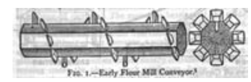
Chapter 14: Screws and Fasteners

Fastening (more complex shapes = better function)

- Non-permanent
  - Bolted
- Permanent
  - Bolted
  - Welded
  - Bonded

Screws



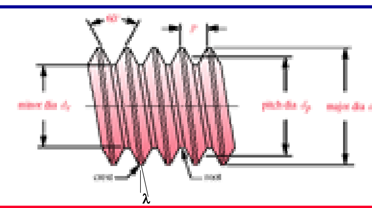
with several figures from:
MACHINE DESIGN - An Integrated Approach, 2ed by Robert L. Norton, Prentice-Hall 2000

Outline

- General Thread Nomenclature & Types
- Power Screws
- Stresses in Threads
- Preloading Fasteners/Joints
- Fasteners in Shear

Threads

Thread is a helix that casuses the screw to advance into the workpiece or nut when rotated



Single thread
L = p
Double thread
L = 2p

p	**pitch : the distance between adjacent threads**
d	**diameter (major)**
d_p	**pitch diameter**
d_r	**(root) minor diameter**
L	**Lead: the distance the nut moves parallel to the screw axis when the nut is given one turn.**
λ	**Lead angle: the angle defining the inclination of the thread.**

Screw Classifications

	Unified National Standard	ISO (Metric)
Thread Pitch	UNC –coarse UNF –fine UNEF –extra fine	coarse fine
Tolerance	Class 1 Class 2 Class 3	several levels

d=0.25" → ¼-20 UNF –2A
fine
Class 2
20 threads/in.
A: external
B: internal

metric → M12 x 1.75
d=12mm
p=1.75 mm

****see Tables 14-1 and 14-2 for standard sizes****

Table 14.2: Screw threads (ISO/ metric)
Example: M4 x 0.7, implies 4 mm diameter and 0.7 mm pitch

Table 14-2 Basic Dimensions of ISO Metric Screw Thr

Coarse Threads

Nominal Diameter d (mm)	Pitch p (mm)	Minor Diameter d_r (mm)	Stress Area A_t (mm²)
3	0.5	2.39	5.03
3.5	0.6	2.76	6.78
4	0.7	3.14	8.78
5	0.8	4.02	14.2
6	1	4.77	20.1
7	1	5.77	28.9

Types of Screw Fasteners

Classification by Intended Use

The same fastener may take on a different name when used in a particular manner.
For example, a bolt is a fastener with a head and straight threaded shank intended to be used with a nut to clamp an assembly together.
However, the same fastener is called machine screw or cap screw when it is threaded into a tapped hole rather than used with a nut.

A stud is a headless fastener, threaded on both ends and intended to semipermanently threaded into one-half of an assembly. A hole in the mating part then drops over the protruding stud and is secured with a nut.

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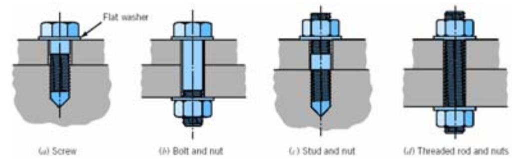
FIGURE 14-10

Types of Screw Fasteners



Types of Screw Fasteners

Classification by Thread Type

All fasteners intended to make their own hole or make their own threads are called tapping screws.

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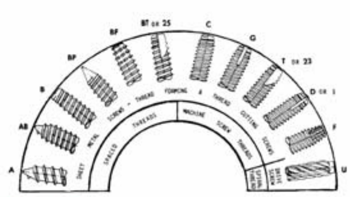

FIGURE 14-11
Various Styles of Threads Used on Tapping Screws Courtesy of Cordova Bolt Inc., Buena Park, Calif. 90621

Types of Screw Fasteners

Classification by Head Style

A) Slotted Screws: Head shape can be flat, round, oval, etc.
The head style can slotted or Phillips grooves.
We thread them into a hole using a screw driver.

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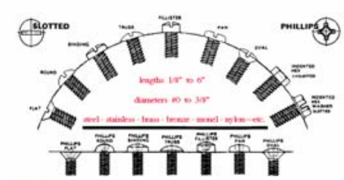

FIGURE 14-12
Various Styles of Heads Used on Small Machine Screws Courtesy of Cordova Bolt Inc., Buena Park, Calif.

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B) Socket-Head Cap Screws

These are extensively used in machinery.
The hex socket allows sufficient torque to be applied with hexagonal Allen wrenches

Allen wrench

FIGURE 14-13

Nuts and Washers

Castle nut is used with a pin to prevent loosening

Standard Nuts

FIGURE 14-15

Lock Nuts: eliminates loosening of nuts due to vibration

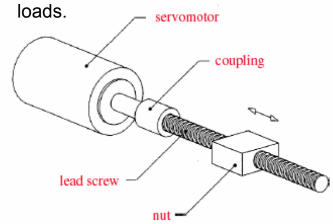
Lock Washers: eliminates loosening of standard nuts due to vibration

Outline

- General Thread Nomenclature & Types
- Power Screws
  - Threads
  - Loads
  - Self-locking
  - Efficiency
- Stresses in Threads
- Preloading Fasteners/Joints
- Fasteners in Shear

Power Screw

Power screws, also called lead screw, are used to convert rotation to linear motion in actuators, machine tools, clamps, and jacks. They can lift or move large loads.

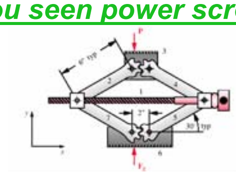


Servo-motor driven lead screw

Power Screw Applications

Where have you seen power screws?

jacks for cars



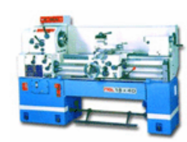
C-clamps

vises

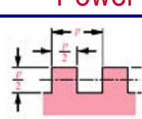
Where have you seen power screws?

Material testing machines

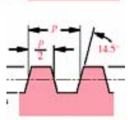
machine tools

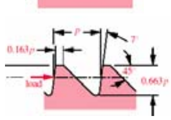


Power Screw Types



Square thread
$d_p = d - p/2$
$d_r = d - p$

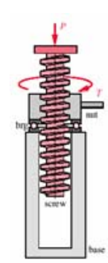


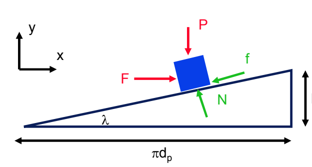


- Square
  - strongest
  - no radial load
  - hard to manufacture
- Acme
  - 29° included angle
  - easier to manufacture
  - common choice for loading in both directions
- Buttress
  - great strength
  - only unidirectional loading

Load Analysis

A screw thread is essentially an inclined plane that has been wrpapped around a cylinder to create helix.





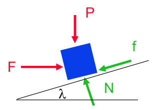
LIFTING

$$\tan\lambda = \frac{L}{\pi d_p}$$

Load Analysis

1) Sum of horizontal forces = 0

$$F - f\cos\lambda - N\sin\lambda = 0$$



2) Sum of vertical forces = 0

$$N\cos\lambda - f\sin\lambda - P = 0$$

From Eqs 1 and 2:

$$F = P\left[\frac{\mu\cos\lambda + \sin\lambda}{\cos\lambda - \mu\sin\lambda}\right]$$

Load Analysis

The screw torque (T_{su}) required to lift load is

$$T_{S_u} = F\frac{d_p}{2} = \frac{Pd_p}{2}\frac{(\mu\cos\lambda + \sin\lambda)}{(\cos\lambda - \mu\sin\lambda)}$$

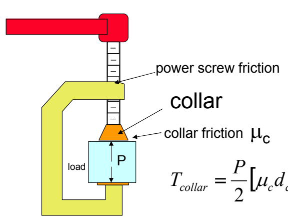
$$L = (\tan\lambda)(\pi d_p)$$

$$T_{S_u} = \frac{Pd_p}{2}\frac{(\mu\pi d_p + L)}{(\pi d_p - \mu L)}$$

Collar Torque

LIFTING

$$T_u = T_{S_u} + T_{collar} = \frac{P}{2}\left[d_p\frac{(\mu\pi d_p + L)}{(\pi d_p - \mu L)} + \mu_c d_c\right]$$

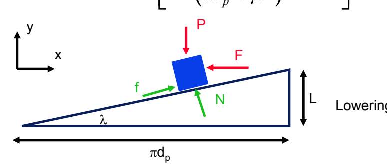


$$T_{collar} = \frac{P}{2}[\mu_c d_c]$$

Load Analysis

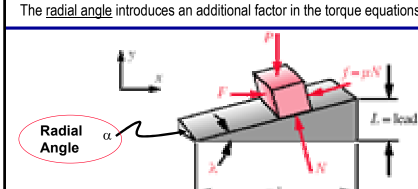
LOWERING

$$T_d = \frac{P}{2}\left[d_p\frac{(\mu\pi d_p - L)}{(\pi d_p + \mu L)} + \mu_c d_c\right]$$



For Acme Threads

The radial angle introduces an additional factor in the torque equations



LIFTING

$$T_u = T_{S_u} + T_{collar} = \frac{P}{2}\left[d_p\frac{(\mu\pi d_p + L\cos\alpha)}{(\pi d_p\cos\alpha - \mu L)} + \mu_c d_c\right]$$

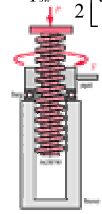
LOWERING

$$Td = \frac{P}{2}\left[d_p\frac{(\mu\pi d_p - L\cos\alpha)}{(\pi d_p\cos\alpha + \mu L)} + \mu_c d_c\right]$$

Self-Locking

Self-locking screw cannot be turned from applied load P. In other words, self-locking screw will hold the load in place <u>without any application of torque</u> (Tsu=0).

$$T_{su} = \frac{P}{2}\left[d_p\frac{(\mu\pi d_p - L\cos\alpha)}{(\pi d_p\cos\alpha + \mu L)}\right] = 0 \quad\Rightarrow\quad \mu\pi d_p - L\cos\alpha = 0$$



for self-locking:

$$\mu \ge \frac{L}{\pi d_p}\cos\alpha \quad or \quad \mu \ge \tan\lambda\cos\alpha$$

since $L = (\tan\lambda)(\pi d_p)$

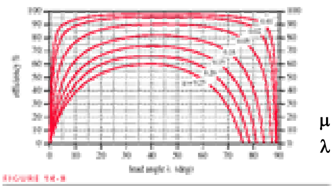
If it is a <u>square thread</u> (cos α = 1):

$$\mu \ge \frac{L}{\pi d_p} \quad or \quad \mu \ge \tan\lambda$$

Efficiency

e= work delivered by the screw in one revolution/ work done on a power screw

$$e = \frac{W_{out}}{W_{in}} = \frac{PL}{2\pi T} = \frac{\cos\alpha - \mu\tan\lambda}{\cos\alpha + \mu\cot\lambda}$$



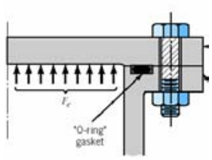
$\mu\downarrow \Rightarrow e\uparrow$

$\lambda\uparrow \Rightarrow e\uparrow$ **(0<λ<40 degrees)**

Outline

- General Thread Nomenclature & Types
- Power Screws
- Stresses in Threads
  - Body Stresses
    - Axial
    - Torsion
  - Thread Stresses
    - Bearing
    - Bending
  - Buckling
- Preloading Fasteners/Joints
- Fasteners in Shear

Fasteners: Static and Fatigue Analysis

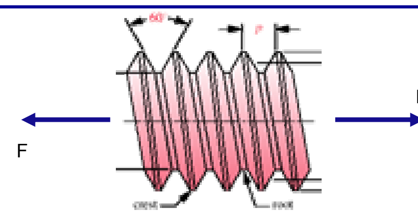


Static problem: Fixed pressure
- What size and material bolt to use?
- How much to tighten?

Fatigue problem: Varying pressure
- What size and material bolt to use?
- How much to tighten?
- Predict life in cycles

Possible failure locations:
- Threads
- Body
- Neck

Axial Tensile Stress



$$\sigma_t = \frac{F}{A_t} \qquad A_t = \frac{\pi}{4}\left(\frac{d_p}{2} + \frac{d_r}{2}\right)^2$$

A_t also in Tables 14-1 and 14-2

Torsional Stress

depends on friction at screw-nut interface

For screw and nut,
- if totally locked (rusted together), the screw experiences all of torque
- if frictionless, the screw experiences none of the torque

$$\tau = \frac{Tr}{J} = \frac{16T}{\pi d_r^3}$$

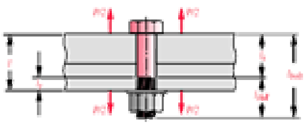
For power screw,
- if low collar friction, the screw experiences nearly all of torque
- if high collar friction, the nut experiences most of the torque

Outline

- General Thread Nomenclature & Types
- Power Screws
- Stresses in Threads
- Preloading Fasteners/Joints
  - Proof Strength
  - Spring Behavior
  - Loading & Deflection
  - Separation of Joints
- Fasteners in Shear

Preloading & Proof Strength

- Bolts and screws are typically preloaded and the proof strength is taken as the reference for preloading (taking yield strength as reference for preloading may cause a damage on the material): S_p is the stress at which bolt begins to take a permanent set and it is close to, but lower than yield strength of the material.



$$l = l_s + l_t$$

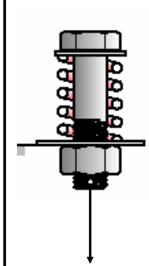
$$l_t = \begin{cases} 2d + 6\ mm & l \le 150 \\ 2d + 12\ mm & l > 150 \end{cases}$$

Preloading

- static loading: preload at roughly 90% of S_p
- dynamic loading: preload at roughly 75% of S_p

Spring Behavior

BOTH material being clamped and bolt behave as springs



$$k = \frac{AE}{l}$$

$$\sigma = E\varepsilon \qquad \frac{F}{A} = E\frac{\delta}{l} \qquad \delta = \frac{Fl}{AE} \qquad k = \frac{F}{\delta} = \frac{AE}{l}$$

for the bolt, threaded vs unthreaded have different spring constants and are modeled as springs in series:

threaded length; length of the untreaded shank

$$\frac{1}{k_b} = \frac{l_t}{A_t E_b} + \frac{l_s}{A_b E_b}$$

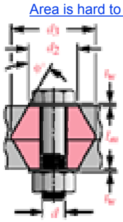
see Table 14-2 for A_t (tensile stress area)
use major diameter in calculating A_b

Affected Area of Material

For material, basic model is as follows:

$$\frac{1}{k_m} = \frac{l_m}{A_m E}$$

Area is hard to define… from experiments, the following is accurate:

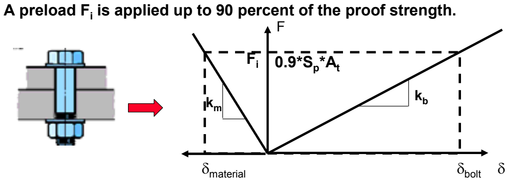


$$A_m \cong \frac{\pi}{4}\left[\left(\frac{d_2 + d_3}{2}\right)^2 - d^2\right]$$

See Figure 14-31 for the definition of parameters !

Loading & Deflection: Preloading

A preload F_i is applied up to 90 percent of the proof strength.



- **Slope of the bolt line is positive because its length increases with increased force.**
- **Slope of the material is negative as its length decreases with increasing force.**
- **Bolt streches more than the material compresses.**
- **Material is typically stiffer than the bolt ($k_m > k_b$ since $A_m >> A_b$)**

Preloading

- static loading: preload at roughly 90% of S_p

$F_i = 0.9*S_p*A_t$

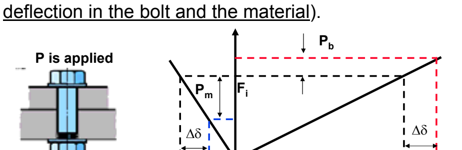
Proof strength depends on material.
See Table 14.7

Table 14-7 Metric Specifications and Strengths for Steel Bolts

Class Number	Size Range Outside Diameter (mm)	Minimum Proof Strength (MPa)	Minimum Yield Strength (MPa)	Minimum Tensile Strength (MPa)	Material
4.6	M5–M36	225	240	400	low or medium carbon
4.8	M1.6–M16	310	340	420	low or medium carbon
5.8	M5–M24	380	420	520	low or medium carbon
8.8	M3–M36	600	660	830	medium carbon, Q&T
9.8	M1.6–M16	650	720	900	medium carbon, Q&T
10.9	M5–M36	830	940	1 040	low-carbon martensite, Q&T
12.9	M1.6–M36	970	1 100	1 220	alloy, quenched & tempered

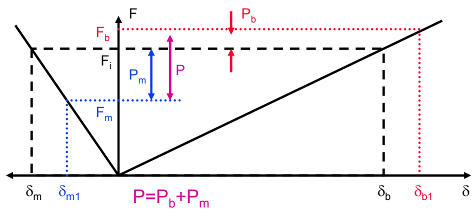
Loading & Deflection

An external load P is applied later, which results in additional deflection $\Delta\delta$ (same amount of deflection in the bolt and the material).



- **The external load P is split into two components:** one taken by the material (P_m) and one taken by the bolt (P_b). Material takes most of the applied load ($P_m > P_b$). However, if $P_m >= F_i$, the joint will separate.

Loading & Deflection



MATERIAL

$F_m=F_i-P_m$

BOLT

$F_b=F_i+P_b$

Distribution of Applied Load

$$\Delta\delta_b = \Delta\delta_m$$

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

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

$$P_b = CP, \quad where$$

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

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

Yielding Safety Factor

$F_m = F_i + P_m$
$F_b = F_i + P_b$ $\longrightarrow$ $F_m = F_i + P(C-1)$
$F_b = F_i + CP$

$$\downarrow$$

$$\sigma_b = \frac{F_b}{A_t}$$

$$\downarrow$$

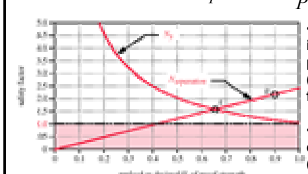
$$N_y = S_y/\sigma_b$$

Separation

Separation occurs when

$P_m - F_i >= 0$
$F_m <= 0$
$F_i + P(C-1) <= 0$ $\Rightarrow$ $P_0 = \frac{F_i}{1-C}$

$$N_{separation} = \frac{P_0}{P} = \frac{F_i}{(1-C)P}$$



- **The seperation safety factor increases linearly with increasing preload (i.e, tighting the bolt is good for reducing separation)**
- **The yielding safety factor decreases with inceasing preload (i.e. tighting the bolt too much increases the static failure)**

Dynamic Loading of Fasteners

- Bolt only absorbs small % of P
- Stresses
  - Bolt is in tension
  - Material is in compression
- Fatigue is a tensile failure phenomenon
- ∴ Preloading helps tremendously in fatigue

Dynamic Loading of Fasteners

P is a function of time, varying some P_{min} and maximum P_{max} values, both positive. A very common situation is that of a fluctuating load such as in a bolted pressure vessel that is cycled from zero (P_{min}=0) to maxiumum pressure.

For the general case (P_{min} > 0, P_{max} > 0)

$F_{bmax} = P_{bmax} + F_i$
$F_{bmin} = P_{bmin} + F_i$

$F_{bmean} = (F_{bmax} + F_{bmin})/2$
$F_{balt} = (F_{bmax} - F_{bmin})/2$

where,
$P_{bmax} = C\,P_{max}$
$P_{bmin} = C\,P_{min}$

Dynamic Loading of Fasteners

For the special case (P_{min} = 0, P_{max} > 0)

$P_{bmin} = 0$ (since $P_{min} = 0$)
$F_{bmin} = F_i$
$F_{balt} = P_{bmax} / 2 = (F_{bmax} - F_i) / 2$
$F_{bmean} = F_i + (P_{bmax} / 2) = (F_{bmax} + F_i) / 2$

$$\sigma_a = K_f \frac{F_{balt}}{A_t}$$

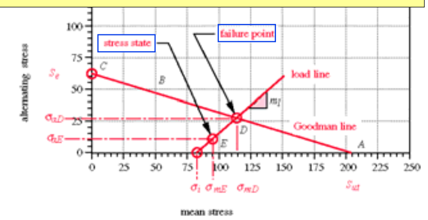
$$\sigma_m = K_{fm} \frac{F_{bmean}}{A_t}$$ Take K_{fm} = 1 for preloaded fasteners

$$\sigma_i = K_{fm} \frac{F_i}{A_t}$$

At : bolt's tensile stress area (Table 14-1, 14-2)
Kf : fatigue stress concentration factor (Table 14-8, pp. 910)
Kfm : mean fatigue stress concentration factor

Dynamic Loading of Fasteners: Goodman Diagram

$$N = \frac{\sigma_{altD}}{\sigma_{altE}} = \frac{(\sigma_{meanD} - \sigma_i)}{(\sigma_{meanE} - \sigma_i)} = \frac{S_e(S_{ut} - \sigma_i)}{S_e(\sigma_{meanE} - \sigma_i) + S_{ut}\sigma_{altE}}$$

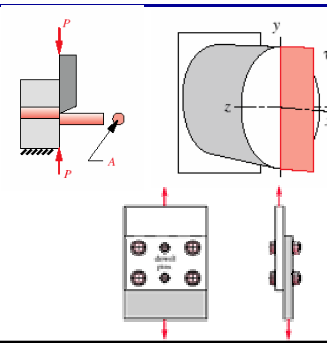


Modified-Goodman Diagram Showing Load Line and Data Needed for Safety-Factor Calculation of a Dynamically Loaded Fasteners

Outline

- General Thread Nomenclature & Types
- Power Screws
- Stresses in Threads
- Preloading Fasteners/Joints
- Fasteners in Shear
  - What is Shear?
  - Straight Direct Shear
  - Eccentric Shear

Direct Shear



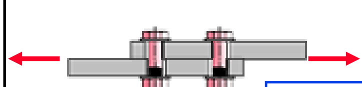
$$\tau = \frac{P}{A_{shear}}$$

Doweled Joints

"It is not considered good practice to use bolts or screws in shear to locate and support precision machine parts under shear loads"

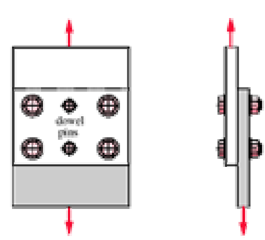
Norton

- Shear can be handled by friction caused by bolts… but, better practice is to use dowels
- Bolts need clearances… at best 2 out of a 4 bolt pattern will bear all of load



dowels support shear, but not tensile loads
bolts support tensile loads, but not shear

Direct Shear

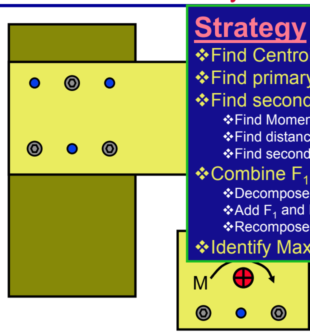


$$\tau = \frac{F}{A_{shear}}$$

$$N = \frac{Ssy}{\tau} = \frac{0.577 S_y}{\tau}$$

dowels support shear, but not tensile loads
bolts support tensile loads, but not shear

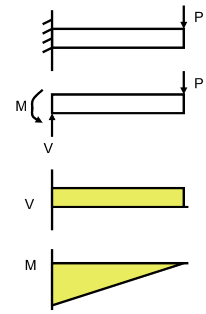
Eccentrically Loaded Shear

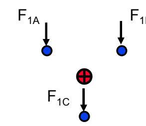


Strategy

- Find Centroid
- Find primary shear F_1
- Find secondary shear F_2
  - Find Moment about centroid
  - Find distances from centroid
  - Find secondary shear F_2 and angles
- Combine F_1 and F_2
  - Decompose to x and y
  - Add F_1 and F_2
  - Recompose into F_{net}
- Identify Max $F_{net,}$ find τ, safety factor

Primary Shear

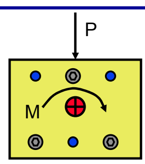




$$|F_1| = \frac{P}{n}$$

n – number of dowels

Moment/Secondary Shear



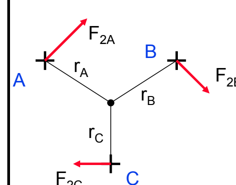
the moment will add further shear to the dowels, $\mathbf{F_2}$

the moment is centered around the center of gravity of the dowels

$$\bar{x} = \frac{A_1x_1 + A_2x_2 + A_3x_3}{A_1 + A_2 + A_3} = \frac{\sum_1^n A_i x_i}{\sum_1^n A_i}$$

$$\bar{y} = \frac{A_1y_1 + A_2y_2 + A_3y_3}{A_1 + A_2 + A_3} = \frac{\sum_1^n A_i y_i}{\sum_1^n A_i}$$

Finding Forces from Moment

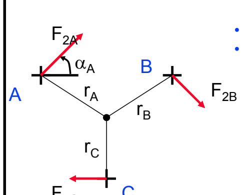


$M = F_{2A}r_A + F_{2B}r_B + F_{2C}r_C$

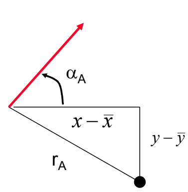
$$\frac{F_{2A}}{r_A} = \frac{F_{2B}}{r_B} = \frac{F_{2C}}{r_C}$$

$$F_{2i} = \frac{Mr_i}{r_A^2 + r_B^2 + r_C^2 + \cdots} = \frac{Mr_i}{\sum_1^n r_j^2}$$

Angles and Vectors

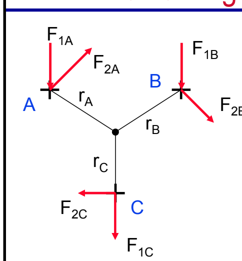


- Force is perpendicular to radial lines
- From known dimensions and trig, calculate α



$$\frac{y - \bar{y}}{x - \bar{x}} = \tan(90 - \alpha_A)$$

Remaining Steps



- Decompose F_{2i} into x and y components
- Add x and y components of F_{2i} to F_{1i}
- Recompose x and y components into $F_{net,i}$ and determine angle of F_{net}

Safety Factor

Calculate safety factor for most heavily loaded dowel

$$\tau = \frac{F}{A_{shear}}$$

$$N = \frac{Ssy}{\tau} = \frac{0.577 S_y}{\tau}$$

Strategy Review

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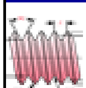
Outline Revisited




- General Thread Nomenclature & Types
- Power Screws
- Stresses in Threads
- Preloading Fasteners/Joints
- Fasteners in Shear