Finite Element Analysis of Radius and Ulna

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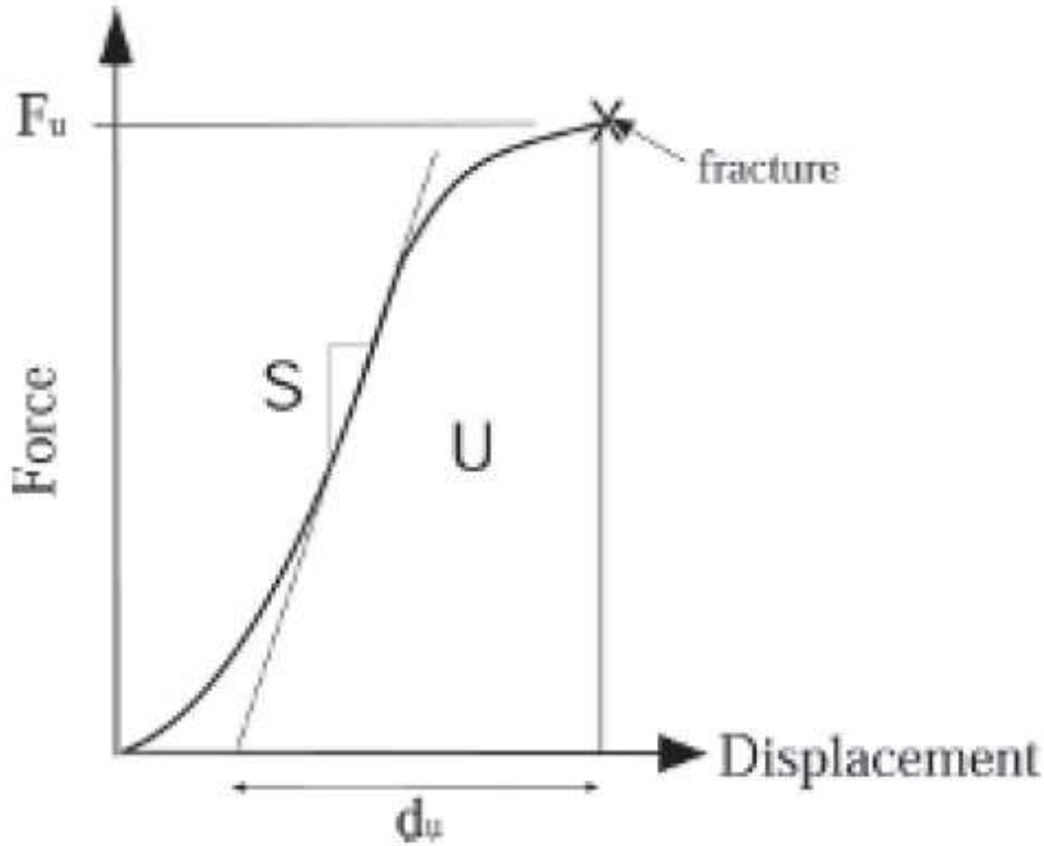
Outline

- Review bone biomechanics
  - bone behavior during fracture
- Stress analysis concepts
  - properties of bone for models
- Fracture simulations
- Analysis results
- Conclusion

Why Bones Break

- Key relationship: force applied to a structure and displacement

S → stiffness
F_u → ultimate force
U → work to failure
d_u → ultimate displacement

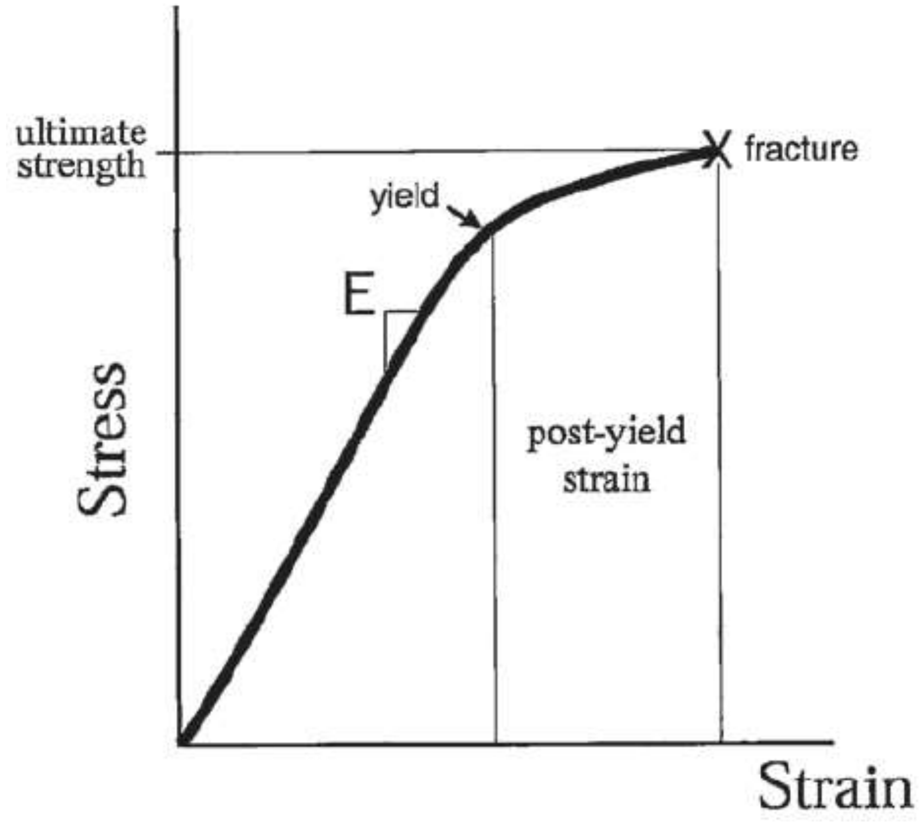


Why Bones Break

- Re-express force and displacement as stress and strain
- Stress $\sigma = \frac{F}{A} = \frac{N}{m^2} = Pa$
  - 1 Pa ≈ 1 apple on square meter tabletop
- Strain $\varepsilon = \frac{\Delta l}{L}$
  - ratio of lengths so unitless

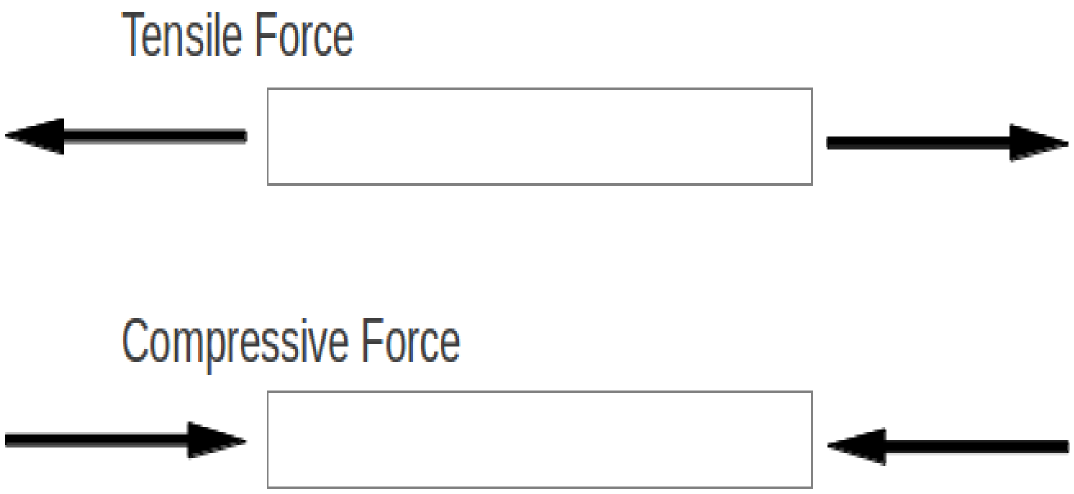
Why Bones Break

- Similar to force-displacement curve
- E = intrinsic stiffness
- Strength is intrinsic property of bone
- Force required to break varies with bone size
- Post yield = permanent



Analysis Concepts

- Young's Modulus
- Shear Modulus
- Poisson's Ratio
- No density

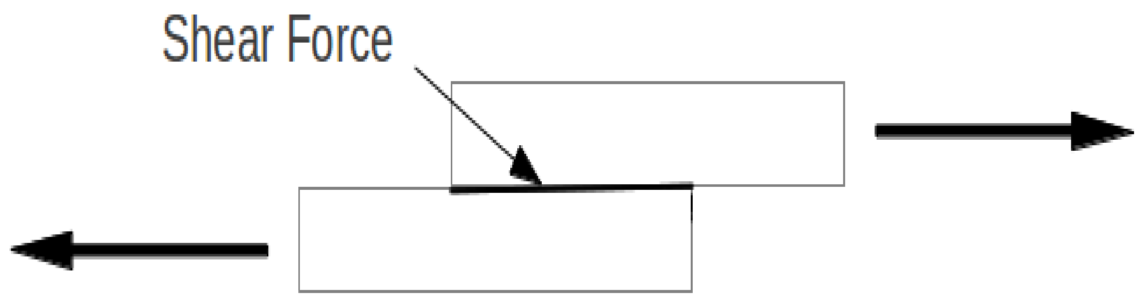


$$E = \frac{F_n/A}{\varepsilon_l}$$

E = Young's modulus
F_n = force normal to faces
A = area
ε_l = linear strain

Analysis Concepts

- Young's Modulus
- Shear Modulus
- Poisson's Ratio
- No density



$$S = \frac{F_p/A}{\varepsilon_s}$$

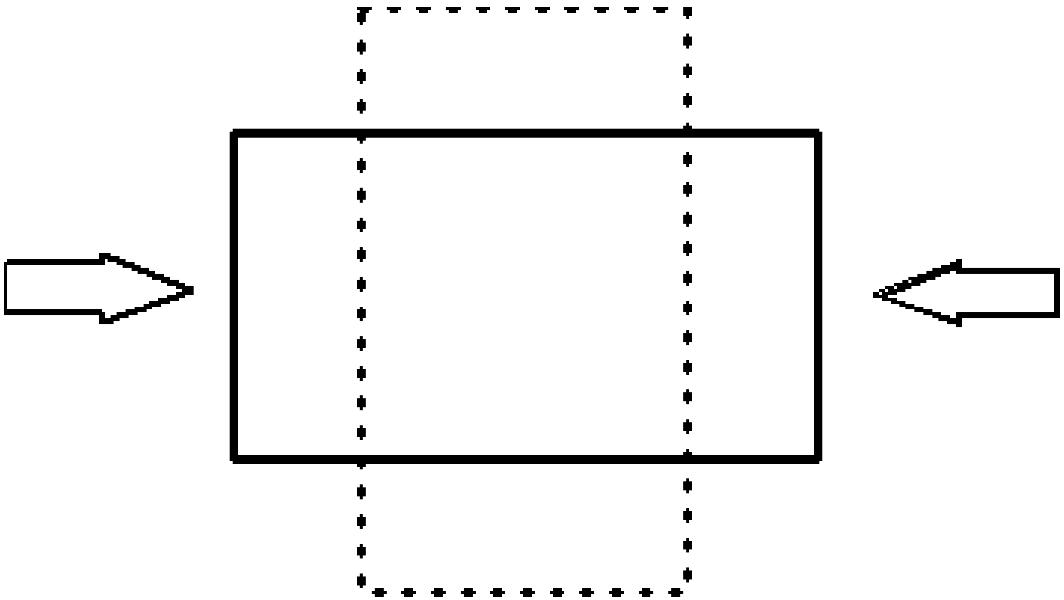
S = shear modulus
F_p = force parallel to faces
A = area
ε_s = shear strain

Analysis Concepts

- Young's Modulus
- Shear Modulus
- Poisson's Ratio
- No density

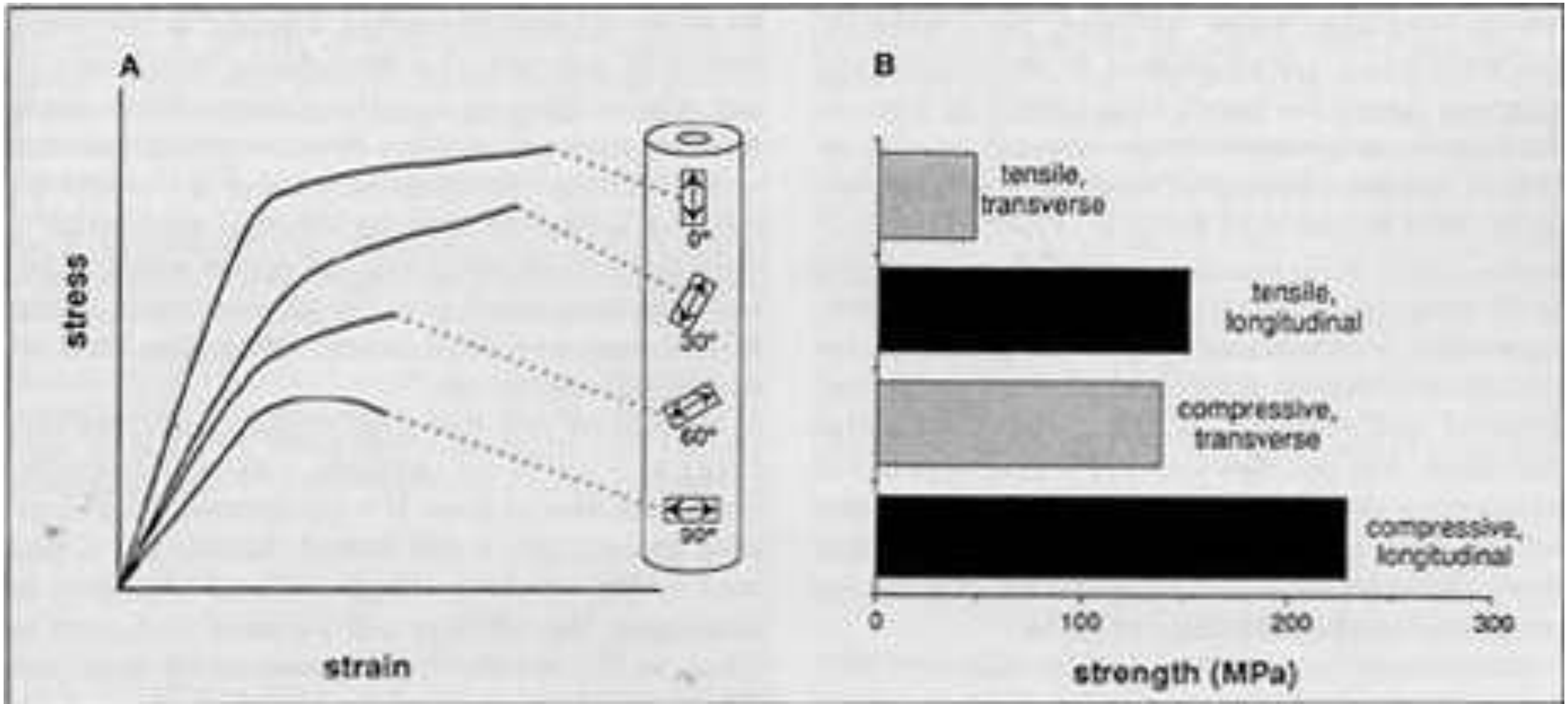
$$\upsilon = -\frac{\varepsilon_t}{\varepsilon_l}$$

υ = Poisson's ratio
ε_t = transverse strain
ε_l = longitudinal or axial strain



Analysis Concepts

- Ultimate stress increases from transverse to longitudinal force
- Also dependent on tensile or compressive force

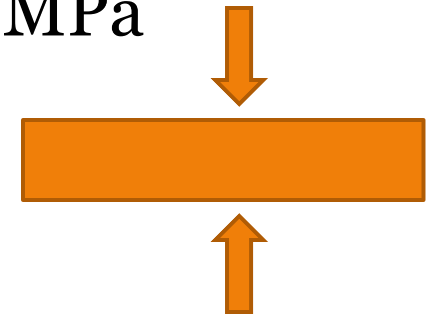


Analysis Concepts

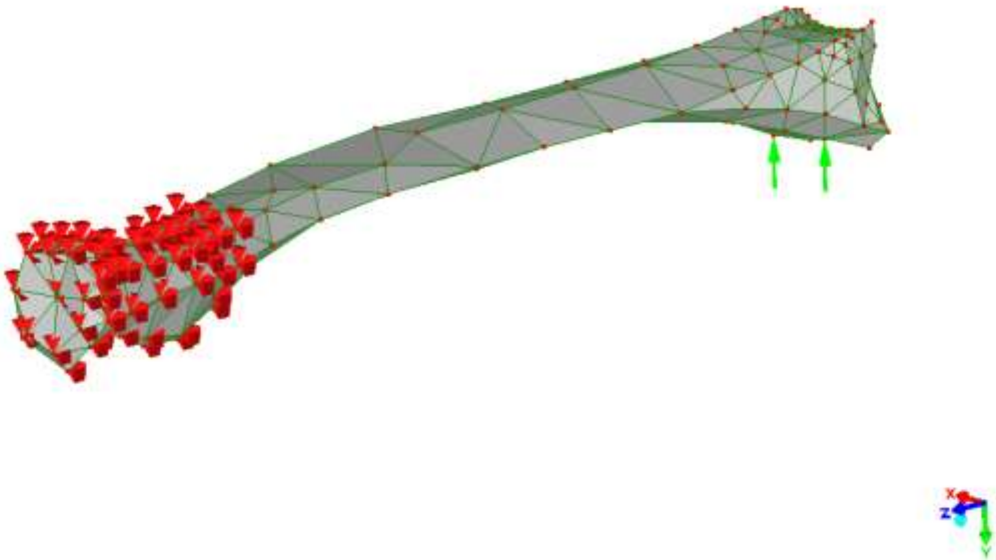
- Bone property values

	Longitudinal	Transverse
Young's Modulus	17 GPa	11.5 GPa
Shear Modulus	3.6 GPa	3.3 GPa
Poisson's Ratio	0.6	0.3

- Ultimate stresses:
  - Longitudinal compression: 200 MPa
  - Longitudinal tension: 140 MPa
  - Transverse compression: 130 MPa

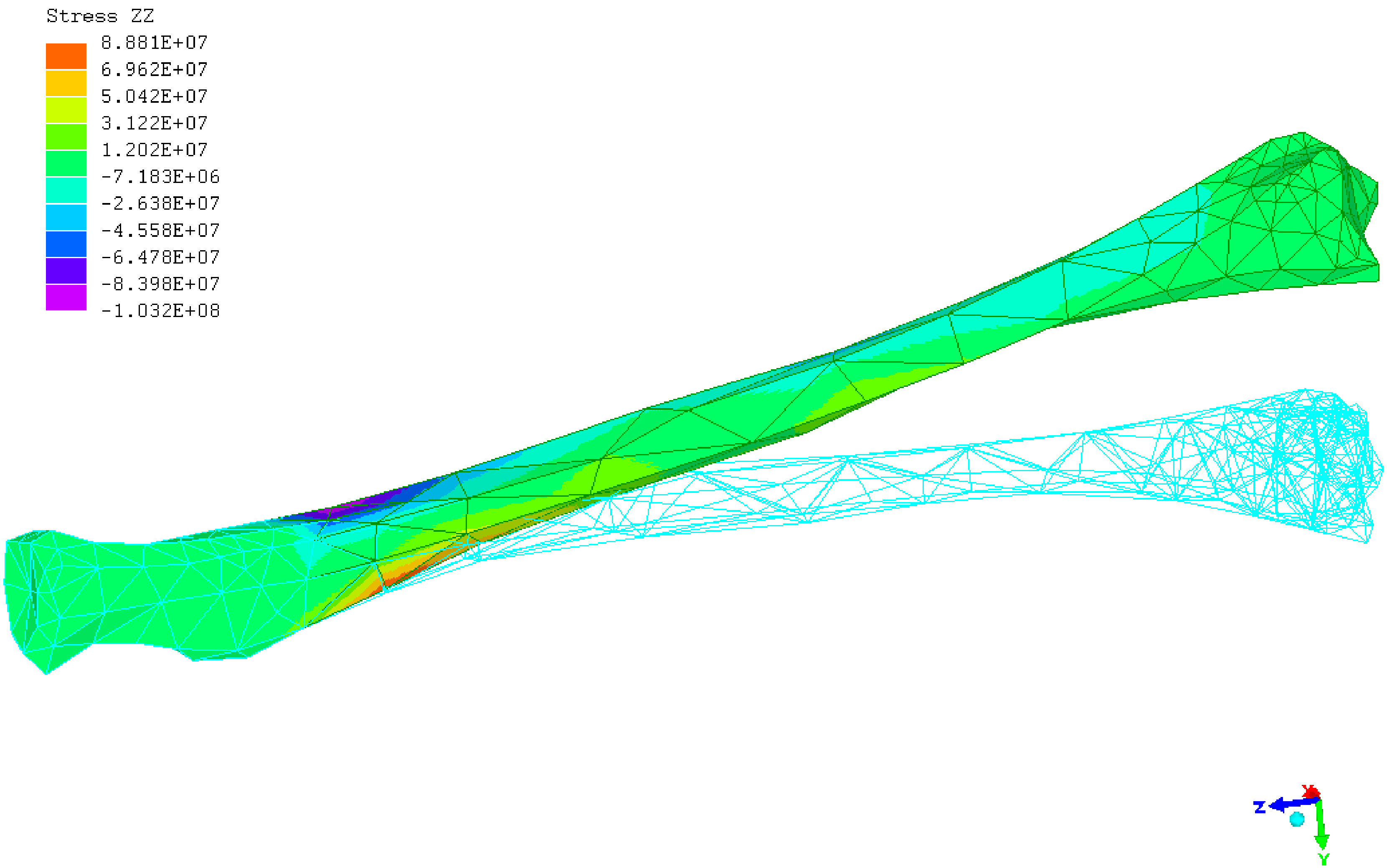


Radius
Catching Fall



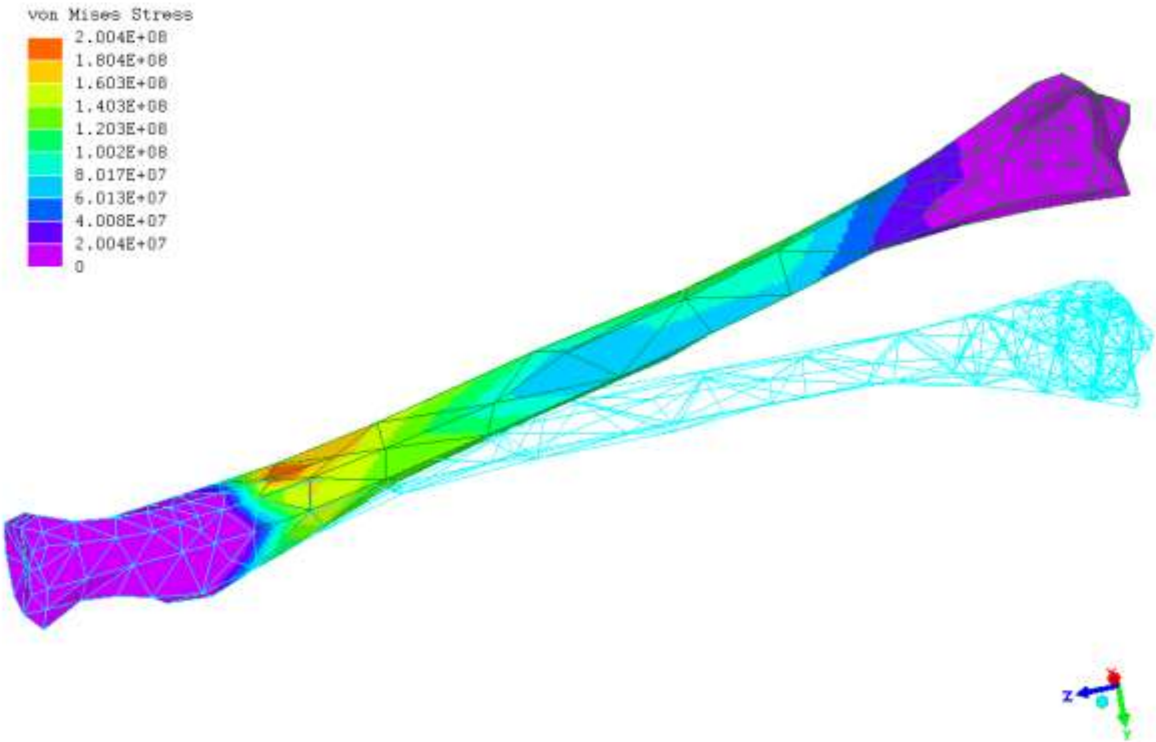
- Hold proximal end fixed
- Forces applied to underside of distal end
- Expected stresses:
  - Compression on top near constraints
  - Tension on opposite side

Radius Catching Fall



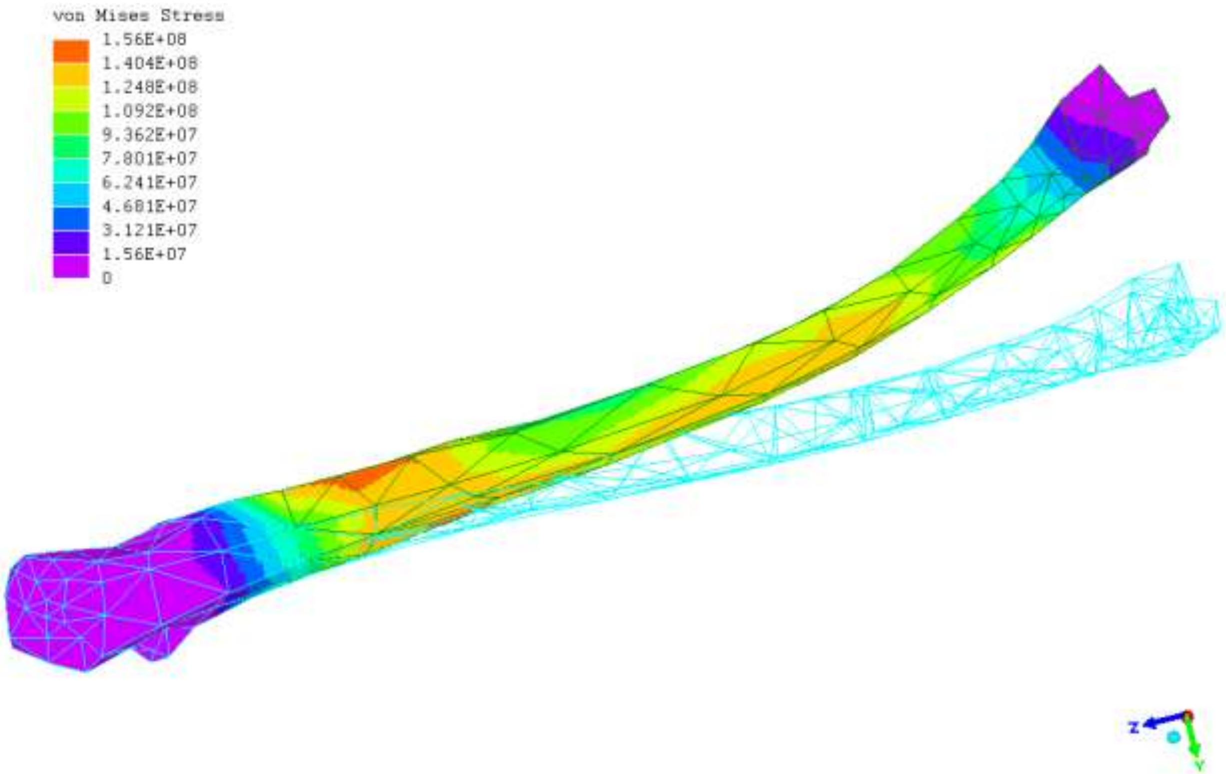
Radius Catching Fall

- Von Mises Stress: combines linear and shear stresses from all directions into one value
- Max compression: 180 MPa – 200 MPa
- Max tension: 140 MPa – 160 MPa
- Fracture from tension most likely
- Applied force of 1160 N

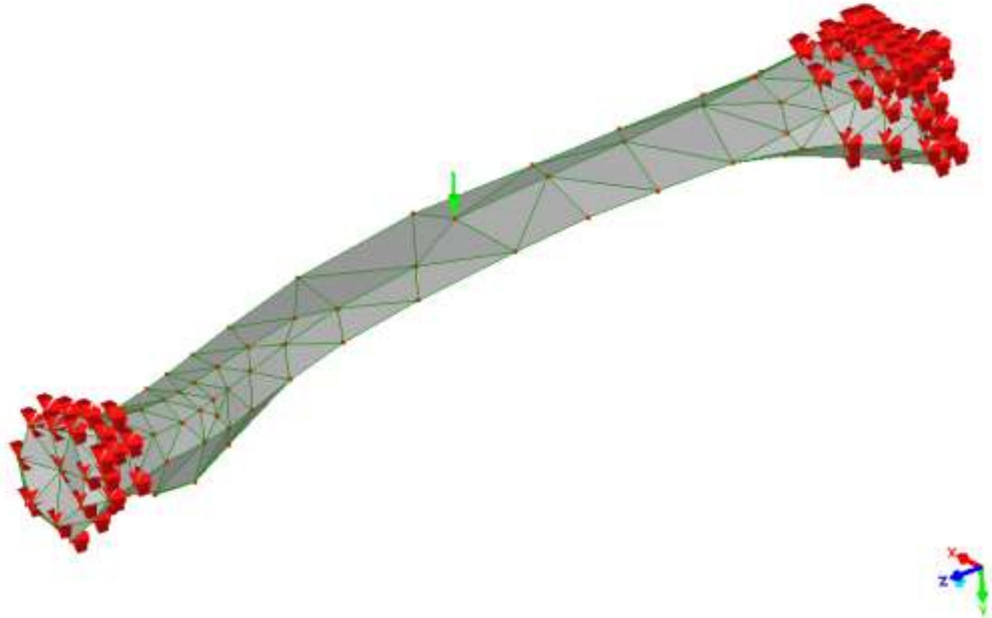


Ulna Catching Fall

- Max compression and tension: 140 MPa – 156 MPa
- Tension only cause of fracture
- Applied force of 1610 N

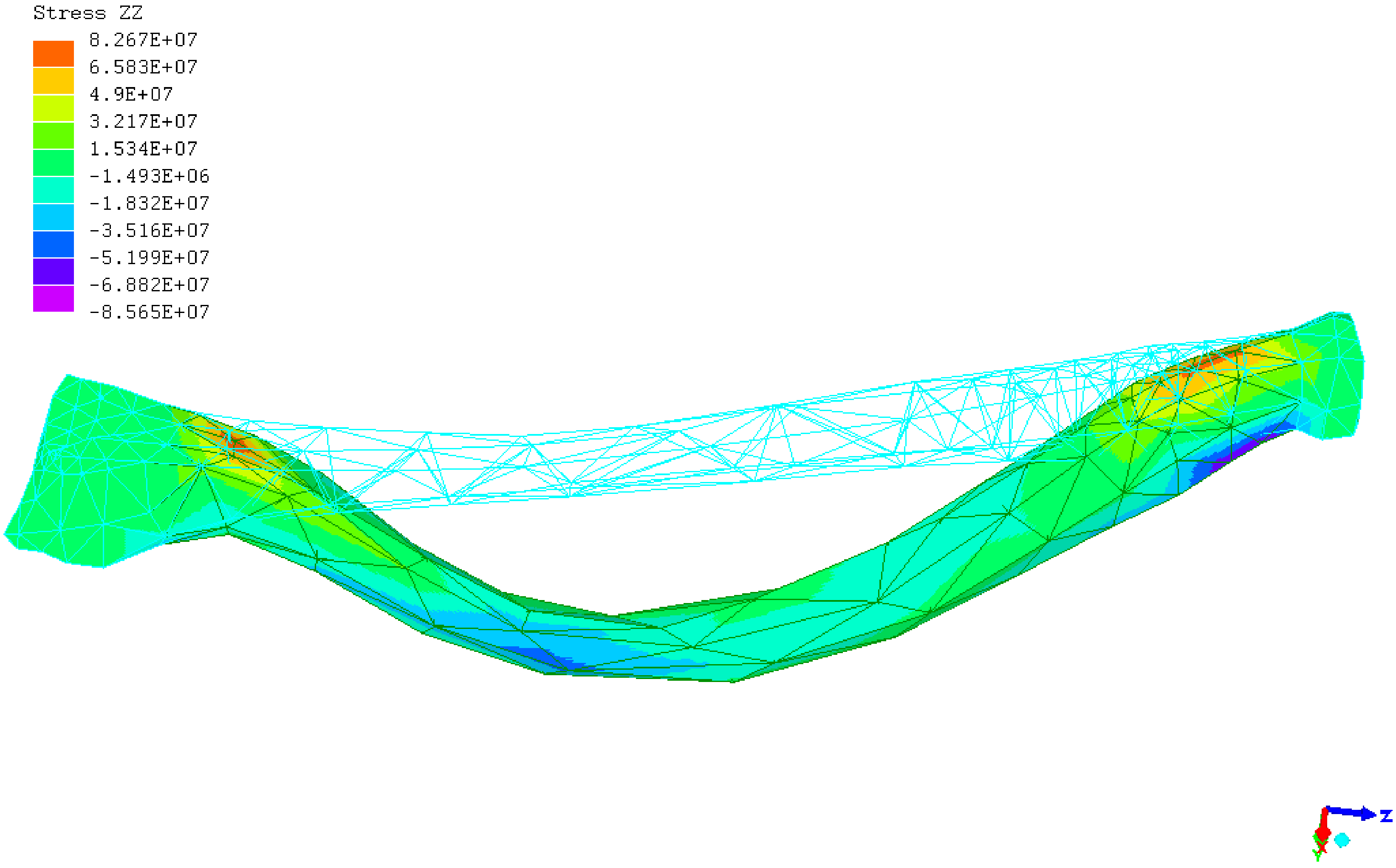


Radius Middle Load



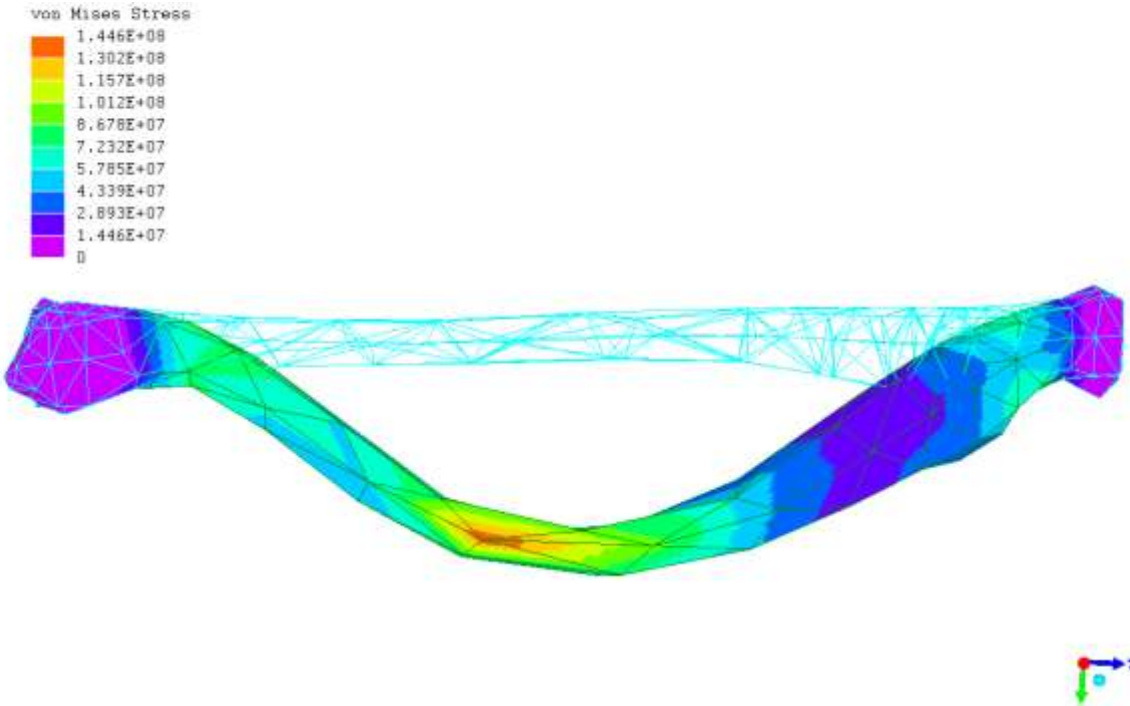
- Proximal and distal ends fixed
- Load applied at midpoint of bone
- Expected stresses:
  - Compression/tension near constraints
  - Transverse compression at midpoint

Radius Middle Load



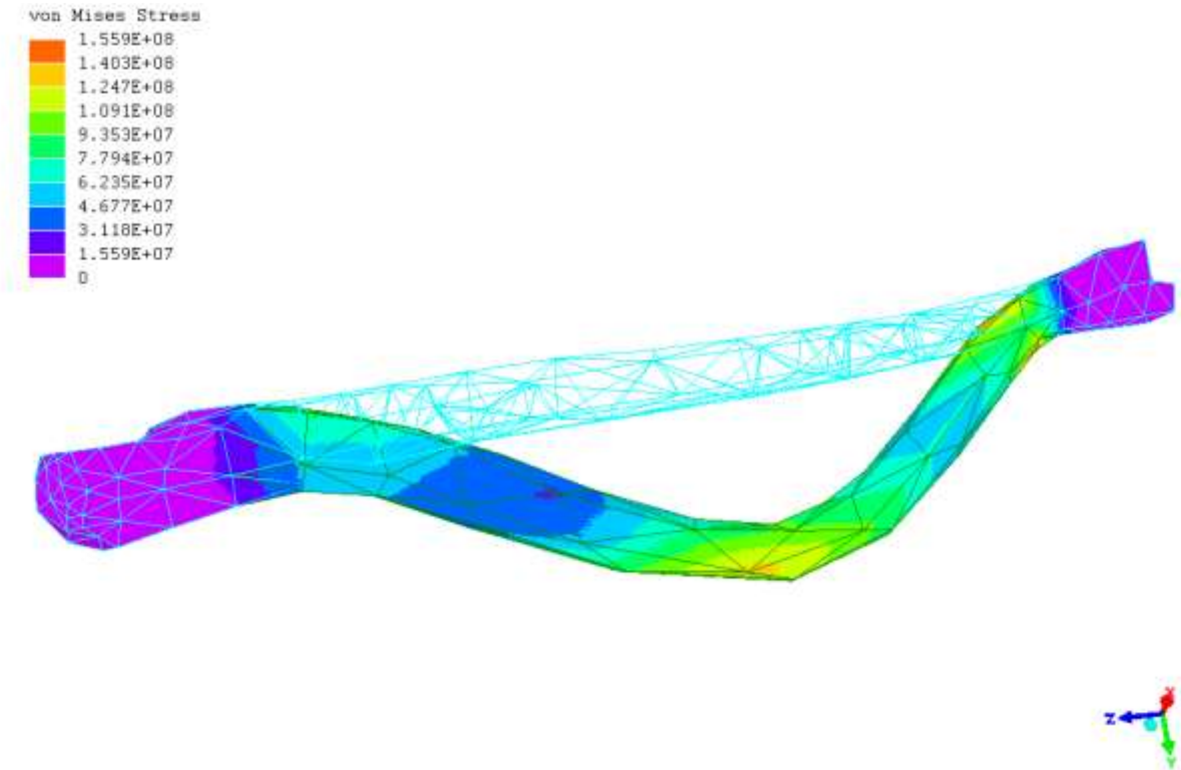
Radius Middle Load

- Max compression: 130 MPa – 145 MPa
- Max tension: 72 MPa – 87 MPa
- Fracture near center due to compression
- Applied force of 4720 N

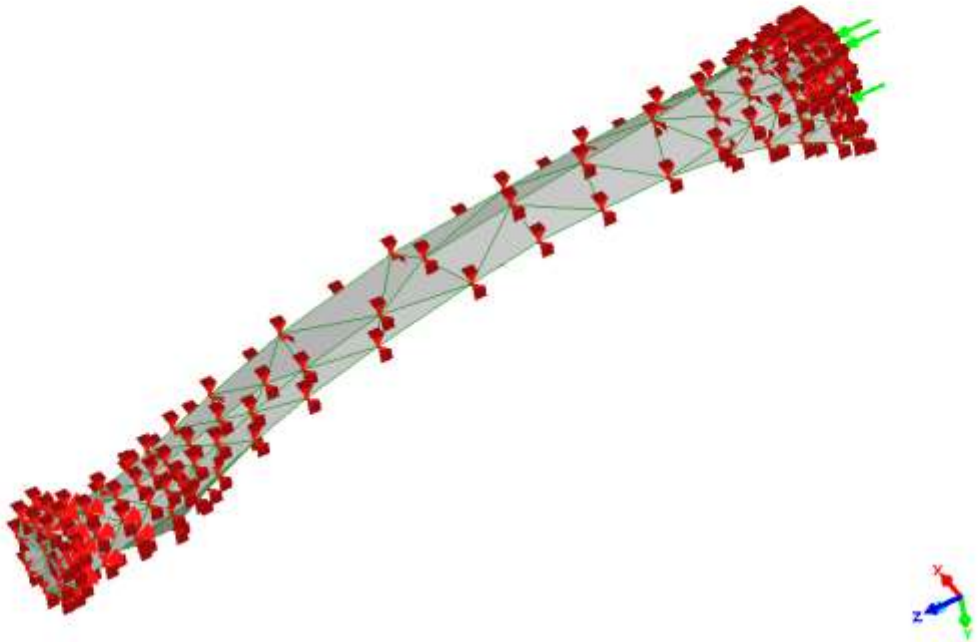


Ulna Middle Load

- Max compression: 125 MPa – 140 MPa
- Max tension: 140 MPa – 156 MPa
- Fracture near midpoint from compression
- Fracture from tension at wrist
- Applied force of 7450 N

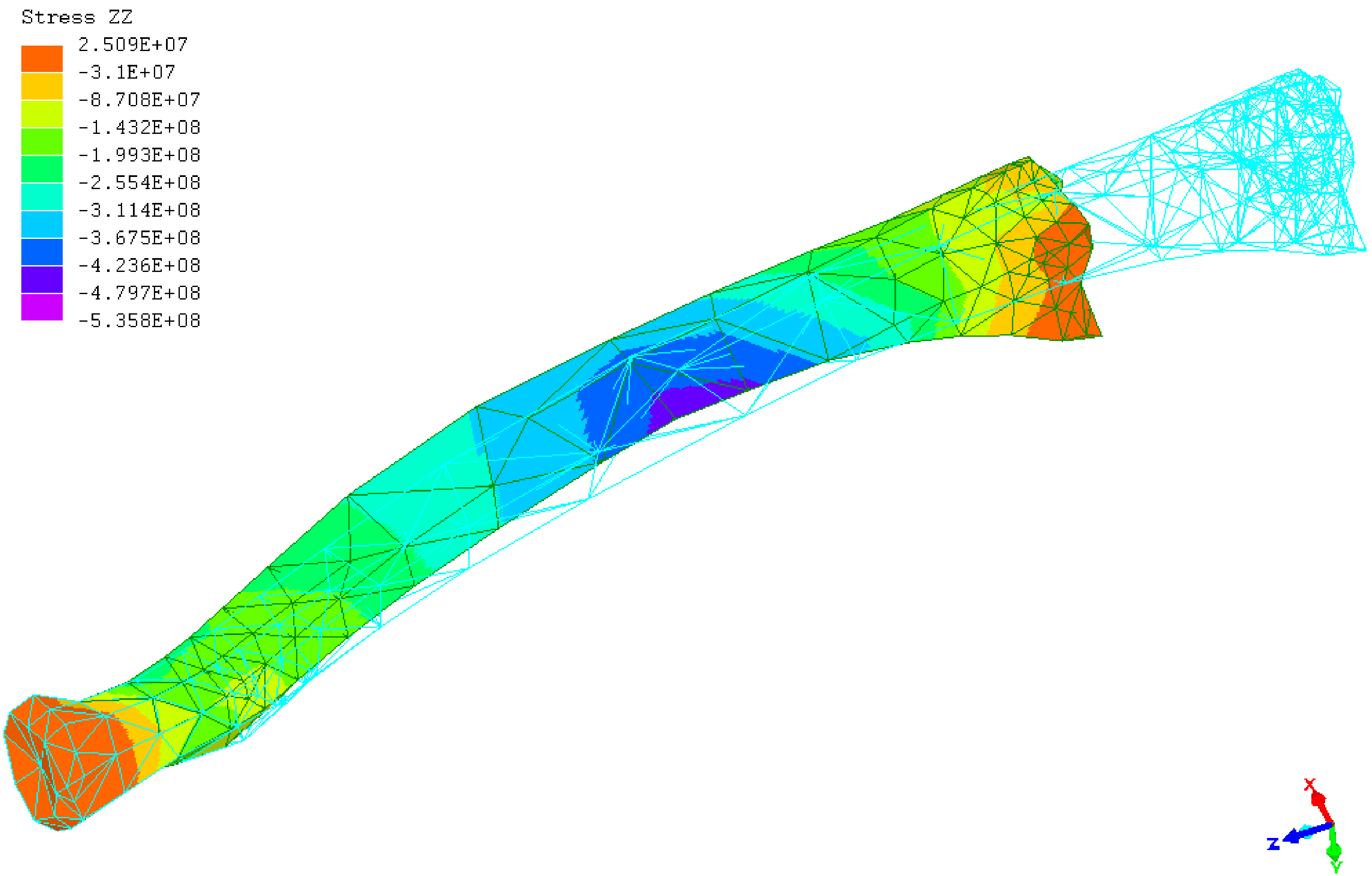


Radius
Compress Ends



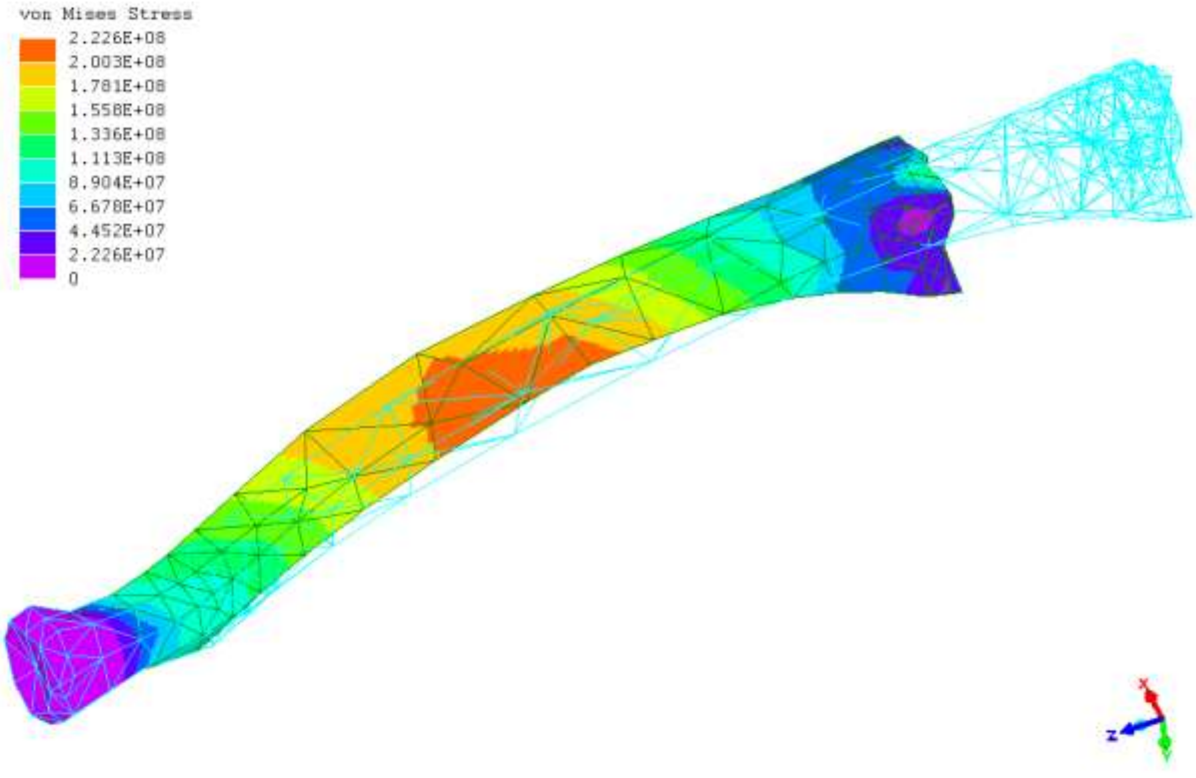
- Proximal end fixed
- Rest of bone limited to motion along z-axis
- Expected stresses:
  - compression throughout bone

Radius Compress Ends



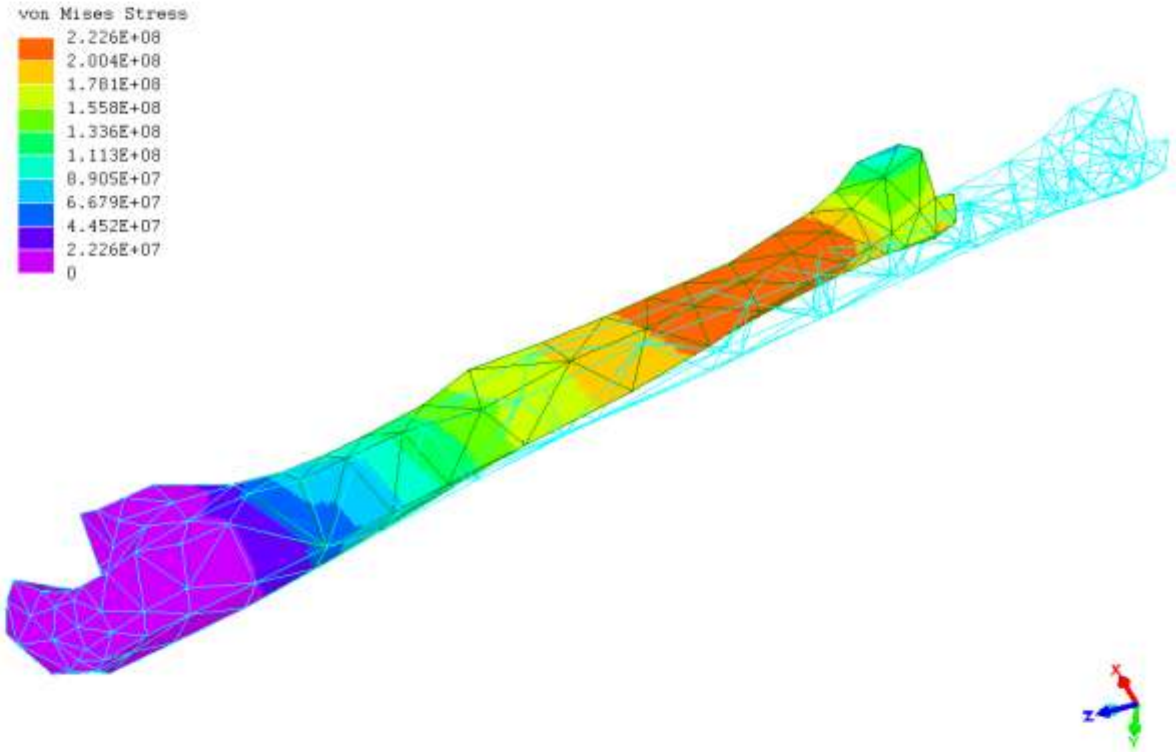
Radius Compress Ends

- Max compression: 200 MPa – 223 MPa
- No tension
- Fracture near center due to longitudinal compression
- Applied force of 34,200 N



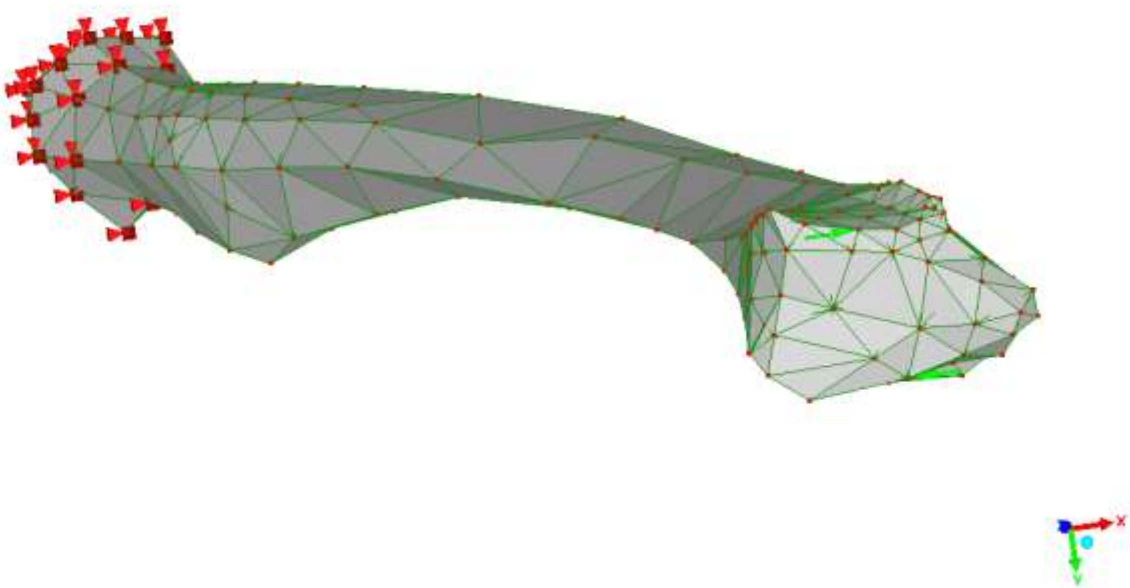
Ulna Compress Ends

- Max compression: 200 MPa – 223 MPa
- No tension
- Fracture more toward distal end than for radius
- Applied force of 40,200 N

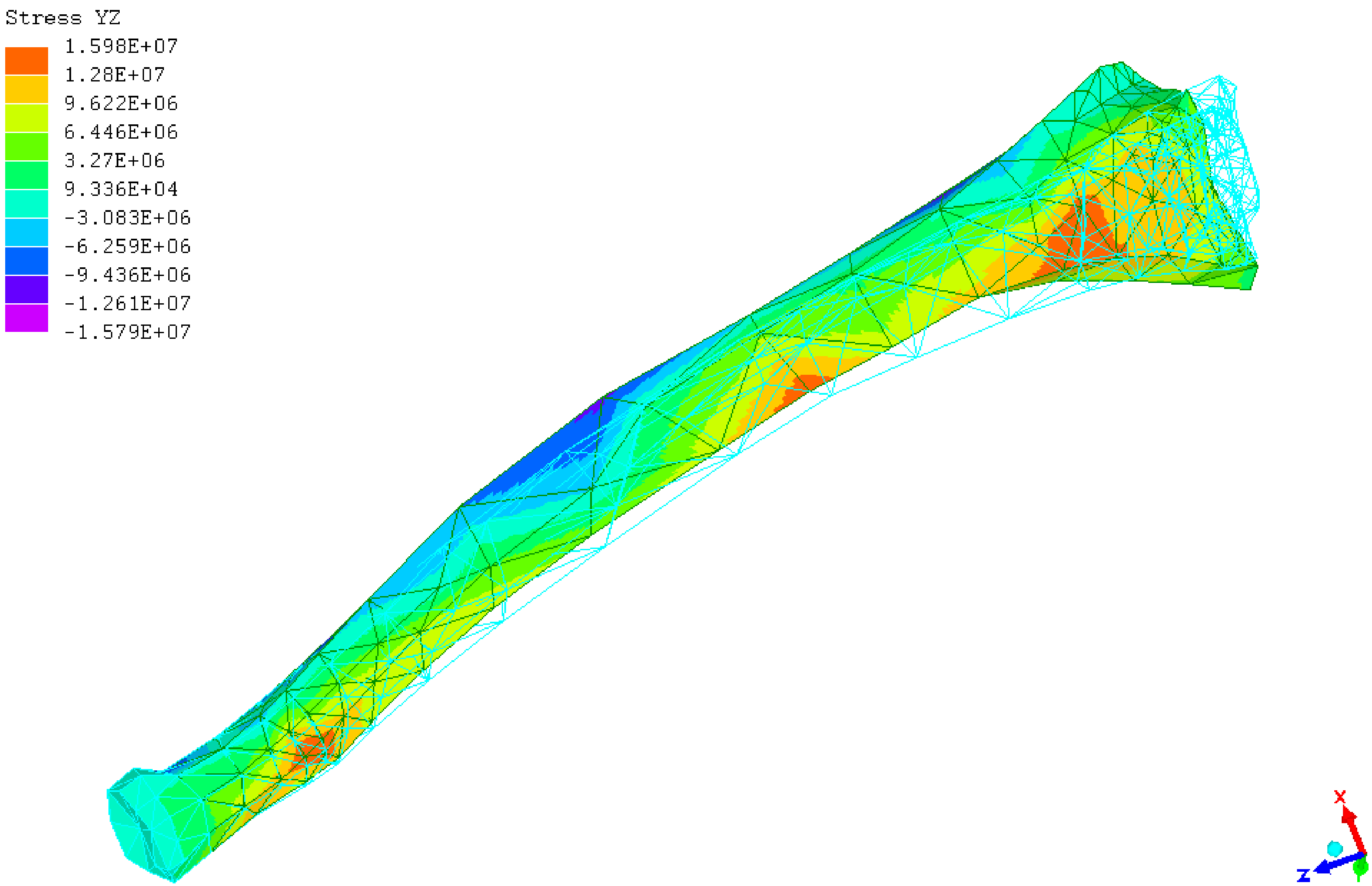


Radius Twist

- Proximal end fixed as before
- "Force Couple" used to simulate twist
- Expected stresses
  - Torsion around z-axis

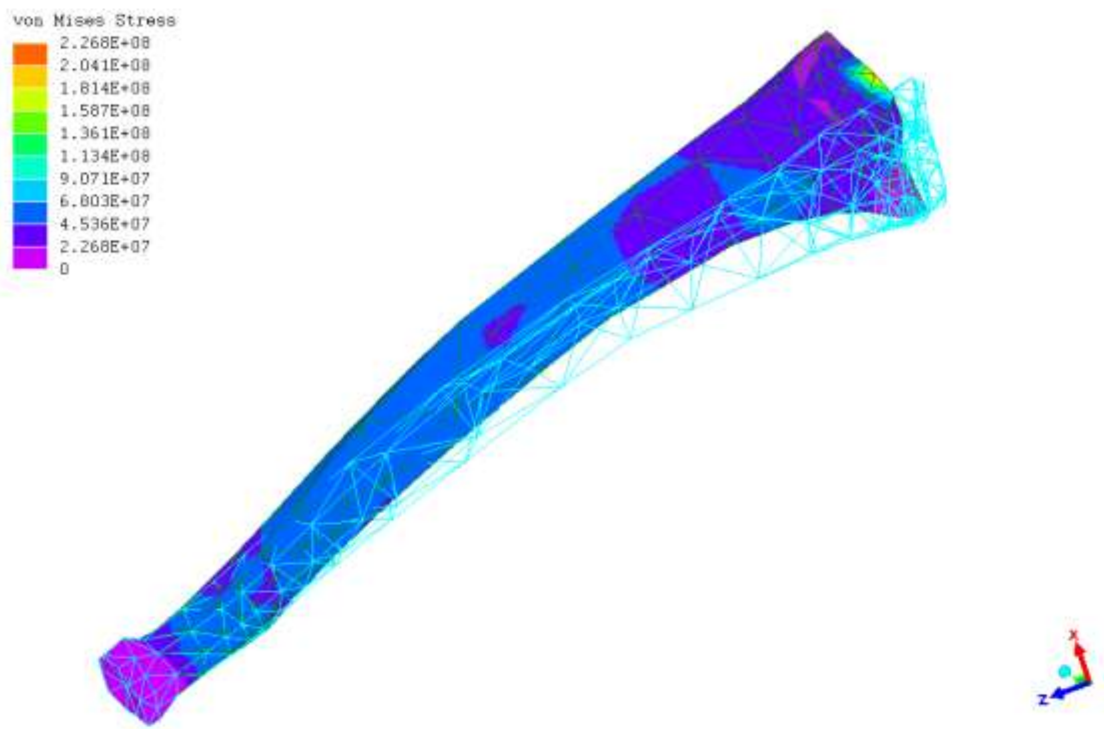


Radius Twist



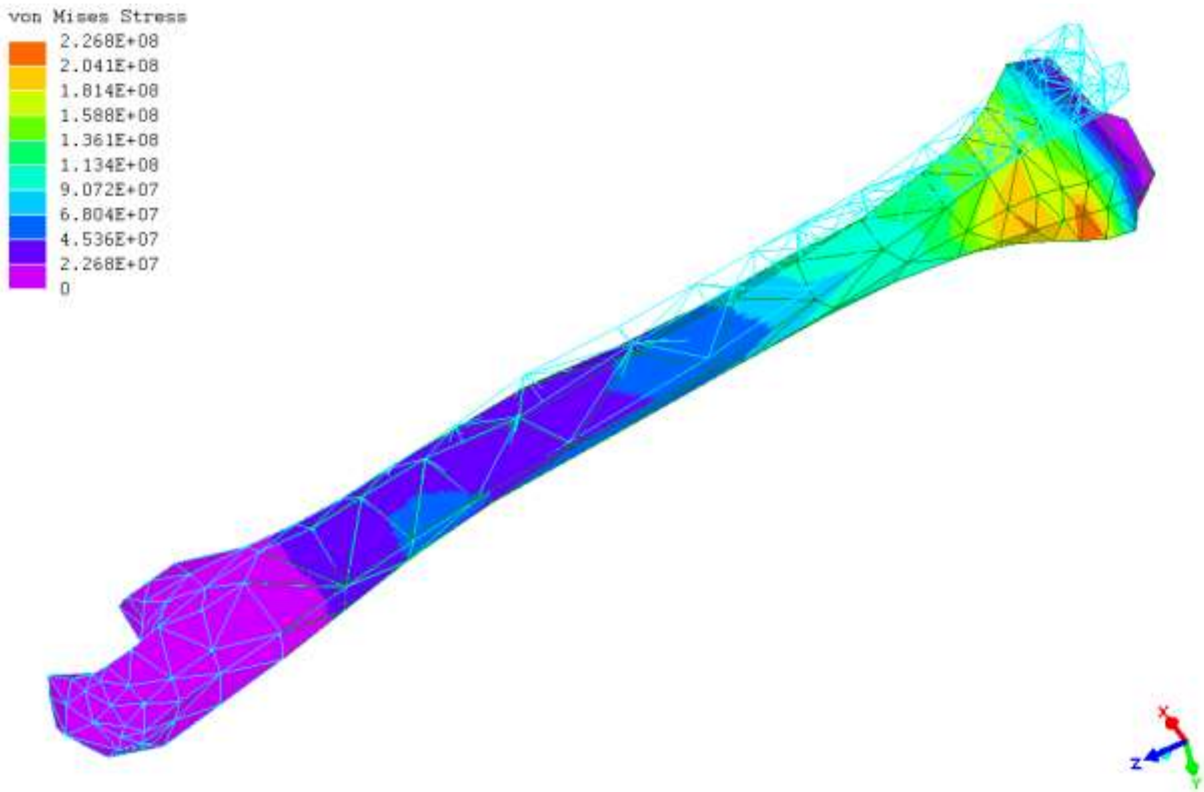
Radius Twist

- Ultimate stress = 49 – 68 MPa
- Max torsion: 45 MPa – 68 MPa
- Fracture risk for much of bone
- Applied force of 3020 N
- Torque of 54.66 N·m



Ulna Twist

- Use region with only torsion stress
- Max torsion: 45 MPa – 68 MPa
- Fracture from torsion near middle
- Applied force of 4,400 N
- Torque of 78.59 N·m



Summary of Forces

	Radius	Ulna
Catching Fall	1,160 N	1,610 N
Mid	4,720 N	7,450 N
Comp	34,200 N	40,200 N
Stretch	23,895 N	28,100 N
Twist	54.66 N·m	78.59 N·m

Conclusion

- Was able to find fracture locations in radius and ulna for different simulations
- Resulting forces agreed with accepted models of bone anisotropy
- Ulna required larger forces
- Due to bone size and shape possibly described by Wolff's Law
  - bone in a healthy person or animal will adapt to the loads under which it is placed

Thank You

- Dr. Voytas
- Dr. George
- Dr. Williams

Sources

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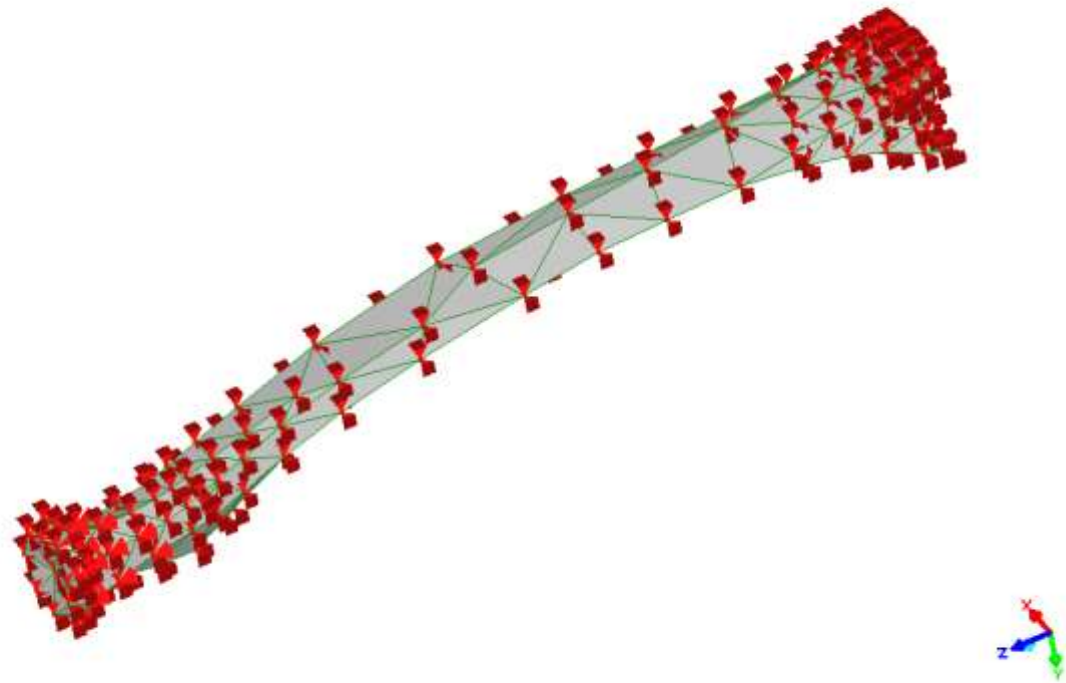
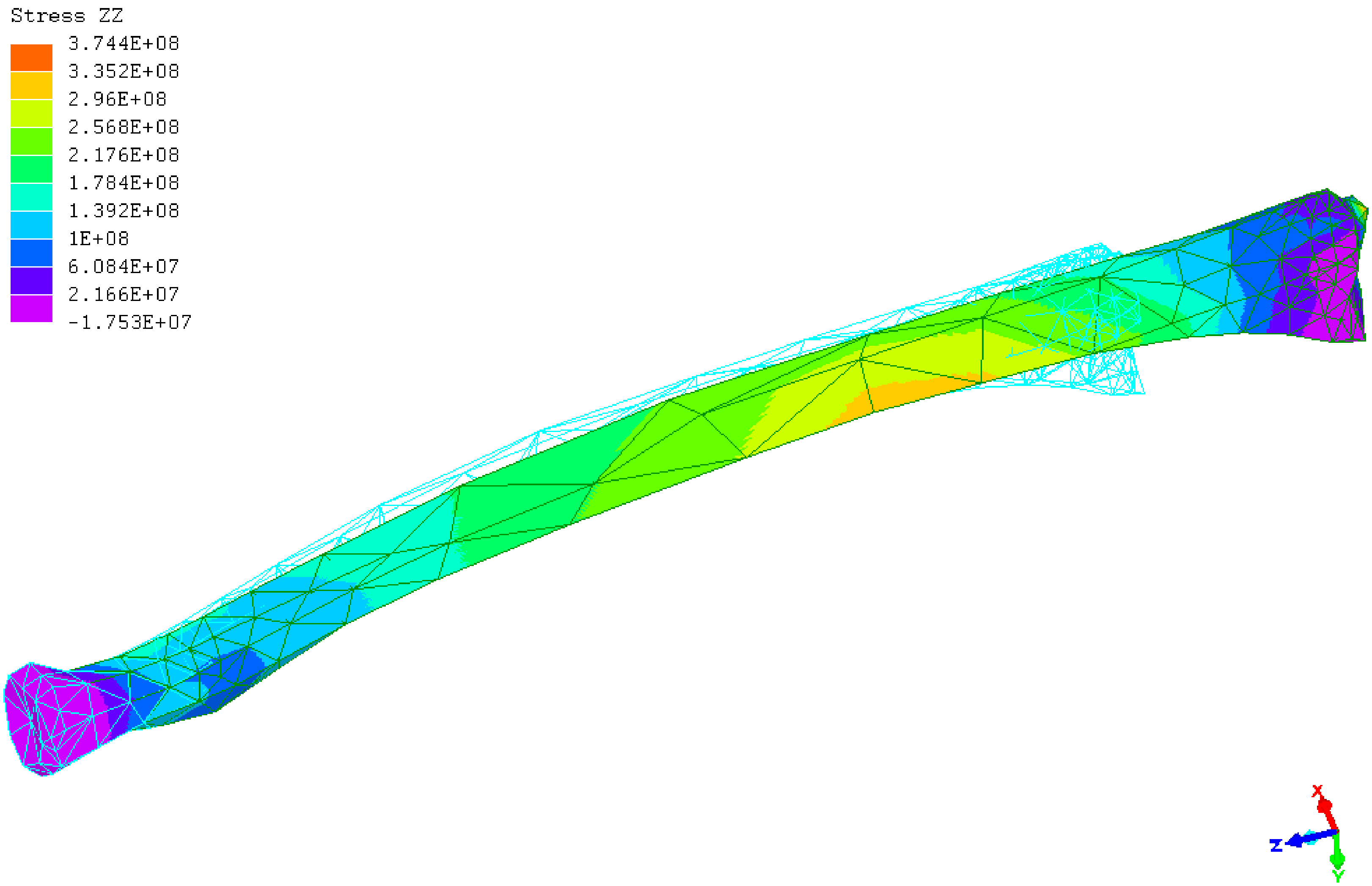
Questions?

Radius
Stretch Ends

- Same constraints used as in compression
- Direction of force flipped
- Expected stresses:
  - Tension along entire bone

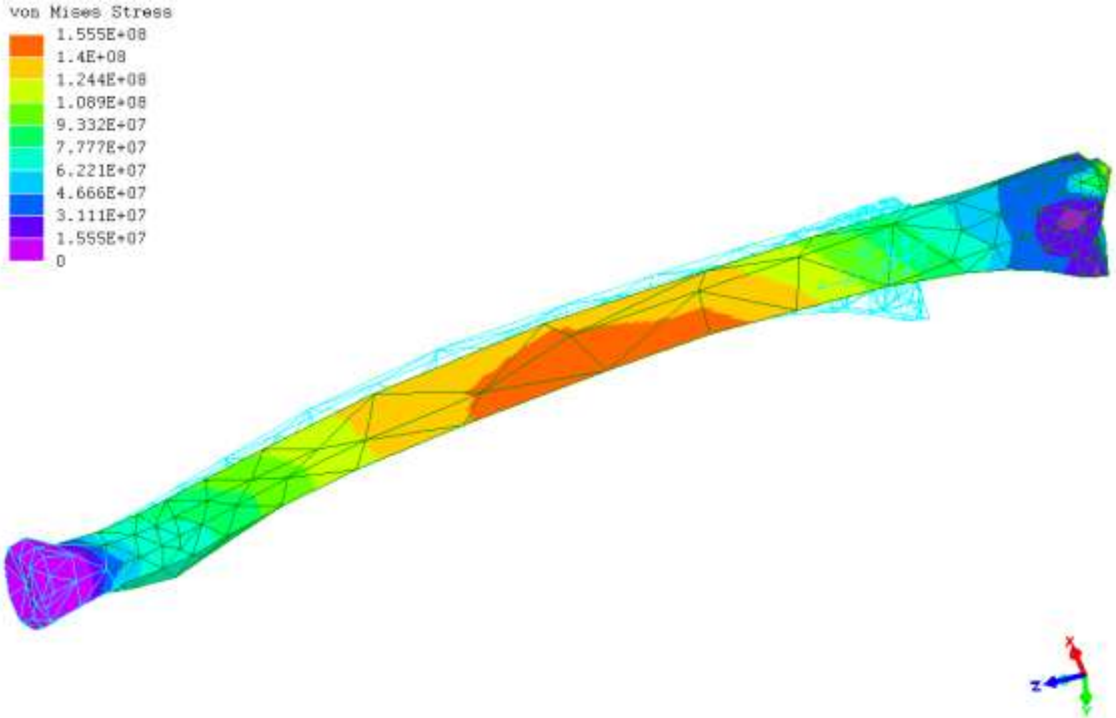


Radius Stretch Ends



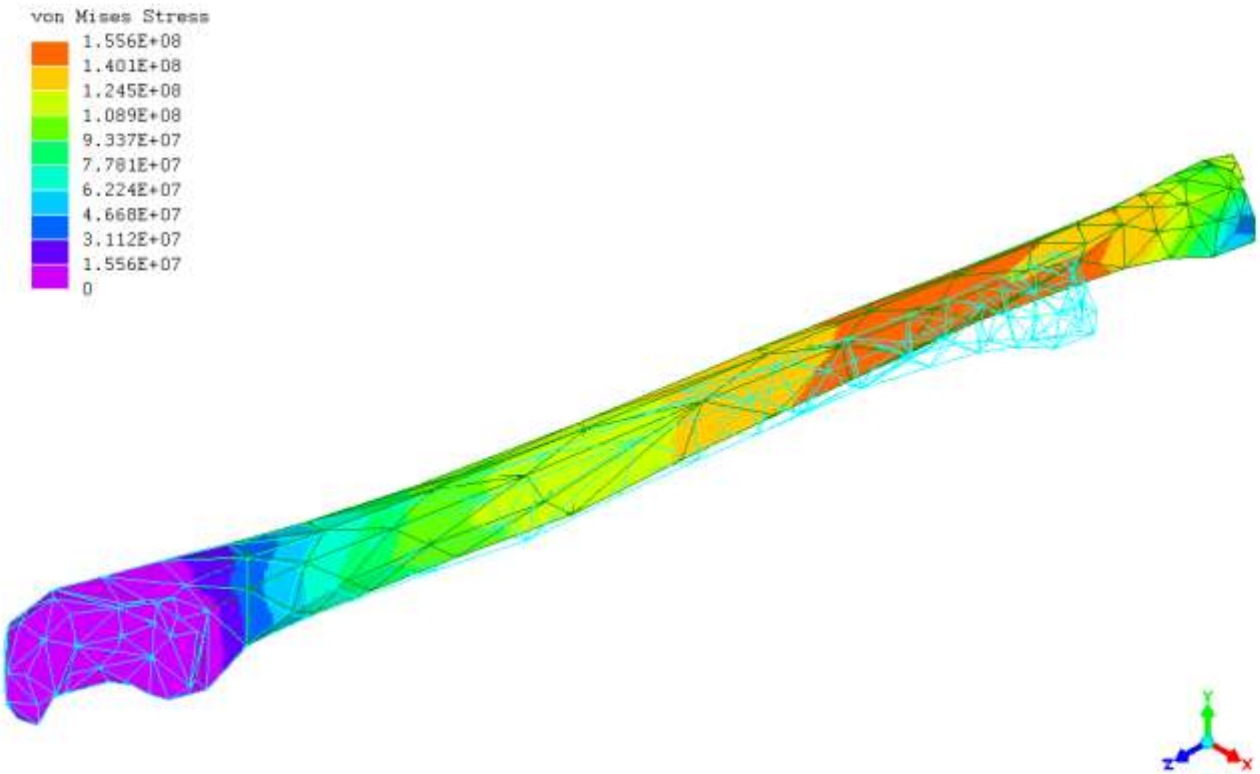
Radius Stretch Ends

- No compression
- Max tension: 140 MPa – 156 MPa
- Fracture due to longitudinal tension
- Similar to position of compression fracture
- Applied force of 23,895 N



Ulna Stretch Ends

- No compression
- Max tension: 140 MPa – 156 MPa
- Fracture again closer to wrist
- Applied force of 28,100 N



Analysis Basics

- Stress $\sigma = \frac{F}{A}$

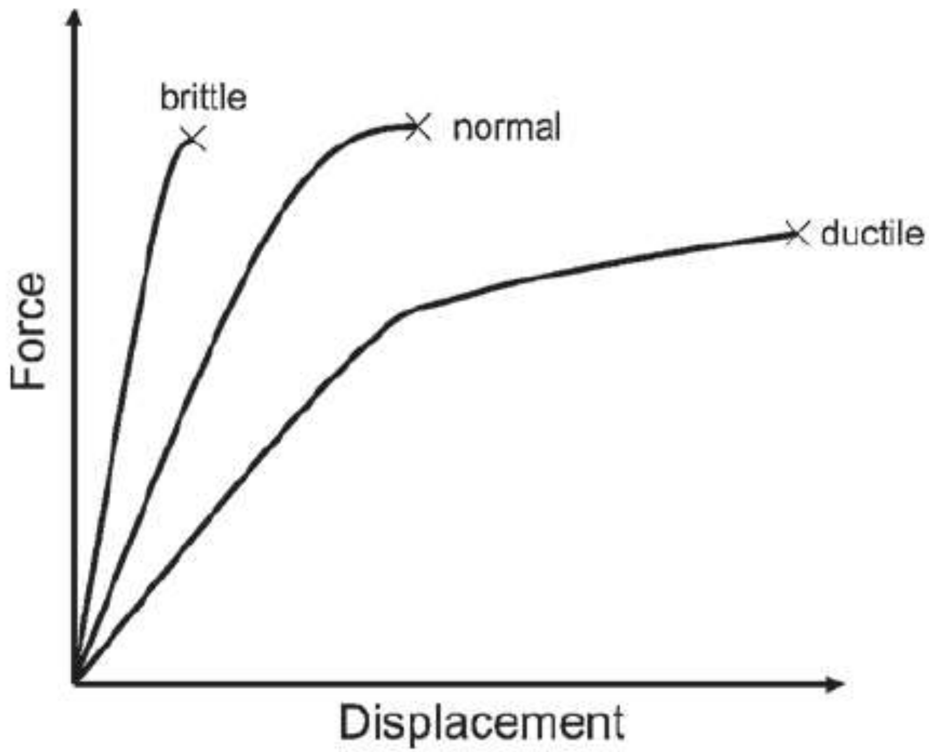
$$\frac{N}{m^2} = Pa$$

$$\sigma = \sqrt{0.5\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right]}$$
$$+ \sqrt{+ 3\left(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2\right)}$$

- Strain $\varepsilon = \frac{\Delta l}{L}$

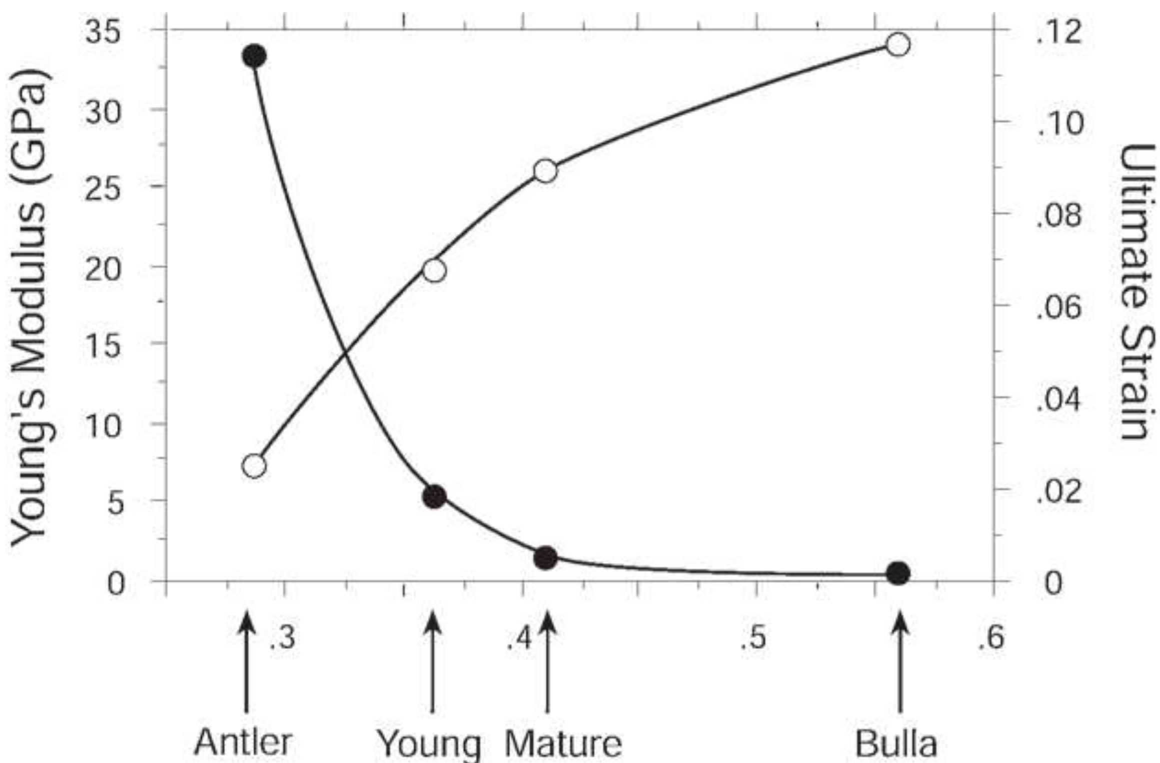
Why Bones Break

- Biomechanical status of bone may be poorly described by just one of these properties
- Osteopetrotic patient
  - stiff, but brittle
- Young child
  - poorly mineralized and weak, but ductile



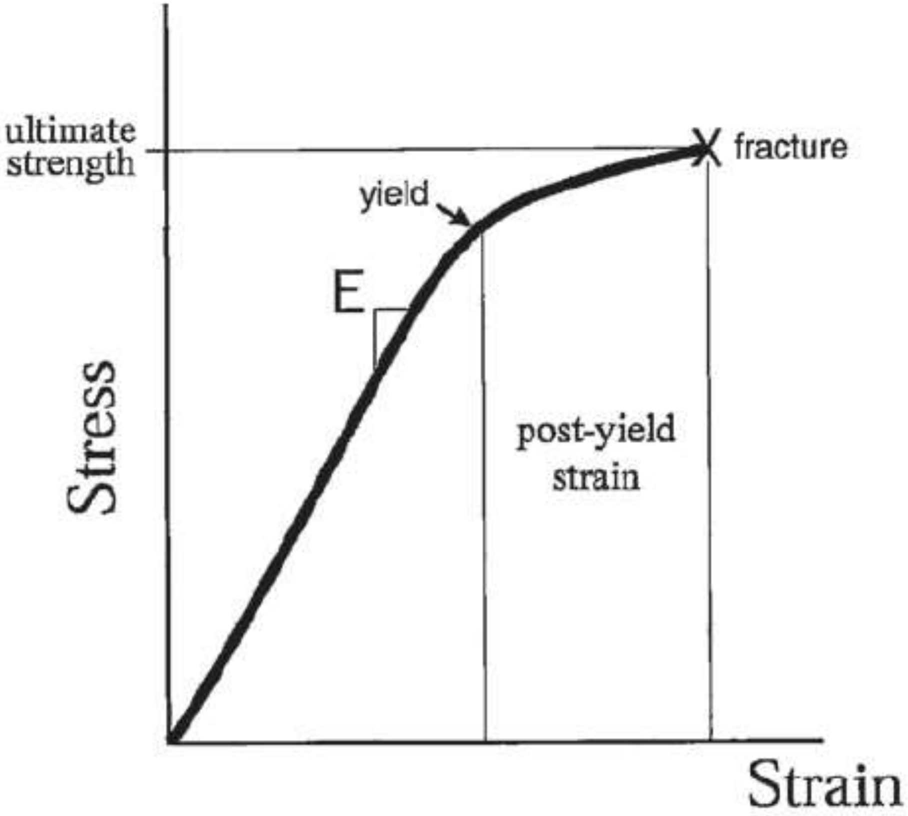
Why Bones Break

- Inverse relationship between Young's modulus and ultimate strain
- Antler: ↓ mineralization, ↑ strain, ↓ E

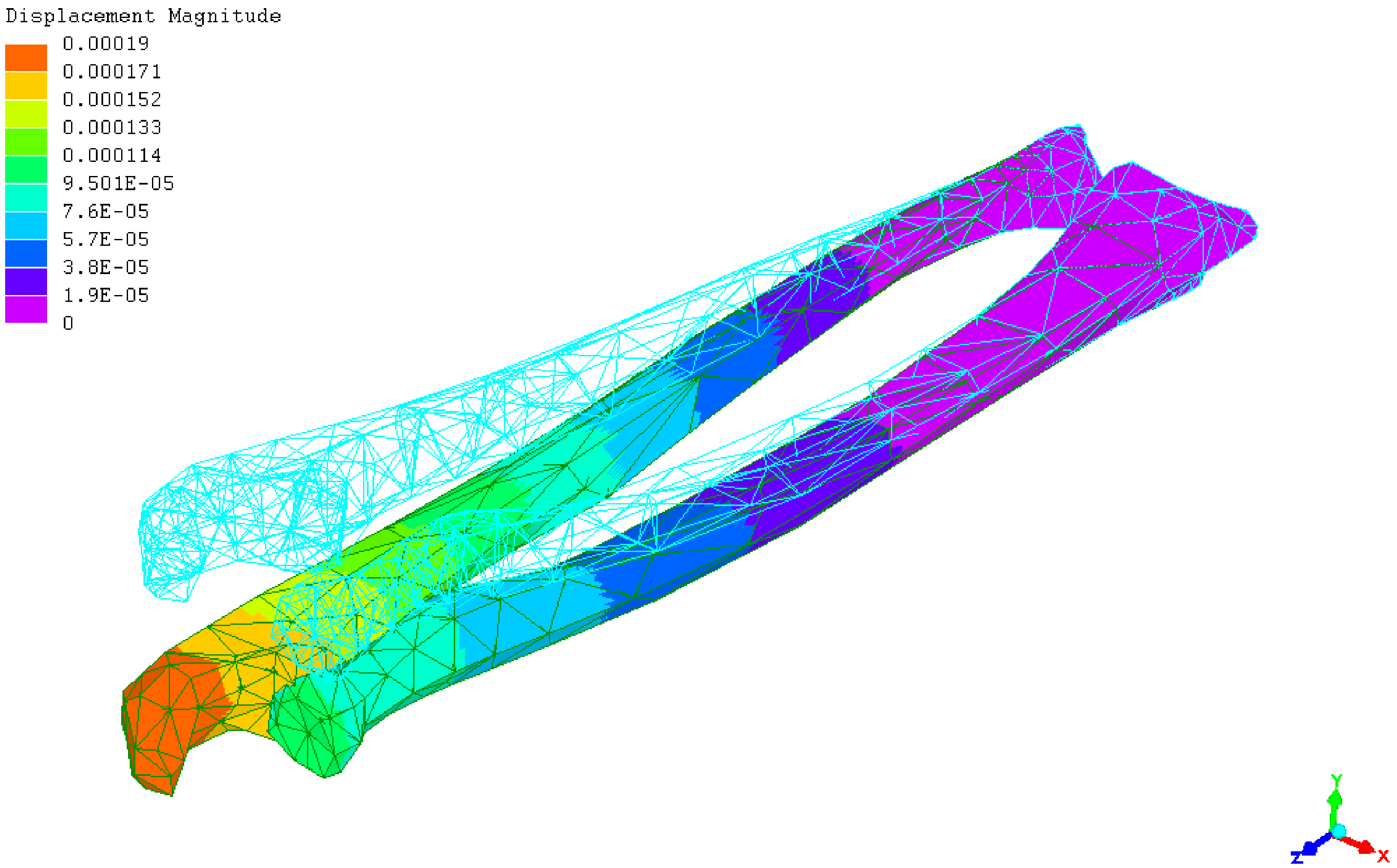


Why Bones Break

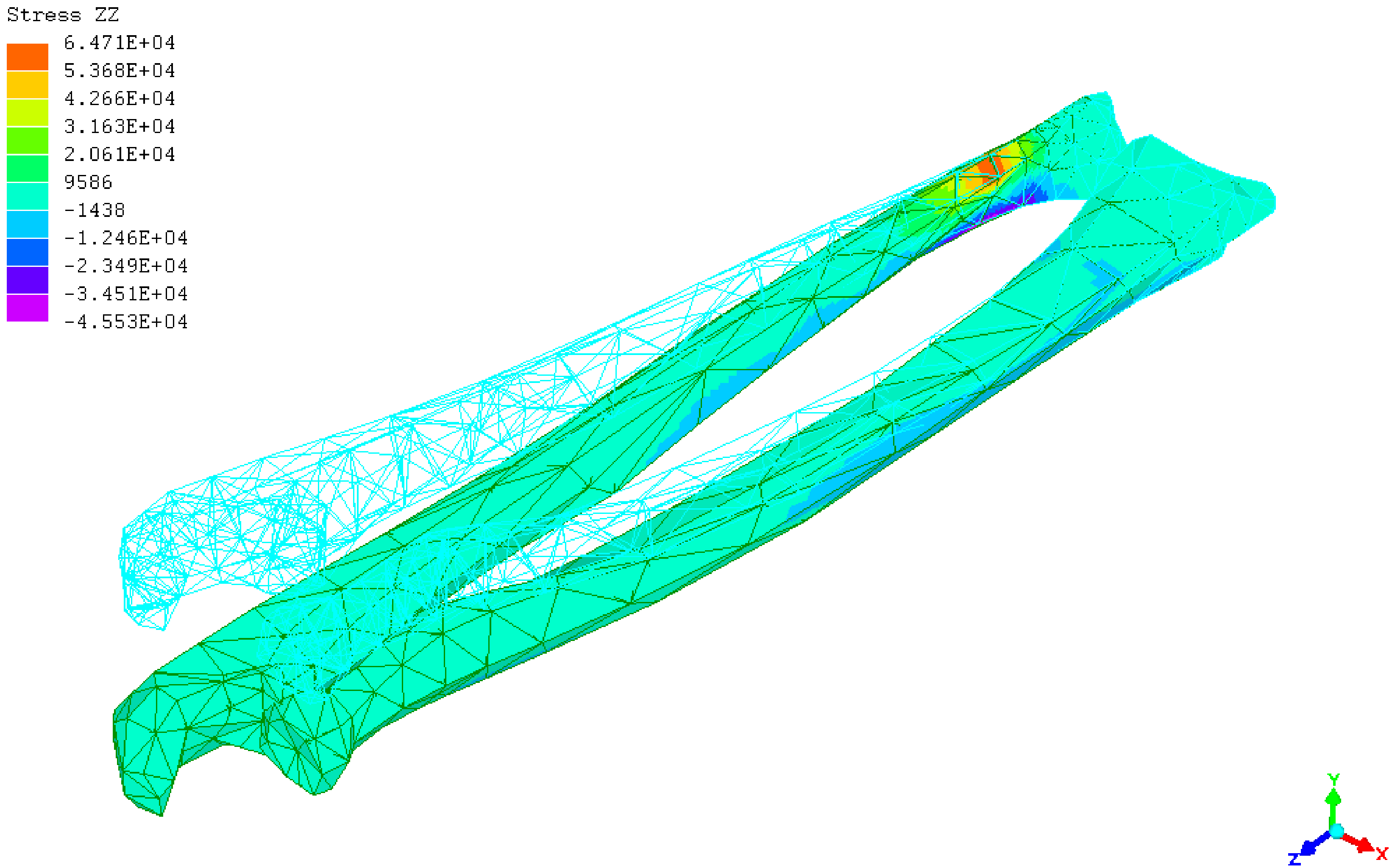
- For my project, using curve for typical bone strength
- Will be looking for ultimate strength value given by program



Current Model



Current Model

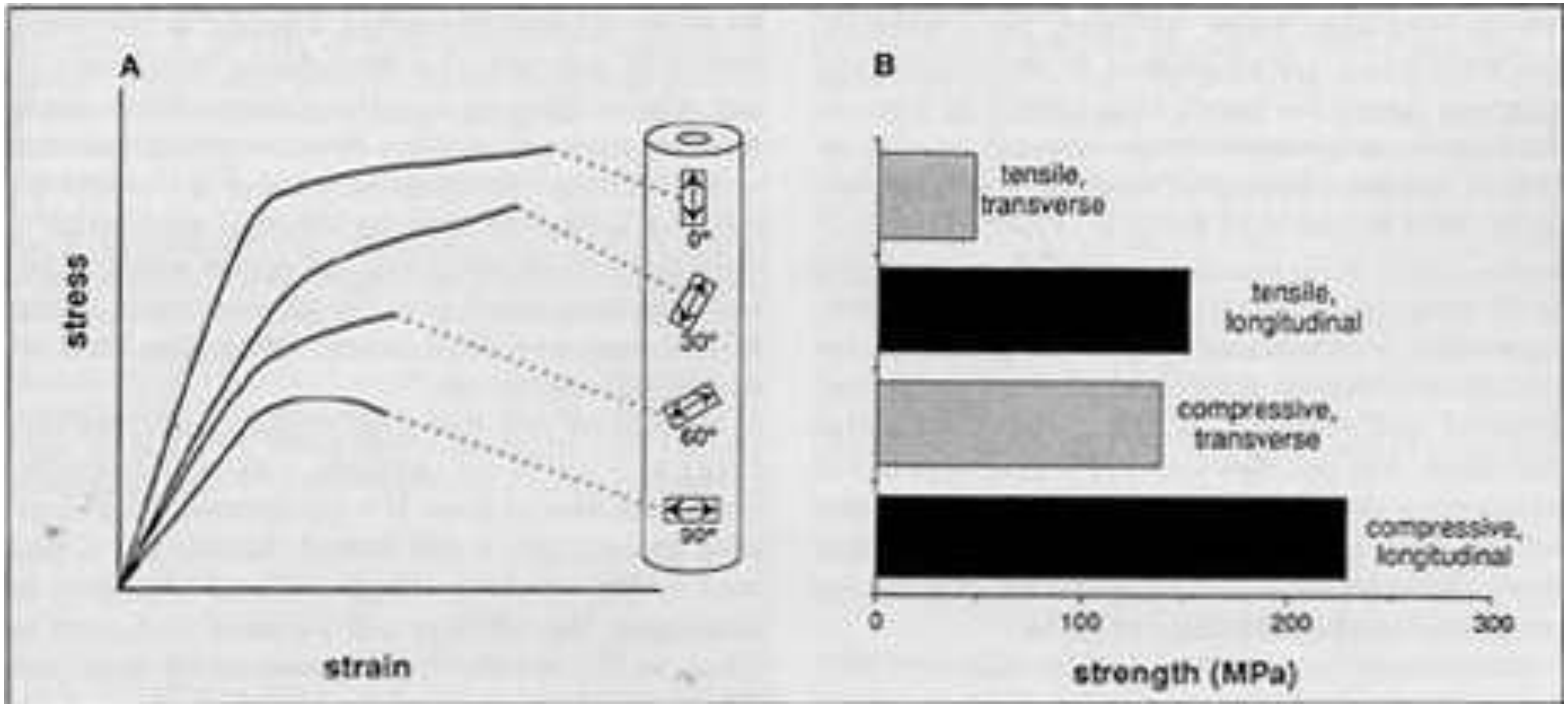


Future Work

- Want to find stresses necessary to cause fractures of arm bones
- Current issues:
  - Thickness of the model
  - Obtaining sensible units
  - Creating realistic fracture scenarios

Future Work

- Want to consider the anisotropic nature of bone



Conclusion

- Bone fractures depend on multiple factors
- Want to find fracture point by examining maximum stress
- Next step is to get meaningful units and realistic fracture models
- Then want to consider anisotropic behavior

Works Cited

http://www.melioguide.com/media/121650/turner_bone_strength.pdf

http://en.wikipedia.org/wiki/Fracture

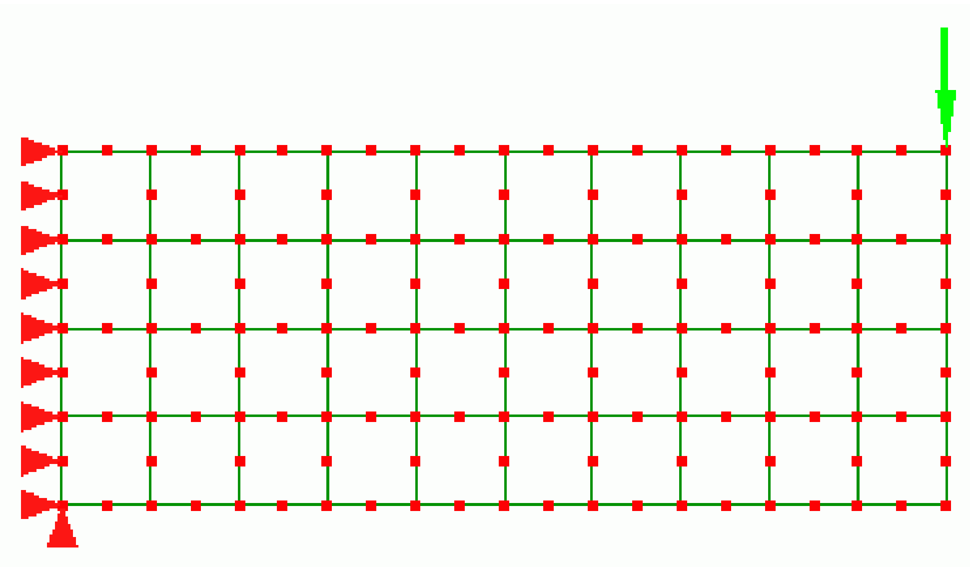
http://www.brown.edu/Departments/EEB/EML/background/bone.htm

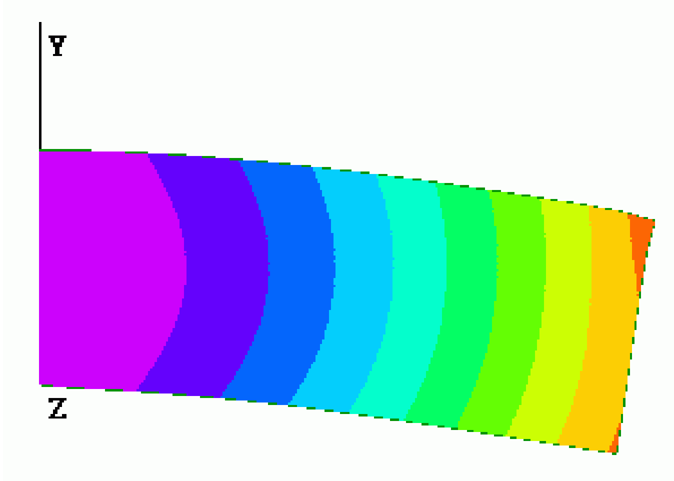
FEA Review

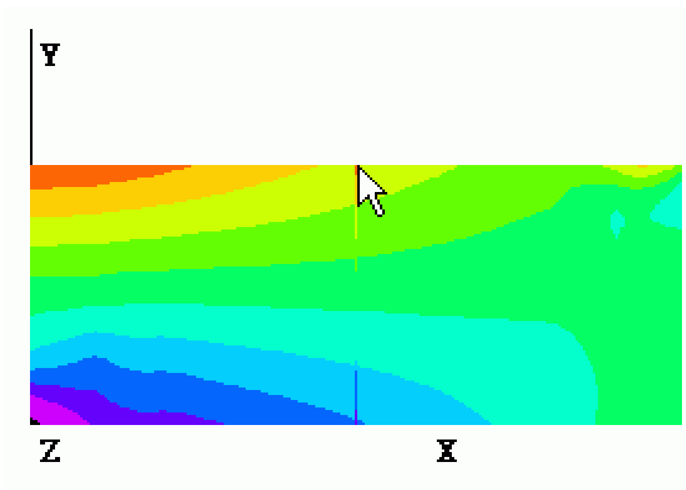
- FEA is numerical method which provides solutions to difficult problems
  - stress analysis, fluid flow, heat transfer, etc.
- Math behind analysis relies heavily on use of matrices
- LISA and other programs allow complex computations to be carried out quickly
- Want to use LISA to perform static analysis on bone fractures

FEA Review

- Beam Example







Node 54 X 5 Y 4 Z 0 stressxx 46.872266646973

Node 10 X 5 Y 0 Z 0 stressxx -46.8726816675875

Why Bones Break

1. Ultimate tensile strength
2. Yield strength
3. Proportional limit stress
4. Fracture
5. Offset strain
   (typically 0.2%)