Structures & Materials 1A

Structural Design

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7.3.2017 IRF StM1 Structural Design 1

Aims & Objectives

Aim

to introduce the design of structural elements, joints and assembled structures.

Objective

At the end of this lecture series you should be able design structural elements, joints and assembled structures to a preliminary level.

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Contents

These notes are intended for teaching purposes - for your personal use only - and must not be copied or used for publication.

References

- **Niu** "Airframe Structural Design"
  Conmilit press, ISBN 962-7128-04-X
- **Bruhn** "Analysis & Design of Flight Vehicle Structures"
  Tri-State Offset Company
- Roark & Young "Formulas for Stress & Strain"
  McGraw-Hill, ISBN 0-07-100373-8

Terminology

- Limit
- Ultimate
- Allowable
- Reserve Factor

Courtesy of Airbus UK

Limit & Ultimate "Lim", "Ult"

Limit Load (N) - the maximum load anticipated in operation. It can be considered as the specification for the component. Normally any uncertainties in the loading will be included when establishing the limit load.

Ultimate Load = Limit Load x Ultimate factor of Safety
- the maximum loading the component must withstand without failure - although plastic deformation is permitted and the component may not be fit for further service after withstanding the ultimate load.

Ultimate Stress = Ult' load per unit area (N/mm^2: MPa)
- the stress in the material when the ult' load is applied

Limit & Ultimate

Ultimate Factor of Safety - (or Safety Factor) establishes a design load that makes allowance for uncertainties in design and load analysis

A typical Ultimate factor for aerospace applications is 1.5 although other factors may be used where greater uncertainty exists.

Allowable Stress

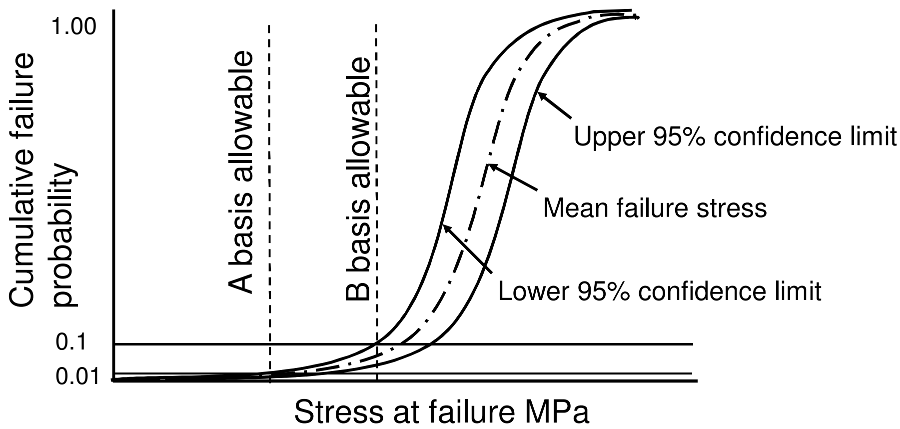
Allowable Stress - the stress that the material will carry with a specified probability of survival. (The loading conditions and environment must also be specified, e.g. fatigue loading, elevated temperature, contact with moisture, fuel, chemicals etc.).

Two standards are commonly used:

- The "A" basis allowable is the value above which at least 99% of the population of values is expected to fall, with a confidence of 95%.
- The ''B'' basis allowable is the value above which at least 90% of the population of values is expected to fall, with a confidence of 95%.

The "A" basis allowable represents a more stringent value and is used for primary (critical) structures, whereas the "B" basis allowable tends to be used for secondary structure.

Allowable values



Reserve Factor "RF"

Reserve Factor (RF) = comparison of Allowable Stress with Ultimate stress

$$\text{Ultimate RF} = \frac{\text{Allowable stress}}{\text{Ultimate stress}}$$

Where: Allowable stress = the statistically validated strength
Ultimate stress = the stress at ultimate load.

When reporting the RF in stress reports it is a traditional requirement to highlight the value by enclosing within a box placed on the right hand side of the sheet: e.g.: $\boxed{RF = 1.2}$

RF

The RF must never be less than 1.

High RF values - imply the component is over-designed. The general goal is therefore to keep all the RFs just greater than 1.

Where the method of calculating the design loads and resultant stresses is uncertain a higher factor of safety may be required for certain elements of the design **BUT** it is preferred to hold the safety factor constant and to aim for a higher RF value.

Stress report: All design decisions must be clearly recorded and assumptions laid out, calculations must be illustrated and RF's quoted for all critical components so that a third party can make an unambiguous assessment of the design's safety. This is usually done for the final design, based on the final most refined analysis methods.

Margin of safety

Alternative to Reserve factor

Whereas **Reserve factor**, RF $= \dfrac{\text{allowable stress}}{\text{ultimate stress}}$

Commonly Used in Europe

Margin of Safety, MoS $= \dfrac{\text{allowable stress} - \text{ultimate stress}}{\text{ultimate stress}}$

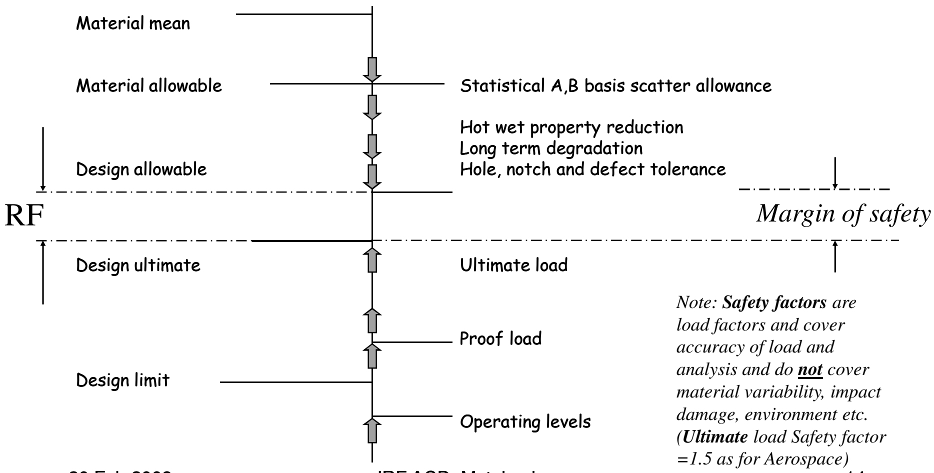
Commonly (used in USA)

MoS < 0 implies failure, MoS > 0 implies margin of safety

MoS $\equiv$ RF-1

Remember the allowable stress is the statistically validated strength and ultimate stress is the stress in the component at ultimate load

Design Allowables & limits



*Note: **Safety factors** are load factors and cover accuracy of load and analysis and do **not** cover material variability, impact damage, environment etc. (**Ultimate** load Safety factor =1.5 as for Aerospace)*

The Design Process

Stages		"**Concurrent design fields**"		
Define		Material,	Structure,	Manufacture
Scheme	*Initial*	~	~	~
Check	*Refined*	~	~	~
Trade-off		~	~	~

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Stages

- **Define** the structural problem in terms of geometric envelope, function, loading, environment, longevity …
- **Scheme** a qualitative trial scheme wrt:structure, materials & manufacture following guidelines, previous experience and engineering judgement.
- **Check** the trial scheme by modelling the structure quantitatively - the simpler the better to start off. Check stiffness, strength and stability. refine model and accuracy and iterate.
- **Trade off** checked trial schemes against fitness for purpose and select final scheme

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Typical Design Procedure

DEFINE
- Identify the greatest loads and allowable deflections
- Identify the way the loads are distributed through the structure. (FBD's and Part models)
- Identify the stresses generated locally by the distributed loads. (Section models)
- Identify the potential failure modes and the allowable material properties for those failure modes.

SCHEME
- Scheme a complete trial solution wrt materials, structure and manufacture
- Sketch out to scale, a rough design, e.g. using squared paper for preliminary sketches.

CHECK
- Perform Stress Analysis - apply appropriate formulae to check stiffness, strength & stability
- Calculate the Reserve Factors for each potential failure mode in the various parts of the structure.

ITERATE
- Modify the sketch
- Refine checks
- Repeat until satisfactory
- Try different schemes

TRADE-OFF
- Select scheme according to fitness for purpose.
- Prepare "proper" engineering drawings for manufacture: CAD!
- Produce a clear, concise and unambiguous stress report.
- Worry! Confidence causes accidents, worry prevents them. So go over your sums many times! "Check stress" departments independently check the design using independent methods.

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Formulas for stress and strain

- Simple formulas for stress, strain and deformation can be obtained from reference texts, e.g. Roark, Bruhn, etc. But for safe use:
- Make sure that you understand what the formula is about.
- Make sure that it really does apply to your particular case.
- Remember that these formulae may take no account of stress concentrations or other special local conditions
- Make sure that you use appropriate consistent dimensions
- Check if the answer feels right!

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Element design

Design of simple structural elements

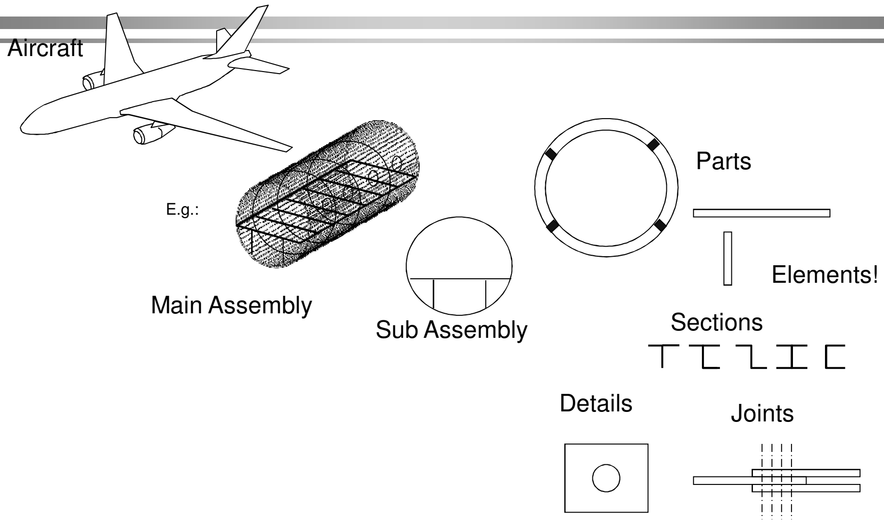
Courtesy BAe Ref: Cutler

Aim: to introduce the design of simple elements in aerospace structures, such as struts, beams and joints .

Learning objectives - Elements

- You should recognise the various types of structural element and the type of primary loading they must carry.
- You should be able to calculate the stiffness, strength and stability of the element.
- You should be able to design an elementary structure and produce stress and mass reports on that design
- You should understand the basics of inelastic response and non-linear behaviour in design.

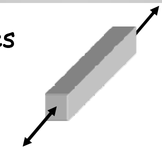
Structural Hierarchy



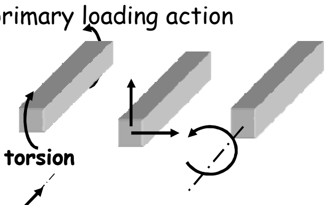
Structural elements

Structural elements can be defined in terms of their primary loading action

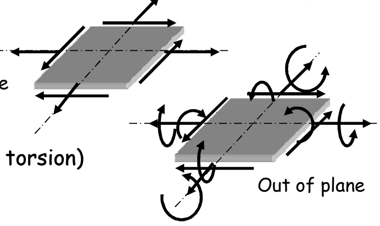
- Bars, rods, struts and ties
  - **Axial** loads only
    - Struts – compression
    - Ties - tension



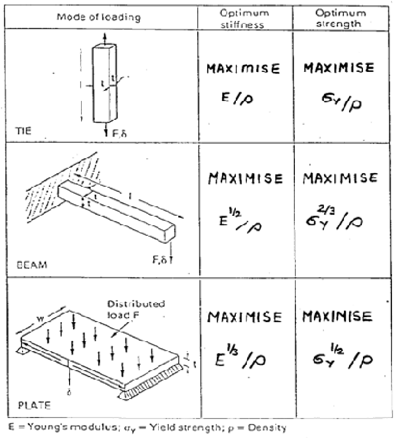
- Beams,shafts
  - Beams: Axial and transverse loads and **bending**
  - Shafts: Axial and transverse loads, bending, and **torsion**



- Membranes
  - Membranes: tension and shear loads
- Shells (Plates)
  - Tension and shear loads, bending and torsion)



Structural indexes



Mode of loading	Optimum stiffness	Optimum strength
TIE	MAXIMISE E/ρ	MAXIMISE σ_Y/ρ
BEAM	MAXIMISE $E^{1/2}/\rho$	MAXIMISE $\sigma_Y^{2/3}/\rho$
PLATE (Distributed load F)	MAXIMISE $E^{1/3}/\rho$	MAXIMISE $\sigma_Y^{1/2}/\rho$

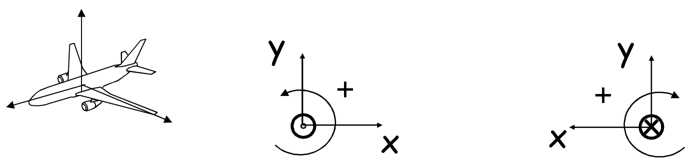
E = Young's modulus; σ_Y = Yield strength; ρ = Density

SEE ASHBY & JONES, BK 2, p 249 OR CRANE, CHAP 8

Structural indexes provide a convenient method for material selection according to the type of structural element to be designed and the specific material strength or stiffness – More in StM2

External sign conventions

Defined by chosen +ve direction of global axes

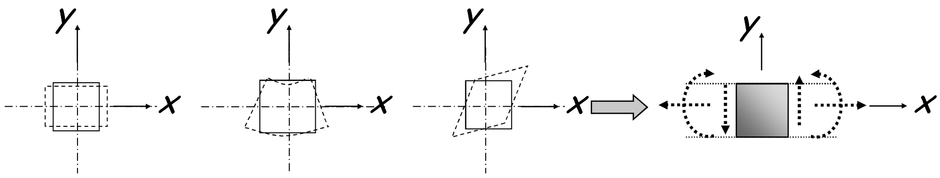


Note, +ve moments and twist are defined by the “right hand rule"

Internal sign convention

Defined by deformation convention

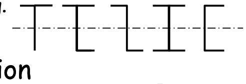
E.g. "extending", "sagging", "++ quadrant shearing": +ve



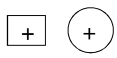
The choice of +ve convention is essentially arbitrary, but once chosen all interpretations must be consistent

Design of members in tension, bending or torsion

- Tension → cross-section area definition
- Compression → cross-section area + shape definition
  - may be more influential than tension to avoid buckling instability
- Bending → cross-section area + shape definition
  -Maximise area distant from the neutral axis of bending, e.g.



- Torsion → cross-section area + shape definition
  - section needs to be closed to carry torsion efficiently, e.g.

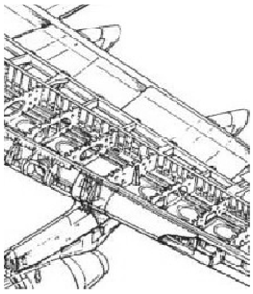


For basic analysis see StM1 Lecture notes:

"Loads in Trusses & Beams and "Stress, Strain & Deformation"

Joint Design

Design of simple pinned and fixed joints



Aim: to introduce the design of simple mechanical joints in aerospace structures, such as riveted and bolted joints.

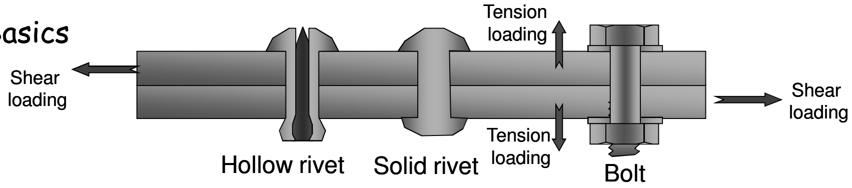
Learning objectives - Joints

You should be able to:

- Recognise the various fastener types and parts of riveted and bolted "pinned" joints and their basic usages.
- Identify the different failure modes of a "pinned" joint, estimate the stresses and check the ultimate RF.
- Estimate the load distribution in a multiple pinned joint and identify the most highly loaded fastener to be checked.
- Write out your calculations in a clear stress report format.

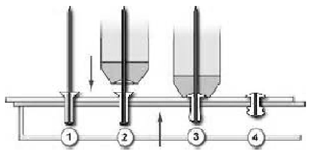
Riveted and bolted joints

Basics

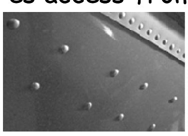


Rivets	Bolts
↗ Light and convenient, ↗ Generally aluminium alloy in aerospace ↗ Cheap ↗ Permanent – drill out to remove ↗ Small diameter, < 10mm ↗ Poor in tensile loading	↗ Strong and reliable attachment ↗ Can be dismantled ↗ Can carry tensile loads ↗ Generally steel or titanium in aerospace

Terminology - Rivets

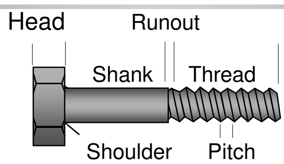


- **"Hollow", "Blind", "Pop", "Cherry" rivets** can be assembled from one side, usually by pulling a stem through the rivet to form a closing rivet head on the blind side. The stem is designed to break off at a predefined load and/or torque.
- **Solid rivets** assembled by hammering the blank stem to form the closing rivet head – requires access from both sides.



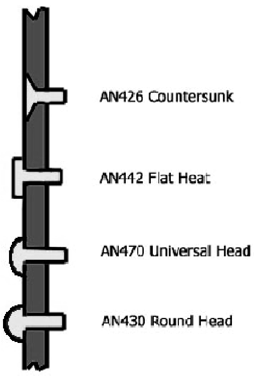
An iron "dolly" would be used on the opposing side to provide a reaction to the hammering.

Terminology – Threaded fasteners

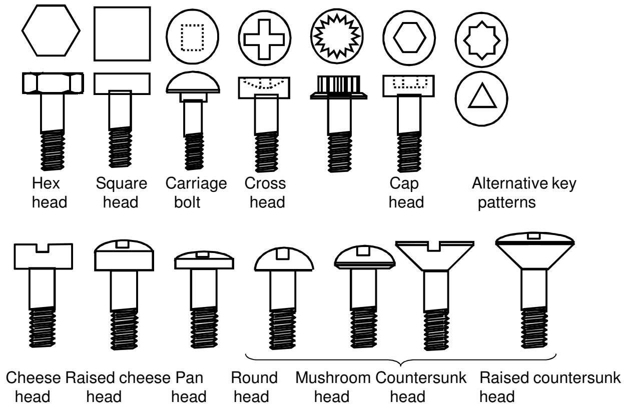


- **Bolts** have a shank "grip length" to carry shear loads and to bear against the holes in the parts being attached).
- **Screws** have no shank and should not be used to carry shear loads (the thread would damage the parts being attached and reduce the strength).
- **Self tapping screws** feature a cutting edge in the front part of the thread that enables it to generate a thread when driven into an untapped hole, these are very rarely used in aerospace applications.
- **Studding** is also sometimes used, this is a threaded rod with no shank or head.

Rivet head styles

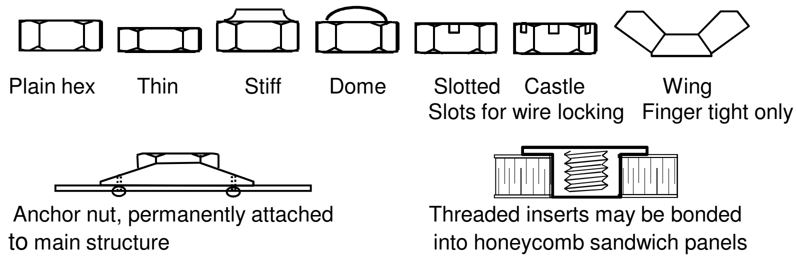


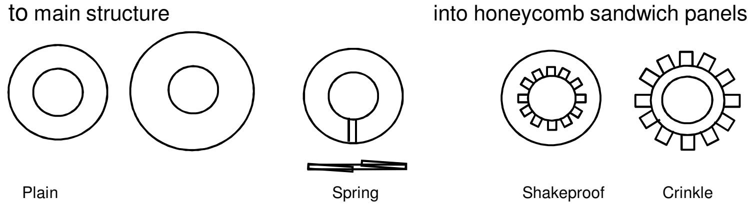
Bolt head styles



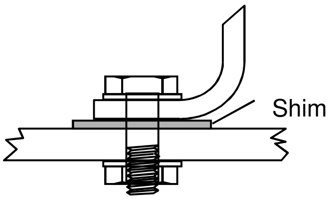
In aerospace the vast majority of bolts are hex, cross or cap heads, often countersunk to reduce drag.

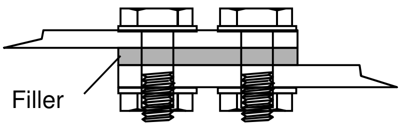
Nut & washer styles





Shims & Fillers



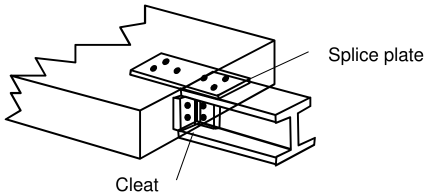


A **shim** is a thin metal packing piece used to obtain correct spacing in bolted joints. Shims are available in a wide range of accurate thicknesses, or as stacks of shims known as a laminated shim that can be taken down at the point of use to the correct thickness

A **filler** is a packing piece of similar thickness to the plates and must cover the whole joint.

The use of fillers or even shims increase the eccentricity of a joint and the risk of pin-bending failures and so should ideally be avoided.

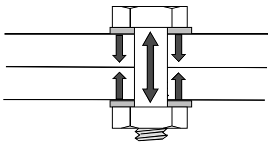
Cleats & Splice Plates



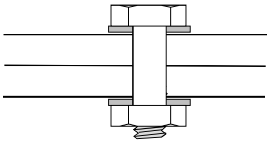
A **cleat** is an angle piece used to connect parts of a structure together (sometimes also known as a clip). Not to be confused with a bracket, which is used to support non-structural equipment from a structural part.

A **splice** plate is a flat plate that connects two pieces of structure together as a strap between them.

Bolt torque setting

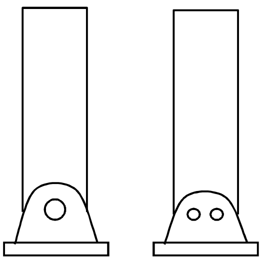


When the bolt is tightened, tensile stresses are set up in the bolt and are reacted by compressive stresses through the plates, clamping them together. Friction then resists rotation



If the bolt is not tightened there is no clamping action and the joint is free to rotate. This is then a pinned joint

Pinned and fixed joints



Pins are joints that permit rotation, therefore they cannot carry moments.

For a joint to be pinned it must use a single pin as more than one pin would prevent rotation.

If rotation is to be avoided it is <u>not</u> adequate to use a single fastener relying on friction to prevent rotation.

A minimum of two fasteners would be needed to avoid rotation and carry moments.

Single and Double Shear Pin Joints

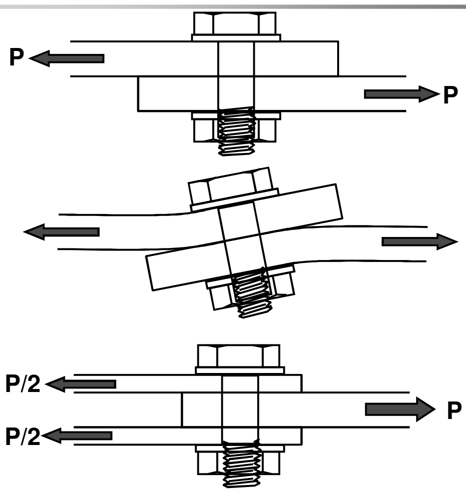
Single shear

Simple overlap of two plates

Single shear joints have a tendency to tilt because of the asymmetry. Essentially the load line tends to straighten up. This can cause problems at high loads, especially with rivets.

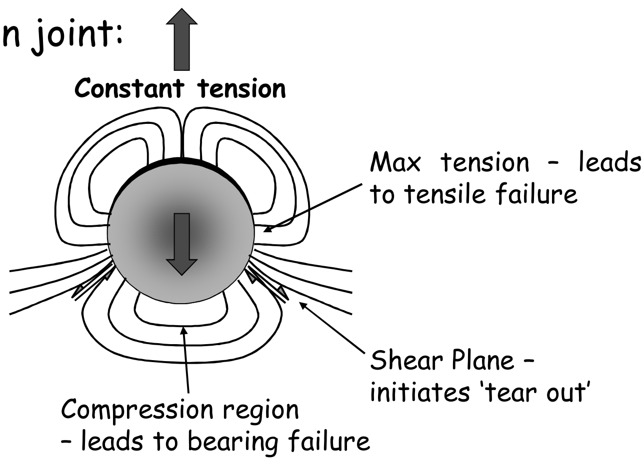
Double shear

A symmetric joint which has no tendency to tilt.

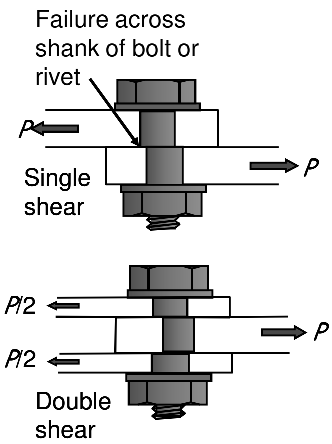


Lug (plate) stress distribution

at a pin joint:



Pin shear failure mode



Area of failure = cross-section of bolt x the number of failure zones, i.e. $\pi r^2 = \pi(d/2)^2$ per failure zone, where r = pin radius, d = pin diameter

τ_{av}= the allowable average shear stress for the material of the bolt. τ_{av} is <u>lower than the ultimate shear strength of the bolt material</u> to allow for statistical effects and non-uniformity of shear stress in the bolt. It is determined by experiment.

- For a pin in single shear the shear strength* is:

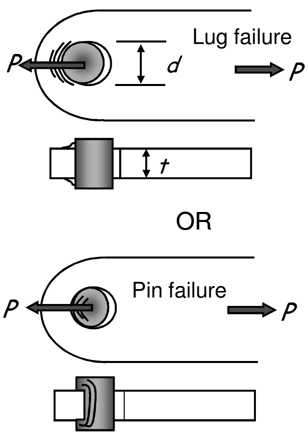
$$P_s = \tau_{av}\pi(d/2)^2$$

- For a pin in double shear the shear strength* is:

$$P_s = \tau_{av}2\pi(d/2)^2$$

* Note, we often refer to failure loads as "strengths" when referring to joint items

Lug or pin bearing failure mode



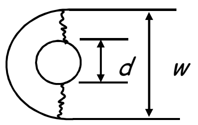
Bearing failure can occur in either the lug or the pin– both cases are shown here.

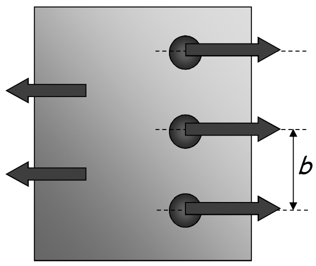
Area over which compressive force acts = $d.t$ where d = pin diameter t = lug thickness

Then bearing strength: $P_b = \sigma_{bav}dt$

where σ_{bav} is the allowable bearing stress which will be different for lug and pin, even if made of the same materials. Allowable bearing stress can be estimated from compressive strength but is best determined experimentally. The bearing strength value can be very sensitive to details such as bolt fit and the level of clamping from the bolt.

Lug tension failure mode





Tensile failure can occur in the region of peak tensile stress across the width of the joint.

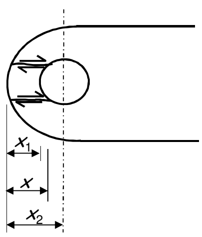
The tensile strength is then: $P_t = (w\text{-}d)t\,\sigma_{tav}$

Where σ_{tav} is the allowable tensile strength and $(w\text{-}d)t$ is the minimum cross-sectional area across the bolt.

As before the effective σ_{tav} value is lower than the material's tensile strength due to non-uniformity of stresses and statistical effects and ideally should be measured experimentally.

For a multi-hole joint the bolt or rivet pitch b can be used in place of the lug width w.

Lug tear-out "shear" failure mode



Tear-out failure occurs when failure occurs in shear along two planes between the bolt and the front of the lug.

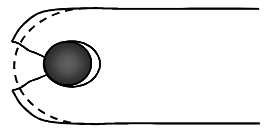
The area is $2tx$, where x is the length of the fracture surface.

The tear out strength is then: $P_{to} = \tau_{to}2tx$

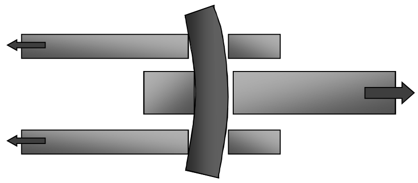
τ_{to} is the allowable tear out shear stress and should, as before, be found by experiment and will be lower than the bulk material shear strength.

x would generally be found by experiment. A safe conservative value of x would be to take x_1, the distance from the end of the hole to the end of the lug but it would be more common to use the distance from the pin centre-line to the end of the lug, which is more accurate but slightly optimistic. The difficulty goes away if the same value of x when measuring τ_{to} is used for calculation.

Lug bursting failure mode
Pin bending failure mode



Bursting failure
Less critical than other modes for metallic lugs but must be considered for fibre laminate composite lugs.



Pin bending failure
Less critical for thin joints but becomes more critical for joints between thick plates, or where there are offsets due to shims or fillers between plates.

Lastly, you need to make sure the bolted joint will not fail away from the bolt hole!

Bolt or hole diameter guideline

- In general, part mass is minimised if all the possible failure modes have the same failure load, i.e. all parts being worked as hard as possible.
- **For the pin** this would suggest: pin shear strength = pin bearing strength,

  I.e. $\tau_{av} \pi d^2/4 = \sigma_{bav} dt$
- But typically shear strength ≈ $\frac{3}{8}$ths of the bearing strength so:

  $\frac{3}{8} \sigma_{bav} \pi d^2/4 \approx \sigma_{bav} dt$

  Giving: $3\pi d/32 \approx t$

  And $\underline{d \approx 3.5t}$ as a general initial guideline for design
- I.e. if the pin diameter is roughly 3.5 times the lug thickness the pin will be roughly equally likely to fail in bearing and shear. Of course if the allowable bearing stress in the lug is lower than in the pin the first failure will occur in the lug and the pin failure modes will not be relevant to the final failure.

Lug sizing guideline

- As before we are aiming for the strengths to be roughly equal in all failure modes for a minimum weight structure.
  i.e. Bearing strength ≈ tensile strength ≈ tear out strength

  $$\sigma_{bav}\, dt \approx \sigma_{tav}(w-d)t \approx \tau_{to}\, 2tx$$ note t can cancels

- In very rough terms experience shows that the bearing strength is about twice the tensile strength and the tear-out shear strength is about ¾ of the tensile strength.

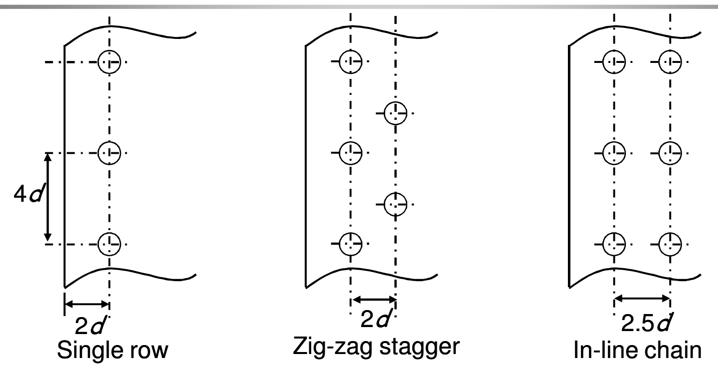
Thus $2\sigma_{tav}\, dt \approx \sigma_{tav}(w-d)t \approx \frac{3}{4}\sigma_{tav}\, 2tx$

So $2d \approx (w-d) \approx 1.5x$

➔ $w = 3d$ ➔ 4d & $x = 4/3d$ ➔ $1.5d$ ➔ $2d$

- As before, this is not a rule, but rather a guideline for design to get the design approximately correct quickly.

Cluster guideline



The figures above would be OK for protruding head fasteners
For countersunk fasteners use - Hole to Hole ≈ $5.5d$ &
- Edge to hole ≈ $2.5d$