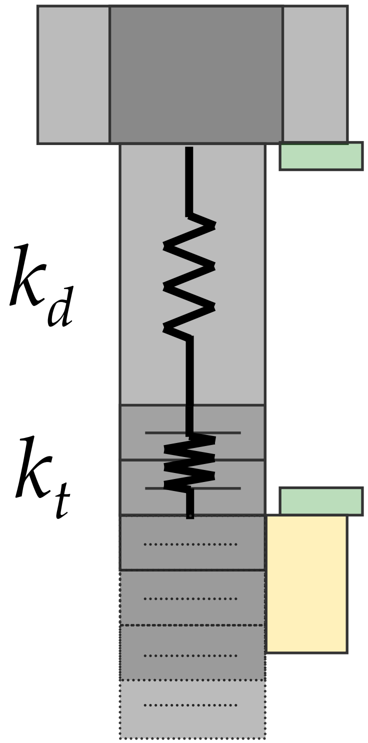


Need to find equivalent bolt and member stiffness

Bolt stiffness

$$k_d = \frac{A_d\ E}{l_d}$$

$$k_t = \frac{A_t\ E}{l_t^*}$$



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

Shoulder bolt/cap screw consists of two different parts

- ❑ Threaded
- ❑ Unthreaded

Each has different

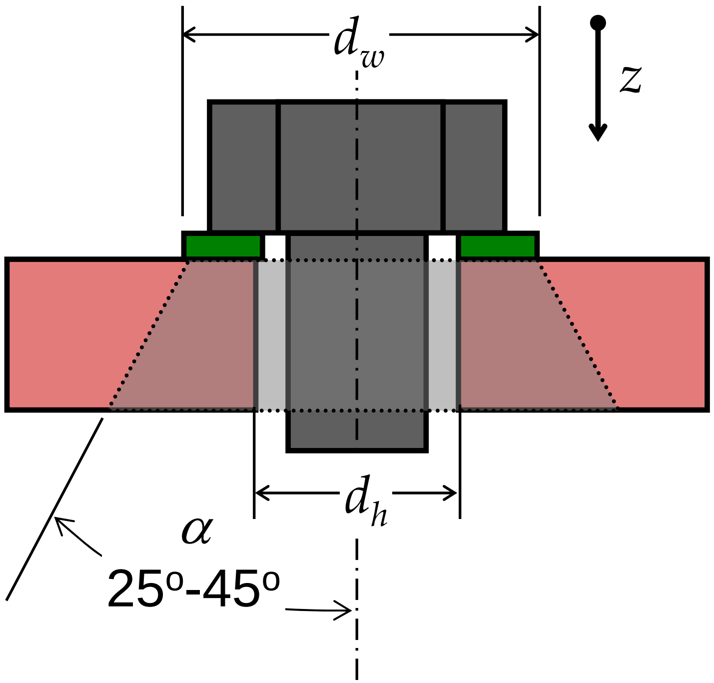
- ❑ Cross sectional area
- ❑ Axial stiffness

The load passes through both

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

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

Member stiffness



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

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

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, α
- Bore clearance, d_h

Stiffness calculation by integration through the depth of the member

$$k_m = \frac{\pi E d\tan(\alpha)}{\ln\left[\frac{(d_w - d_h + 2t\tan(\alpha))(d_w + d_h)}{(d_w + d_h + 2t\tan(\alpha))(d_w - d_h)}\right]}$$

Loading

Tensile loads in bolted joints

F_i

- Preload

P

- External tensile load

P_b

- Portion of P taken by bolt

P_m

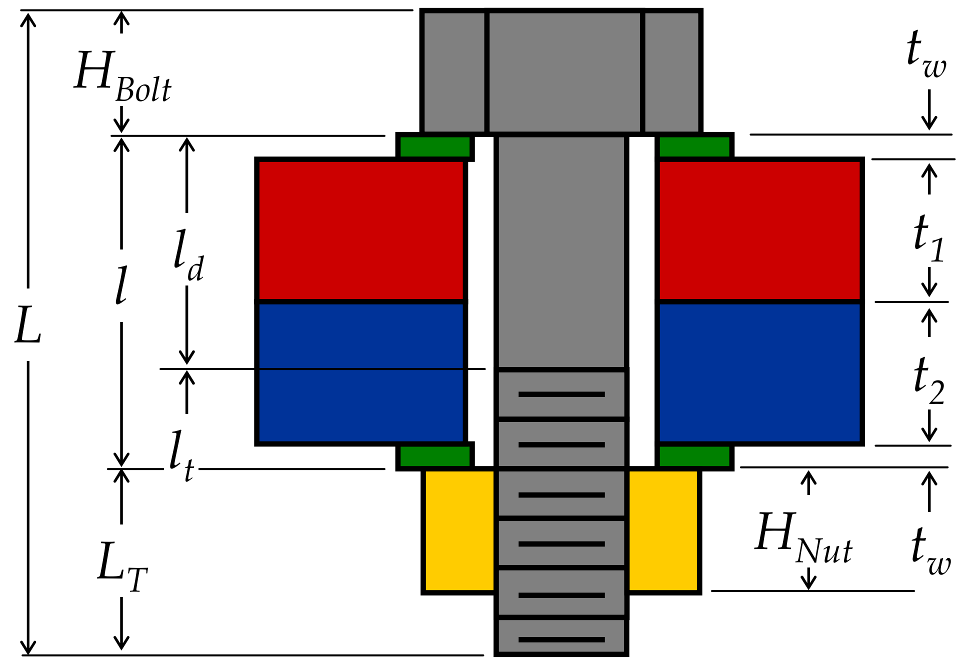
- Portion of P taken by members

C

- Fraction of P carried by bolt

1-C

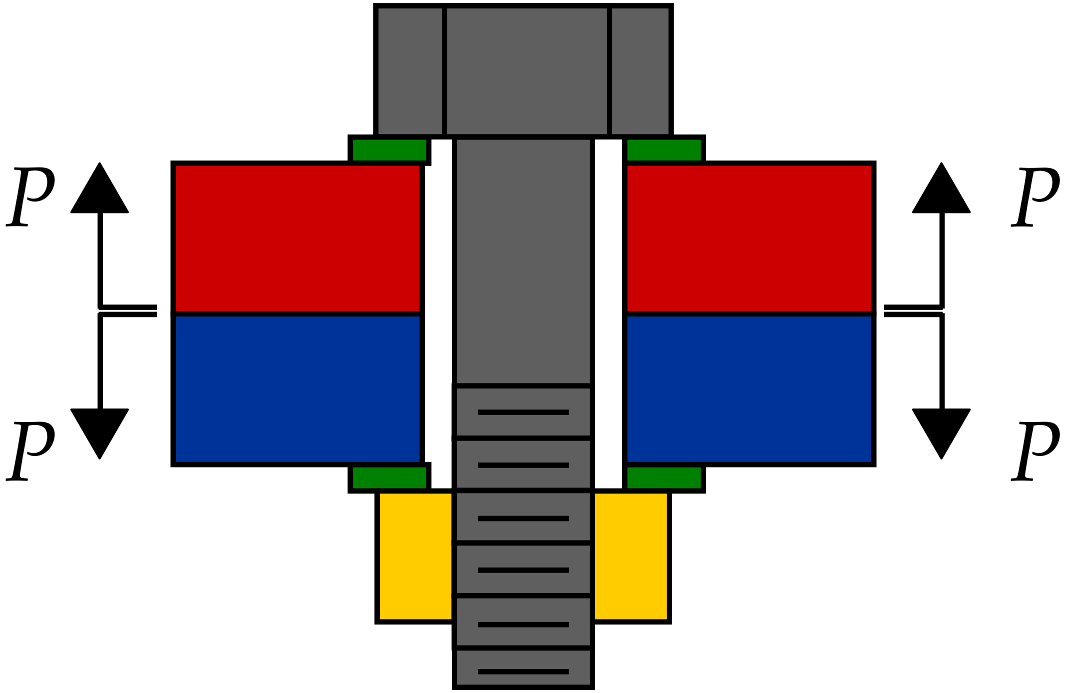
- Fraction of P carried by members

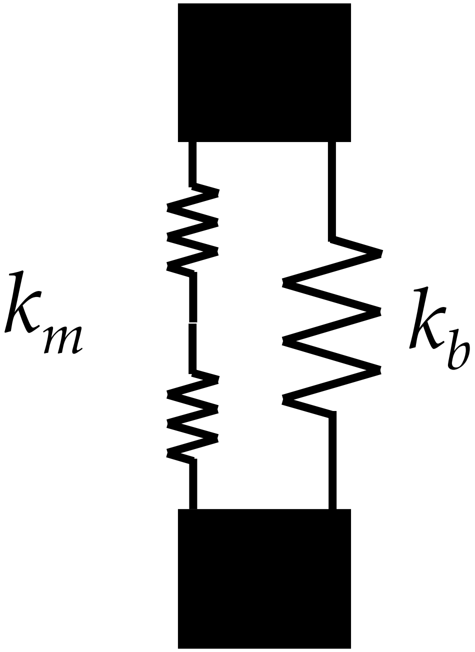


Forces in the bolt and the members

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….



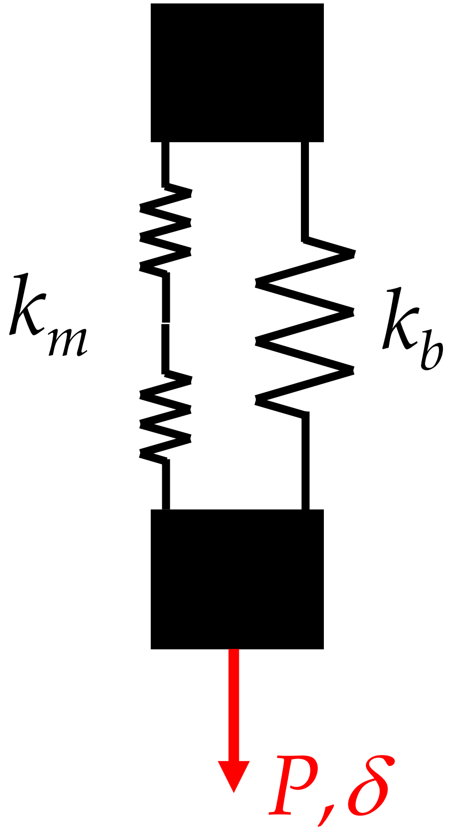


Forces in the bolt and the members

So how much does each see?

- P_m = Portion of P taken by members
- P_b = Portion of P taken by bolt

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



$$P = P_m + P_b$$

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

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

$$F_b = P_b + F_i$$

$$F_m = P_m - F_i$$

High preload = High load capacity

$$F_b = CP + F_i \qquad F_m = \left(1 - C\right)P - F_i$$

What happens when joint separates?

Static load capacity

Typically the bolt fails first, why?

$$\sigma_b = \frac{CP}{A_t} + \frac{F_i}{A_t}$$

- It is the least expensive
- It is the most easily replaced

Proof load and stress

$$\frac{C\ n\ P}{A_t} + \frac{F_i}{A_t} = S_p$$

- S_p = proof stress = Limiting value of σ_b (~ 0.85 σ_y)

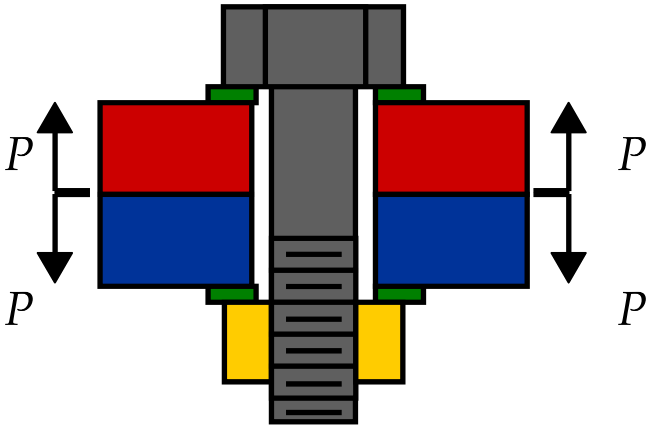
Load factor (like a factor of safety)

$$n = \frac{S_p\ A_t - F_i}{C\ P}$$

- n > 1 ensures $\sigma_b < S_p$

How high should the pre-load be?

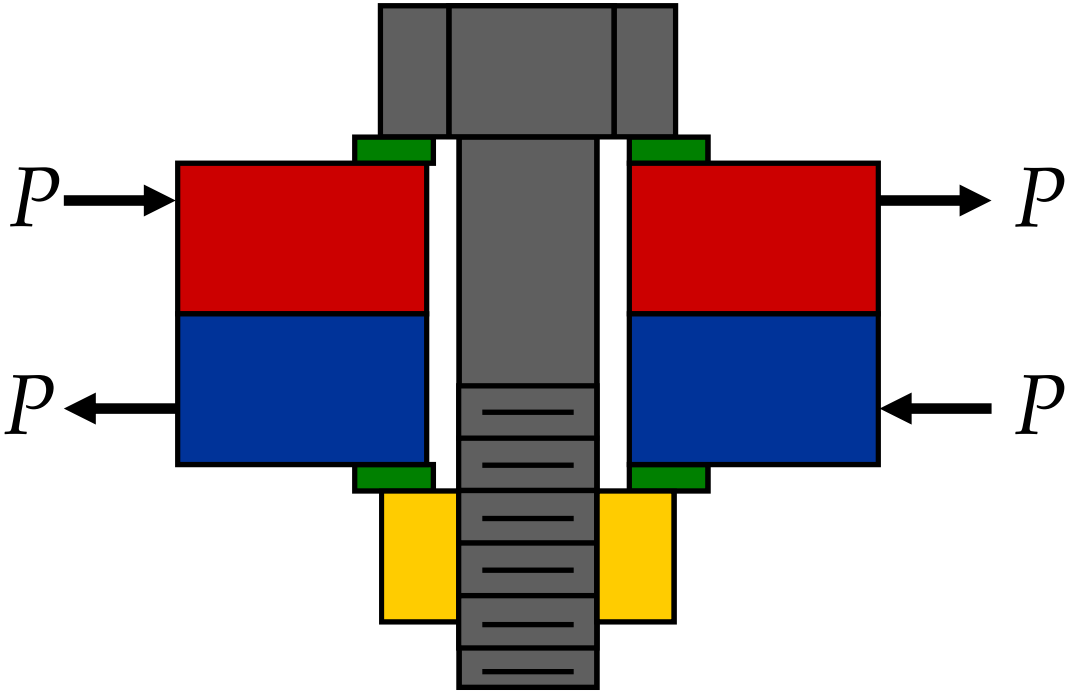
- Non-permanent: Some suggest 0.75 F_p
- Permanent: Some suggest 0.90 F_p



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?

$$E_{Torque} = E_{friction} + E_{stretch}$$

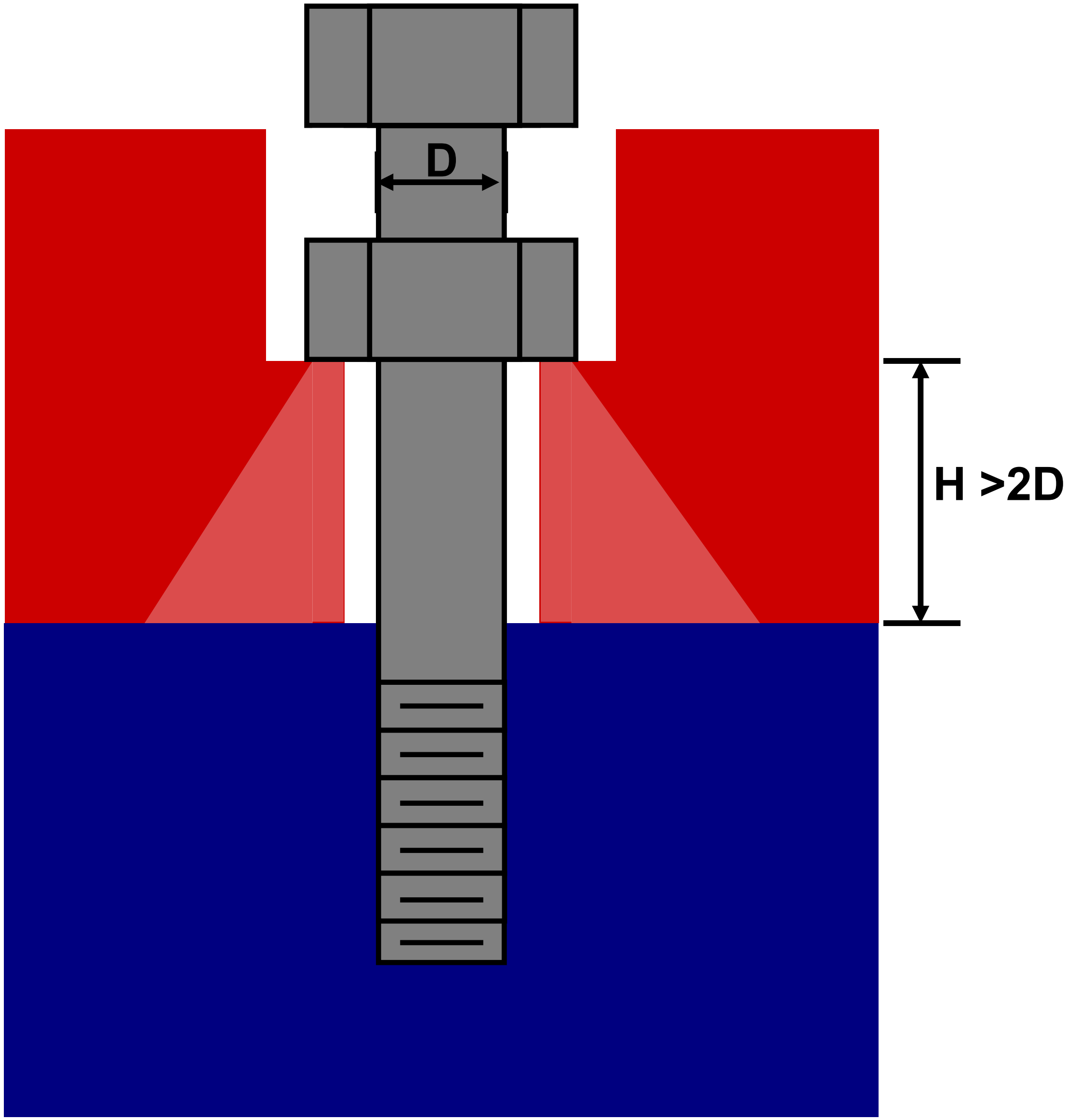
How much do you torque the bolt when tightening?

- 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

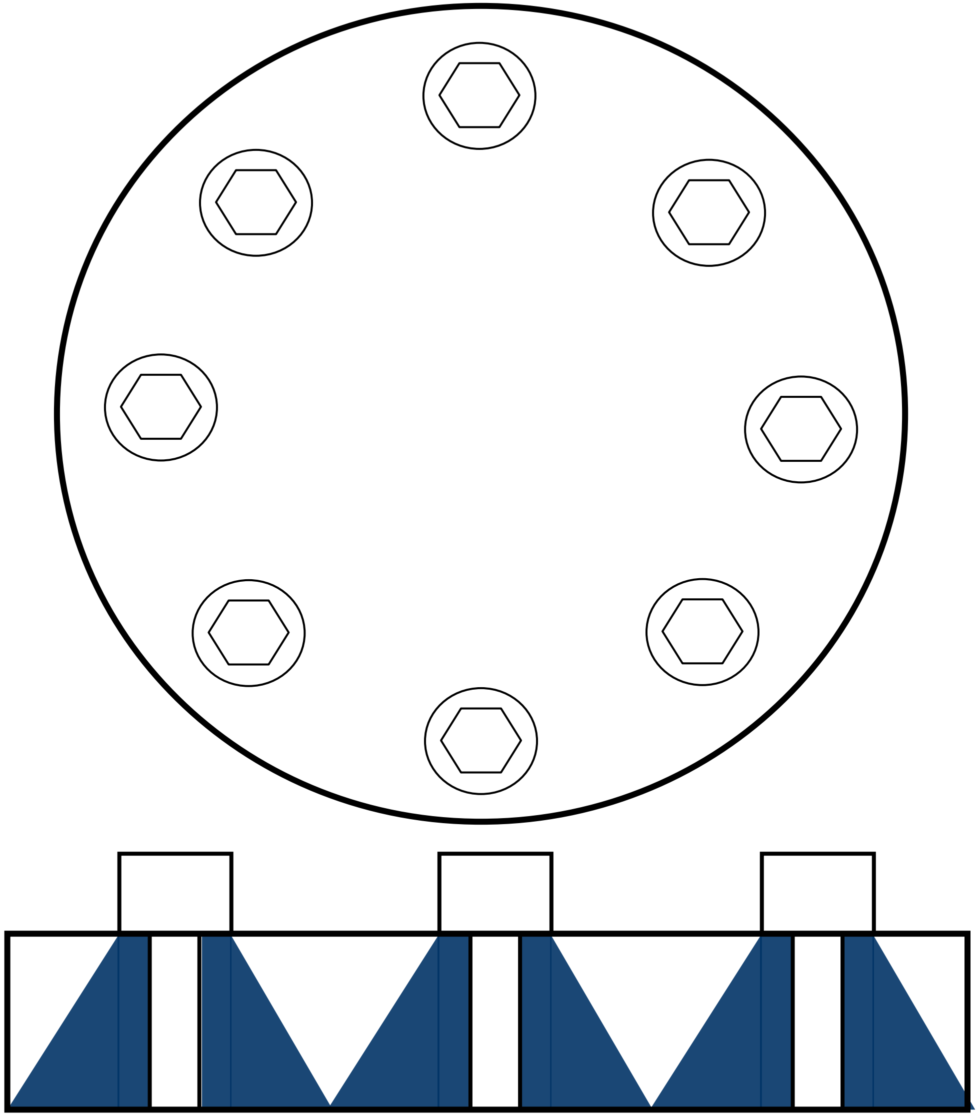
Best practices



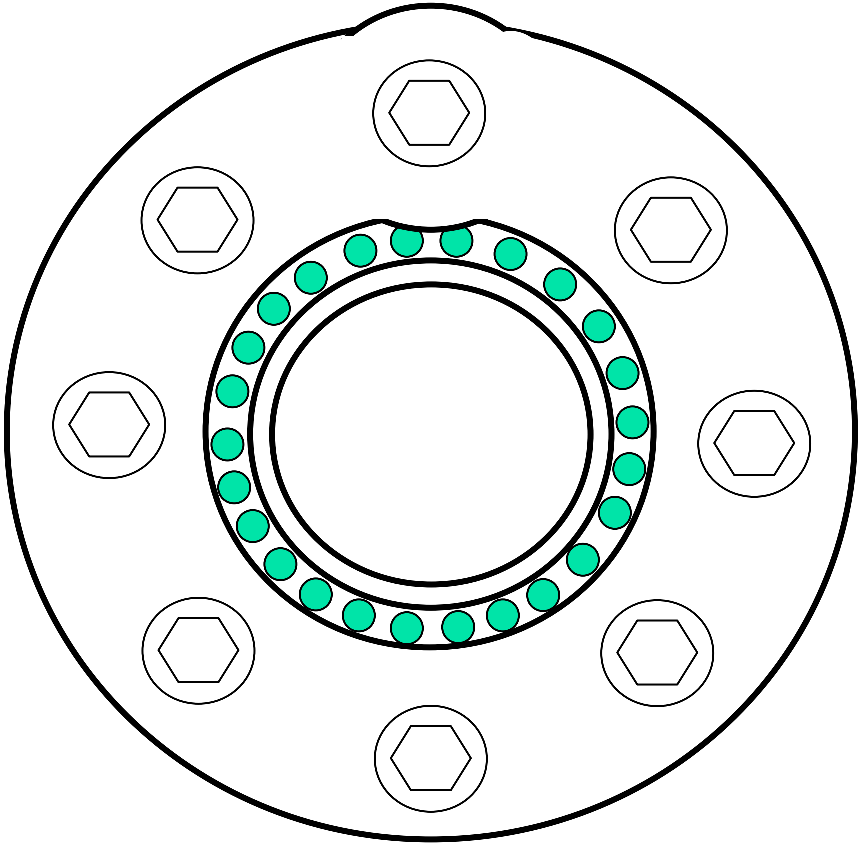
Threads should be at least 1.5 D deep for bolt to reliably hold a load

Applications: Gasket / roller bearings

Gasket



Roller Bearings



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.

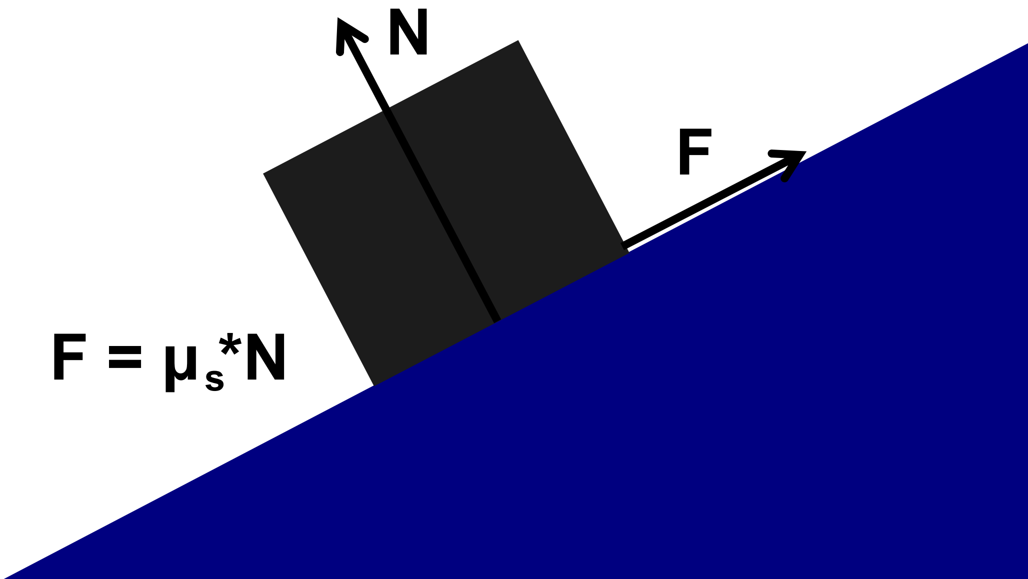
How does the relative stiffness of this compare with the stiffness of other parts in the load path?

- Structure
- Bearings
- Rails
- Etc…

Preventing Bolts from Coming Loose

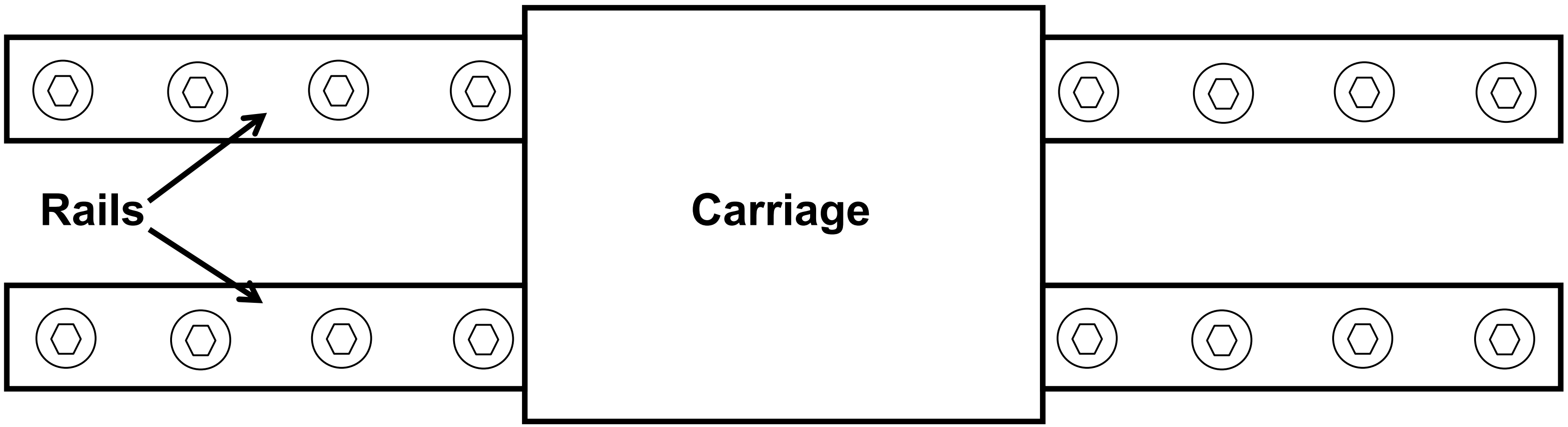
How do you prevent bolts from coming loose?

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**

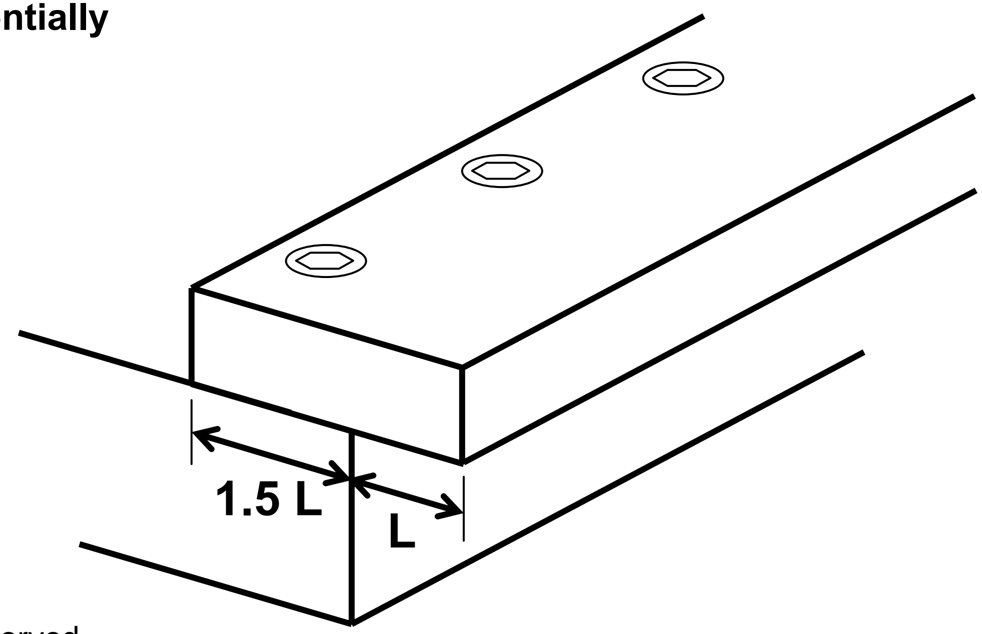


$F = \mu_s * N$

Applications: Bearing Rails



Tighten bolts sequentially



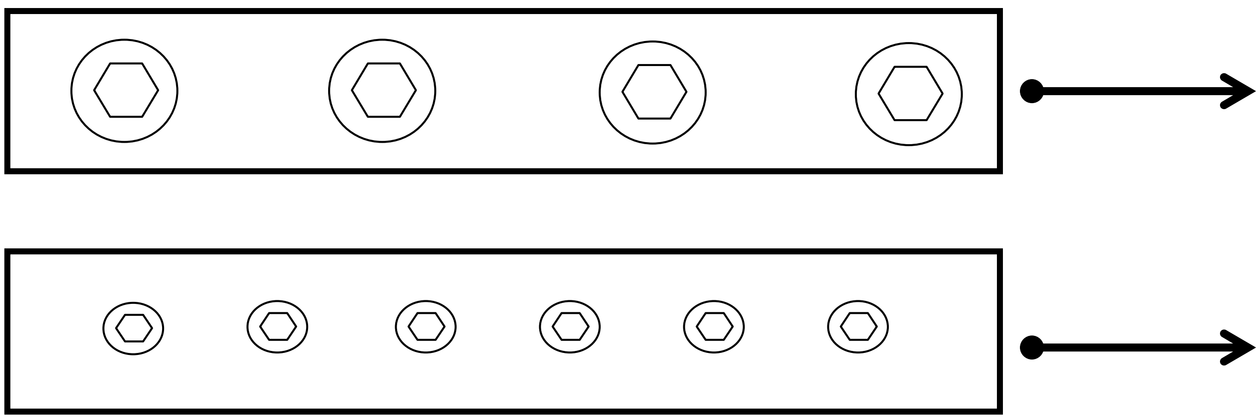
Applications: Bearing Rails

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