Biomechanics of Fractures and Fixation

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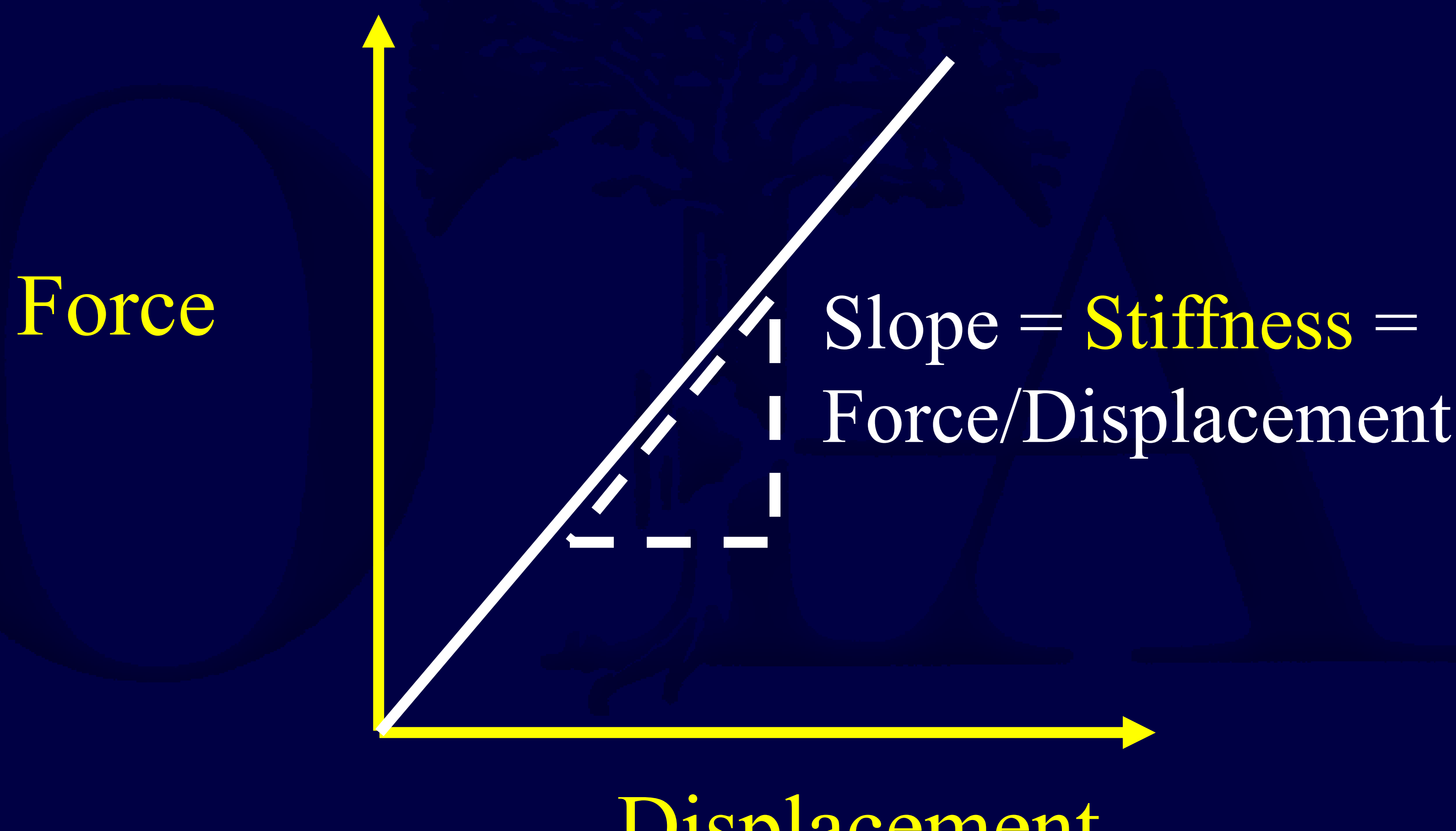
Basic Biomechanics

- Material Properties
  - Elastic-Plastic
  - Yield point
  - Brittle-Ductile
  - Toughness
- Independent of Shape!

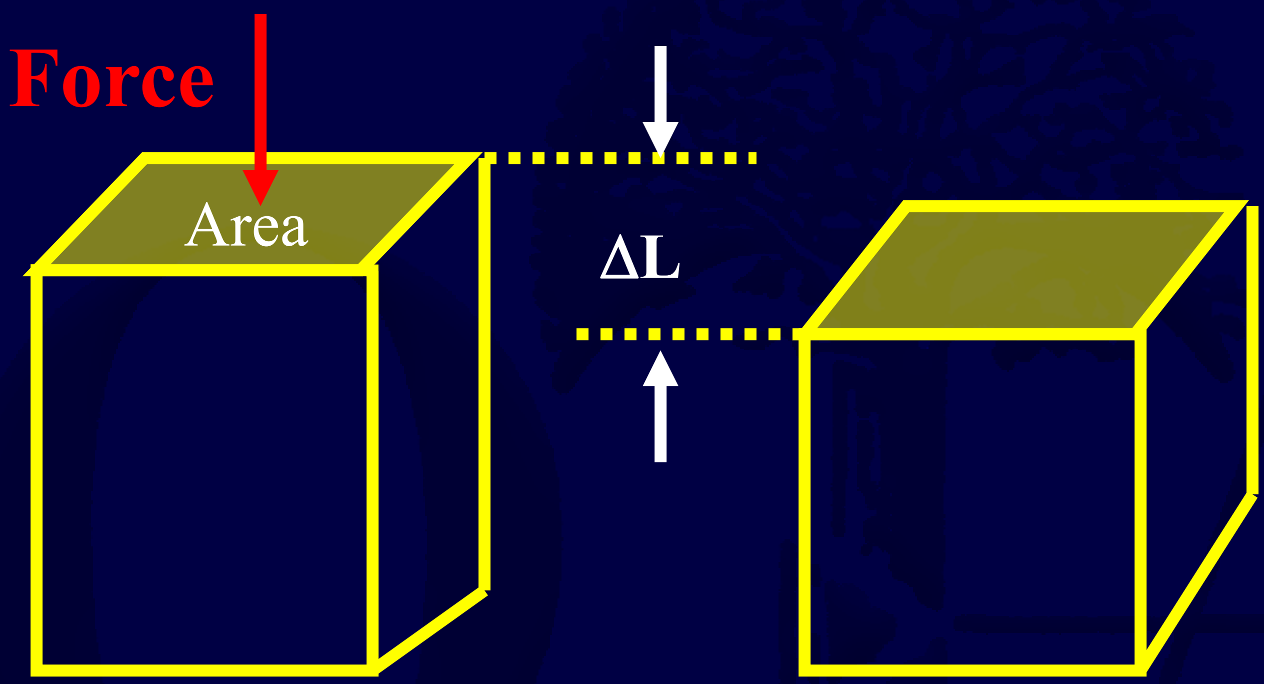
- Structural Properties
  - Bending Stiffness
  - Torsional Stiffness
  - Axial Stiffness
- Depends on Shape and Material!

Basic Biomechanics

Force, Displacement & Stiffness



Basic Biomechanics



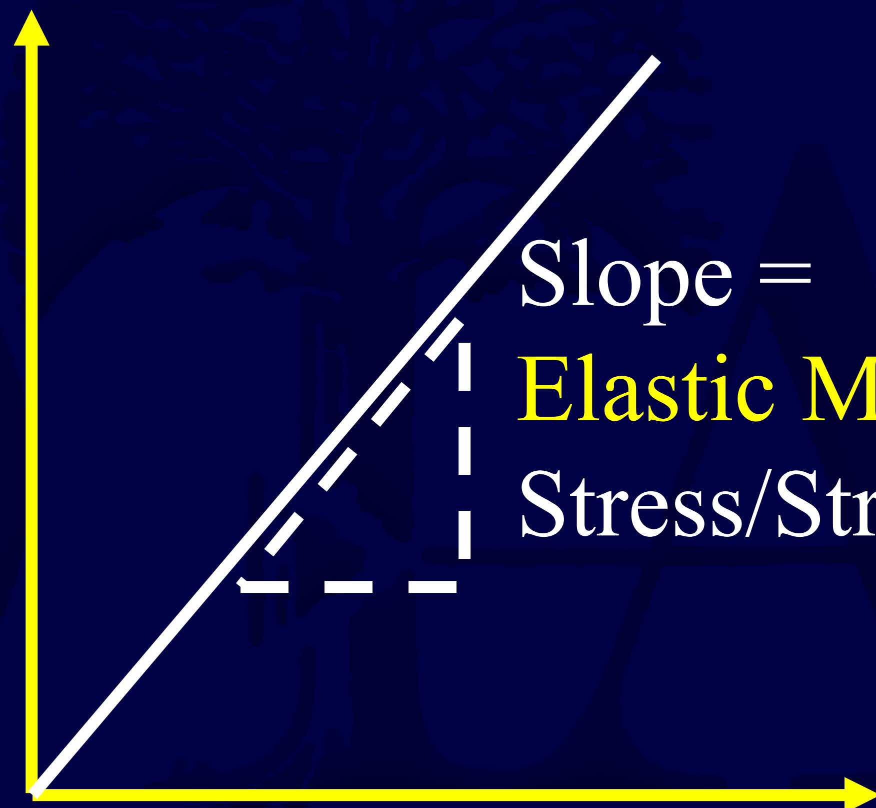
Stress = Force/Area

Strain Change Height (ΔL) / Original Height(L_0)

Basic Biomechanics

Stress-Strain & Elastic Modulus

Stress =
Force/Area



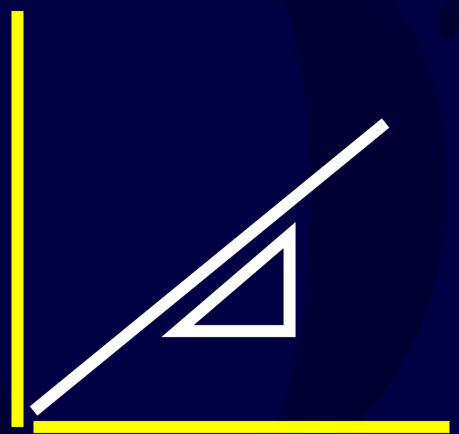
Slope =
Elastic Modulus =
Stress/Strain

Strain =
Change in Length/Original Length ($\Delta L / L_0$)

Basic Biomechanics
Common Materials in Orthopaedics

- Elastic Modulus (GPa)

Stress

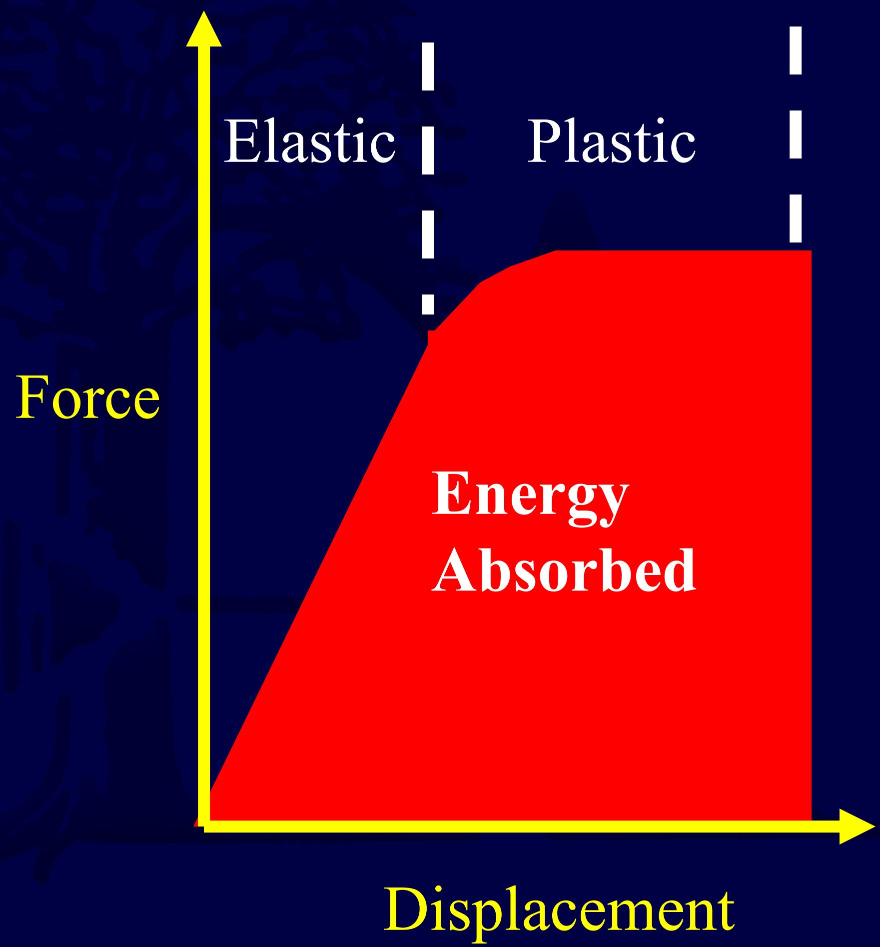


Strain

Stainless Steel	200
Titanium	100
Cortical Bone	7-21
Bone Cement	2.5-3.5
Cancellous Bone	0.7-4.9
UHMW-PE	1.4-4.2

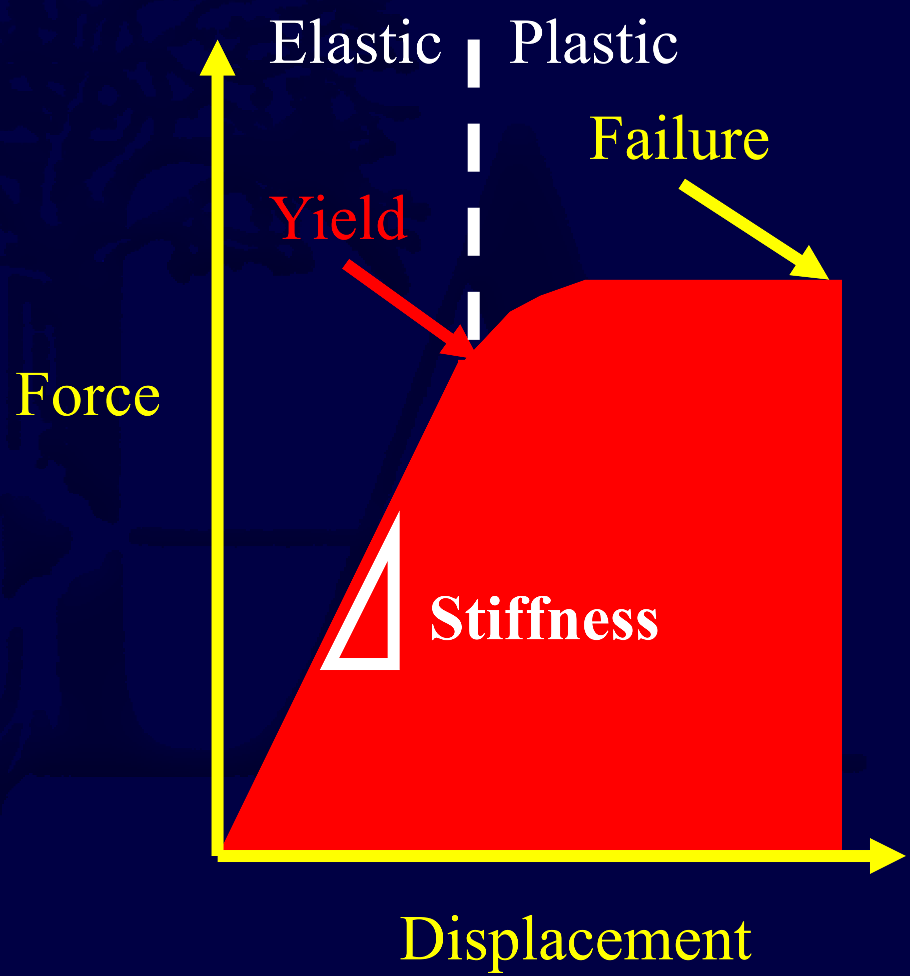
Basic Biomechanics

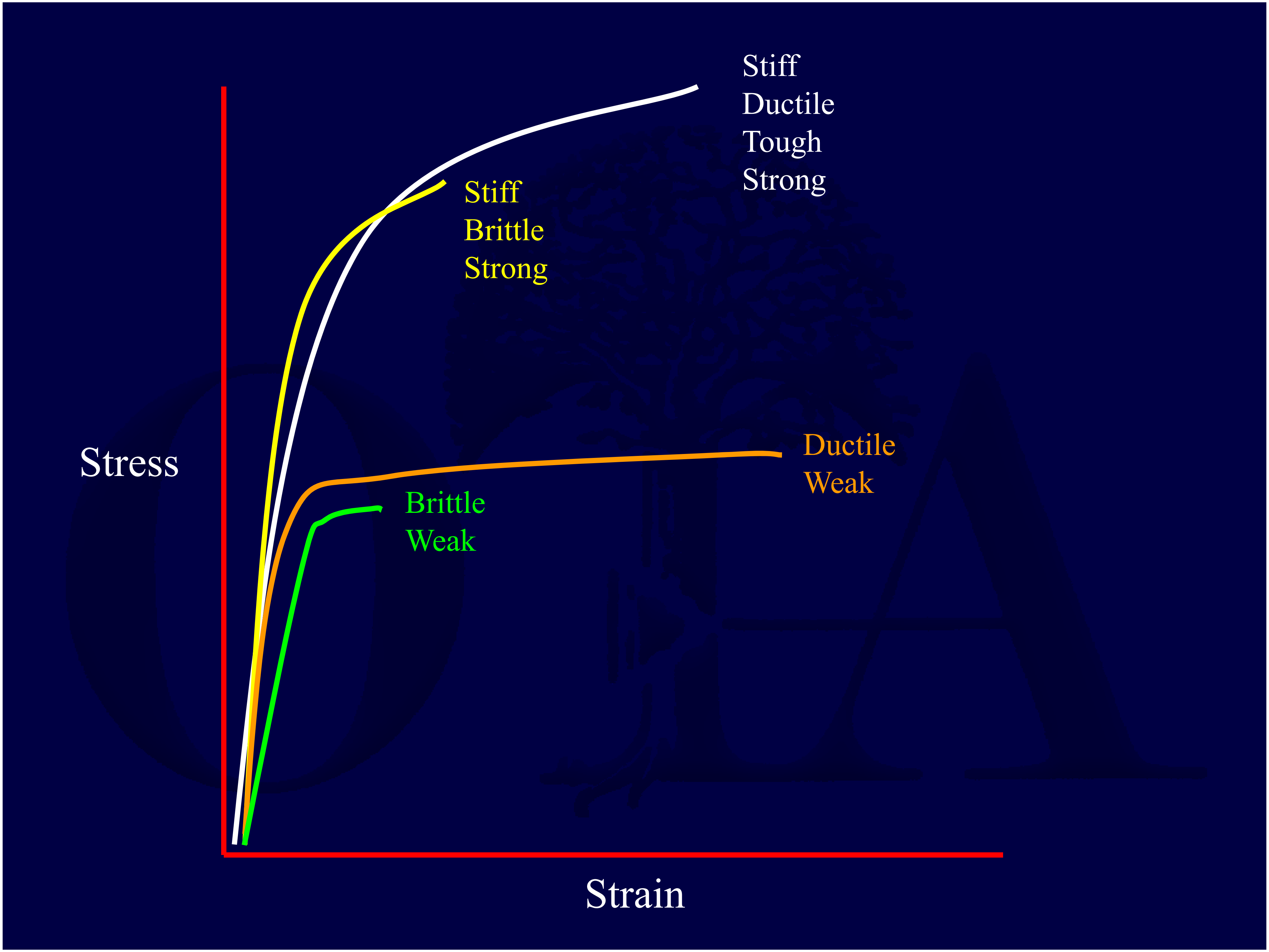
- Elastic Deformation
- Plastic Deformation
- Energy

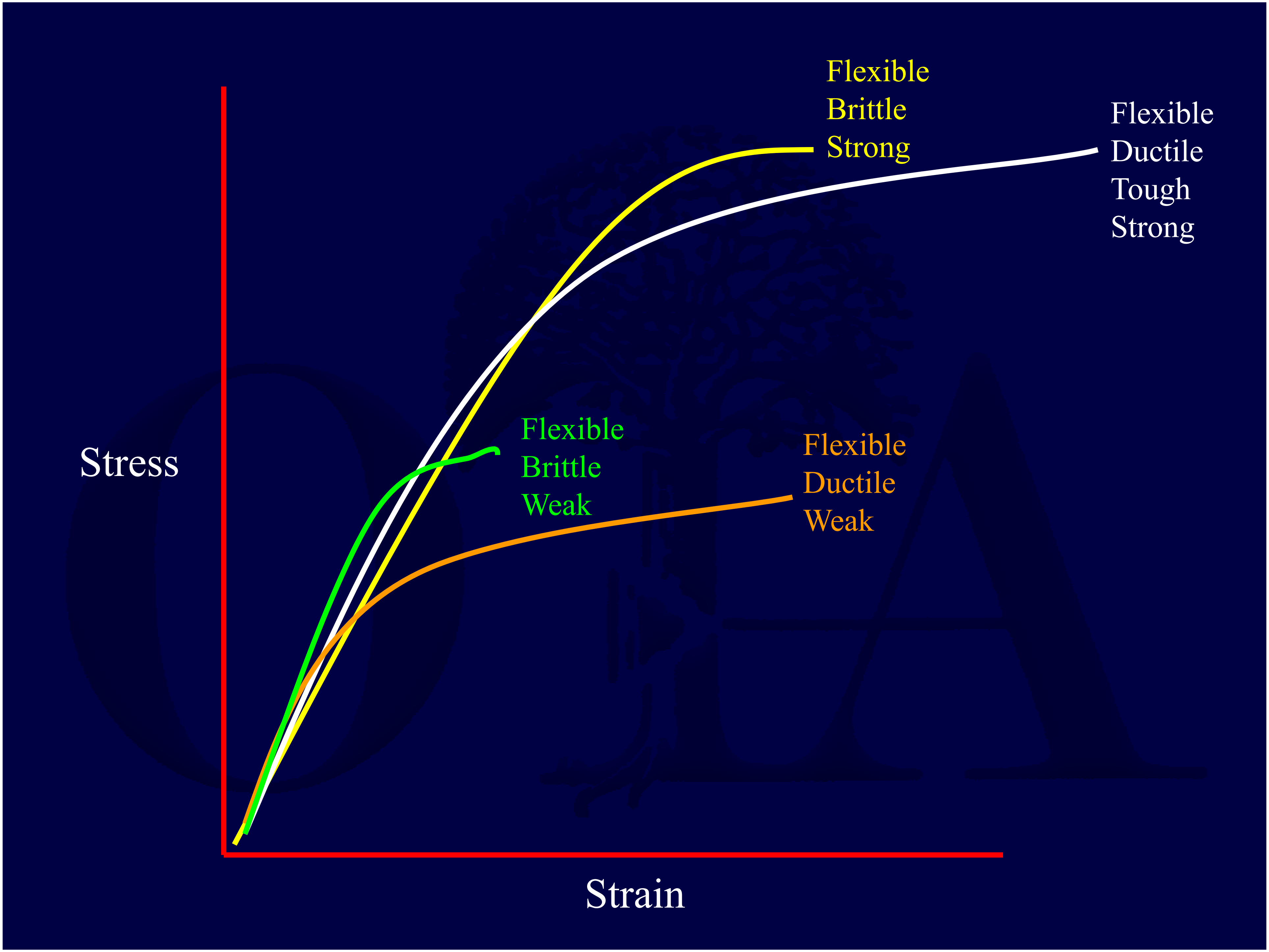


Basic Biomechanics

- Stiffness-Flexibility
- Yield Point
- Failure Point
- Brittle-Ductile
- Toughness-Weakness




Stiff
Ductile
Tough
Strong
Stiff
Brittle
Strong
Stress
Ductile
Weak
Brittle
Weak
Strain


Flexible
Brittle
Strong
Flexible
Ductile
Tough
Strong
Flexible
Brittle
Weak
Flexible
Ductile
Weak
Stress
Strain

Basic Biomechanics

- Load to Failure
  - Continuous application of force until the material breaks (failure point at the ultimate load).
  - Common mode of failure of bone and reported in the implant literature.
- Fatigue Failure
  - Cyclical sub-threshold loading may result in failure due to fatigue.
  - Common mode of failure of orthopaedic implants and fracture fixation constructs.

Basic Biomechanics

- Anisotropic
  - Mechanical properties dependent upon direction of loading
- Viscoelastic
  - Stress-Strain character dependent upon rate of applied strain (time dependent).

Bone Biomechanics

- Bone is anisotropic - its modulus is dependent upon the direction of loading.
- Bone is weakest in shear, then tension, then compression.
- Ultimate Stress at Failure Cortical Bone

Compression	< 212	N/m^2
Tension	< 146	N/m^2
Shear	< 82	N/m^2

Bone Biomechanics

- Bone is viscoelastic: its force-deformation characteristics are dependent upon the rate of loading.
- Trabecular bone becomes stiffer in compression the faster it is loaded.

Bone Mechanics

- Bone Density
  - Subtle density changes greatly changes strength and elastic modulus
- Density changes
  - Normal aging
  - Disease
  - Use
  - Disuse

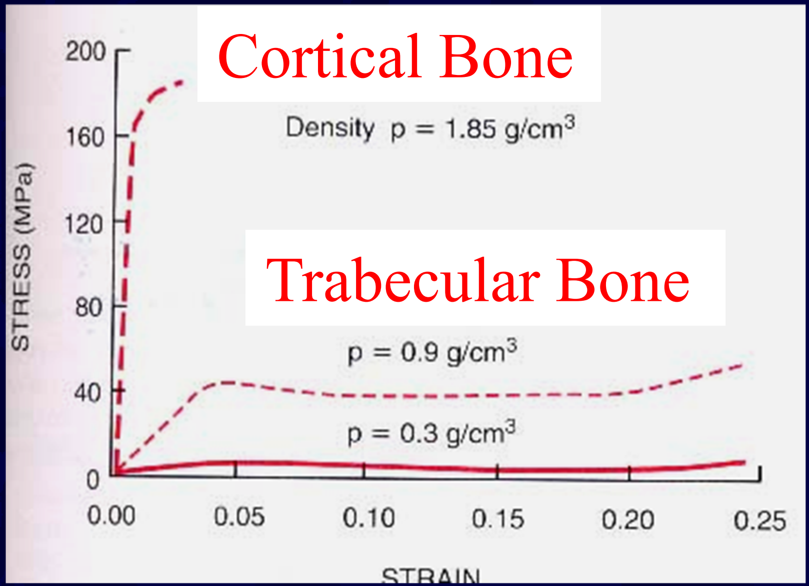
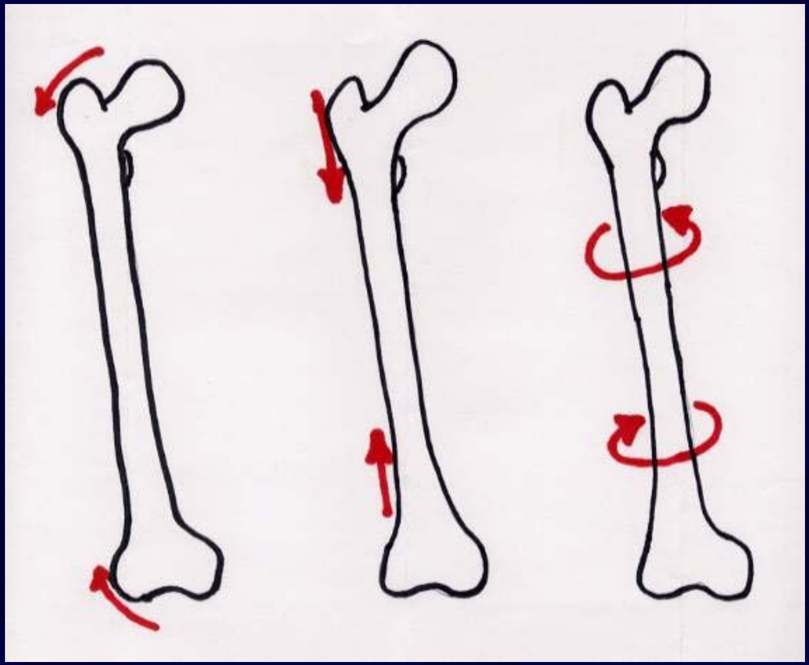


Figure from: Browner et al: Skeletal Trauma 2nd Ed. Saunders, 1998.

Basic Biomechanics



Bending Compression Torsion

- Bending
- Axial Loading
  - Tension
  - Compression
- Torsion

Fracture Mechanics

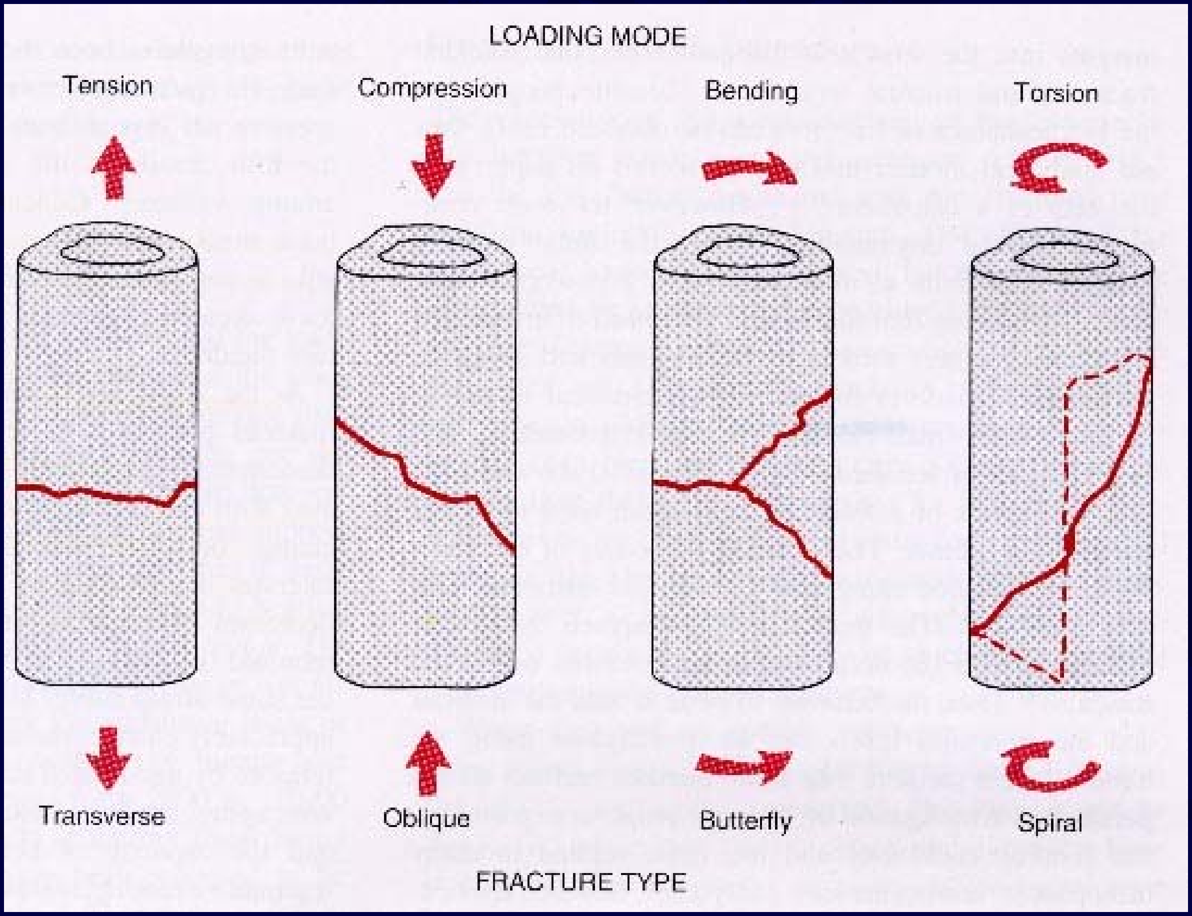
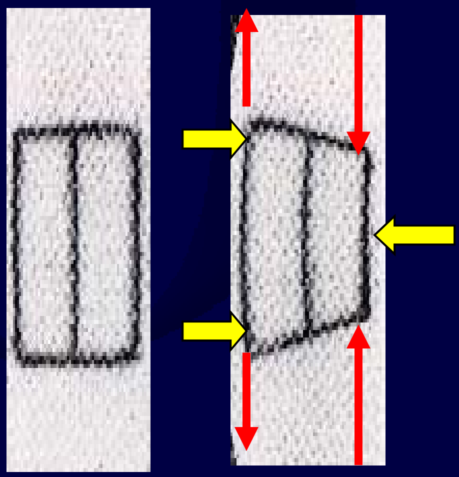


Figure from: Browner et al: Skeletal Trauma 2nd Ed, Saunders, 1998.

Fracture Mechanics

- Bending load:
  - Compression strength greater than tensile strength
  - Fails in tension



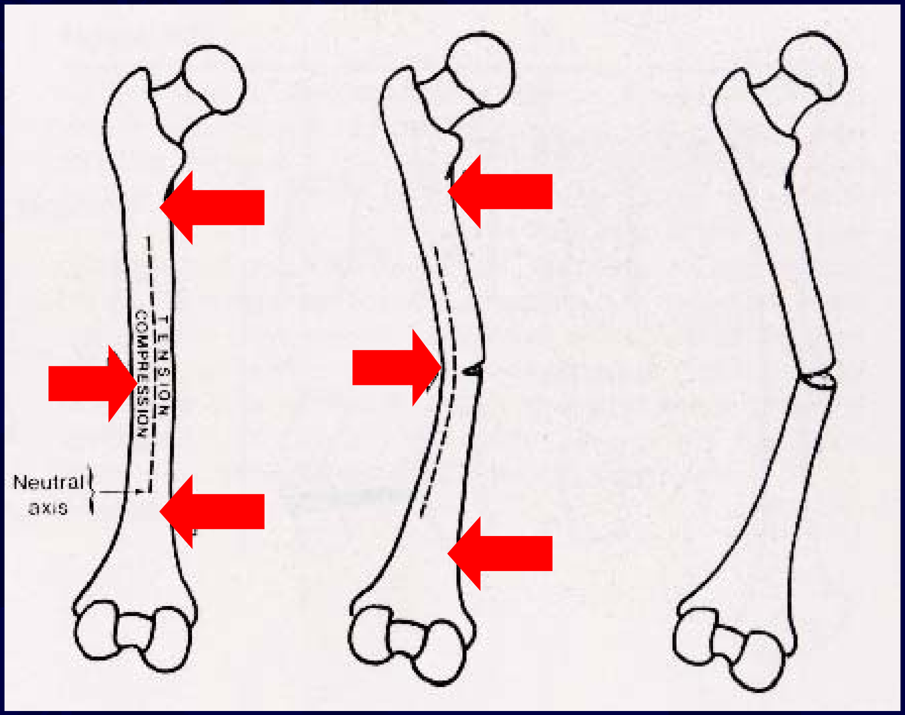
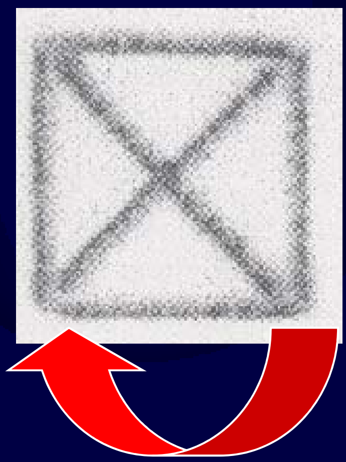
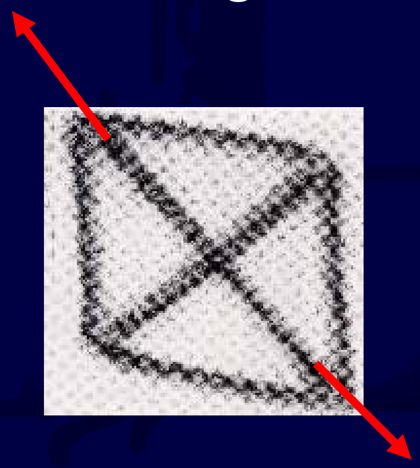


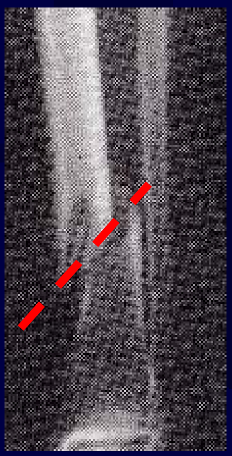
Figure from: Tencer. Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Fracture Mechanics

- Torsion
  - The diagonal in the direction of the applied force is in tension – cracks perpendicular to this tension diagonal
  - Spiral fracture 45º to the long axis







Figures from: Tencer. Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Fracture Mechanics

- Combined bending & axial load
  - Oblique fracture
  - Butterfly fragment

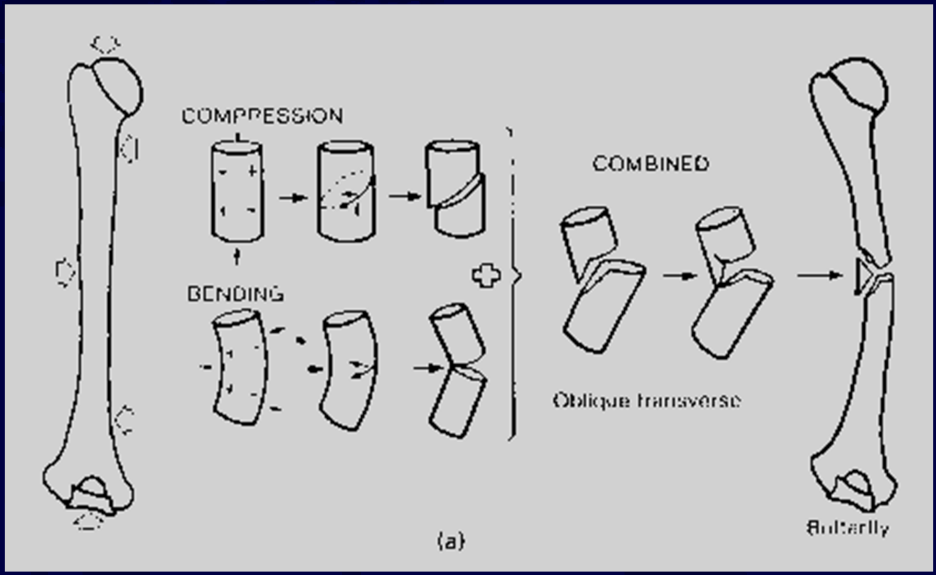


Figure from: Tencer. Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Moments of Inertia

- Resistance to bending, twisting, compression or tension of an object is a function of its shape
- Relationship of applied force to distribution of mass (shape) with respect to an axis.

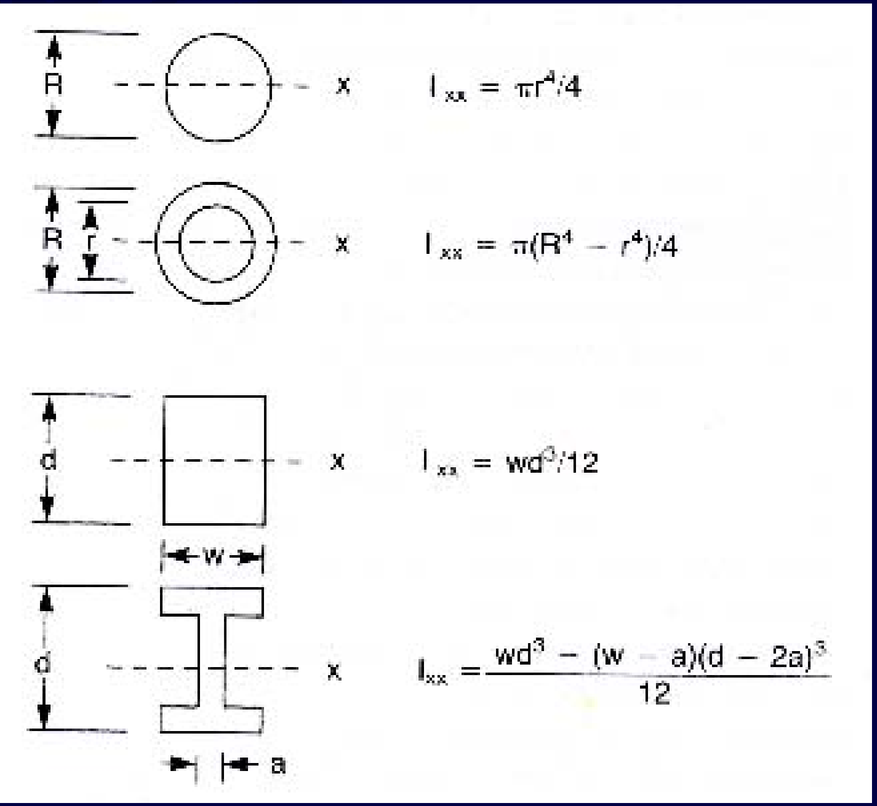
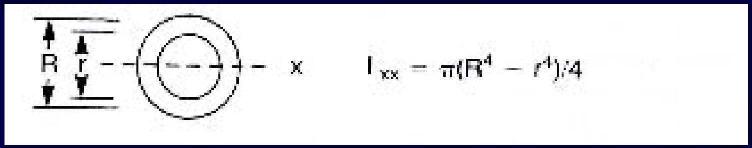


Figure from: Browner et al, Skeletal Trauma 2nd Ed, Saunders, 1998.

Fracture Mechanics

- Fracture Callus
  - Moment of inertia proportional to r^4
  - Increase in radius by callus greatly increases moment of inertia and stiffness

1.6 x stronger



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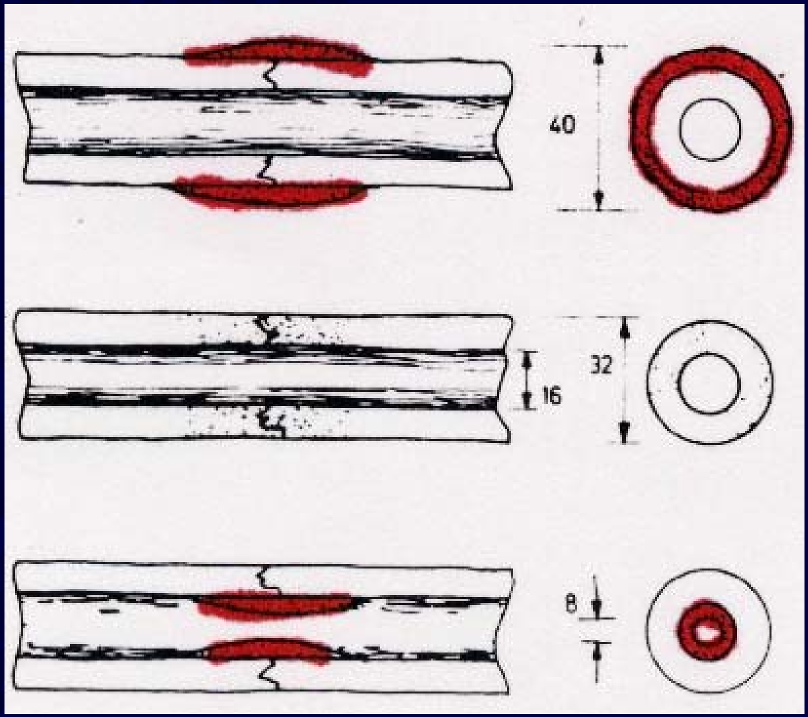


0.5 x weaker

Figure from: Tencer et al: Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Fracture Mechanics

- Time of Healing
  - Callus increases with time
  - Stiffness increases with time
  - Near normal stiffness at 27 days
  - Does not correspond to radiographs

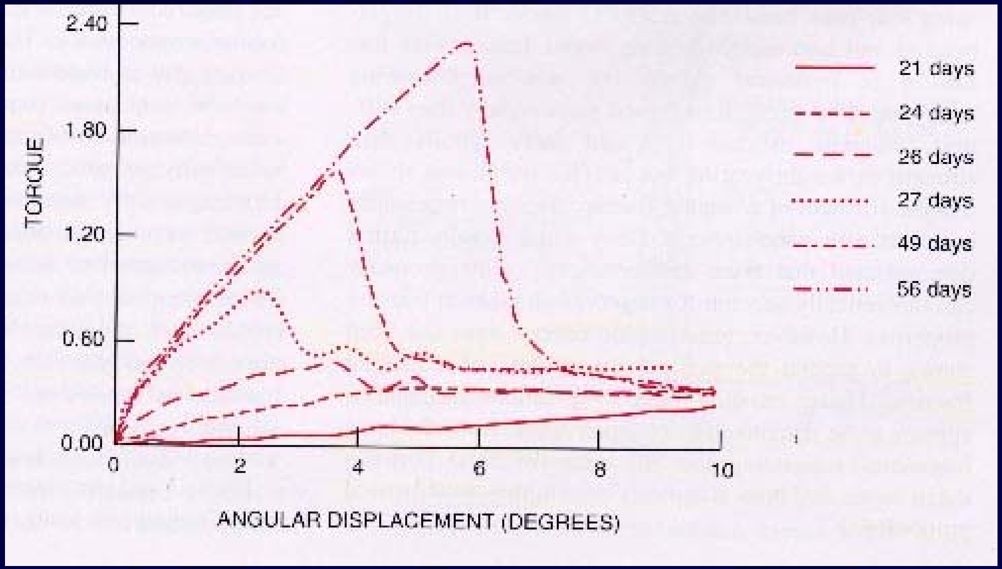
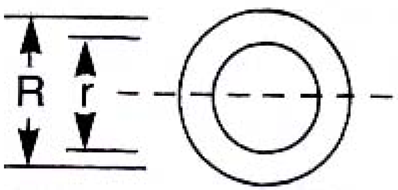


Figure from: Browner et al, Skeletal Trauma, 2nd Ed, Saunders, 1998.

IM Nails
Moment of Inertia

- Stiffness proportional to the 4th power.



$$I_{xx} = \pi(R^4 - r^4)/4$$

Figure from: Browner et al, Skeletal Trauma, 2nd Ed, Saunders, 1998.

IM Nail Diameter

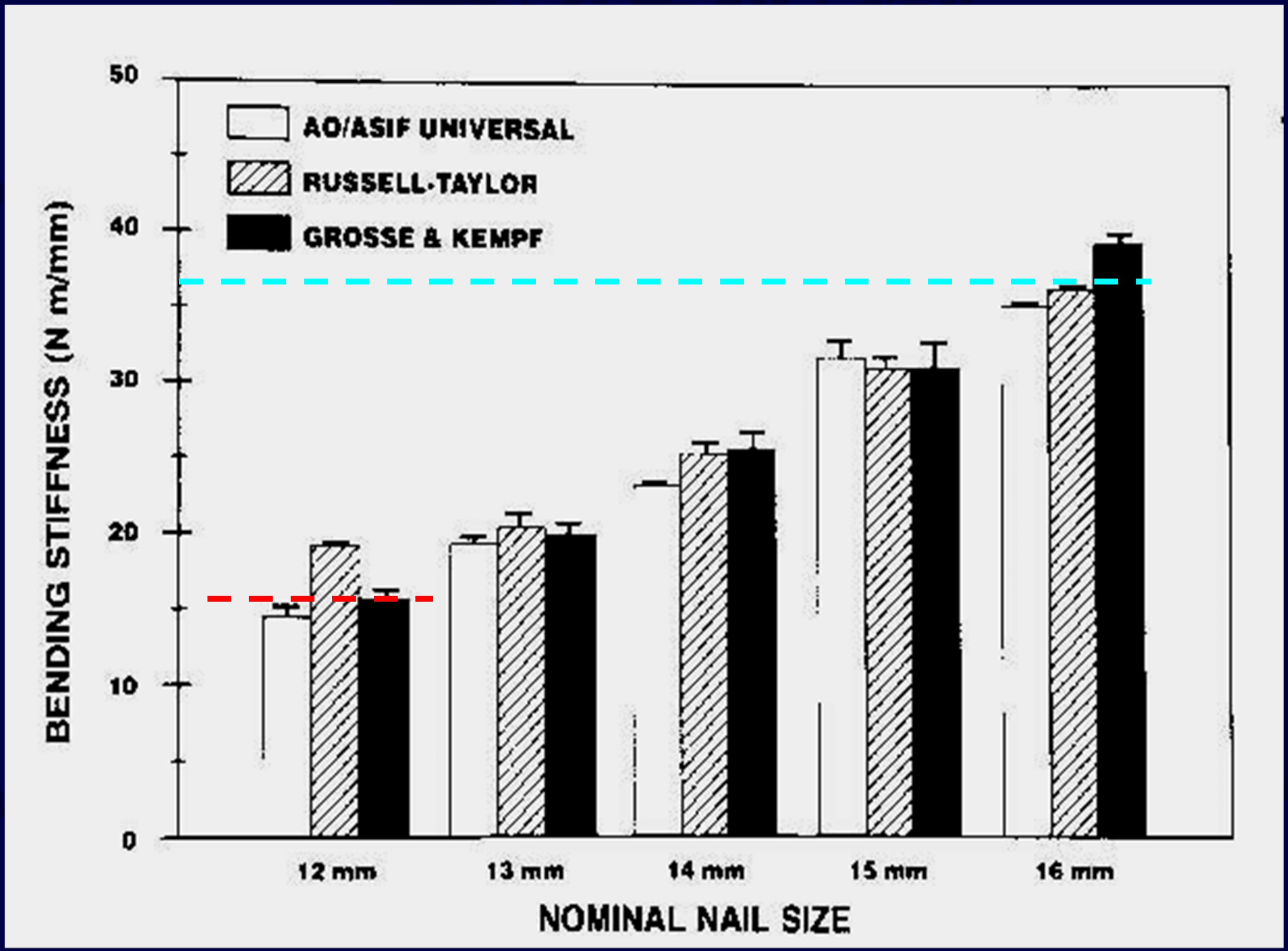
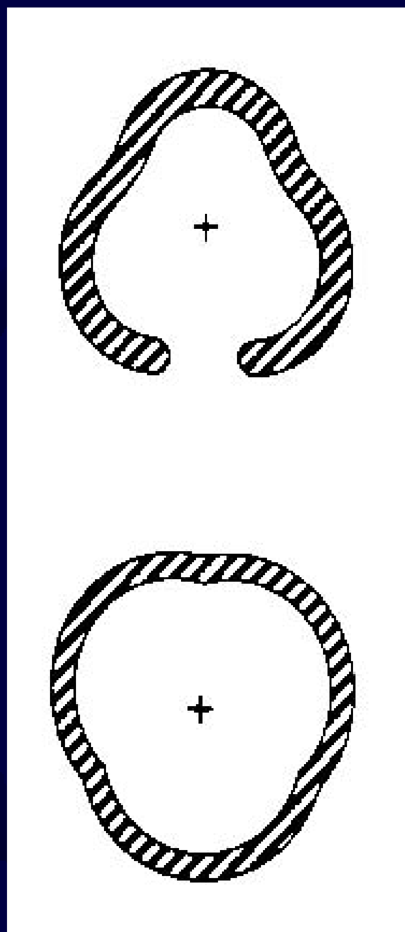


Figure from: Tencer et al, Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Slotting



- Allows more flexibility
    - In bending
- Decreases torsional strength

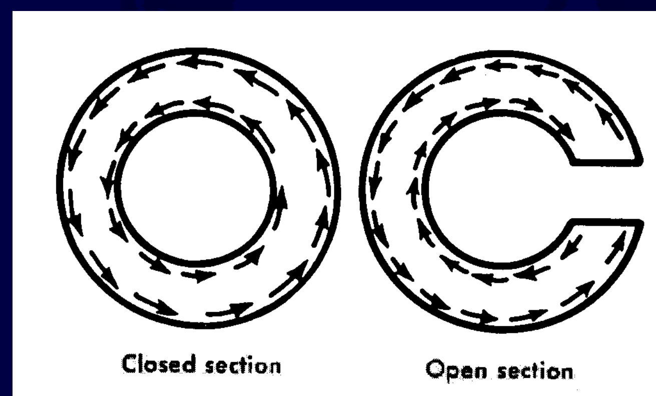


Figure from Rockwood and Green's, 4th Ed

Figure from: Tencer et al, Biomechanics in Orthopaedic Trauma, Lippincott, 1994.

Slotting-Torsion

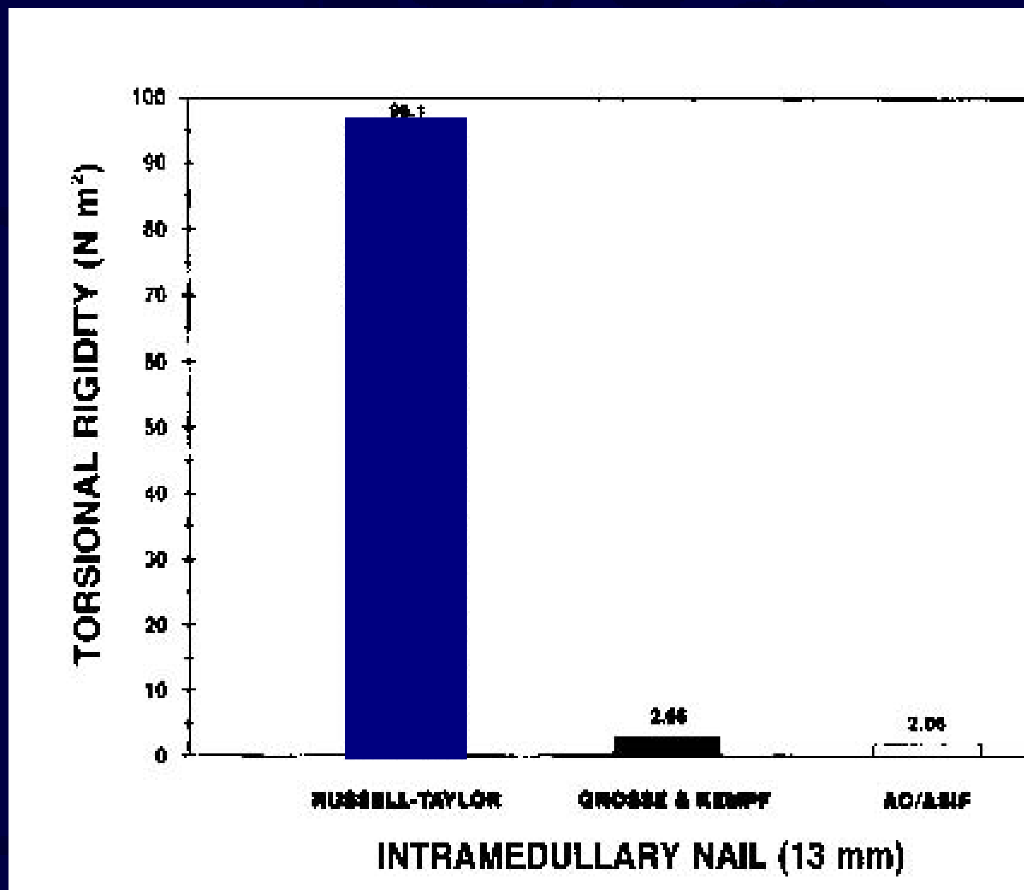


Figure from: Tencer et al, Biomechanics

in Orthopaedic Trauma, Lippincott, 1994.

Interlocking Screws

- Controls torsion and axial loads
- Advantages
  - Axial and rotational stability
  - Angular stability
- Disadvantages
  - Time and radiation exposure
  - Stress riser in nail
- Location of screws
  - Screws closer to the end of the nail expand the zone of fxs that can be fixed at the expense of construct stability

Biomechanics of Internal Fixation

Biomechanics of Internal Fixation

- Screw Anatomy
  - Inner diameter
  - Outer diameter
  - Pitch

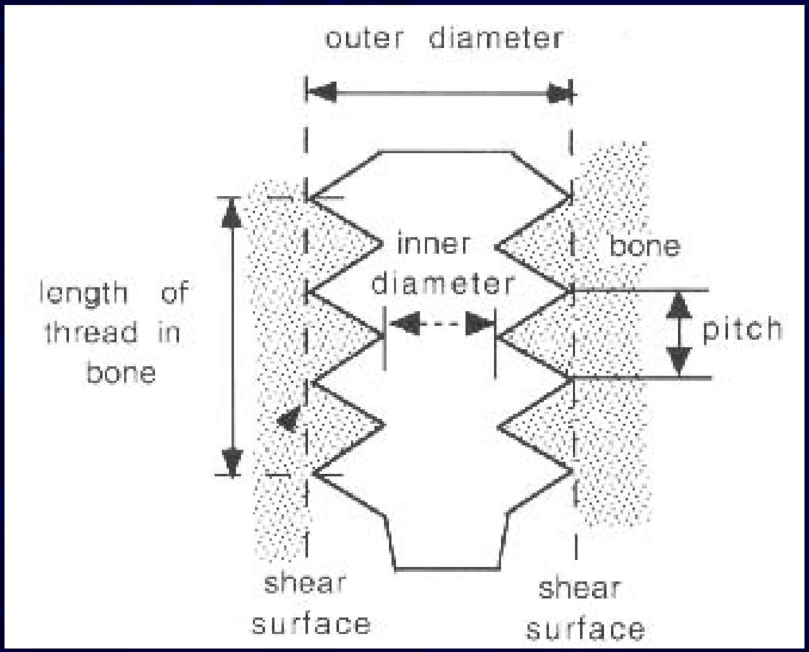


Figure from: Tencer et al, Biomechanics in OrthopaedicTrauma, Lippincott, 1994.

Biomechanics of Screw Fixation

- To increase strength of the screw & resist fatigue failure:
  - Increase the inner root diameter
- To increase pull out strength of screw in bone:
  - Increase outer diameter
  - Decrease inner diameter
  - Increase thread density
  - Increase thickness of cortex
  - Use cortex with more density.

Biomechanics of Screw Fixation

- Cannulated Screws
  - Increased inner diameter required
  - Relatively smaller thread width results in lower pull out strength
  - Screw strength minimally affected

  ($\alpha\ r^4_{outer\ core} - r^4_{inner\ core}$)

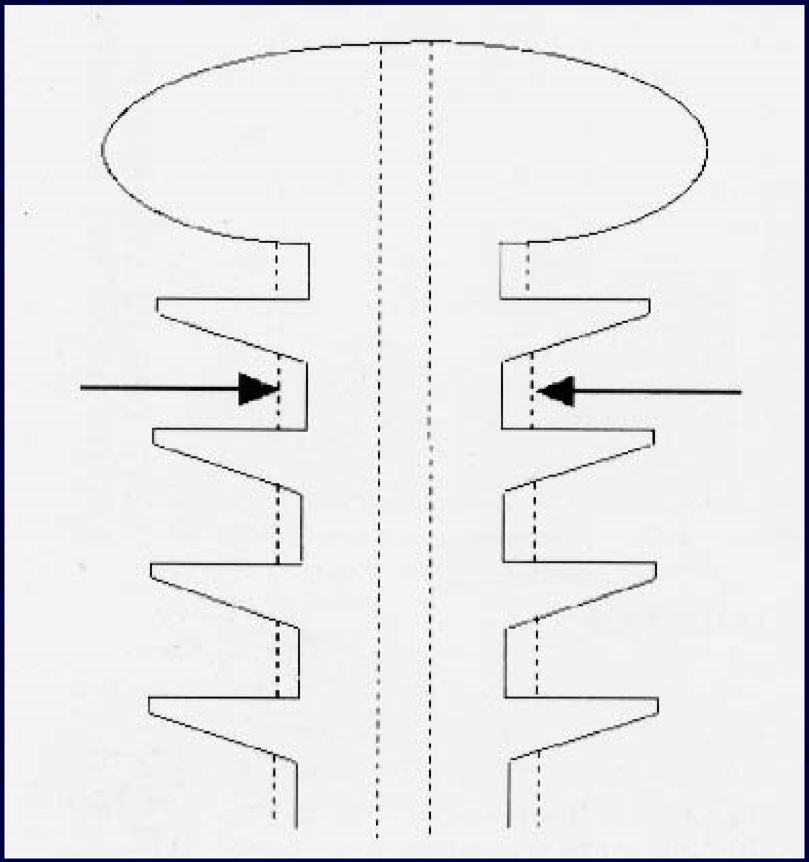
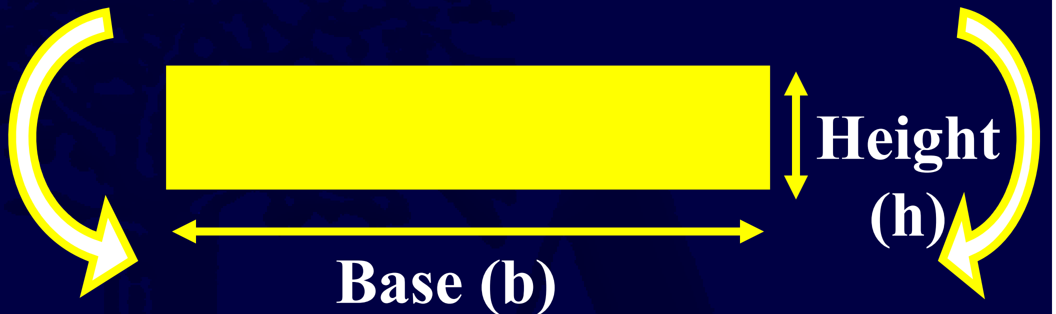


Figure from: Tencer et al, Biomechanics in OrthopaedicTrauma, Lippincott, 1994.

Biomechanics of Plate Fixation

- Plates:
  - Bending stiffness proportional to the thickness (h) of the plate to the 3rd power.



$$I = bh^3/12$$

Biomechanics of Plate Fixation

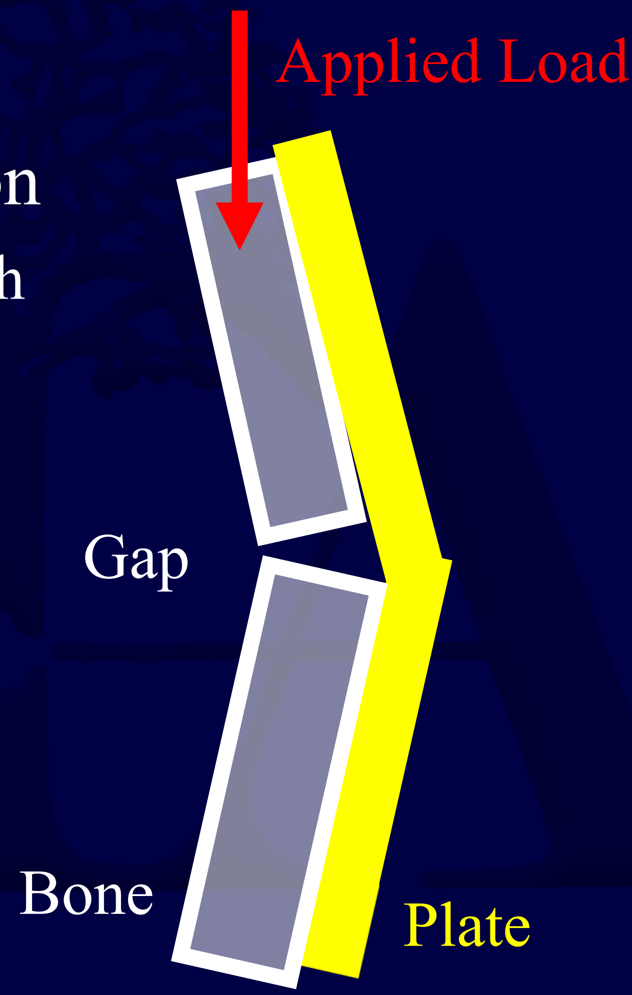
- Functions of the plate
  - Compression
  - Neutralization
  - Buttress
- "The bone protects the plate"

Biomechanics of Plate Fixation

- Unstable constructs
  - Severe comminution
  - Bone loss
  - Poor quality bone
  - Poor screw technique

Biomechanics of Plate Fixation

- Fracture Gap /Comminution
  - Allows bending of plate with applied loads
  - Fatigue failure

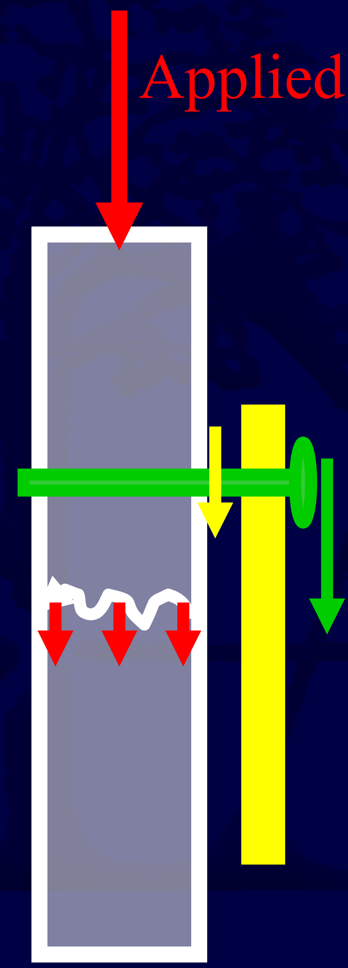


Biomechanics of Plate Fixation

- Fatigue Failure
  - Even stable constructs may fail from fatigue if the fracture does not heal due to biological reasons.

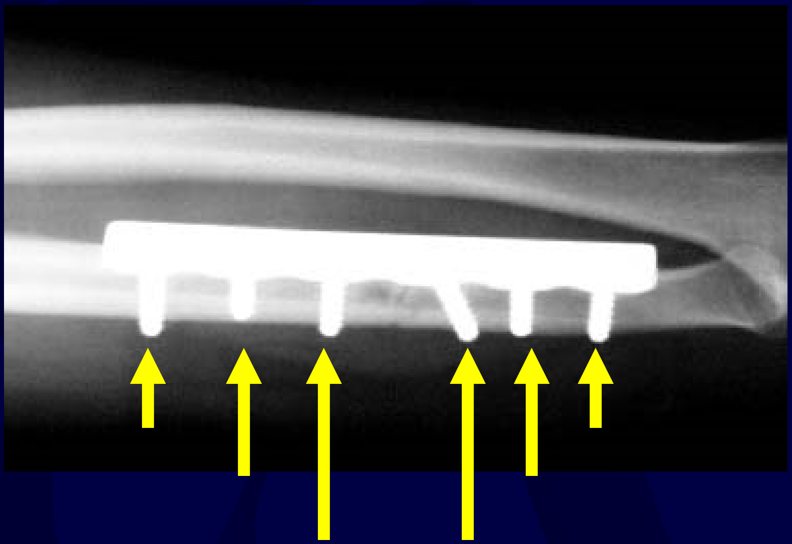
Biomechanics of Plate Fixation

- Bone-Screw-Plate Relationship
  - Bone via compression
  - Plate via bone-plate friction
  - Screw via resistance to bending and pull out.



Biomechanics of Plate Fixation

- The screws closest to the fracture see the most forces.
- The construct rigidity decreases as the distance between the innermost screws increases.



Screw Axial Force

Biomechanics of Plate Fixation

- Number of screws (cortices) recommended on each side of the fracture:

Forearm	3	(5-6)
Humerus	3-4	(6-8)
Tibia	4	(7-8)
Femur	4-5	(8)

Biomechanics of Plating

- Tornkvist H. et al: JOT 10(3) 1996, p 204-208
- Strength of plate fixation ~ number of screws & spacing (1 3 5 > 123)
- Torsional strength ~ number of screws but not spacing

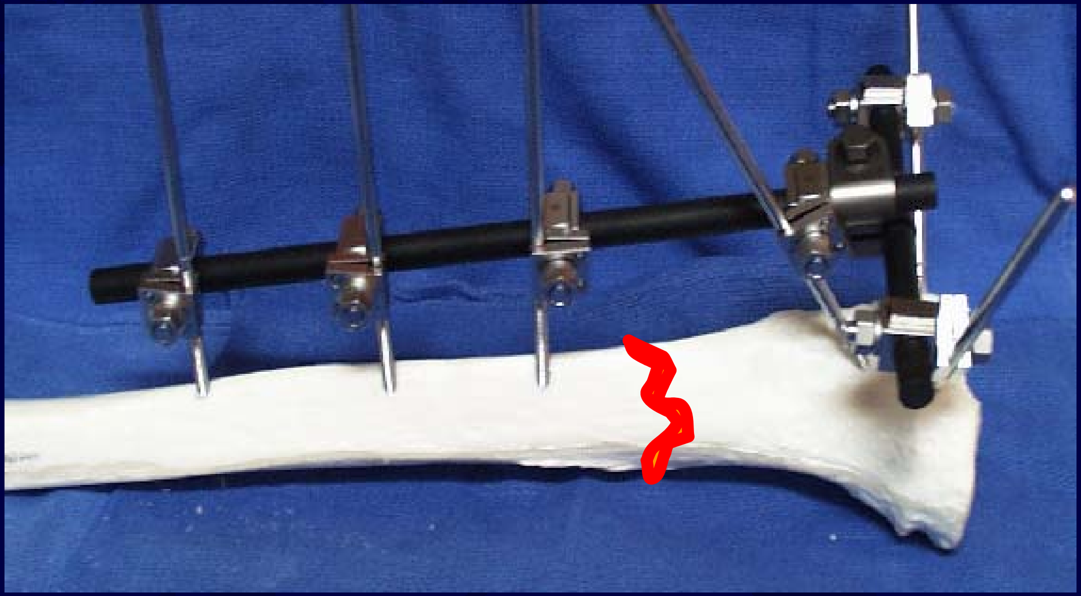
Biomechanics of External Fixation

Biomechanics of External Fixation

- Pin Size
  - {Radius}^{4}
  - Most significant factor in frame stability

Biomechanics of External Fixation

- Number of Pins
  – Two per segment
  – Third pin



Biomechanics of External Fixation

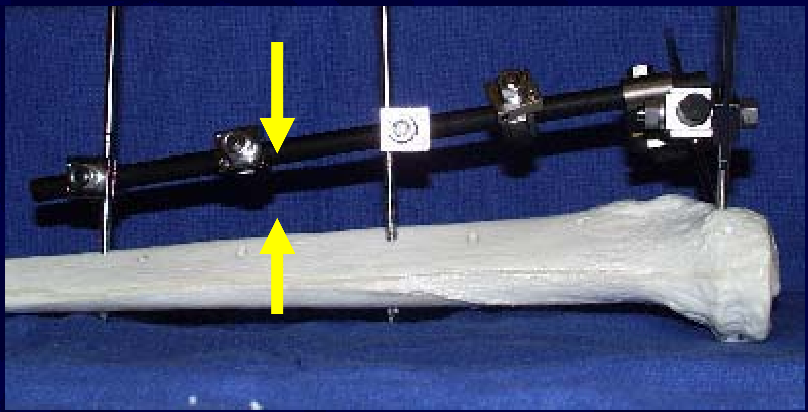
Third pin (C) out of plane of two other pins (A & B) stabilizes that segment.

Biomechanics of External Fixation

- Pin Location
  - Avoid zone of injury or future ORIF
  - Pins close to fracture as possible
  - Pins spread far apart in each fragment
- Wires
  - 90º

Biomechanics of External Fixation

- Bone-Frame Distance
  - Rods
  - Rings
  - Dynamization



Biomechanics of External Fixation

- SUMMARY OF EXTERNAL FIXATOR STABILITY:
  Increase stability by:
  1] Increasing the pin diameter.
  2] Increasing the number of pins.
  3] Increasing the spread of the pins.
  4] Multiplanar fixation.
  5] Reducing the bone-frame distance.
  6] Predrilling and cooling (reduces thermal necrosis).
  7] Radially preload pins.
  8] 90° tensioned wires.
  9] Stacked frames.

**but a very rigid frame is not always good.

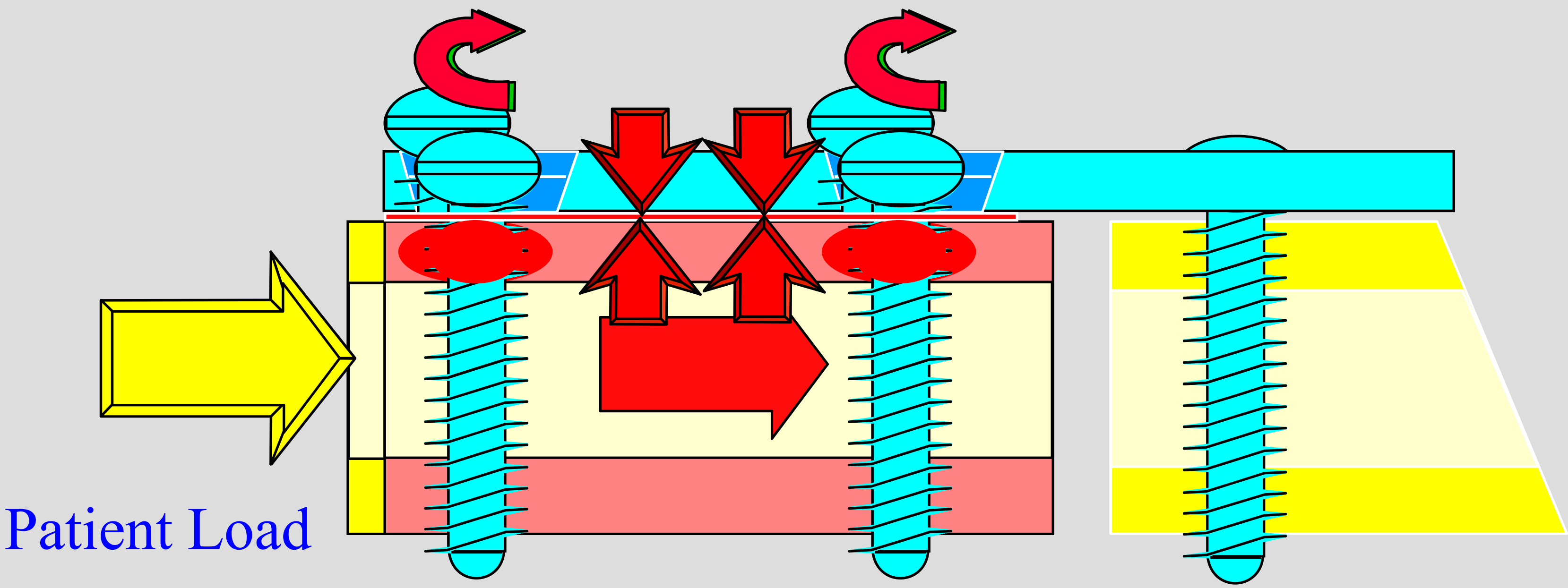
Ideal Construct

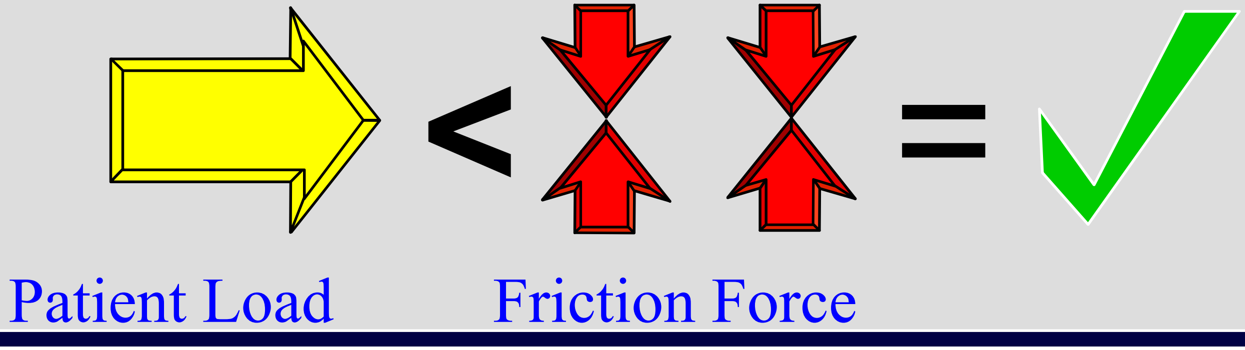
- Far/Near - Near/Far on either side of fx
- Third pin in middle to increase stability
- Construct stability compromised with spanning ext fix – avoid zone of injury (far/near – far/far)

Biomechanics of Locked Plating

Courtesy of Synthes- Robi Frigg

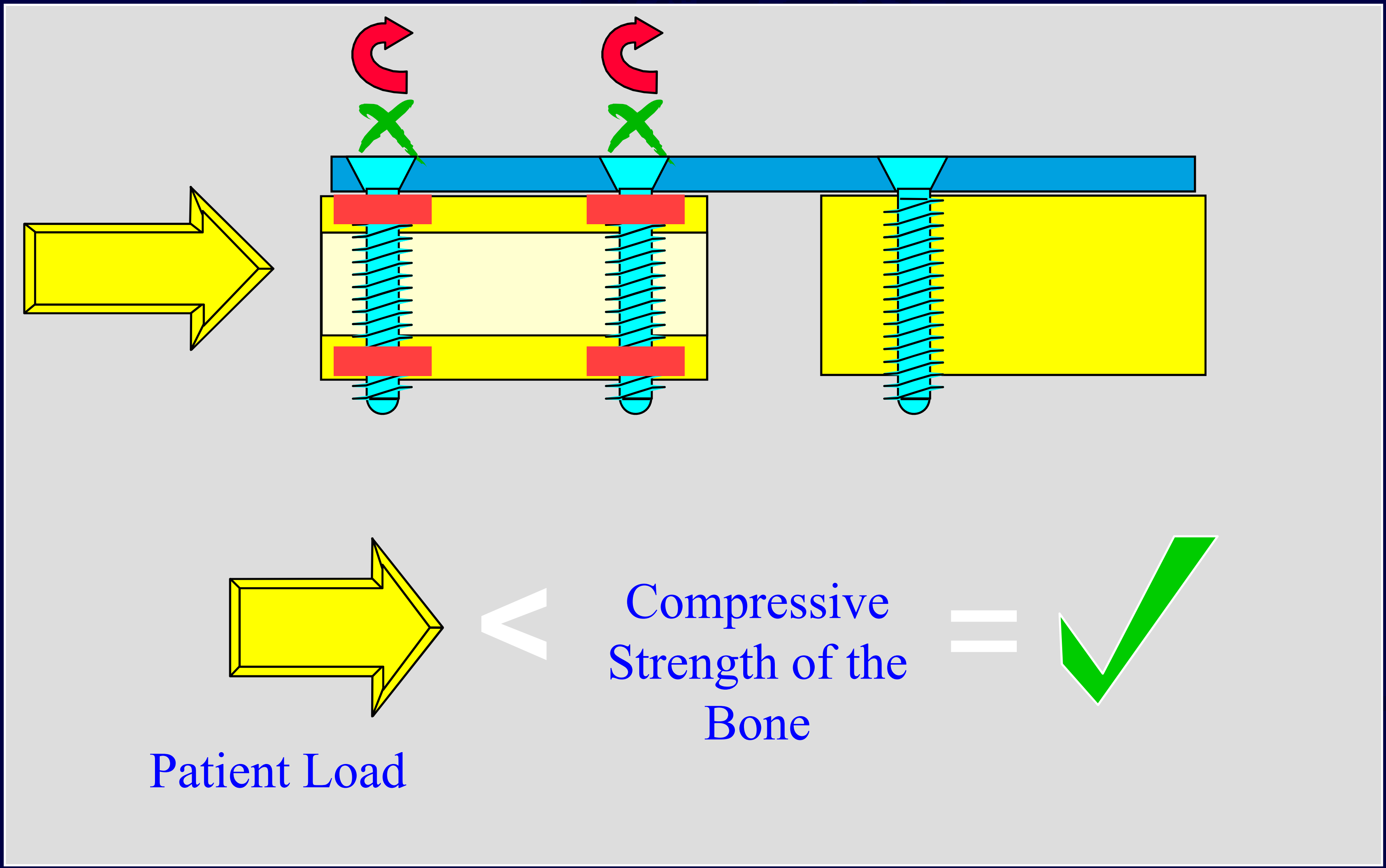
Conventional Plate Fixation





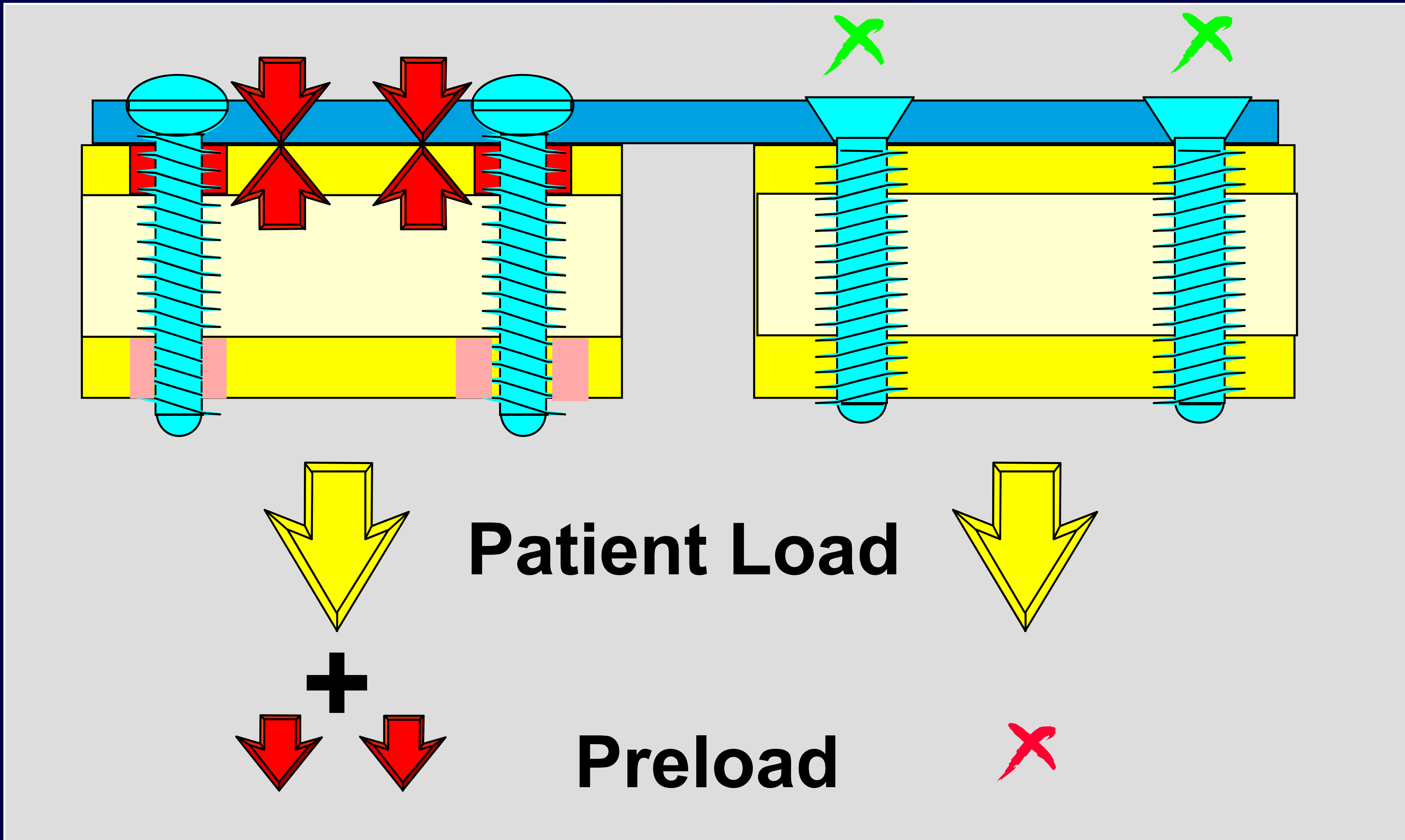
Courtesy of Synthes- Robi Frigg

Locked Plate and Screw Fixation



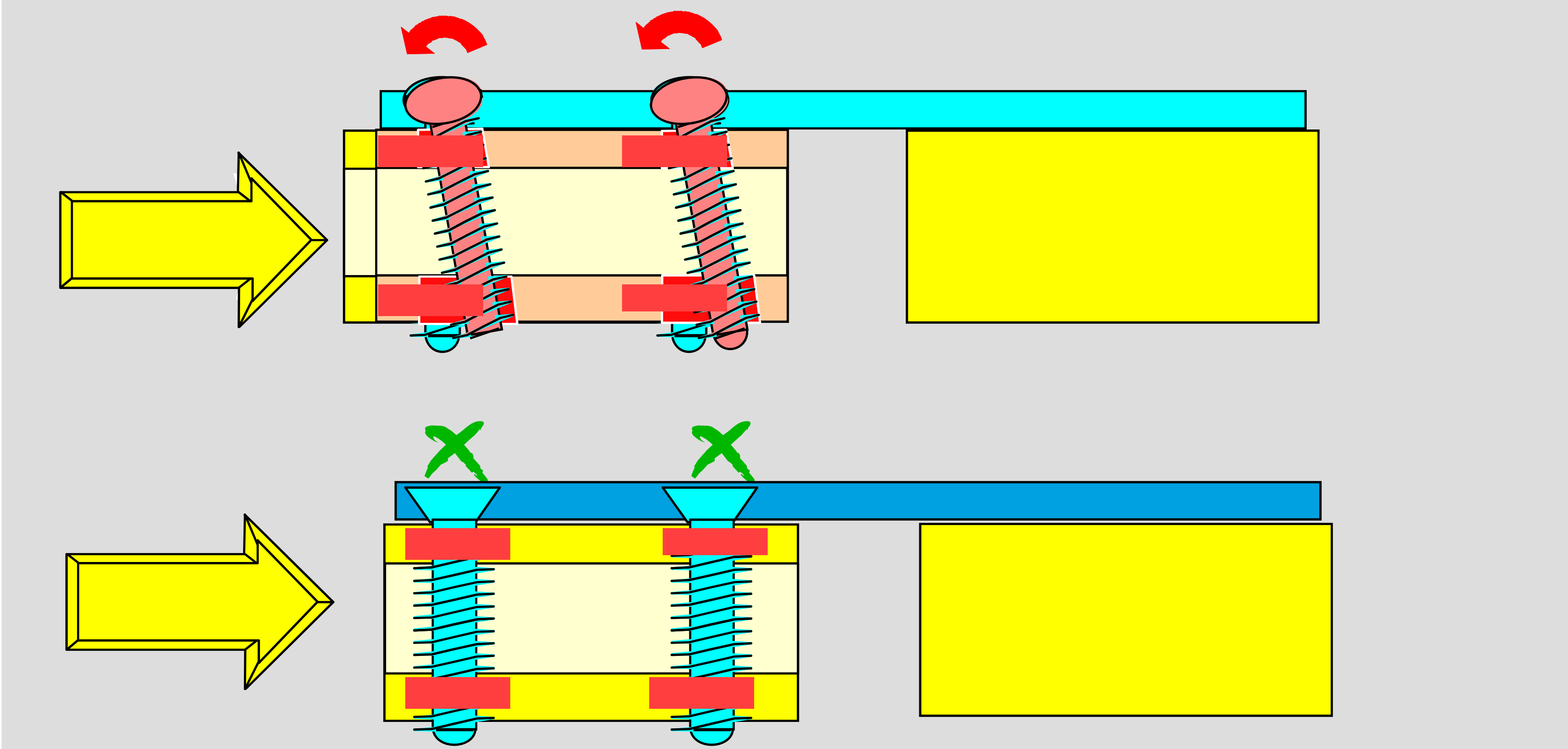
Courtesy of Synthes- Robi Frigg

Stress in the Bone



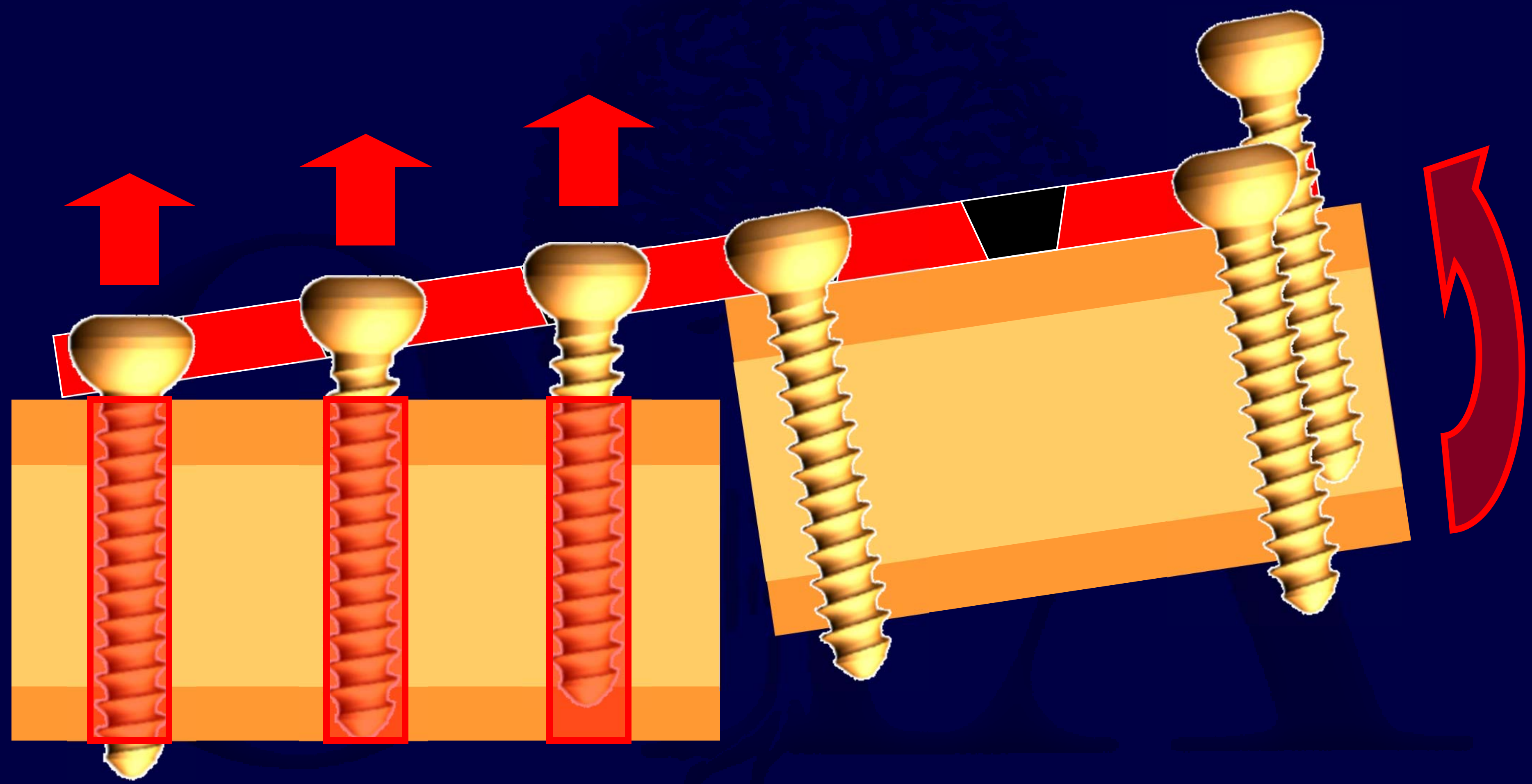
Courtesy of Synthes- Robi Frigg

Standard versus Locked Loading



Courtesy of Synthes- Robi Frigg

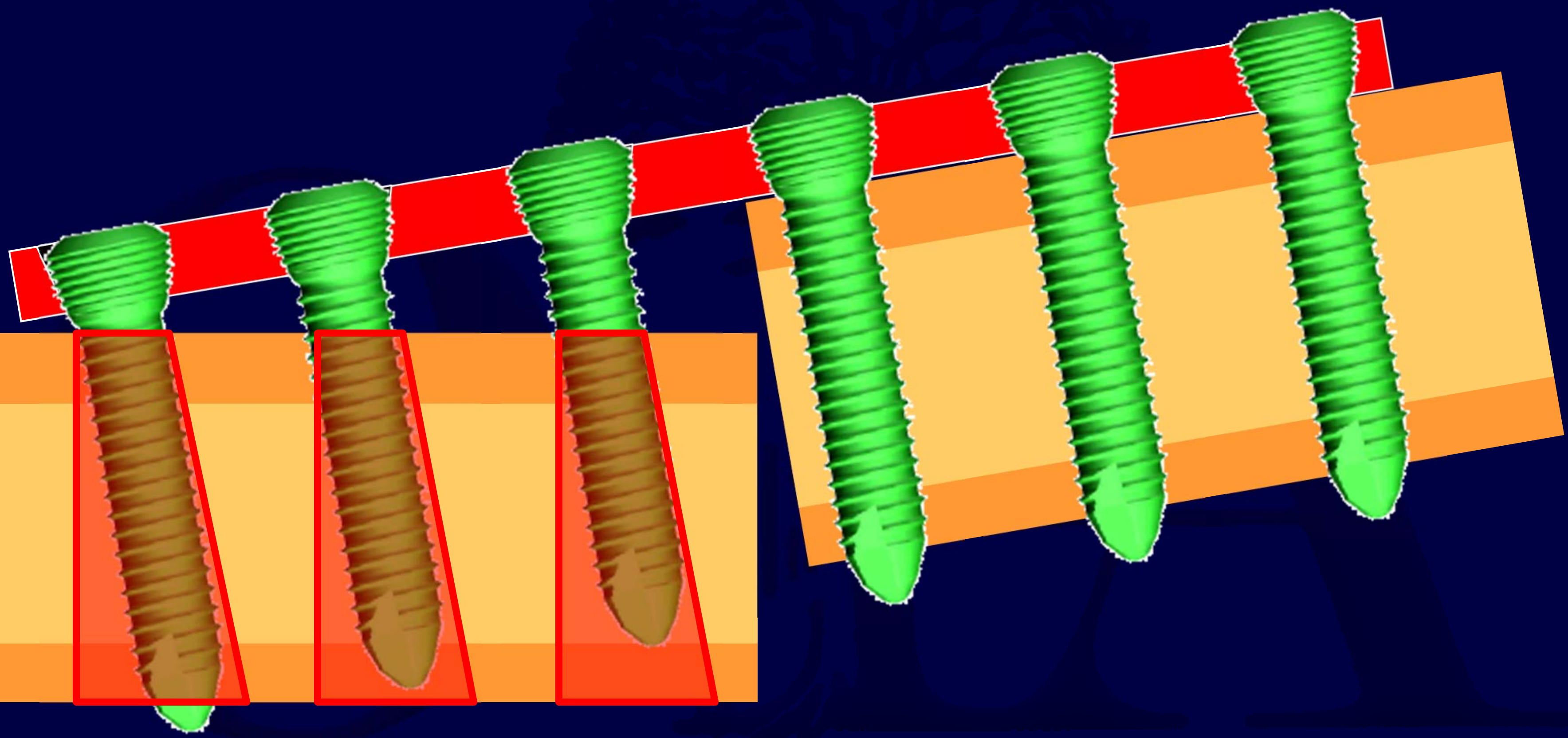
Pullout of regular screws



by bending load

Courtesy of Synthes- Robi Frigg

Higher resistant LHS against bending load

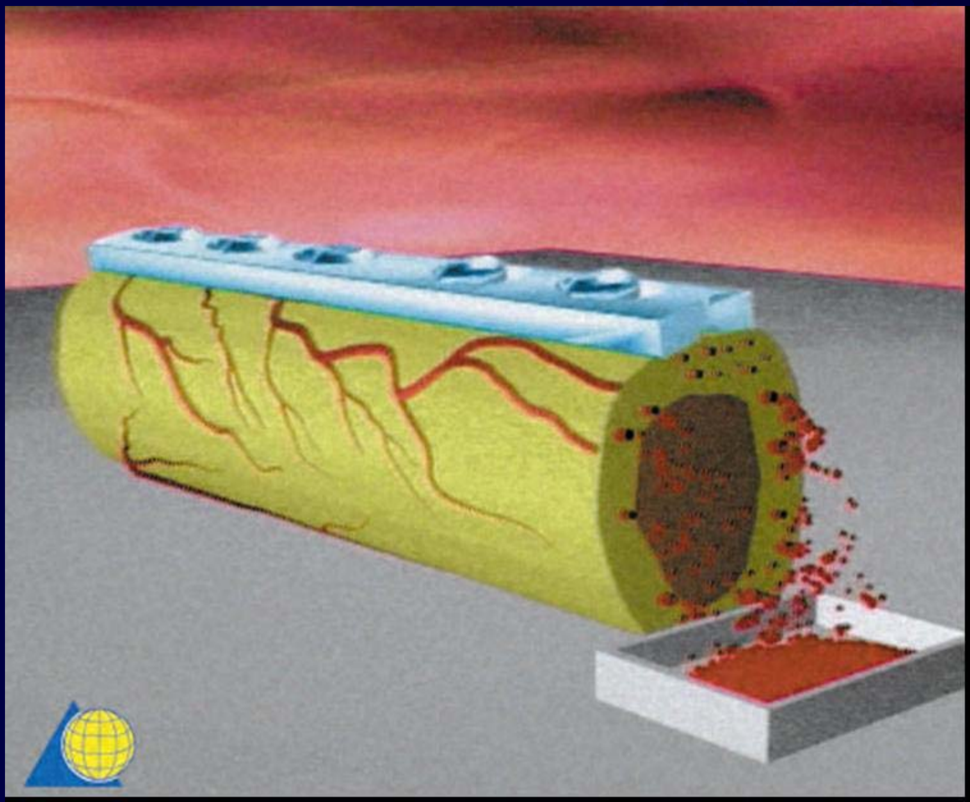


Larger resistant area

Biomechanical Advantages of Locked Plate Fixation

- Purchase of screws to bone not critical (osteoporotic bone)
- Preservation of periosteal blood supply
- Strength of fixation rely on the fixed angle construct of screws to plate
- Acts as “internal” external fixator

Preservation of Blood Supply
Plate Design



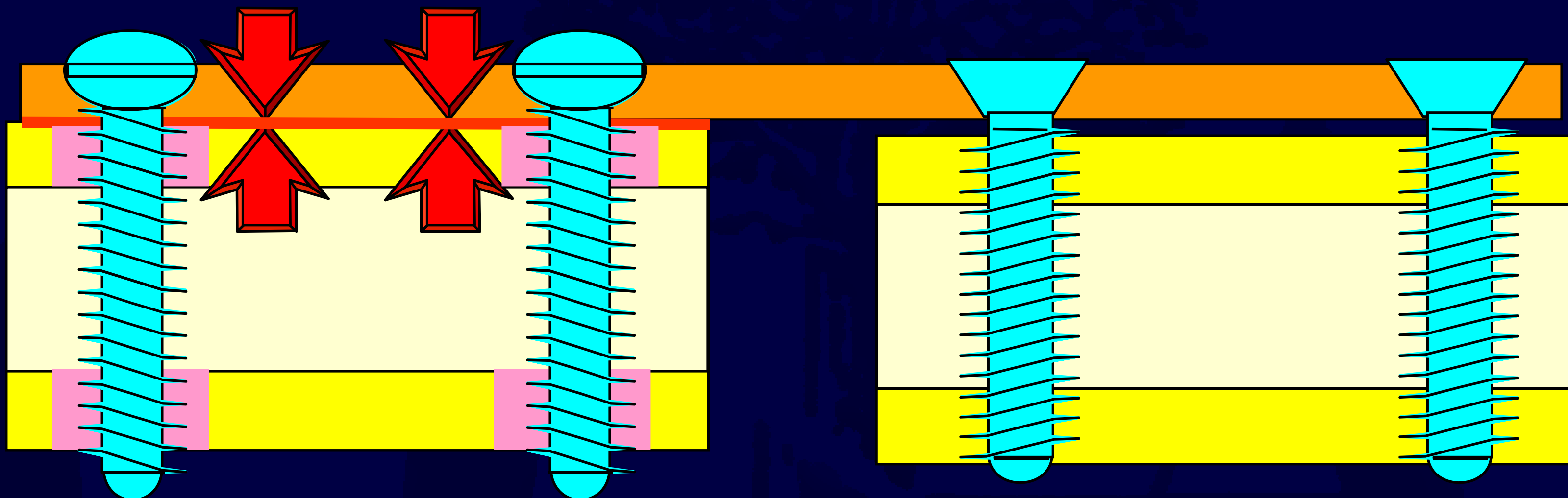
DCP

LCDCP

Courtesy of Synthes- Robi Frigg

Preservation of Blood Supply

Less bone pre-stress



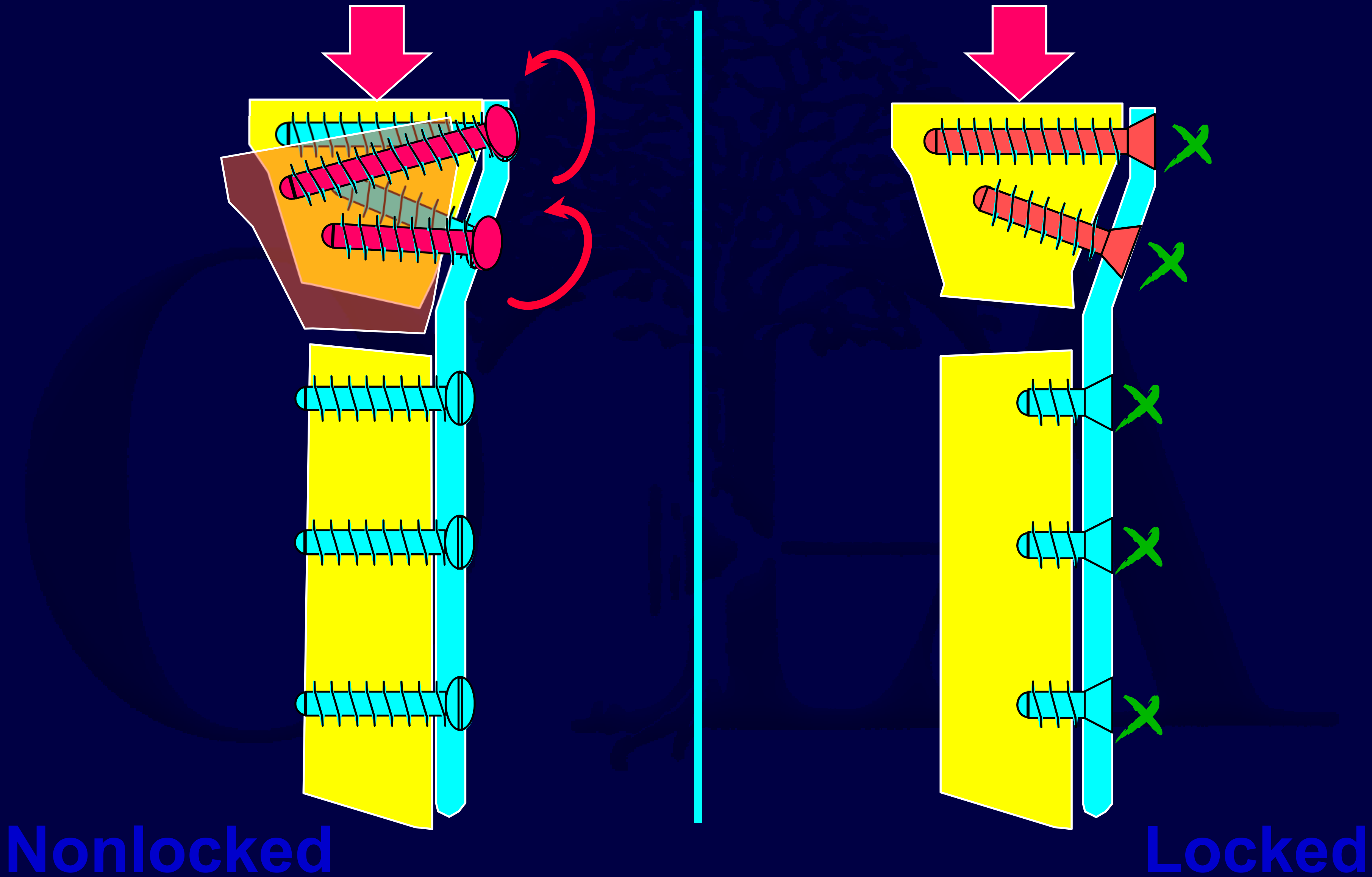
Conventional Plating

- Bone is pre-stressed
- Periosteum strangled

Locked Plating

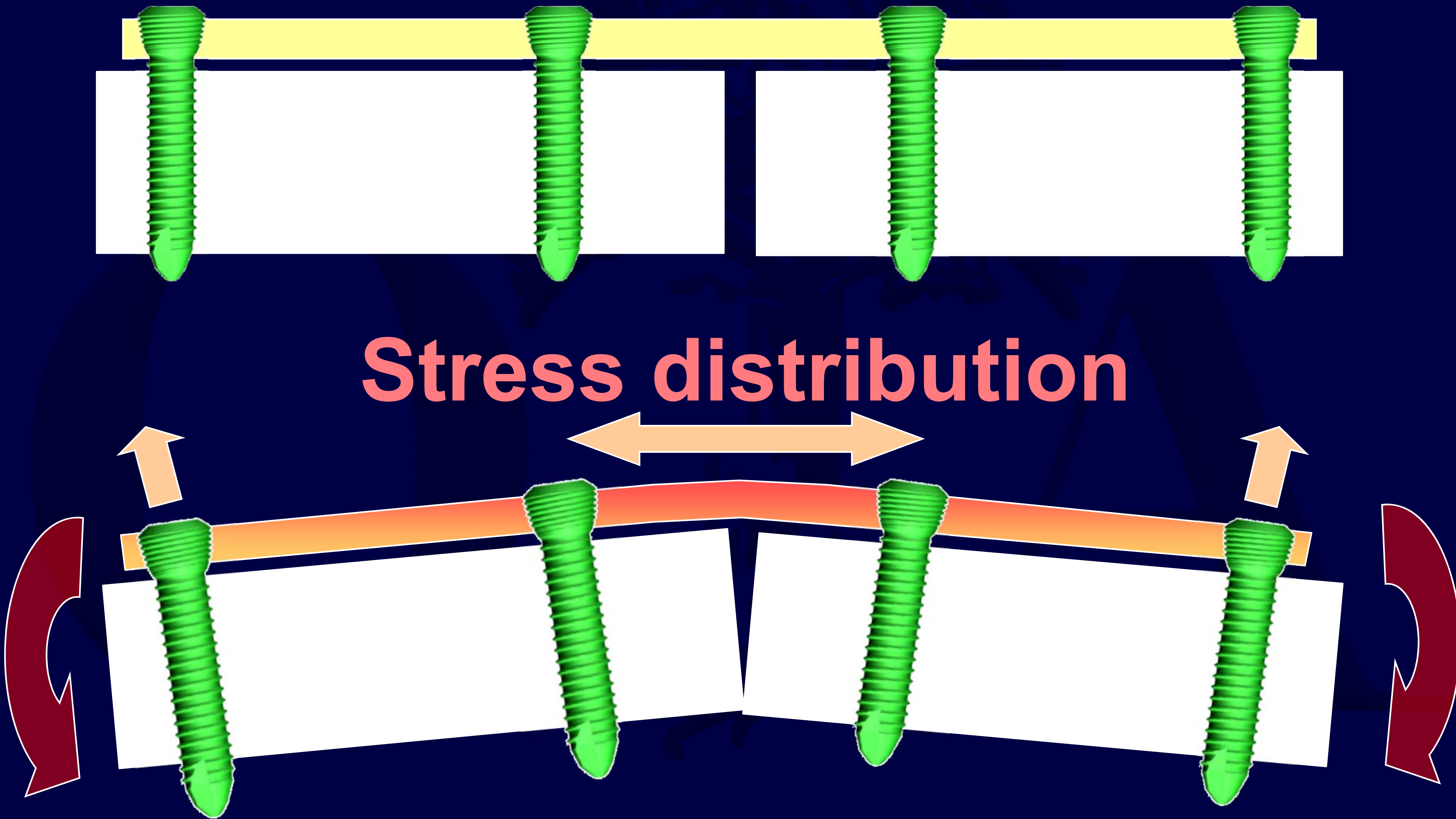
- Plate (not bone) is pre-stressed
- Periosteum preserved

Angular Stability of Screws



Courtesy of Synthes- Robi Frigg

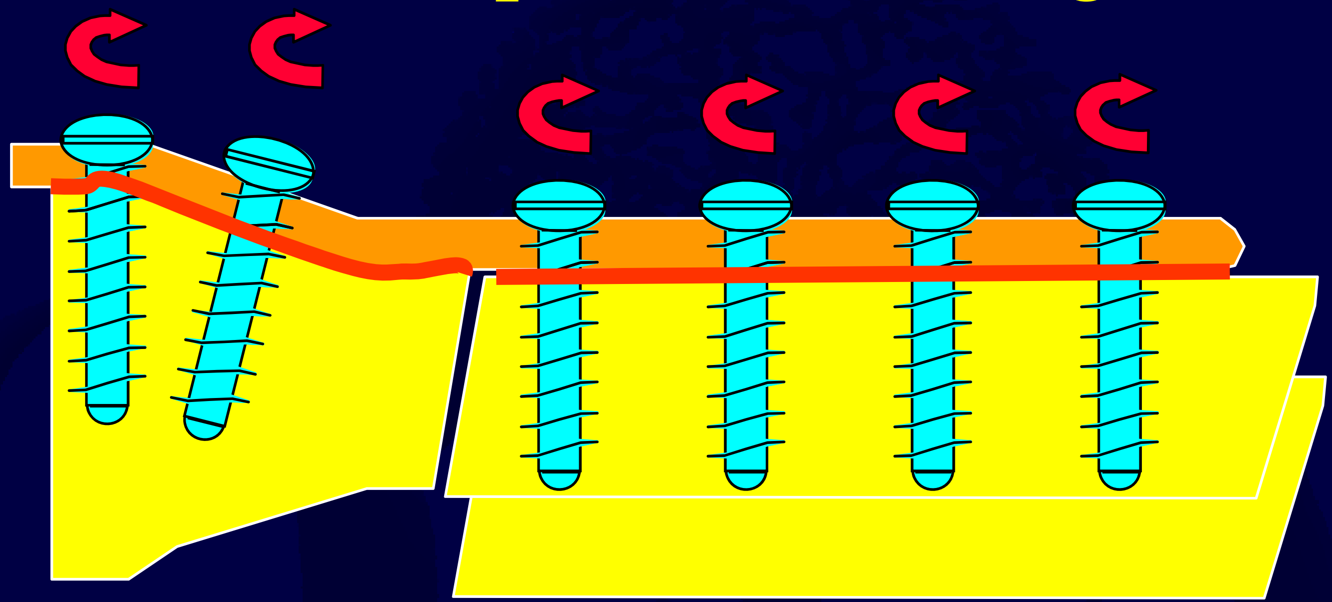
Biomechanical principles similar to those of external fixators



Courtesy of Synthes- Robi Frigg

Surgical Technique

Compression Plating

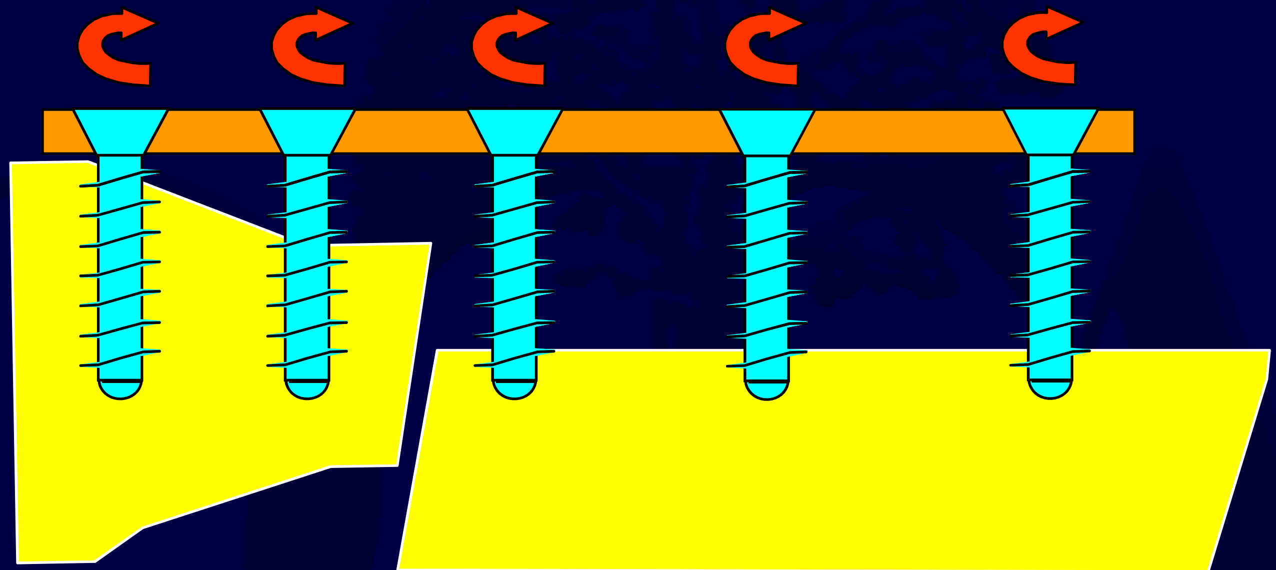


- The contoured plate maintains anatomical reduction as compression between plate and bone is generated.
- A well contoured plate can then be used to help reduce the fracture.

Traditional Plating

Surgical Technique

Reduction



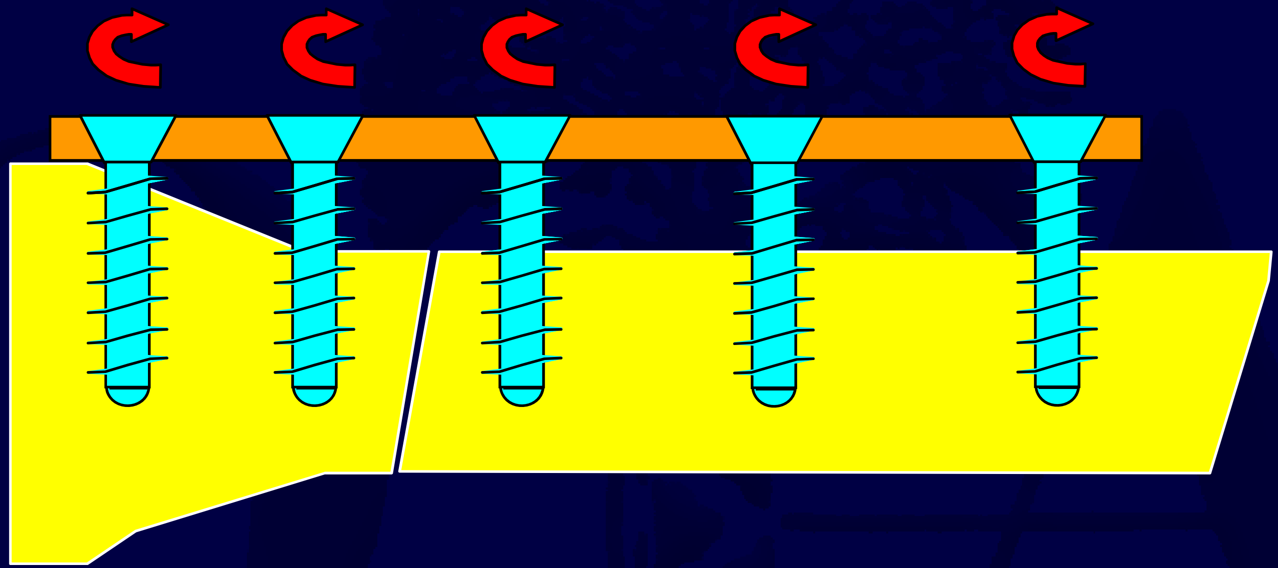
If the same technique is attempted with a locked plate and locking screws, an anatomical reduction will not be achieved.

Locked Plating

Courtesy of Synthes- Robi Frigg

Surgical Technique

Reduction



Instead, the fracture is first reduced and then the plate is applied.

Locked Plating

Surgical Technique

Precontoured Plates

Conventional Plating

1. Contour of plate is important to maintain anatomic reduction.

Locked Plating

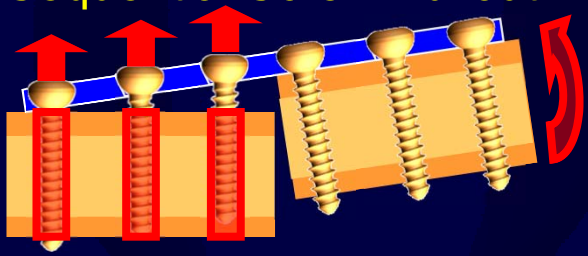
1. Reduce fracture prior to applying locking screws.

Unlocked *vs* Locked Screws

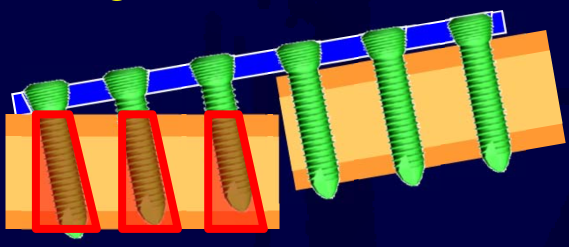
Biomechanical Advantage

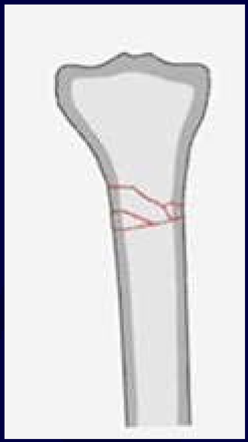
1. Force distribution
2. Prevent primary reduction loss
3. Prevent secondary reduction loss
4. “Ignores” opposite cortex integrity
5. Improved purchase on osteoporotic bone

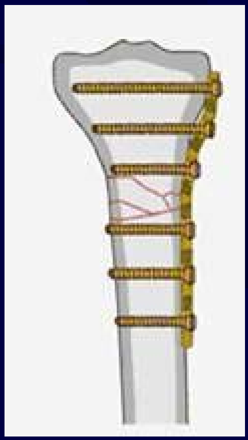
Sequential Screw Pullout



Larger area of resistance



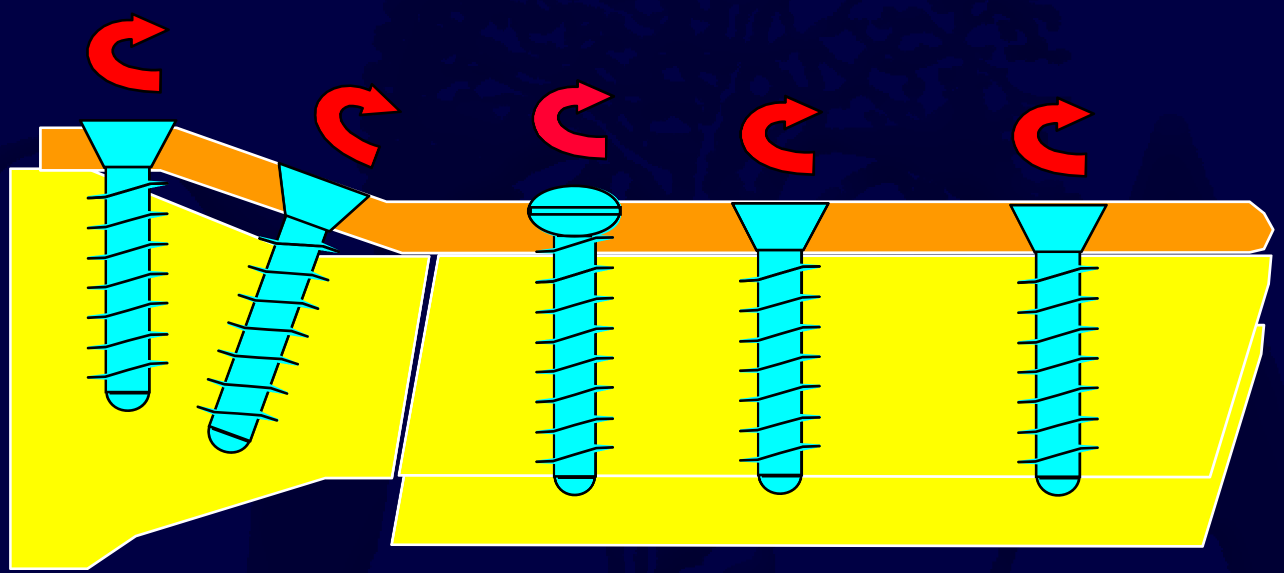




Courtesy of Synthes- Robi Frigg

Surgical Technique

Reduction with Combination Plate



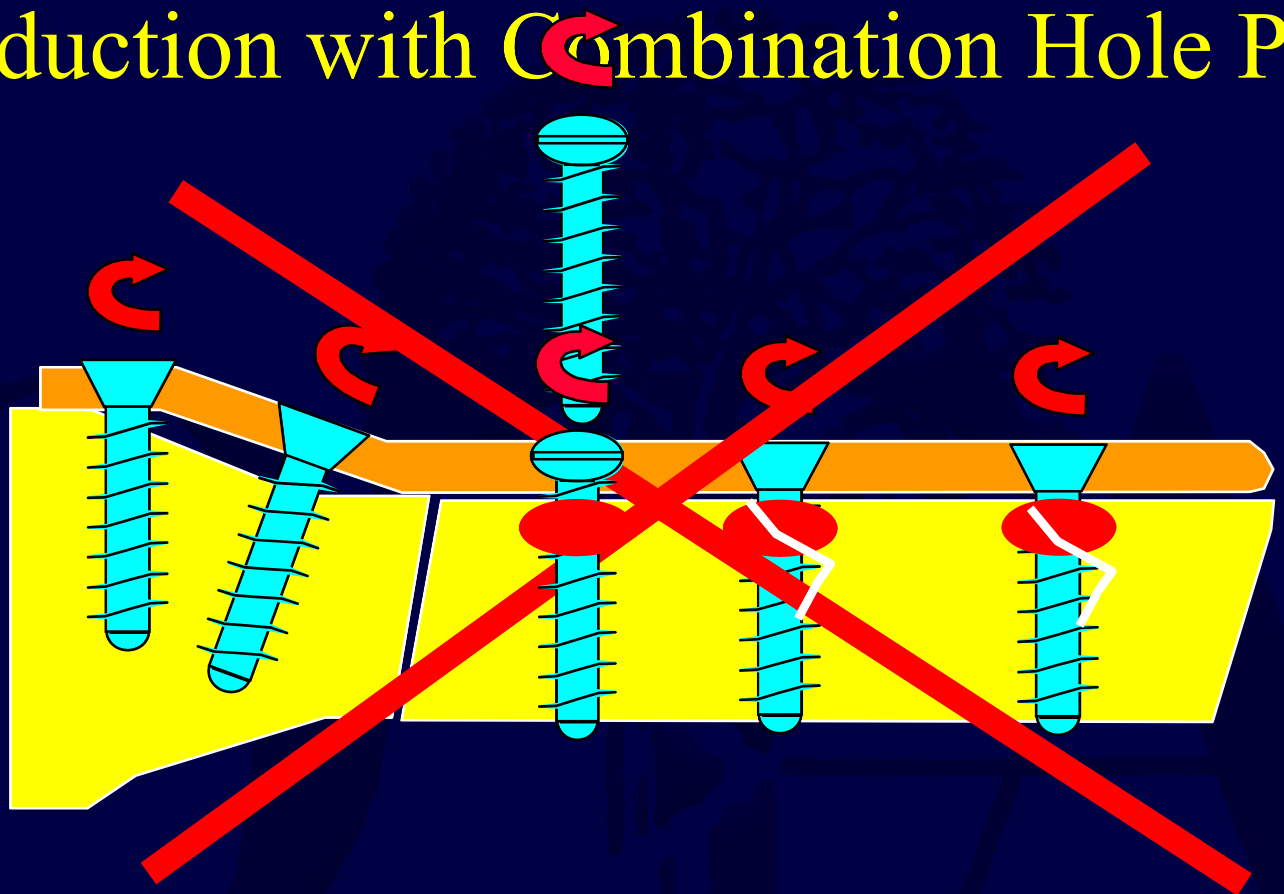
Lag screws can be used to help reduce fragments and construct stability improved w/ locking screws

Locked Plating

Courtesy of Synthes- Robi Frigg

Surgical Technique

Reduction with Combination Hole Plate



Lag screw must be placed 1st if locking screw in same fragment is to be used.

Locked Plating

Hybrid Fixation

- Combine benefits of both standard & locked screws
- Precontoured plate
- Reduce bone to plate, compress & lag through plate
- Increase fixation with locked screws at end of construct

Length of Construct

- Longer spread with less screws
  - "Every other" rule (3 screws / 5 holes)
- < 50% of screw holes filled
- Avoid too rigid construct

Further Reading

- Tencer, A.F. & Johnson, K.D., "Biomechanics in Orthopaedic Trauma," Lippincott.
- "Orthopaedic Basic Science," AAOS.
- Browner, B.D., et al, "Skeletal Trauma," Saunders.
- Radin, E.L., et al, "Practical Biomechanics for the Orthopaedic Surgeon," Churchill-Livingstone.
- Tornkvist H et al, "The Strength of Plate Fixation in Relation to the Number and Spacing of Bone Screws," JOT 10(3), 204-208
- Egol K.A. et al, "Biomechanics of Locked Plates and Screws," JOT 18(8), 488-493
- Haidukewych GJ & Ricci W, "Locked Plating in Orthopaedic Trauma: A Clinical Update," JAAOS 16(6),347-355

Questions?

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