Nitinol FEA: Beyond the Fundamentals

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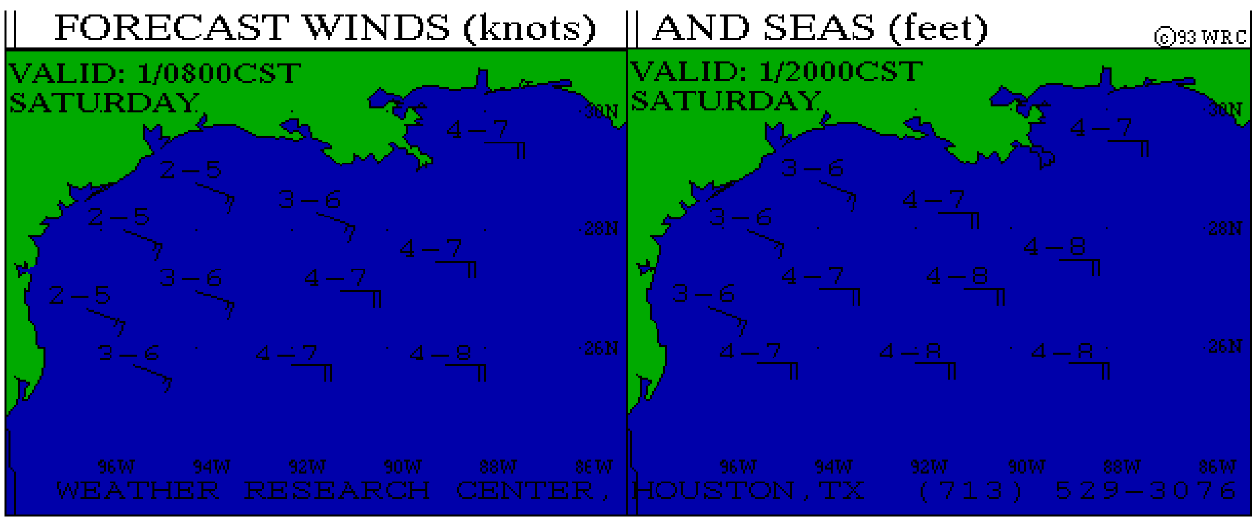
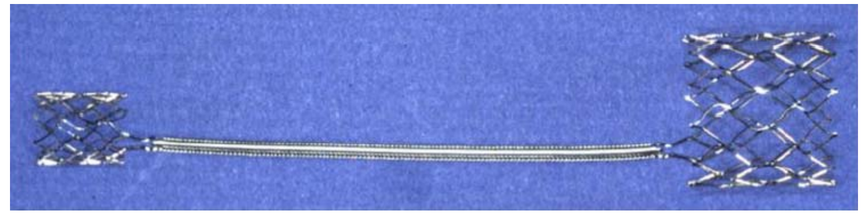
Outline

- Role of FEA in Design
- Nitinol Material Model Calibration
- FEA Fundamentals
- FEA Not so Fundamentals
- Producing Valid Data
- Verification of Results



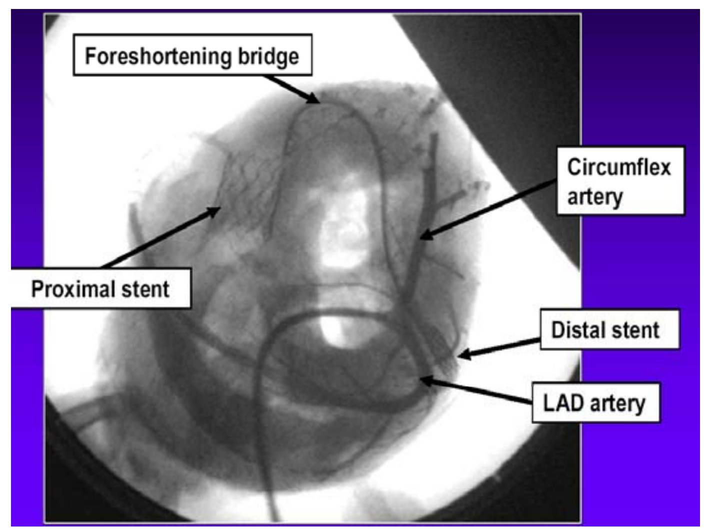
Role of FEA in Design

- Gain understanding
- Explore feasibility
- Optimize a particular solution
- Evaluate safety and efficacy



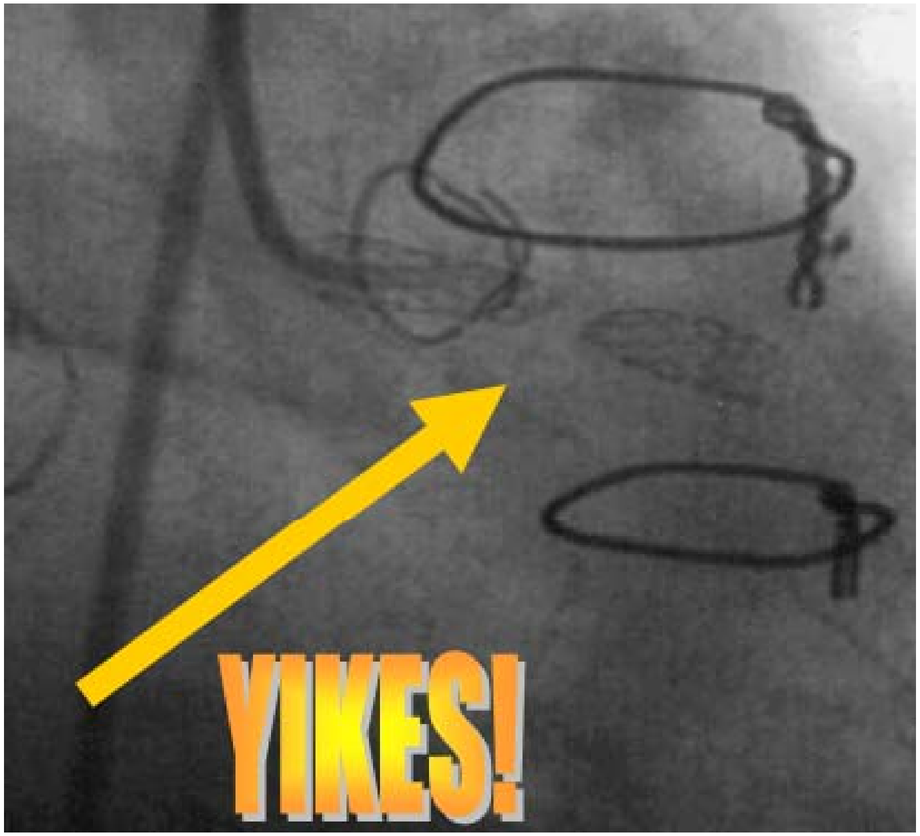
"The purpose of computing is insight, not numbers"

R. W. Hamming

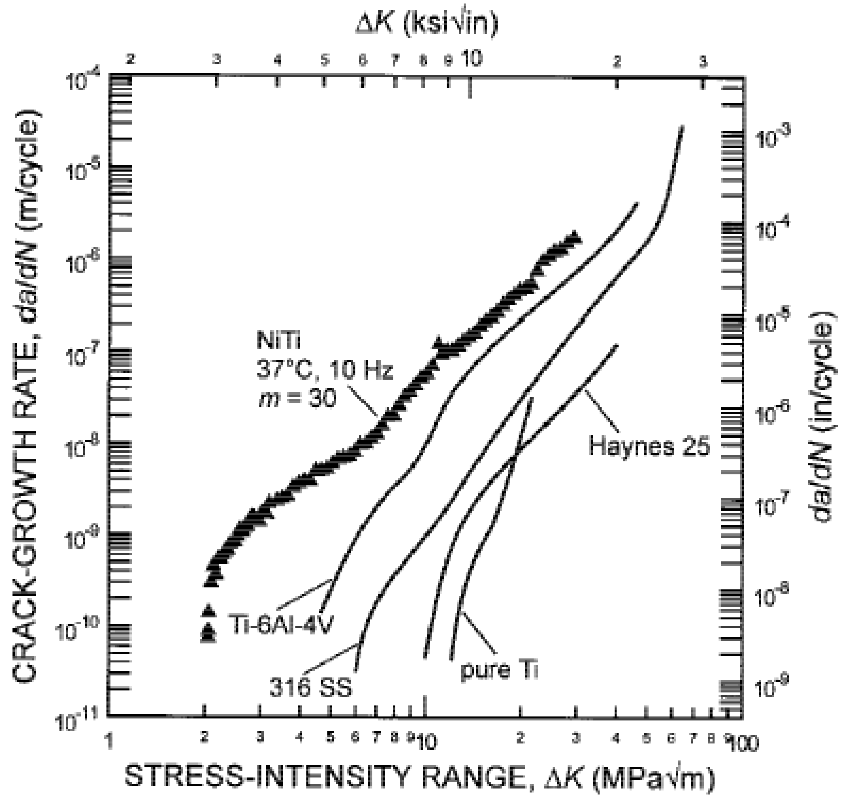


Percutaneous valve therapies, T. Feldman, TCT 2005

Implants Break!



P. Chowdhury, R. Ramos, Coronary-Stent Fracture, New England Journal of Medicine, Volume 347:581, August 22, 2002, Number 8 (Commentary courtesy of B. Berg)



McKelvey AL, Ritchie RO., J. Biomed. Mater. Res. 1999;47(3):301-308.

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General Mechanics of Materials Approach

- Strain-displacement relations

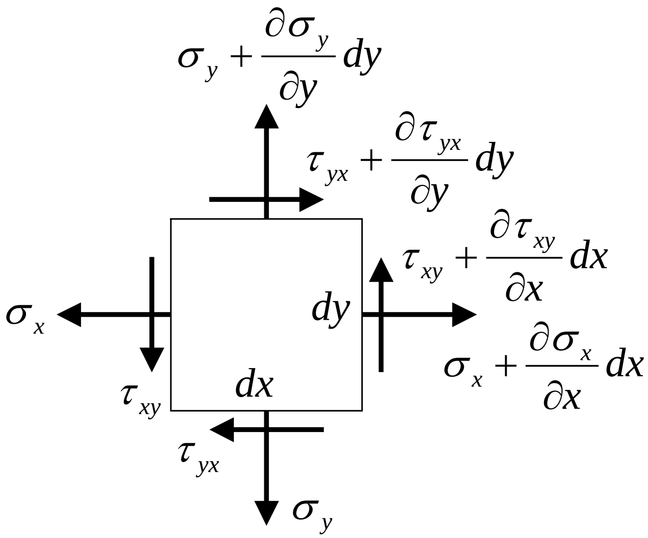
  $\varepsilon_{ij} = ½(u_{i,j} + u_{j,i})$
- Strain compatability

  $\varepsilon_{ij,km} + \varepsilon_{km,ij} = \varepsilon_{ik,jm} + \varepsilon_{jm,ik}$
- Stress equilibrium equations

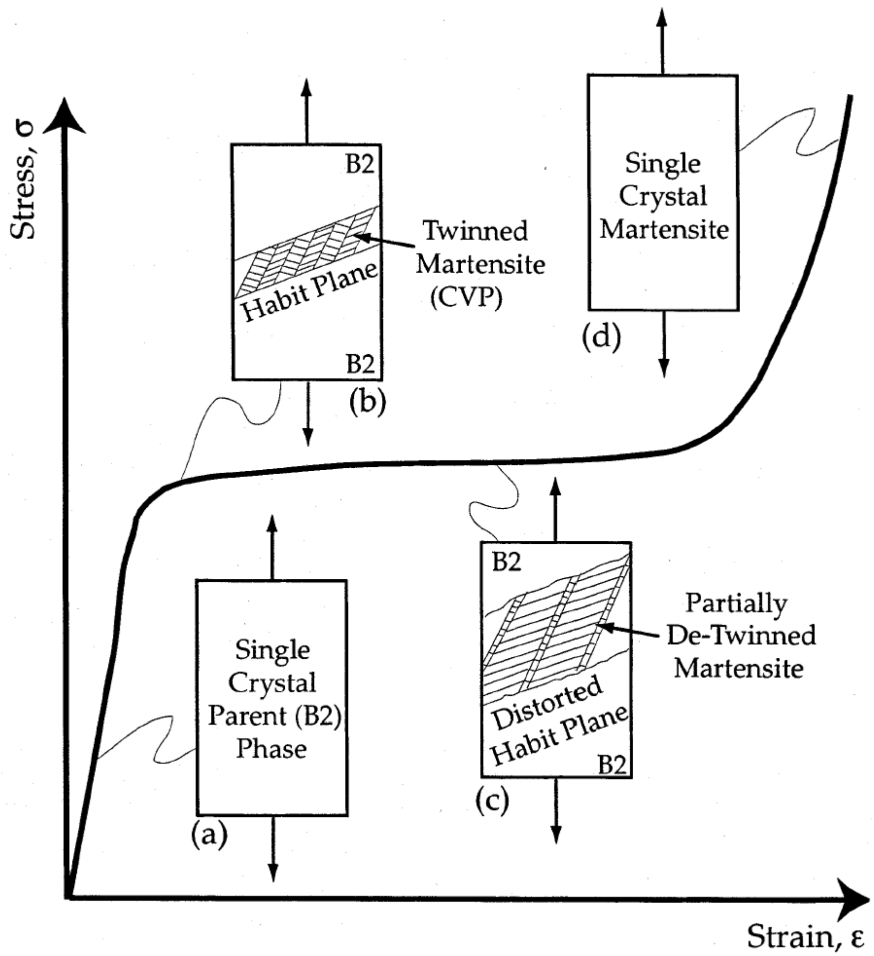
  $\sigma_{ij,j} + \rho\ddot{u}_i = f_i$
- Boundary conditions

  tractions, displacements
- Equation to describe material behavior

  $\sigma_{ij}\,(\varepsilon_{ij}, T, t, \ldots)$

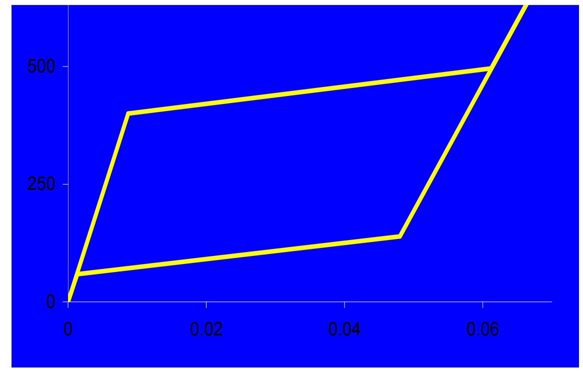


Superelastic Behavior of Nitinol



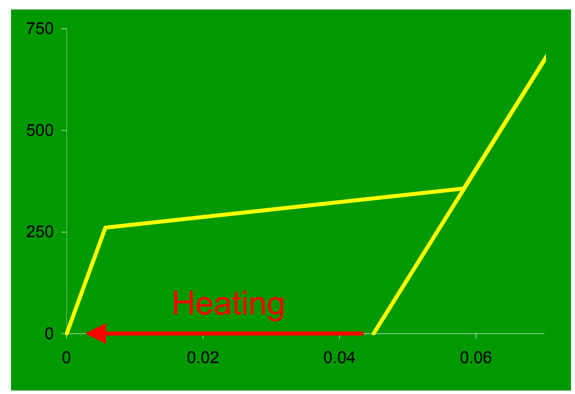
NDC Website, www.nitinol.com

– Stress induced reverse transformation, $T > A_f$



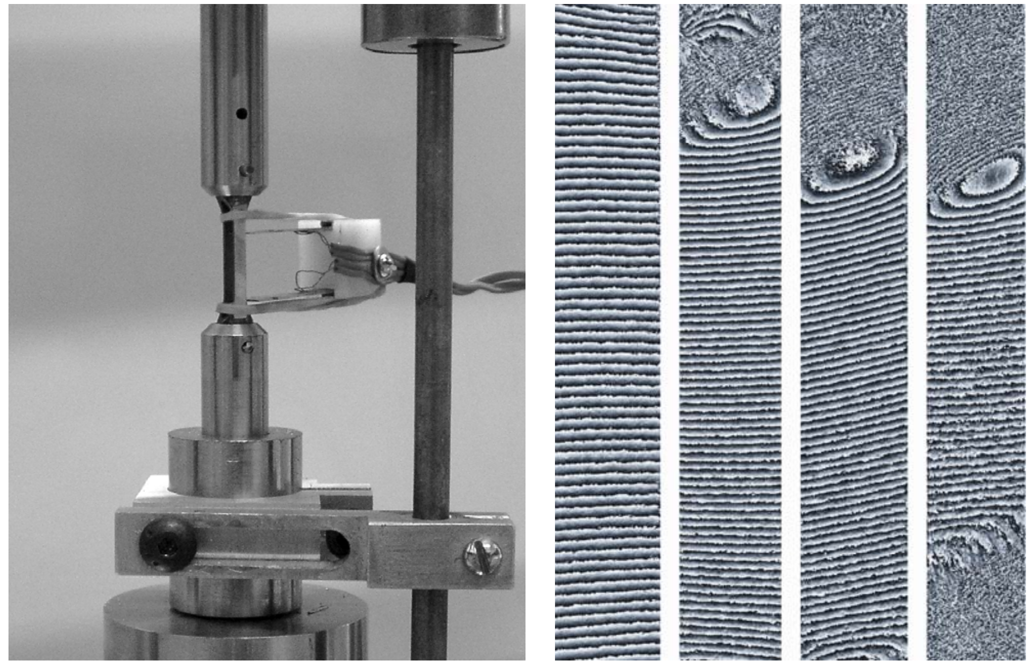
Shape Memory

– Thermally induced reverse transformation, $T < A_f$



Generating Calibration Test Data

- Measurements
  - Load
  - Cross head disp.
  - Extensometer strain
  - Temperature
- Complications
  - Multi-phase material
  - Loading mode dependence
  - Temperature sensitivity
  - Large deformations
  - Anisotropy



K. Perry and P. Labossiere, ASTM 2005

"It is of no use to employ great sophistication in computing outputs if your inputs are wrong"

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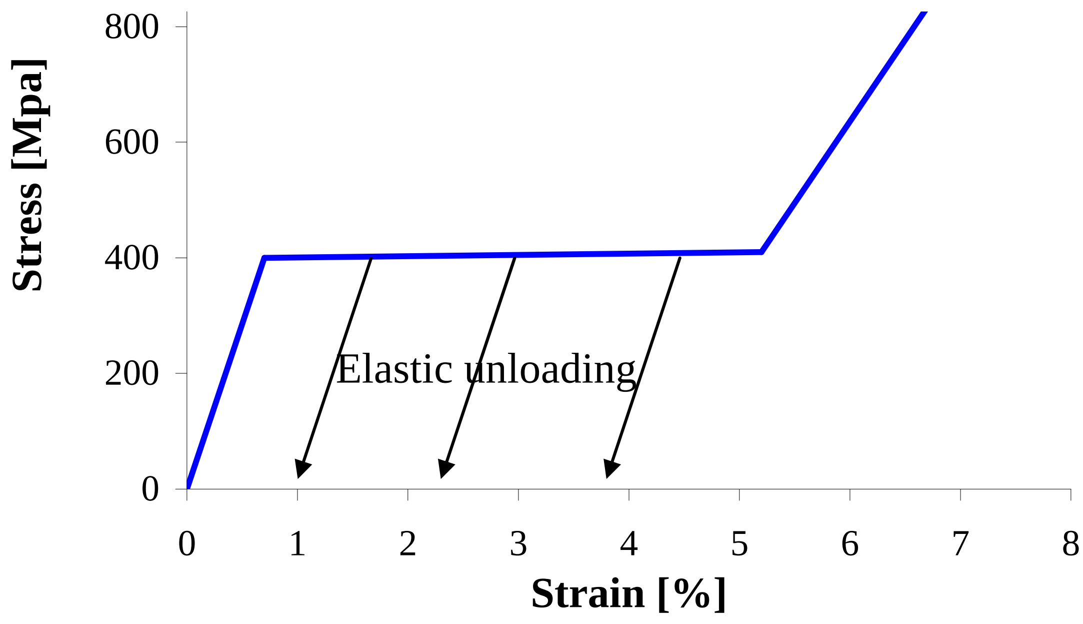
Material Model Approaches

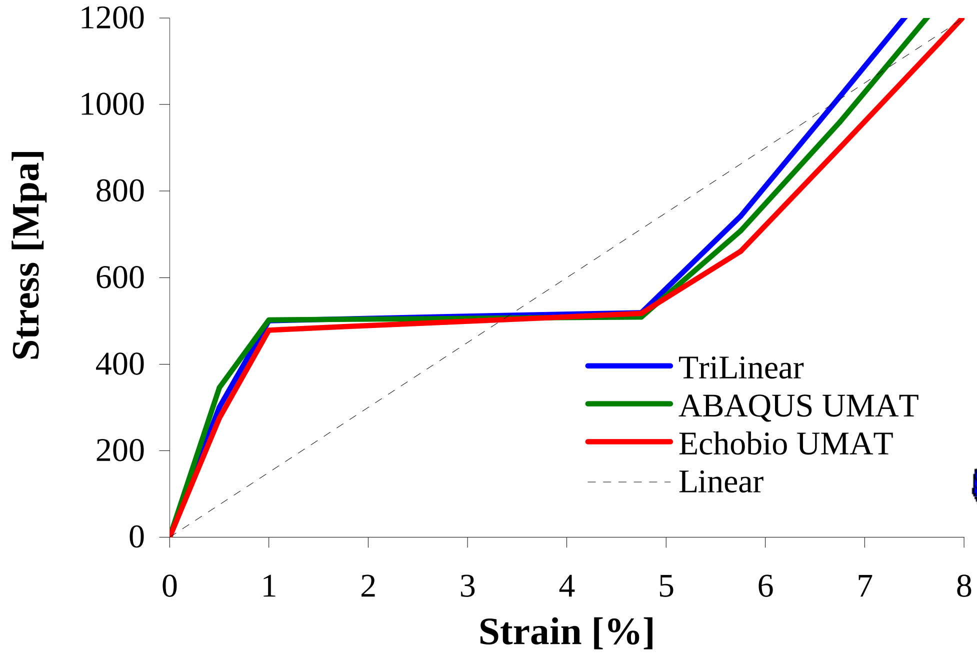
- Piecewise continuous models
- Hyperelasticity models
- User Subroutines (UMATs)
  - Generalized plasticity
  - Multi-phase elasticity

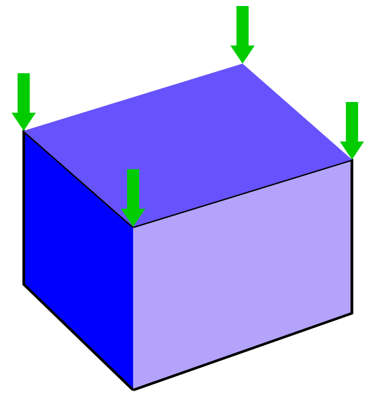
Piecewise Linear and Hyperelasticity Models

- Traditional plasticity based approach
- Yielding with elastic unloading
- Only good for monotonic loading
- Easiest to implement

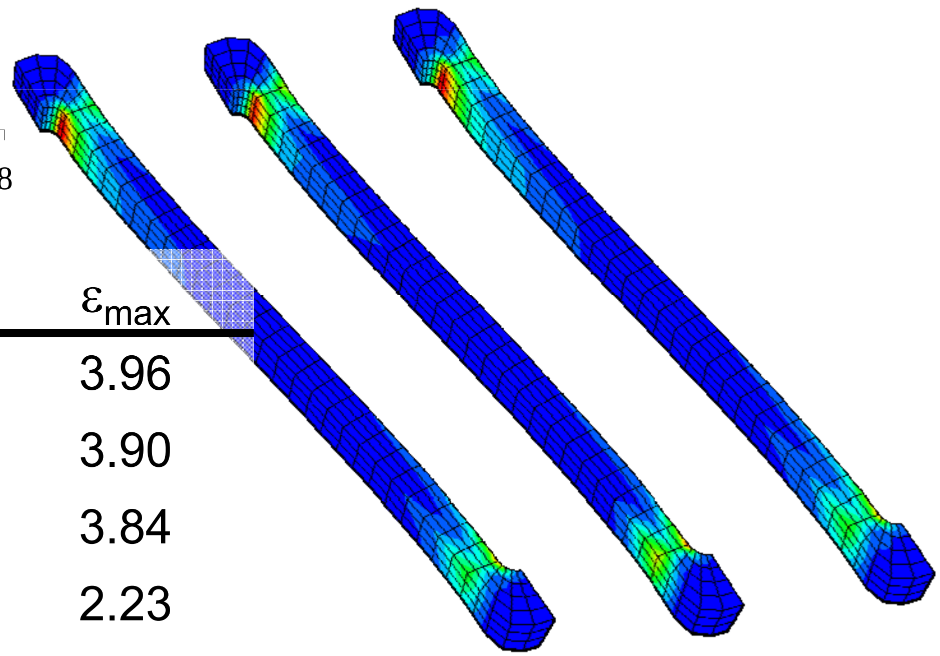


Case Study: Monotonic Loading





One Element Model Implementation Validation



Material Model	increments	cpu	ε_{max}
Tri-Linear	12	9	3.96
ABAQUS UMAT	12	14	3.90
ECHOBIO UMAT	13	13	3.84
Linear Elastic	12	7	2.23

UMATS in ABAQUS

- can be used to define the mechanical constitutive behavior of a material;
- will be called at all material calculation points of elements for which the material definition includes a user-defined material behavior;
- can be used with any procedure that includes mechanical behavior;
- can use solution-dependent state variables;
- must update the stresses and solution-dependent state variables to their values at the end of the increment for which it is called;
- must provide the material Jacobian matrix, for the mechanical constitutive model;
- can be used in conjunction with user subroutine USDFLD to redefine any field variables before they are passed in (see “USDFLD,” Section 25.2.39); and
- is described further in “User-defined mechanical material behavior,” Section 12.8.1

ABAQUS
ABAQUS, Inc.
1080 Main Street
Pawtucket, Rhode Island 02860-4847

Generalized Plasticity: Thermodynamic Description

MATERIAL MODEL VARIABLES

- Elastic modulus, austenite E_a
- Elastic modulus, martensite E_m
- Poisson's Ratios ν
- Coefficient of thermal expansion α
- Martensite start temperature M_s
- Austenite finish temperature A_f
- Maximum transformation strain H
- Stress influence coefficient (A_s vs σ)
- Tanaka coefficients ρ_a, ρ_m
- Material density ρ
- Hardening parameter B
- Initial martensite volume fraction V_m
- Martensite yield stress σ_{maryld}
- Martensite yield hardening parameter B_{marhrd}

EXTERNAL STATE VARIABLES

- Transformation flag
- Transformation direction
- Martensite volume fraction
- Transformation strain tensor
- Modified effective stress
- Yielding flag
- Martensite plastic strain tensor

See for example: M.A. Qidwai and D.C. Lagoudas, Int. J. Numer. Meth. Engr., 47, (2000)

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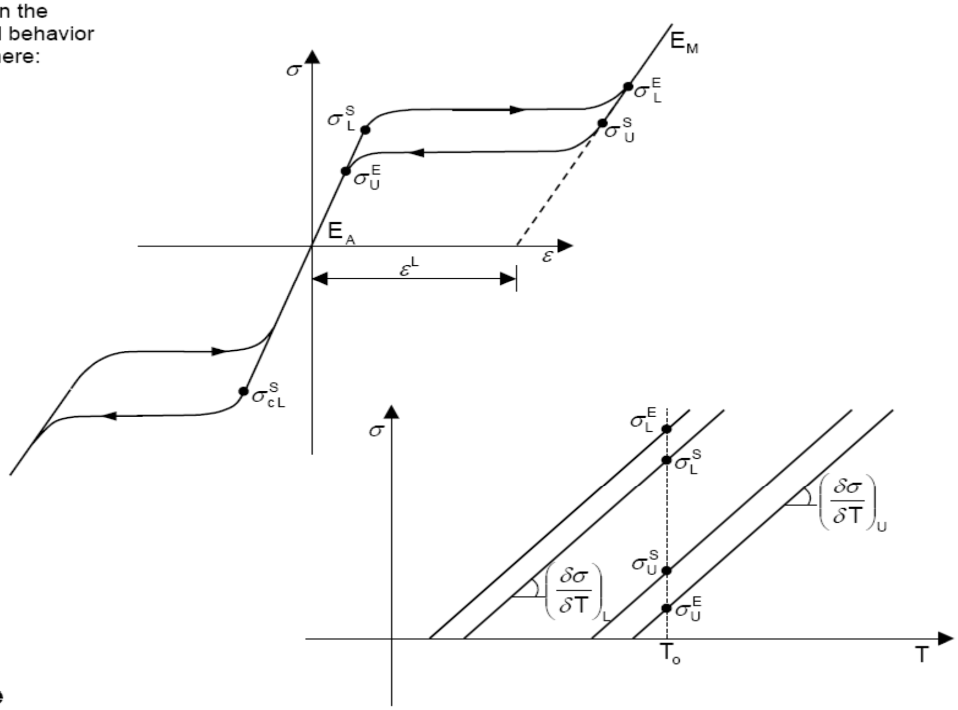
Generalized Plasticity: Uniaxial Curve Fit

UMAT for Superelasticity of shape memory alloys

Superelastic behavior based on the uni-axial behavior shown here:



Usage

∗MATERIAL, NAME=SUPERELASTIC ⌖
∗USER MATERIAL, CONSTANTS=15 + N_A

E_A, ν_A, E_M, ν_M, ε^L, $\left(\frac{\delta\sigma}{\delta T}\right)_L$, σ_L^S, σ_L^E

T_O, $\left(\frac{\delta\sigma}{\delta T}\right)_U$, σ_U^S, σ_U^E, σ_{CL}^S, ε_V^L, N_A, N_{S1}, ...N_{SNA}

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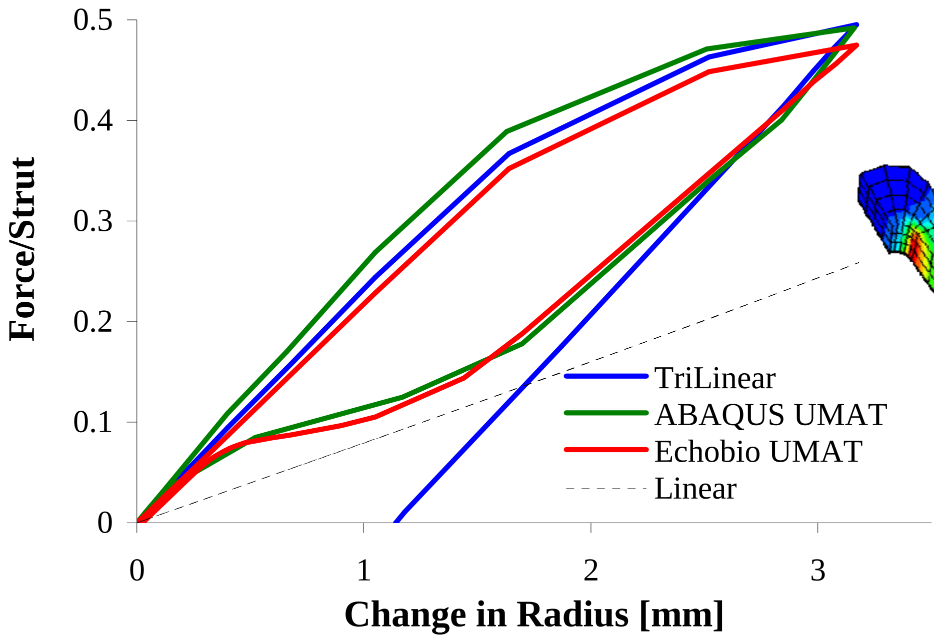
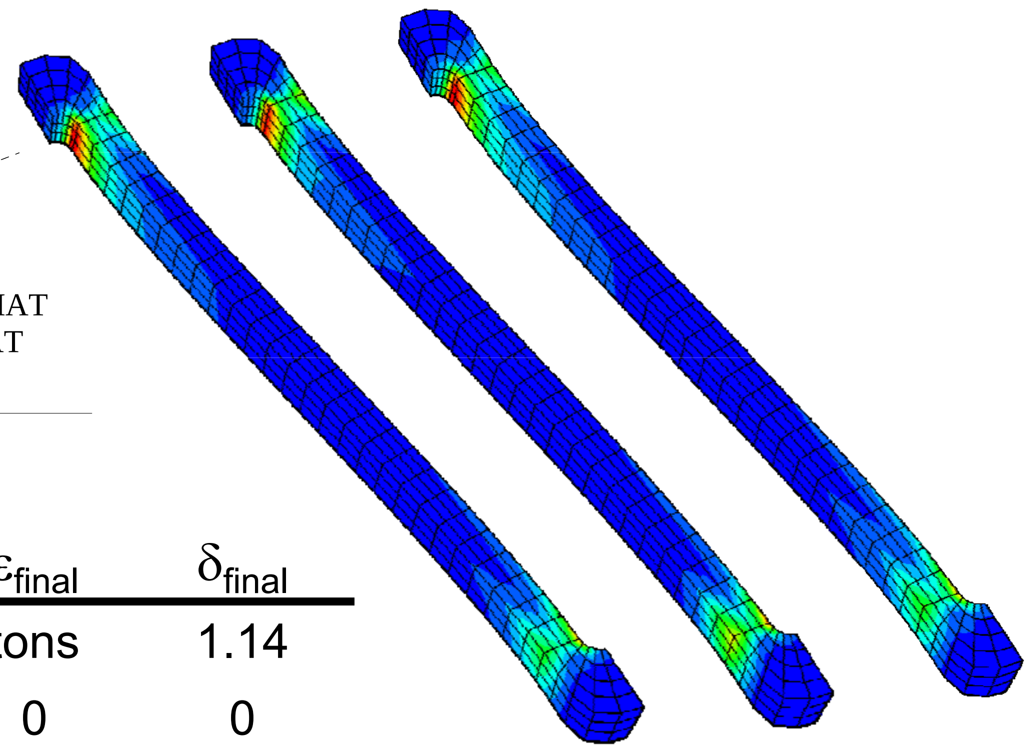
Case Study:
Loading and Unloading

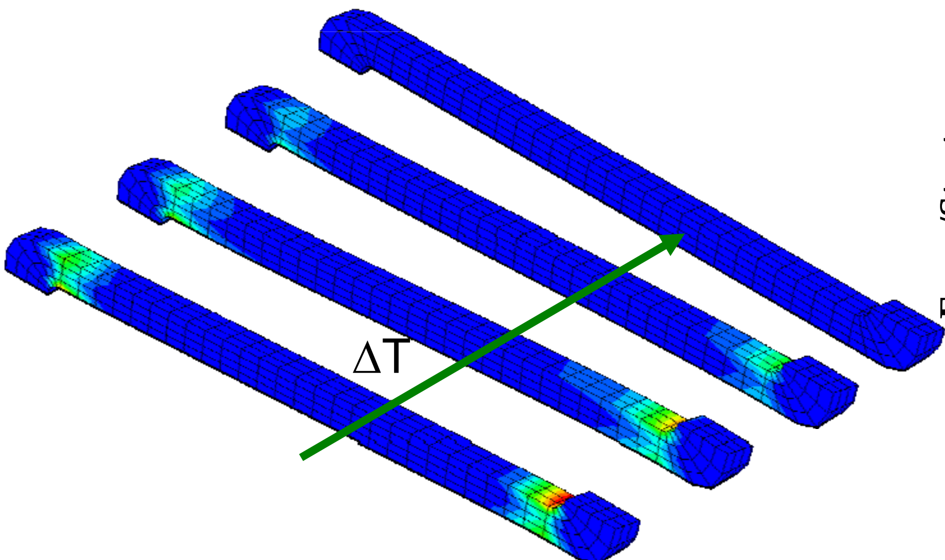


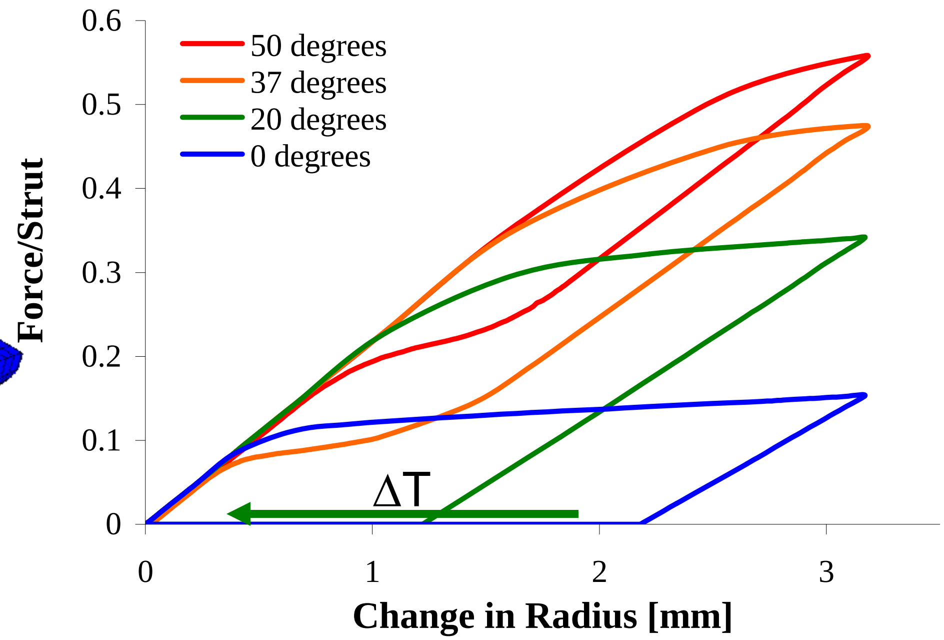


Material Model	cpu	ε_{final}	δ_{final}
Tri-Linear	14	tons	1.14
ABAQUS UMAT	42	0	0
ECHOBIO UMAT	36	0	0
Linear Elastic	12	0	0

Considerations

- 3D formulation?
- Monotonic only loading?
- Temperature dependence?
- History dependence?





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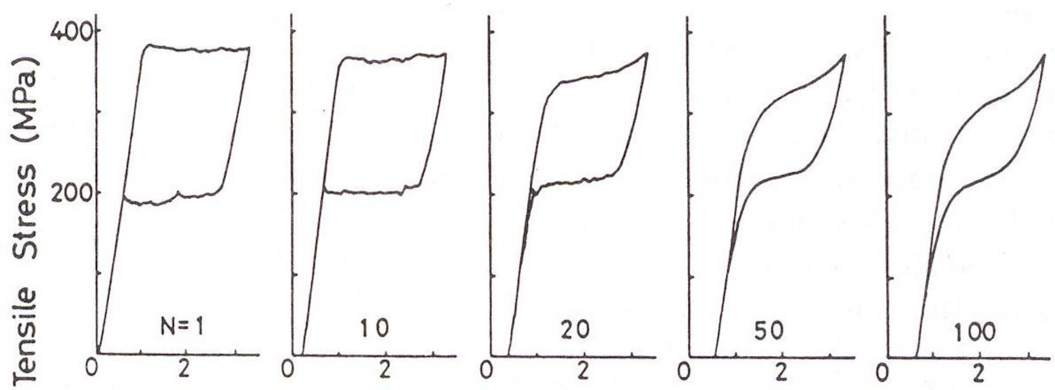
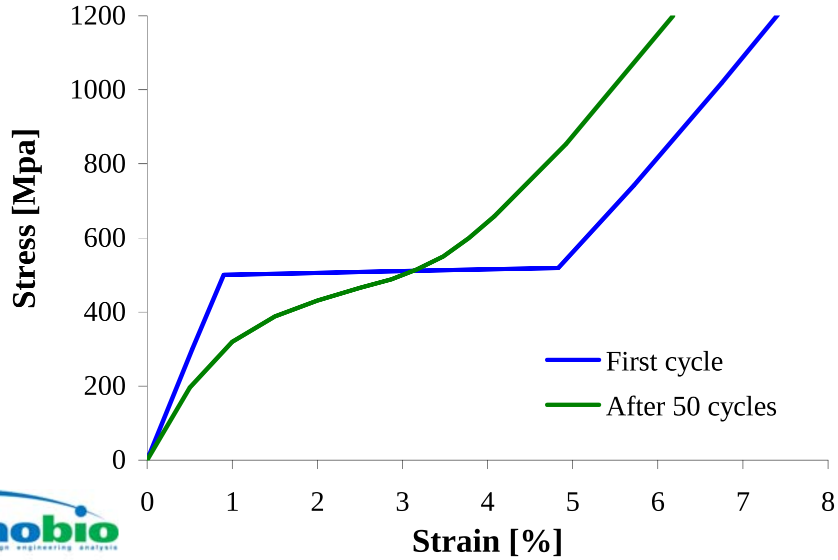
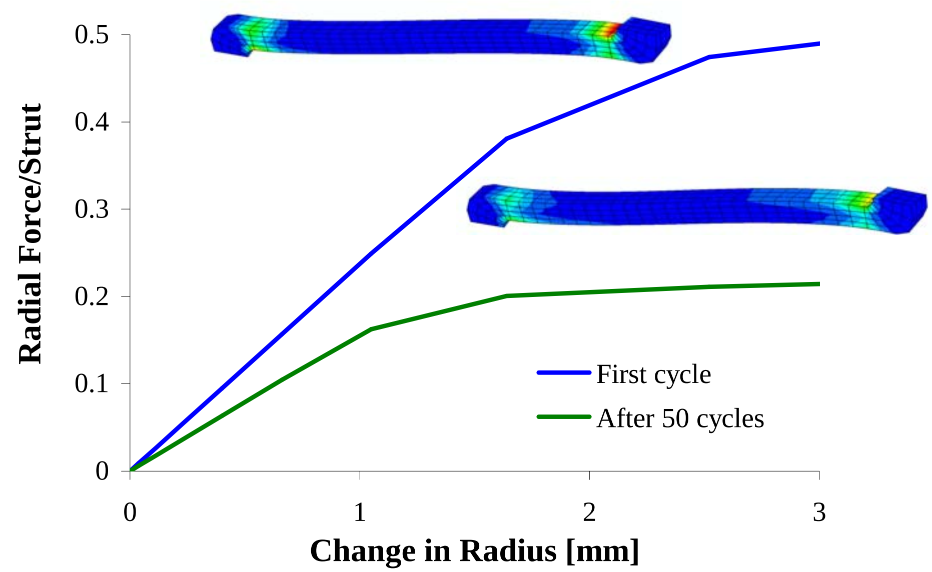
Load History Dependence

- Evolution of the stress-strain behavior after multiple cycles of loading

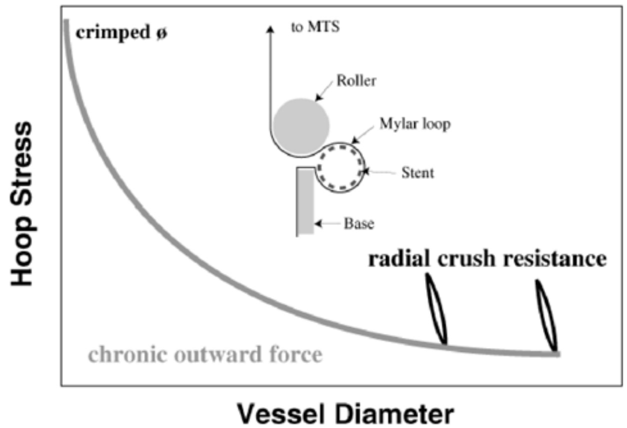


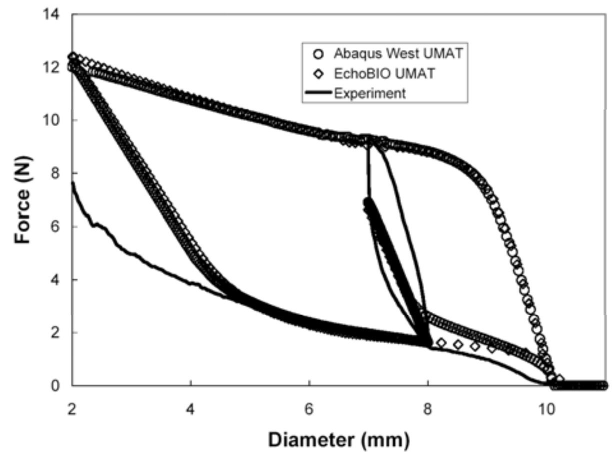
S. Miyazaki, Shape Memory Alloys, 1996

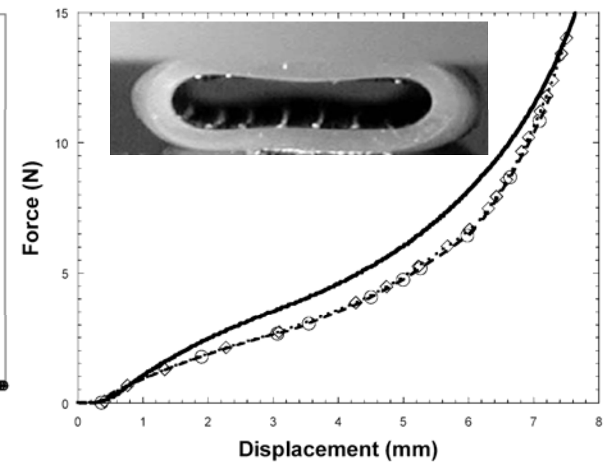




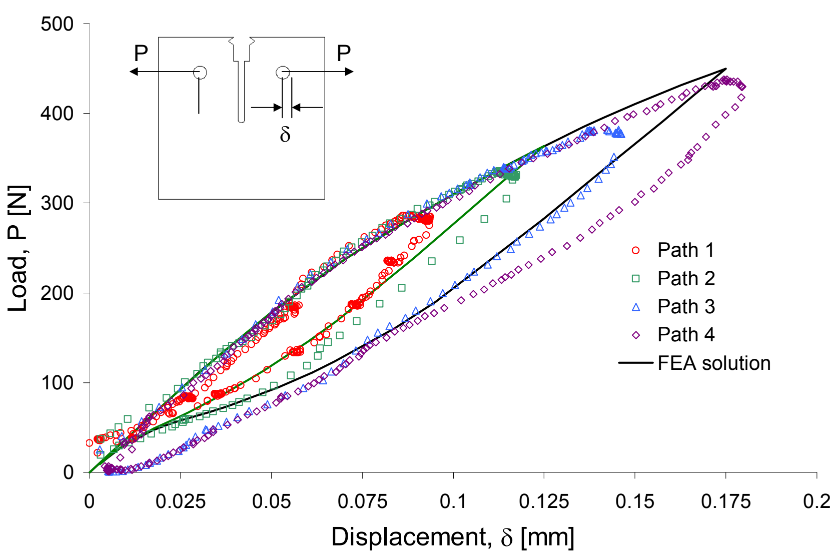
Verification with Experimental Measurements

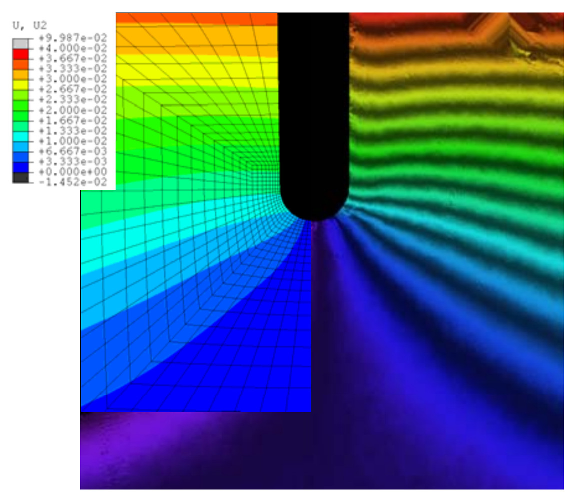






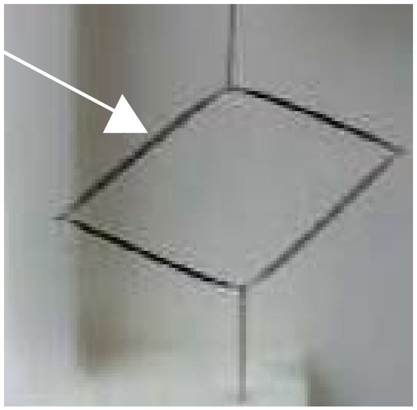
X-Y Gong, A.R. Pelton, T.W. Duerig, N. Rebelo and K.E. Perry, SMST 2003



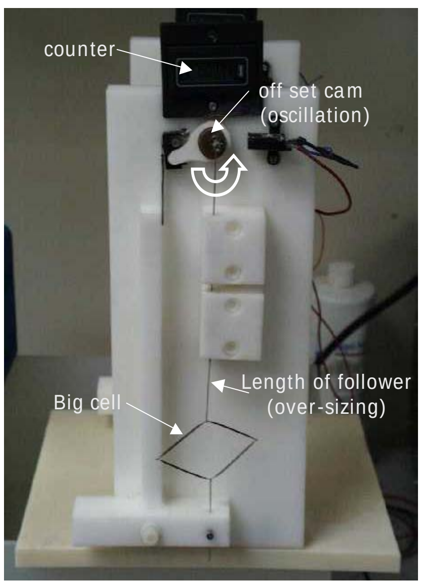


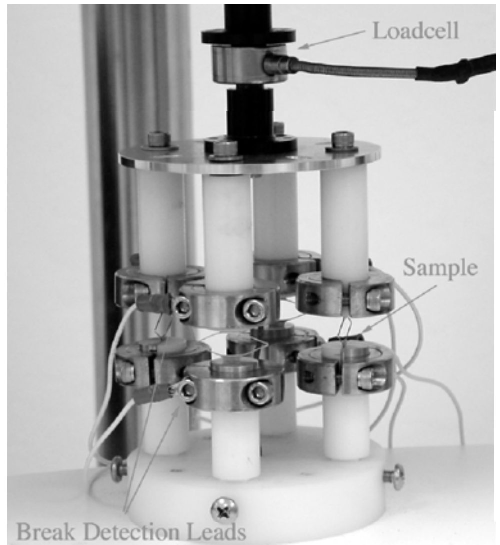
K.E. Perry and P.E. Labossiere, SMST 2003

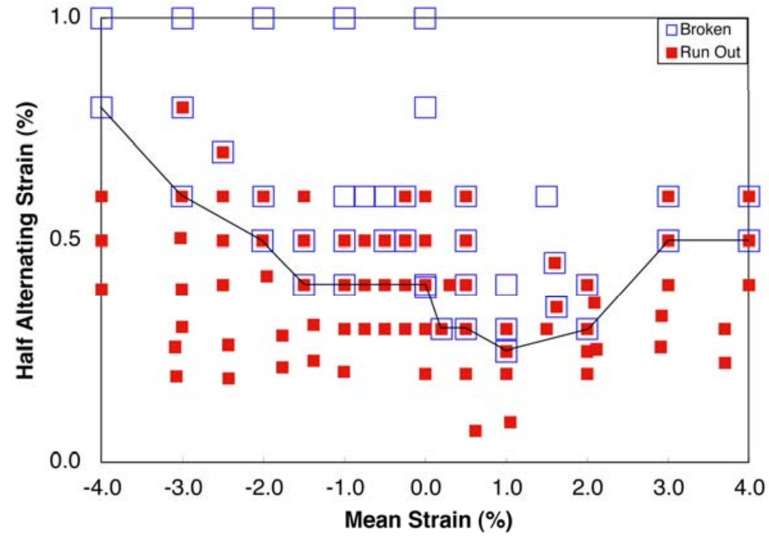
Fatigue Coupon Samples: Calibrate and Verify



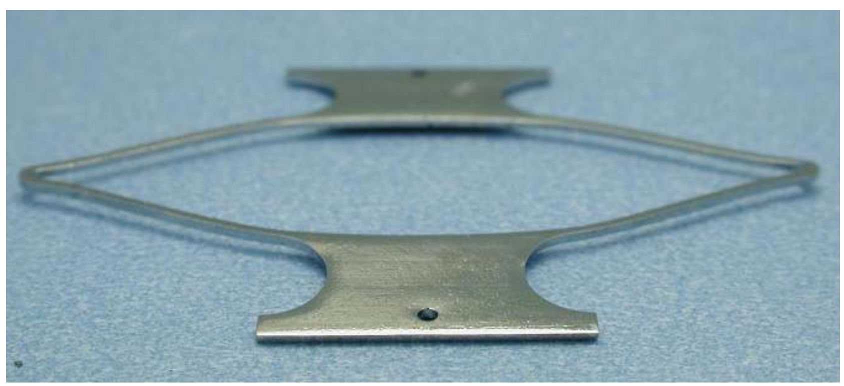
C. Kugler and K. Perry, SMST 2000

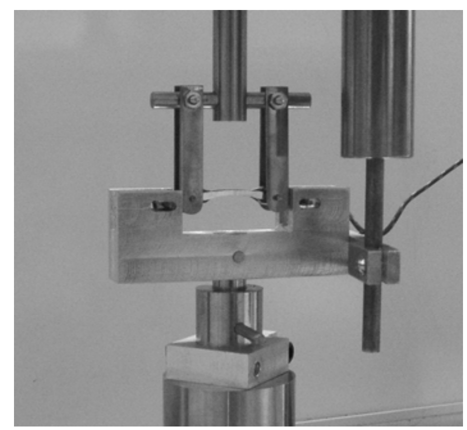






X-Y Gong, T. Duerig, A. Mehta, V. Imbeni, B. Berg, Presented at Society for Experimental Mechanics 2004 Annual Meeting, elsewhere

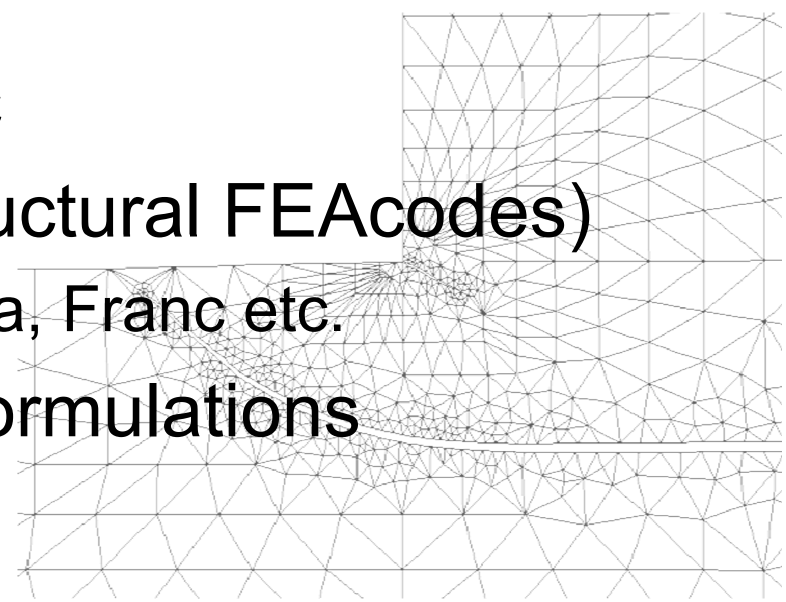




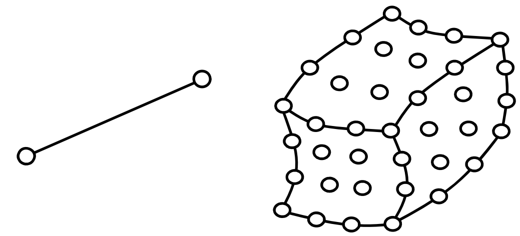
K. Perry and P. Labossiere, ASTM 2005

History of FEA

- Term “Finite Element Method” first used in 1960 (Clough)
- First book published in 1967
- First commercial FEA CODE 1972 (MARC)
- Full-blown codes
  - ABAQUS, ANSYS, MARC
- Specialty codes (>30 structural FEAcodes)
  - Mechanica, Cosmos, Dyna, Franc etc.
- Implicit versus Explicit Formulations



FEA Fundamentals

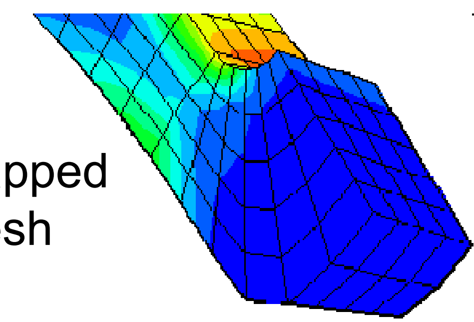


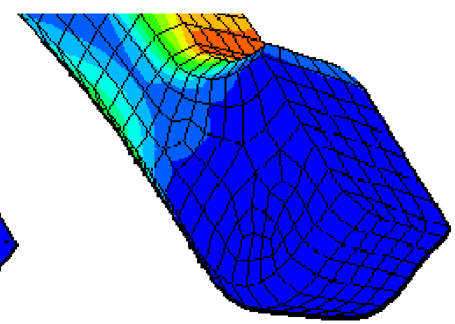
- Element formulations
  - Element types and solution variables

    Most common: Displacement based isoparametric formulation

- Mesh types and element density
  - Seeded outside-inside mesh approach

Mapped Mesh



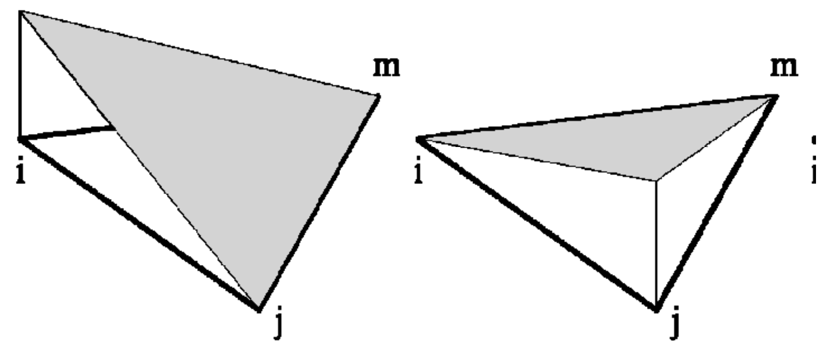


Free Mesh

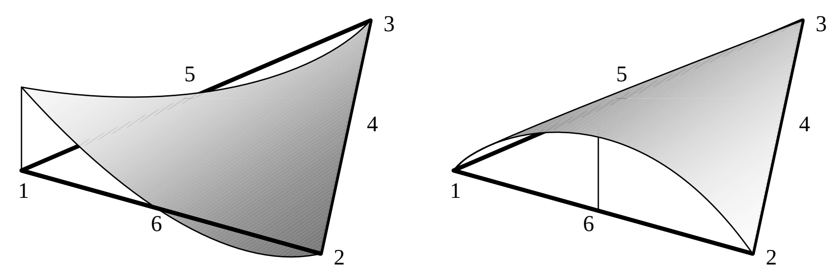
- Boundary conditions and sub-model symmetry/constraints
- Solvers

Element Formulations

- Linear Elements-2 nodes per edge
  - Linear geometrical and displacement description
  - Constant (triangles) or quasi-linear (squares) stress and strain description

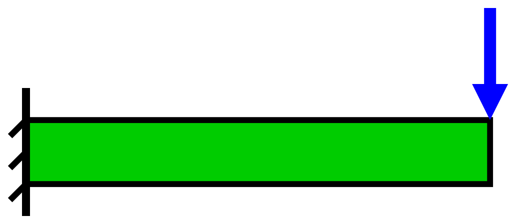


- Quadratic Elements-3 nodes per edge
  - Quadratic geometrical and displacement description
  - Linear (triangles) or quasi-quadratic (squares) stress and strain description



Elements in Bending

- Some elements do not perform well in bending because that deformation is not well described by the element formulation
  - Linear isoparametric elements
- Element that do better in bending
  - Higher order elements (quadratic elements and up)
  - Reduced integration elements
  - Bending specific elements such as incompatible mode elements
- Example



Element Type	# of DOF	Max Deflection
CST	24	0.3
LST	30	0.99
Lin. Brick	24	.69
Quad. Brick	26	1.03
Modified Bilinear	36	1.02
Analytical	-	1.0

FEA Basic Principle

The static FEA solution (for displacement formulation) comes from:

$$\iiint_V \mathbf{B}^T \mathbf{D} \mathbf{B}\, dV \mathbf{u} - \mathbf{P} - \iiint_V \mathbf{N}^T \mathbf{X}_{body}\, dV - \iint_S \mathbf{N}^T \mathbf{T}_{tract}\, dS = 0$$

or simply $\mathbf{K}\,\mathbf{u} - \mathbf{f} = 0$

and with inertial and viscous effects

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{f}$$

With geometric and material nonlinearities, the problem becomes much more complicated

Complications

- Nonlinear Material (ex: plasticity)

$$\mathbf{D}_{ep} = \mathbf{D} - \frac{1}{\mathbf{H}_p + \mathbf{n} : \mathbf{D} : \mathbf{m}} (\mathbf{D} : \mathbf{m} \otimes \mathbf{n} : \mathbf{D})$$

- Large deformations

$$\mathbf{K}_L = \iiint_v \left(\mathbf{B}_O^T \mathbf{D} \mathbf{B}_L + \mathbf{B}_L^T \mathbf{D} \mathbf{B}_L + \mathbf{B}_L^T \mathbf{D} \mathbf{B}_O \right) dV$$

- Finite strains

$$\varepsilon_x = \frac{\partial u}{\partial x} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial x} \right)^2 \right]$$

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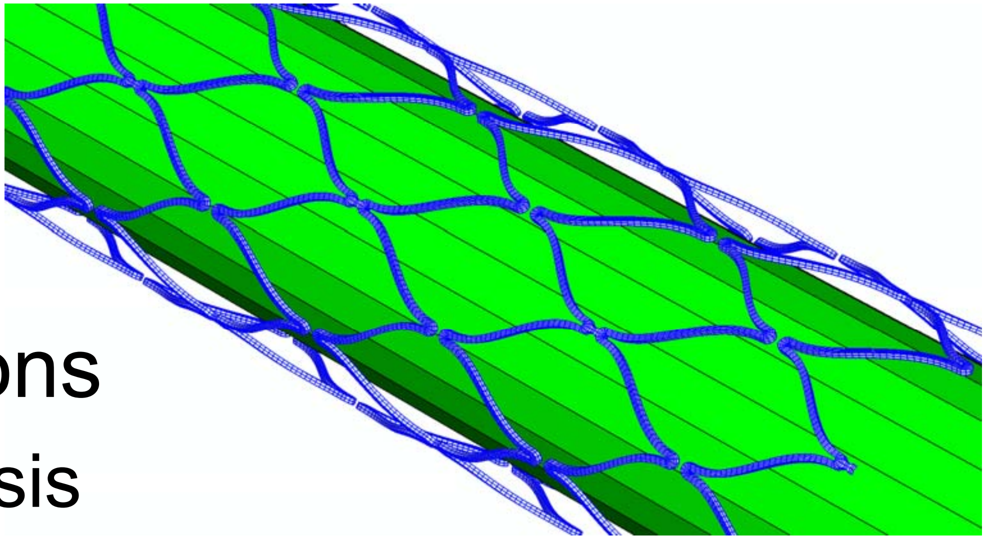
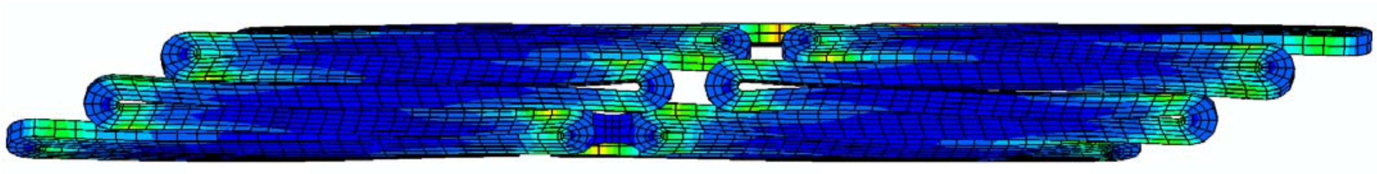
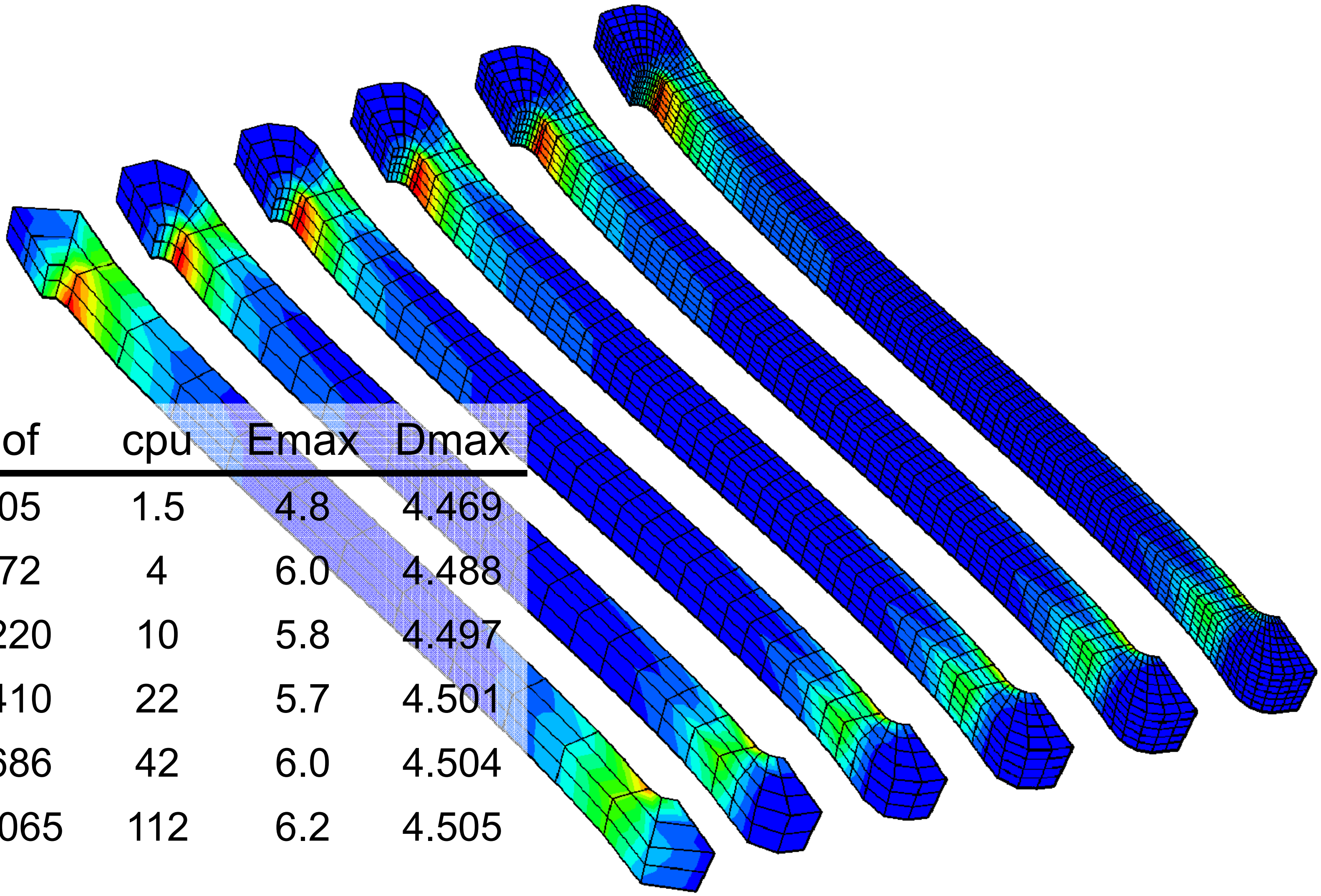
Producing Valid FEA Results

- Element Size and type
  - Mesh Density
- Geometry
  - Chamfer Analysis
- Boundary Conditions
  - Base model analysis
  - Expansion step optimization





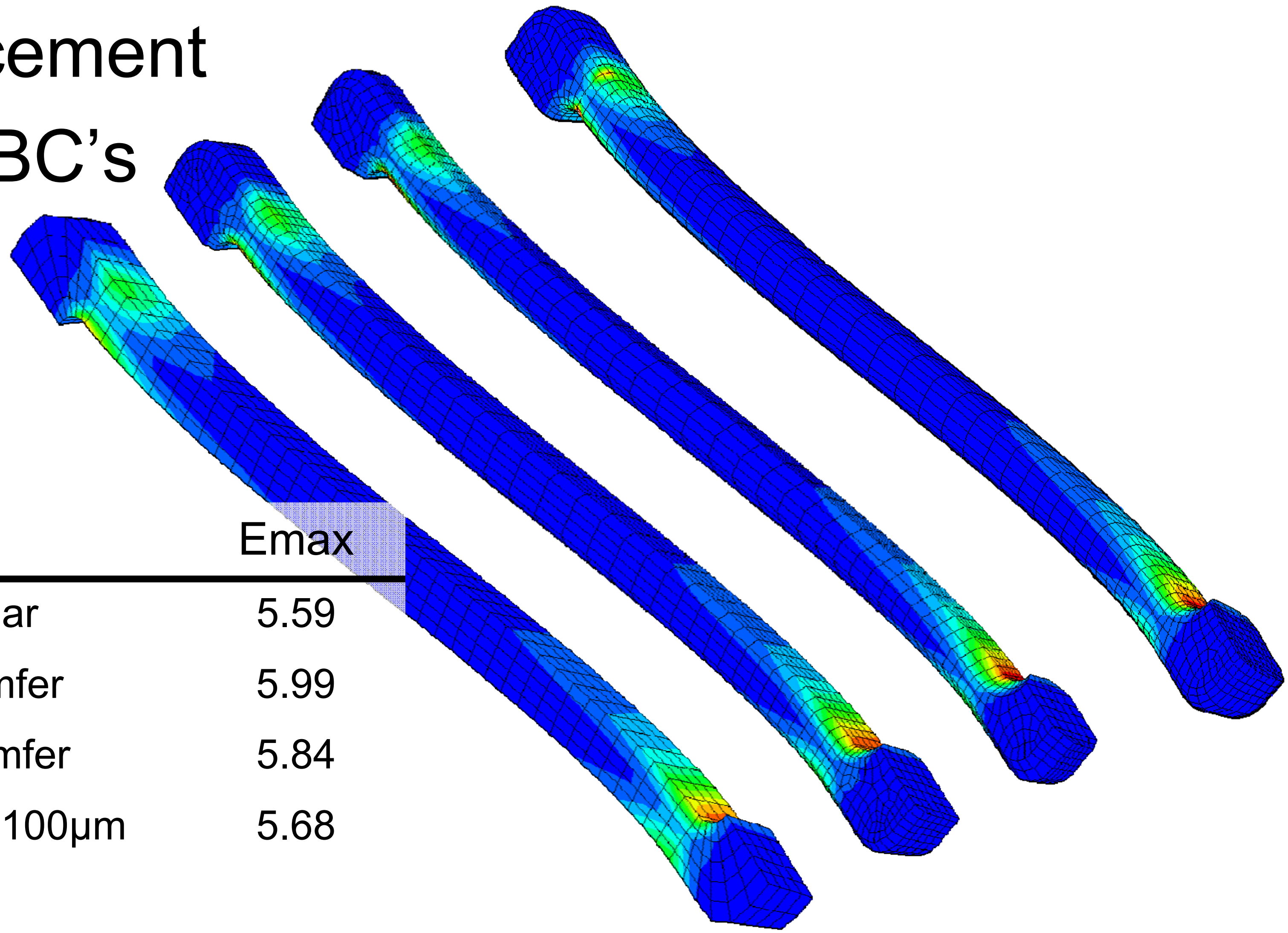
Case Study:
Mesh Density Analysis



Mesh	dof	cpu	Emax	Dmax
2x2	405	1.5	4.8	4.469
3x2	972	4	6.0	4.488
4x3	2220	10	5.8	4.497
5x4	4410	22	5.7	4.501
6x5	7686	42	6.0	4.504
8x6	16065	112	6.2	4.505

Case Study: Chamfer Analysis

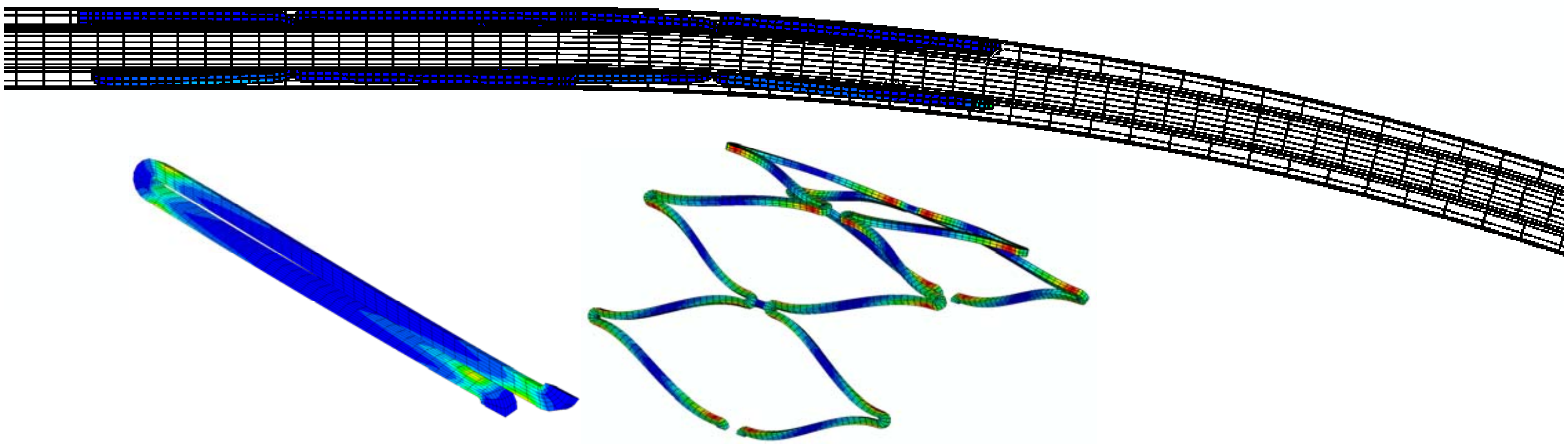
Displacement based BC's



Model	Emax
Rectangular	5.59
50µm Chamfer	5.99
100µm chamfer	5.84
Fillet Radius = 100µm	5.68

Choice of Base Model

- Radial loading or complex loading (combined radial fatigue and bending, extension and torsion

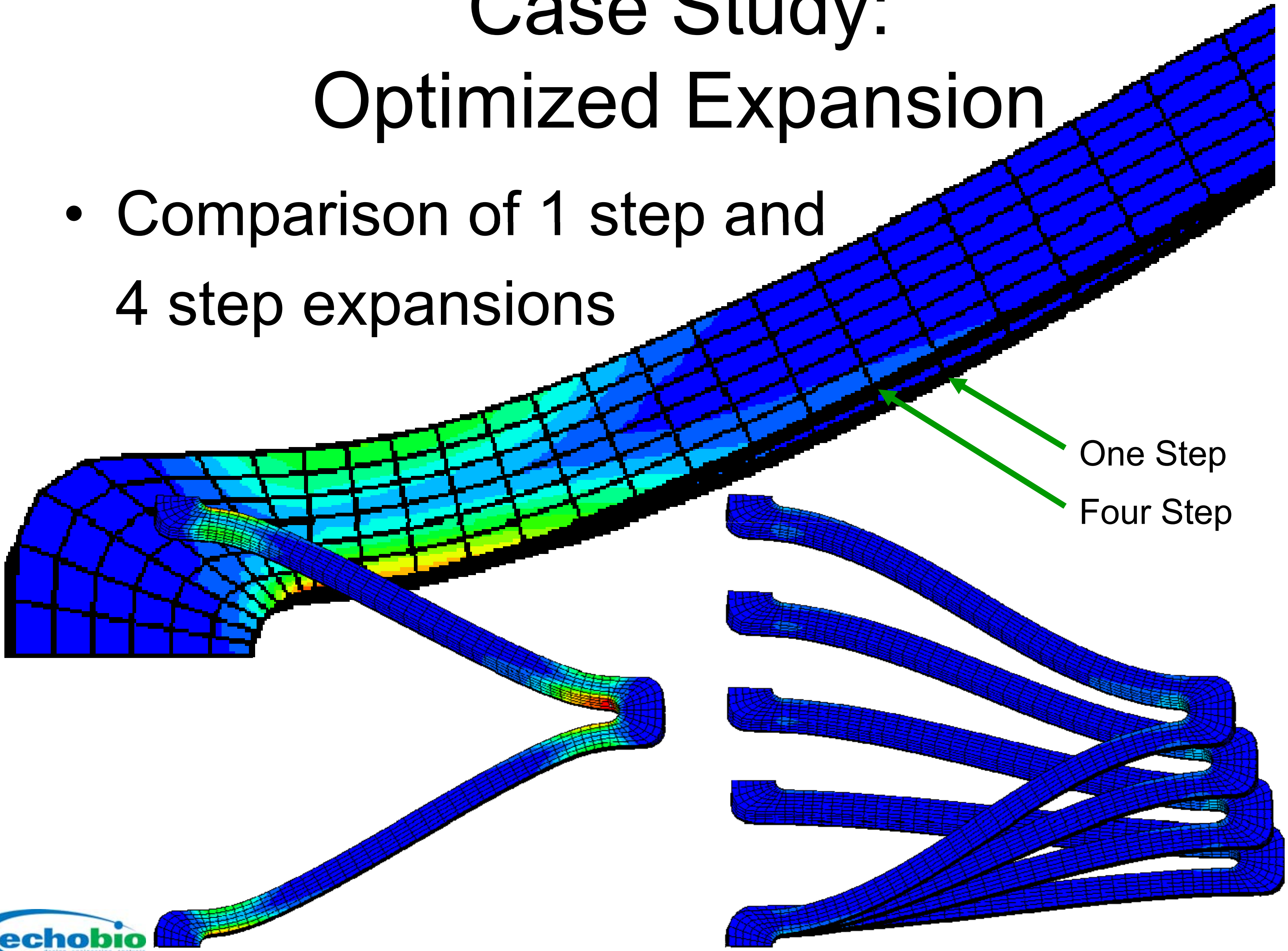


- Vessel interaction and flow effects

Sub Model	cpu	ε_{final}
Small Model - Radial Loading (Two Strut)	15	4.3
Partial Model - Radial Loading (One Bridge)	280	4.5
Full Model with bending	2600	4.6

Case Study: Optimized Expansion

- Comparison of 1 step and 4 step expansions

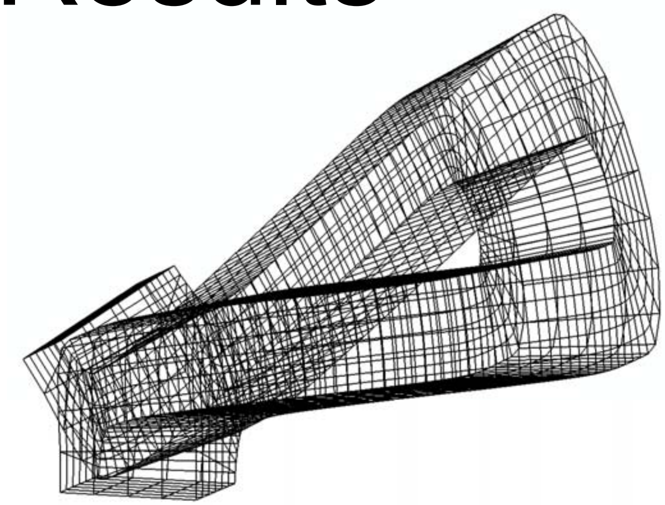


When Building the Model

Watch for:

- unconnected (floating) nodes or elements
- nearly coincidental nodes that are not connected
- elements with large aspect ratios
- elements with highly differing corner angles
- elements that share nodes that do not have the same dof
- midside nodes that are too curved or midside nodes too far from the correct location (ex ¼ point elements)
- shell elements with too great a curvature

When Viewing Results



Watch for:

- Unrealistic deformed shape
  (or exaggerated by the GUI)
- gaps do not overclose, and
  no interpenetration between parts
- stresses that vary by large amounts over too few elements
- verify reaction forces satisfy static equilibrium
- stress plots should be based on unaveraged nodal stresses (look at the “element solution” for stresses and the “nodal solution” for displacements)

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FEA Not So Fundamentals

- Convergence
  - Solution Stabilization
- Nonlinearities
  - Material
  - Geometry (large deformation/finite strain)
- Boundary Conditions and Interactions
  - Contact surfaces
- User Subroutines and working with FEA codes outside of the box
  - UMATS and feedback loops

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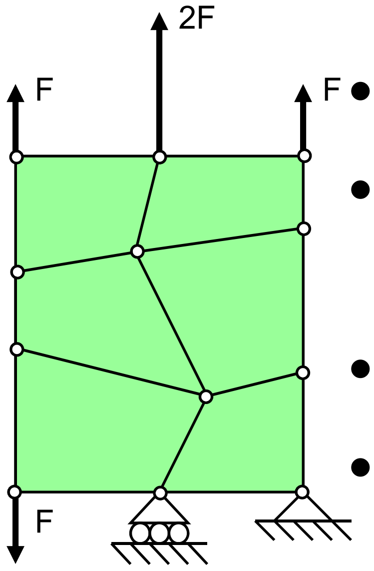
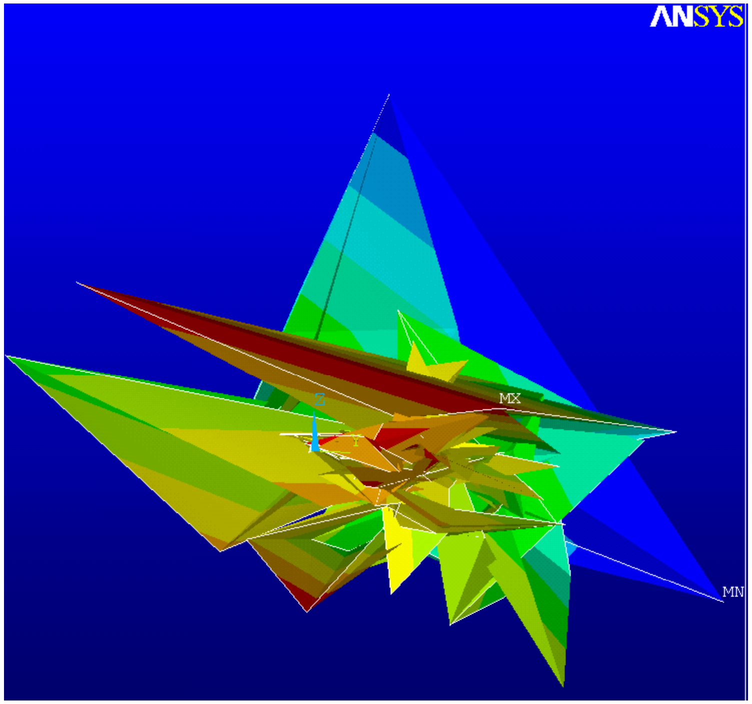
design engineering analysis

Convergence and Stabilization



- Patch test: necessary and sufficient
- Displacement based boundary conditions
- Step size effects
- Stabilization techniques

What to do in the event of a crash!



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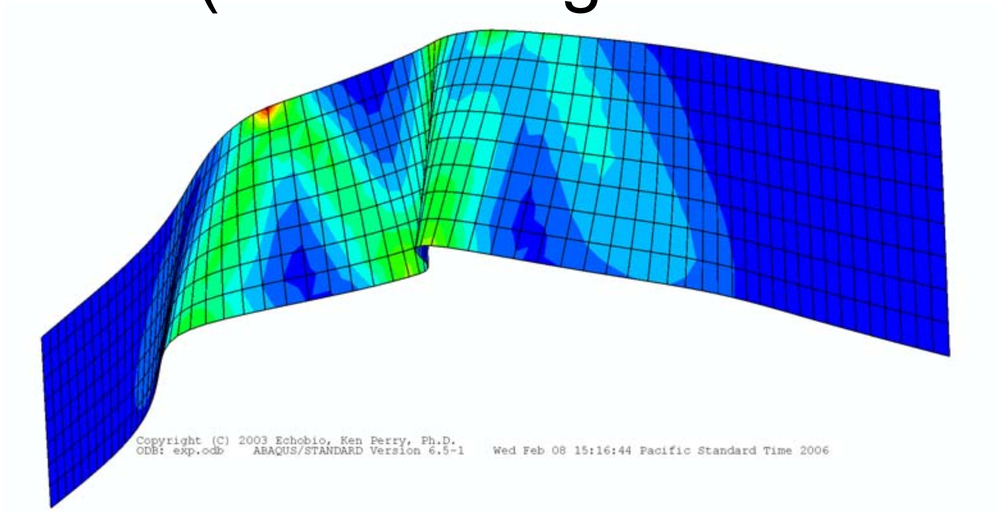
* STATIC, DON’T PANIC

- Check your inputs
- Decrease the step size
- Monitor convergence and tolerance criteria
- Also some codes have stabilization

Abaqus Stabilize=dissipated energy fraction of the automatic damping algorithm (like running the model in JELLO)

- Be patient



Convergence and Solvers

- Steps, Increments and Iterations, Oh MY!

TIME INCREMENT COMPLETED 1.875E-02, FRACTION OF STEP COMPLETED 0.408

STEP TIME COMPLETED 0.408 , TOTAL TIME COMPLETED 0.408

INCREMENT 14 STARTS. ATTEMPT NUMBER 1, TIME INCREMENT 2.813E-02

RSURFU: 0.197892E+01, 0.192755E+01, 1, 0.435937E+00

EQUILIBRIUM ITERATION 1

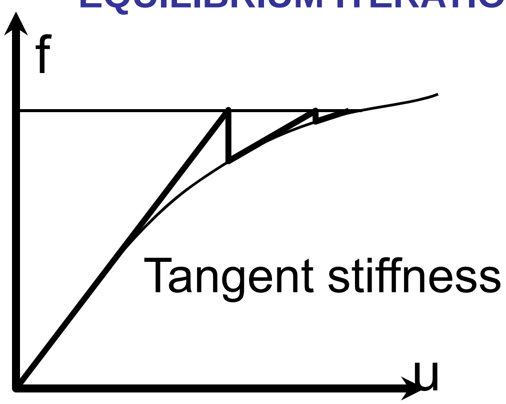
AVERAGE FORCE 8.486E-03 TIME AVG. FORCE 3.888E-03
LARGEST RESIDUAL FORCE -1.097E-03 AT NODE 9057 DOF 3
LARGEST INCREMENT OF DISP. -7.534E-02 AT NODE 3568 DOF 1
LARGEST CORRECTION TO DISP. 2.161E-03 AT NODE 3676 DOF 3

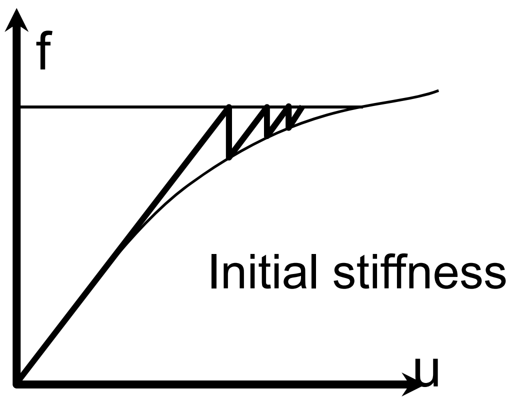
FORCE EQUILIBRIUM NOT ACHIEVED WITHIN TOLERANCE.

AVERAGE MOMENT 2.967E-04 TIME AVG. MOMENT 1.216E-04
ALL MOMENT RESIDUALS ARE ZERO
LARGEST INCREMENT OF ROTATION 4.067E-38 AT NODE 400001 DOF 5
LARGEST CORRECTION TO ROTATION -1.402E-38 AT NODE 400001 DOF 5

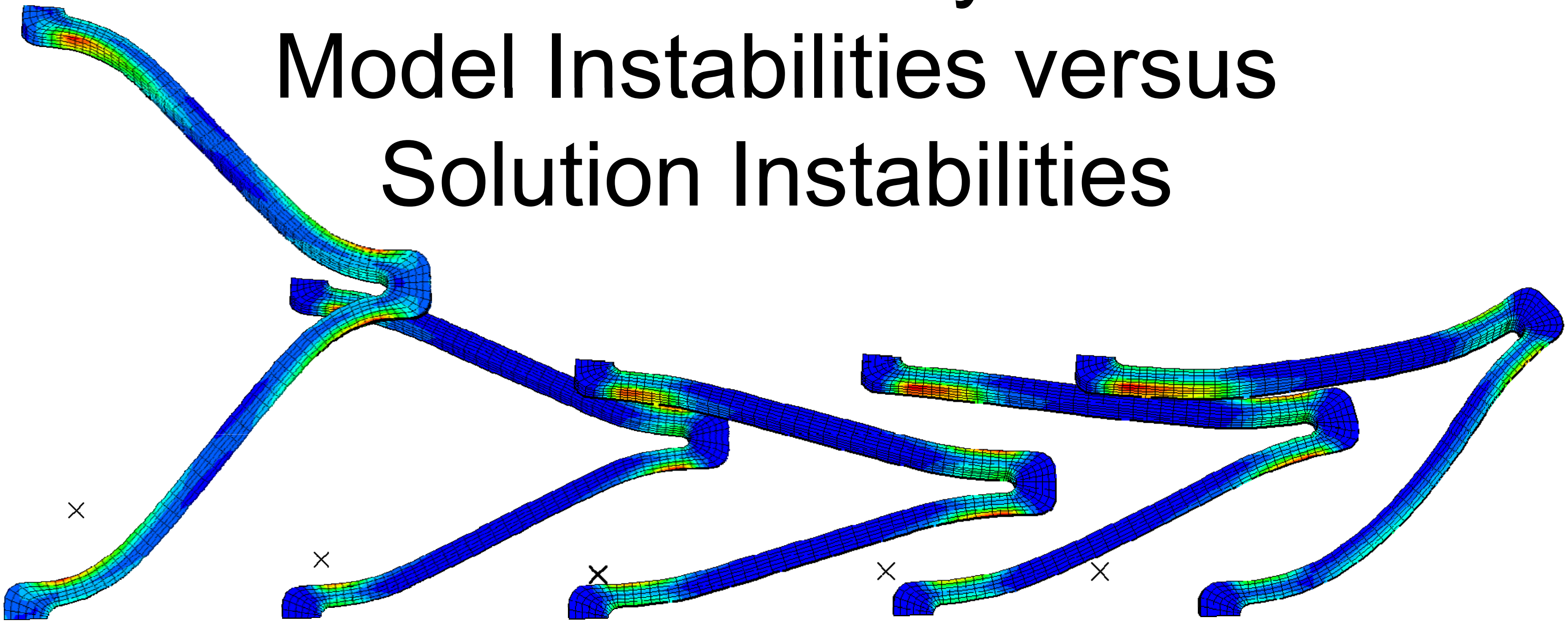
THE MOMENT EQUILIBRIUM RESPONSE WAS LINEAR IN THIS INCREMENT

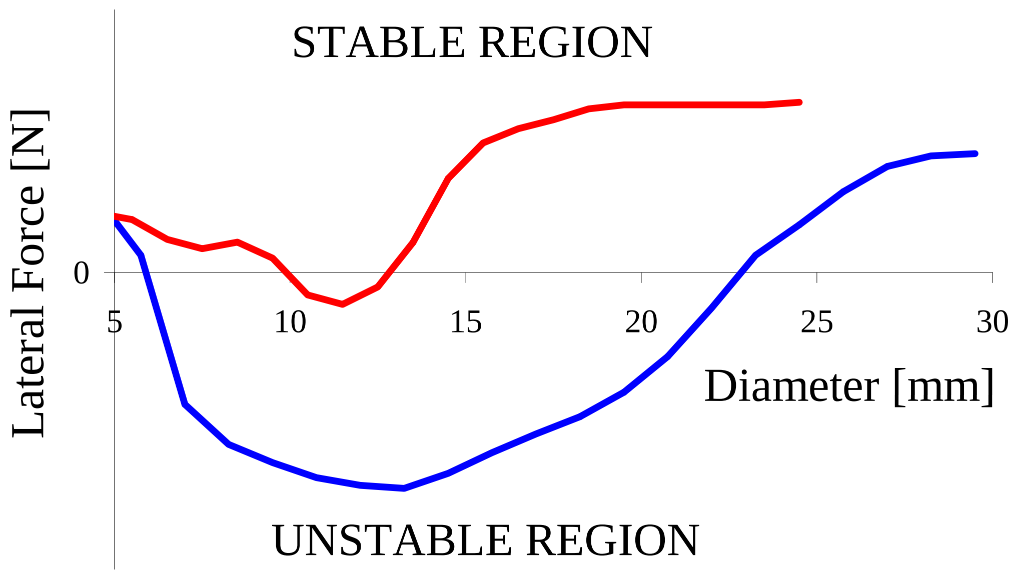
EQUILIBRIUM ITERATION 2…





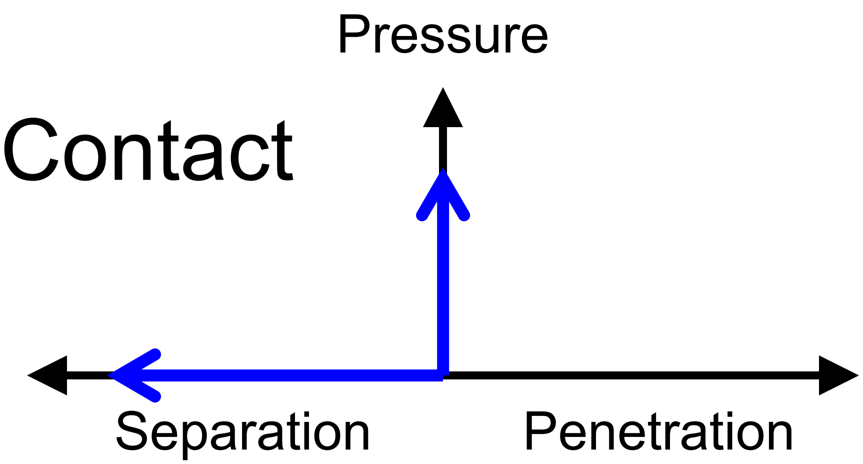
Case Study:
Model Instabilities versus Solution Instabilities



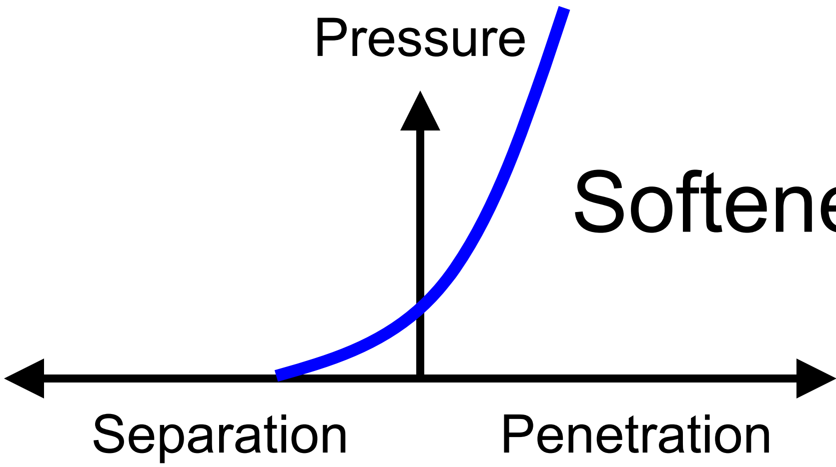


Contact Interactions

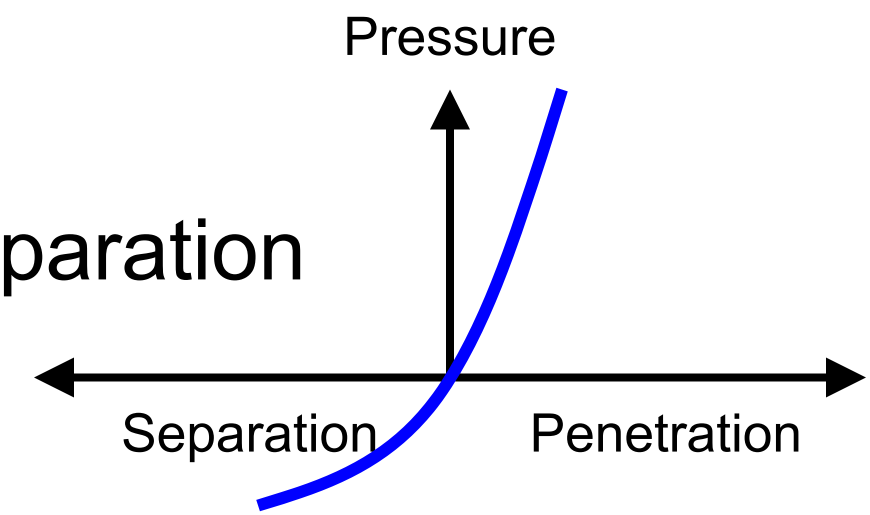
Hard Contact



Softened Contact

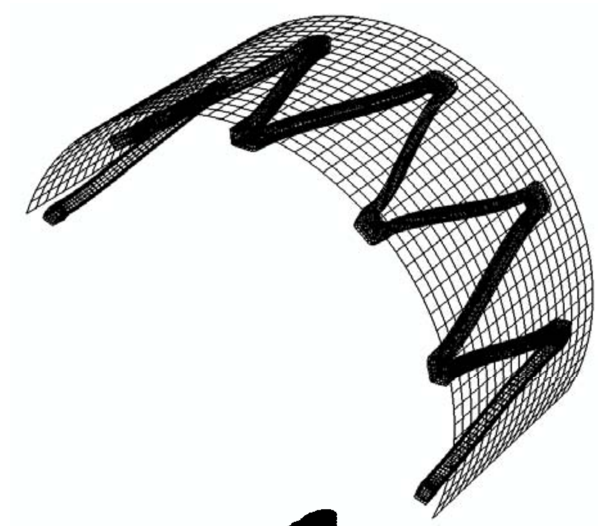


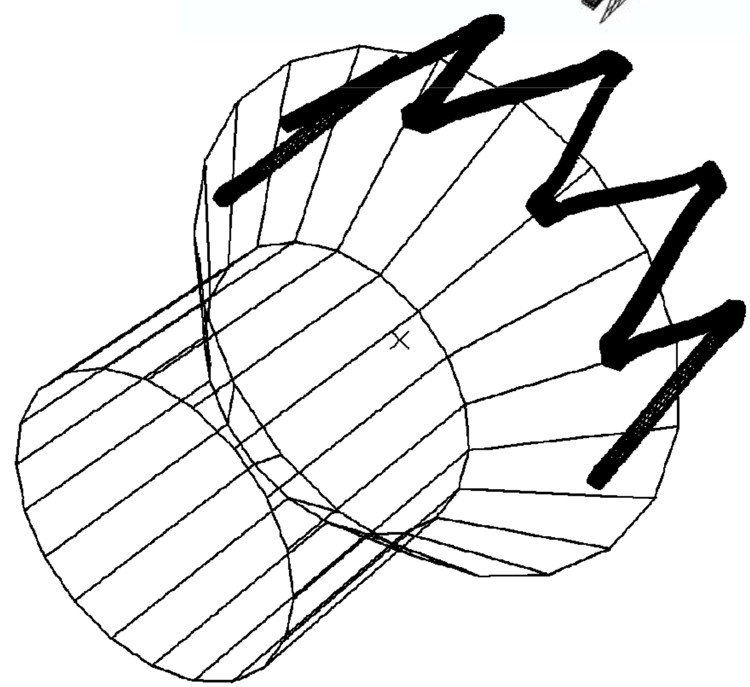
No Separation

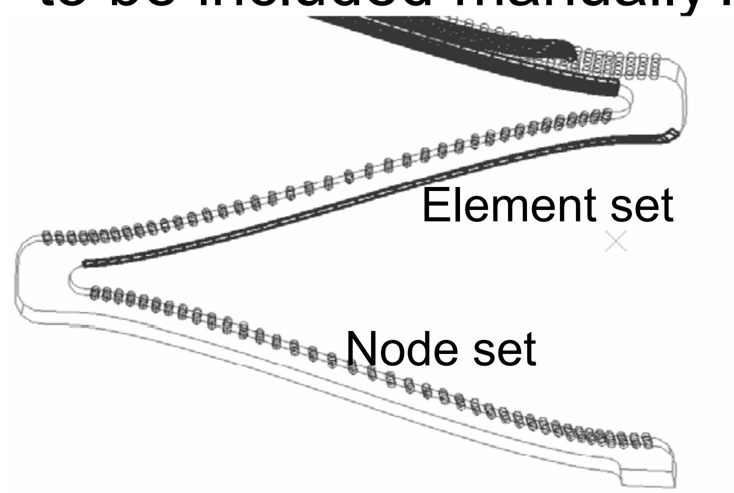


Contact Interactions

- Deformable contact bodies
  - Element based surfaces
  - Node based surfaces
- Rigid surface definitions
- Self Contact
  - to be included manually?

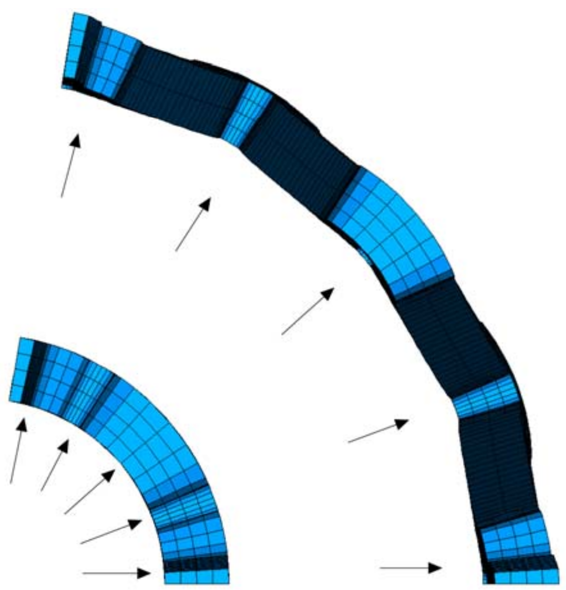


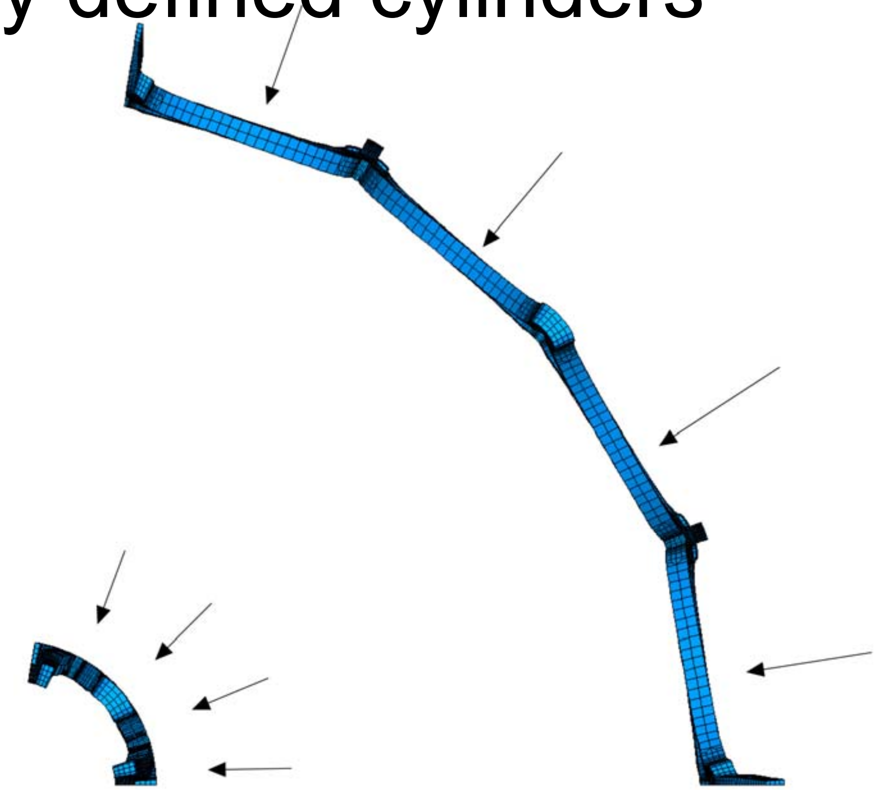




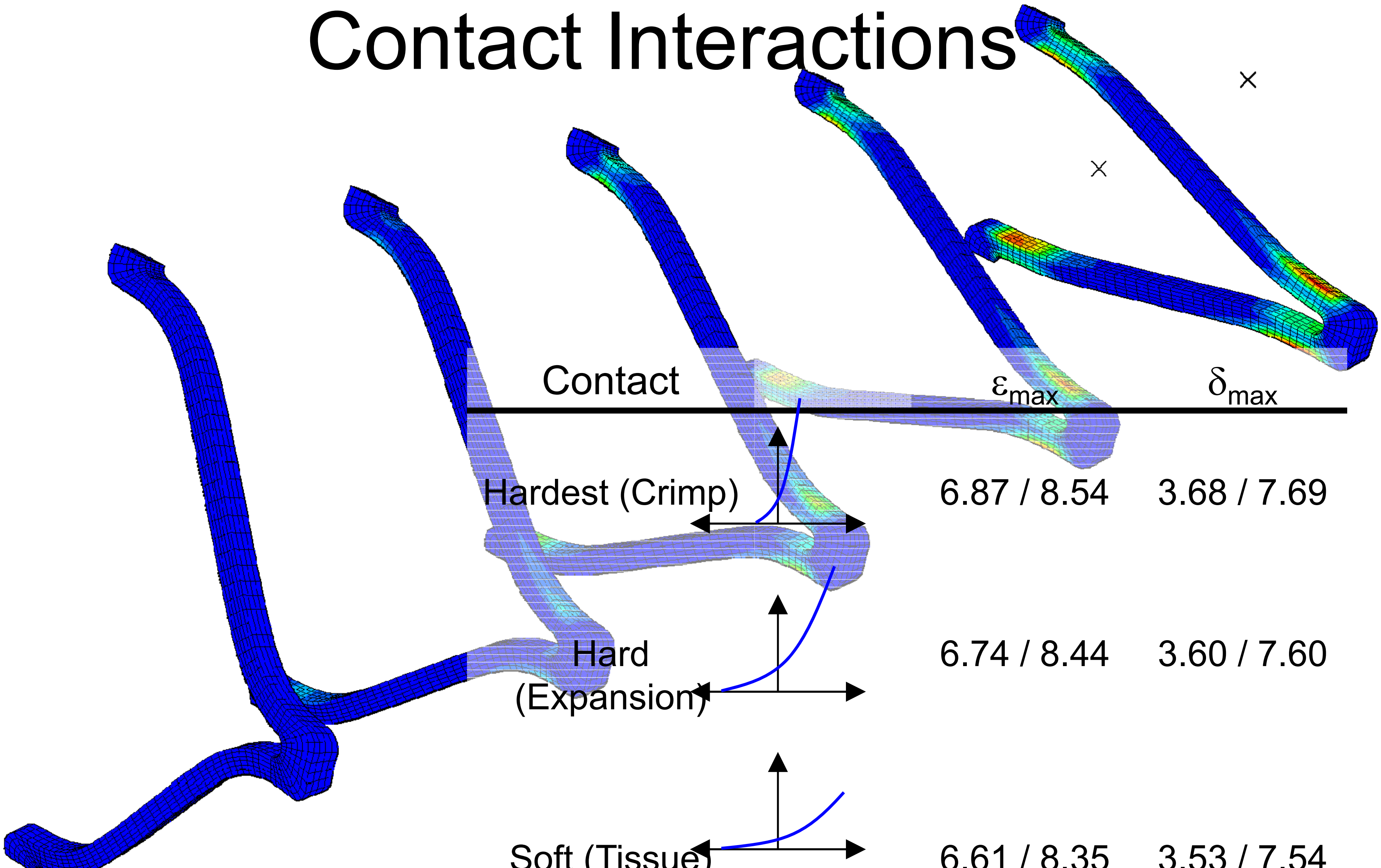
Radial Expansion, Crimp and Fatigue Modeling

- Radial loading with contracting and expanding analytically defined cylinders





Case Study:
Contact Interactions



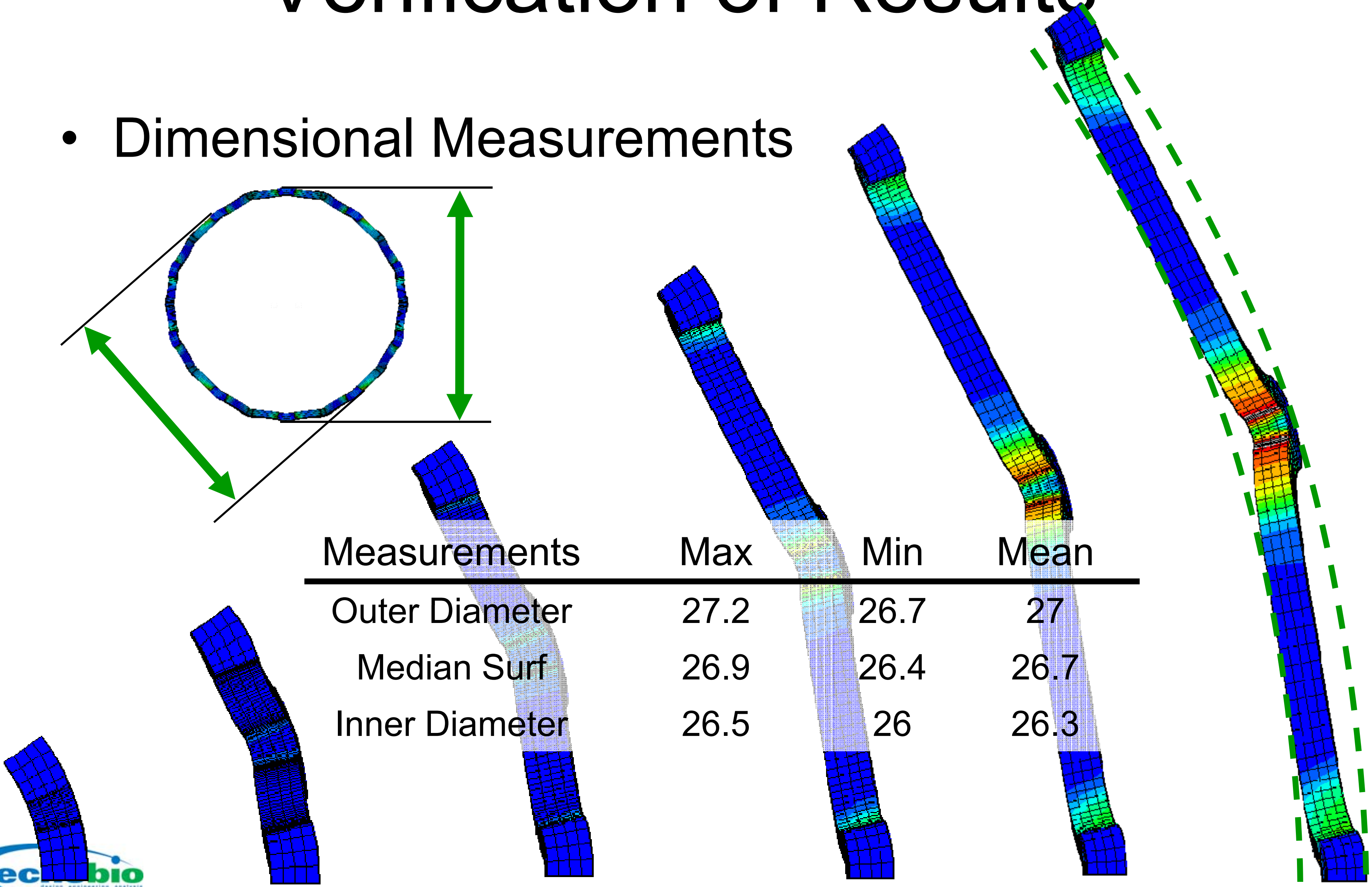
Contact	ε_{max}	δ_{max}
Hardest (Crimp)	6.87 / 8.54	3.68 / 7.69
Hard (Expansion)	6.74 / 8.44	3.60 / 7.60
Soft (Tissue)	6.61 / 8.35	3.53 / 7.54

Verification of Results

- Perhaps a wordy slide to help accentuate the importance of verification…and a list of possible ways verification can be done…
  - Dimensional verification (displacements are consistent)
  - Radial force verification (equilibrium is satisfied)
  - Failure/reliability analysis (material characterization is correct, self consistency)

Verification of Results

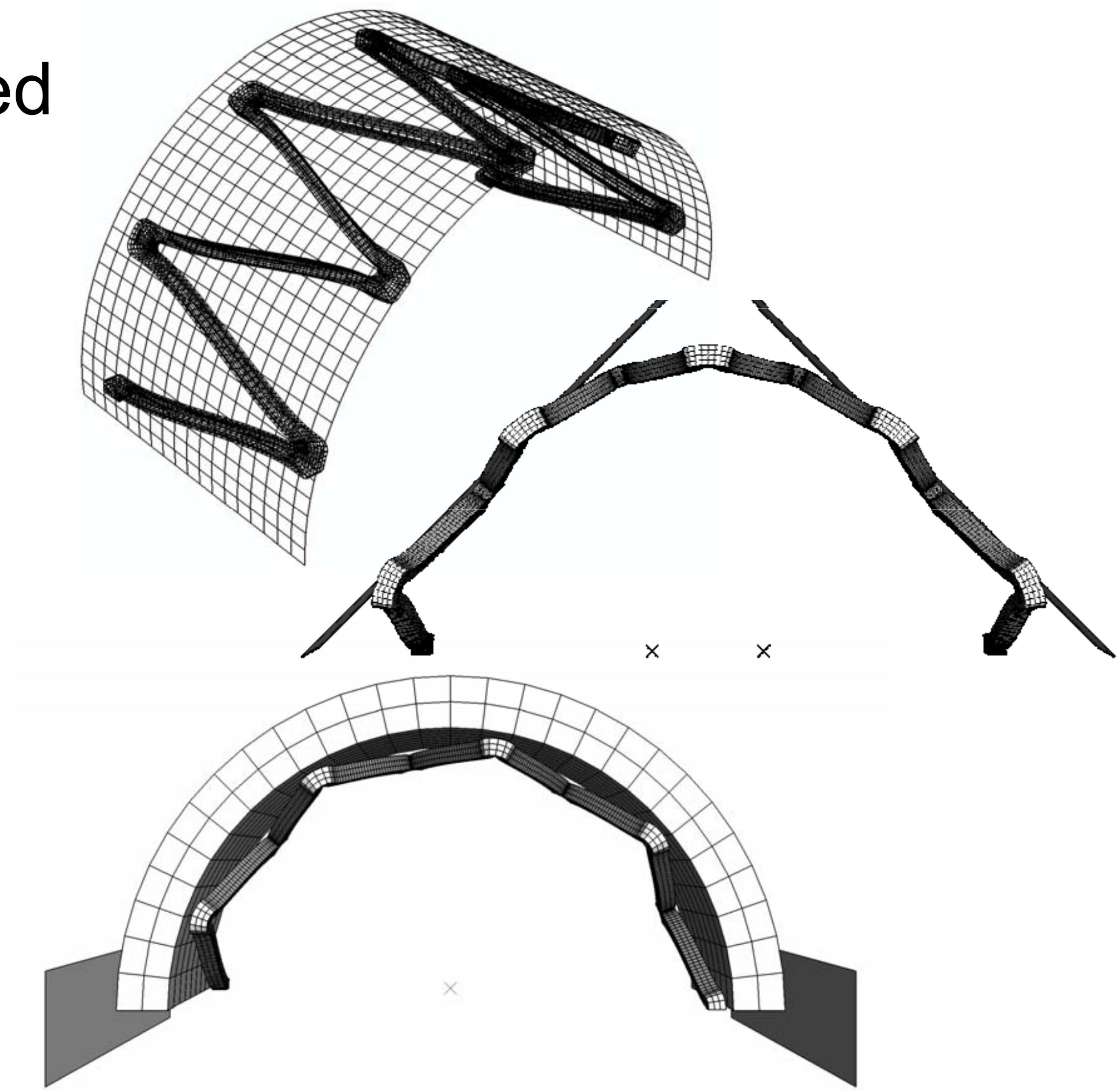
- Dimensional Measurements



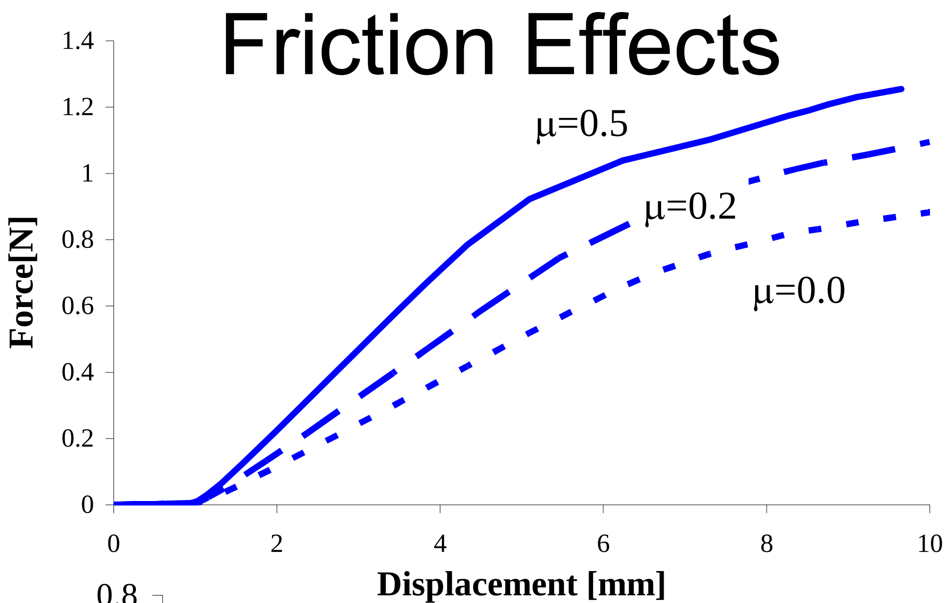
Measurements	Max	Min	Mean
Outer Diameter	27.2	26.7	27
Median Surf	26.9	26.4	26.7
Inner Diameter	26.5	26	26.3

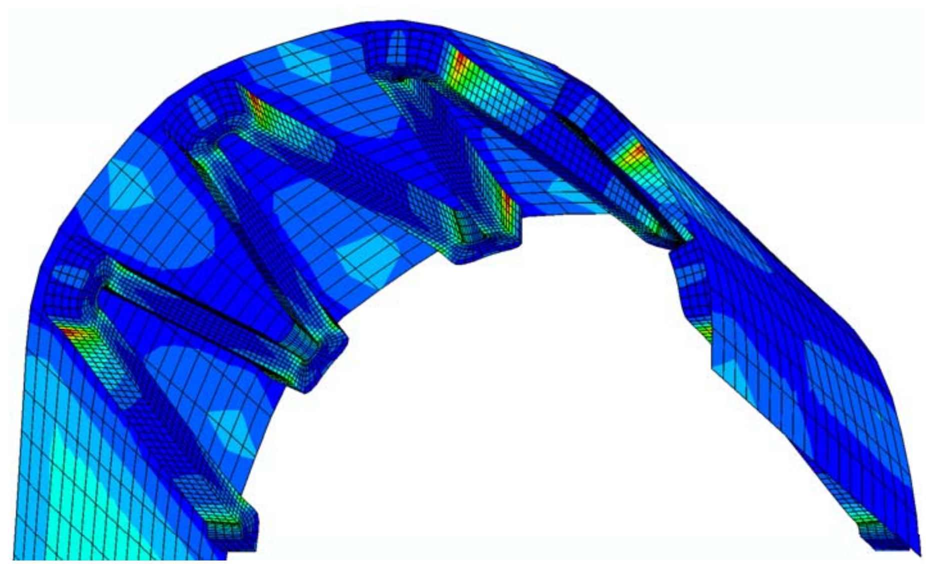
Case Study: Radial Force Measurements

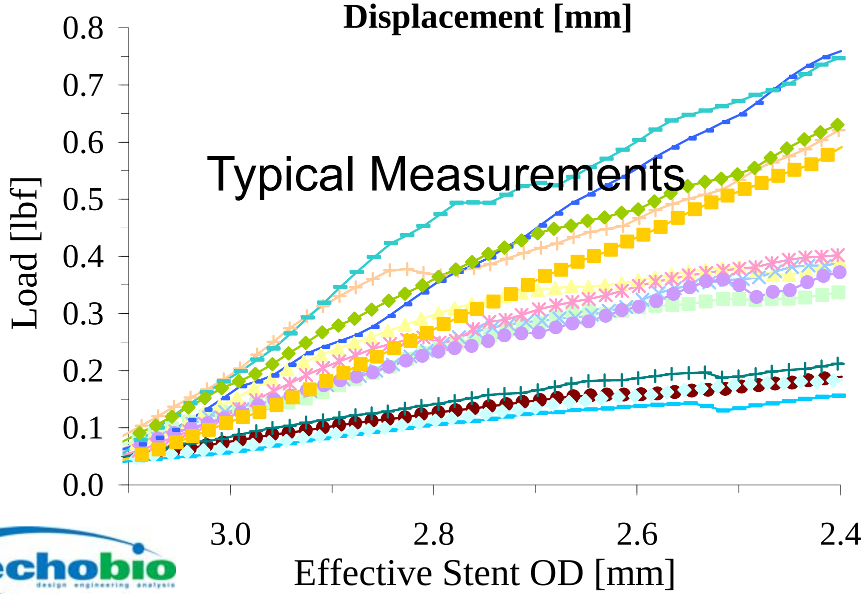
- Analytically defined contracting rigid cylinder
- Loop test
- Clam shell test
- Flat Plate Squish

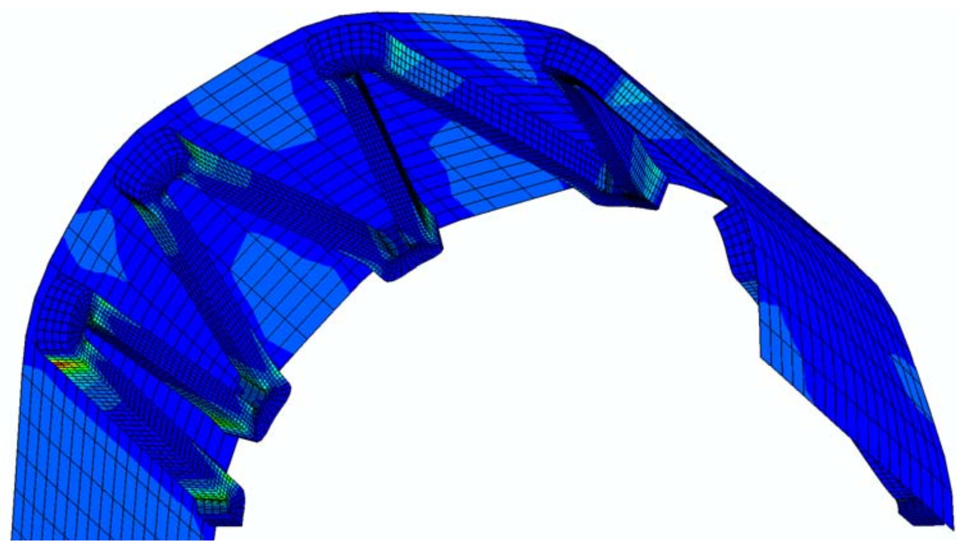


Loop Test Simulation



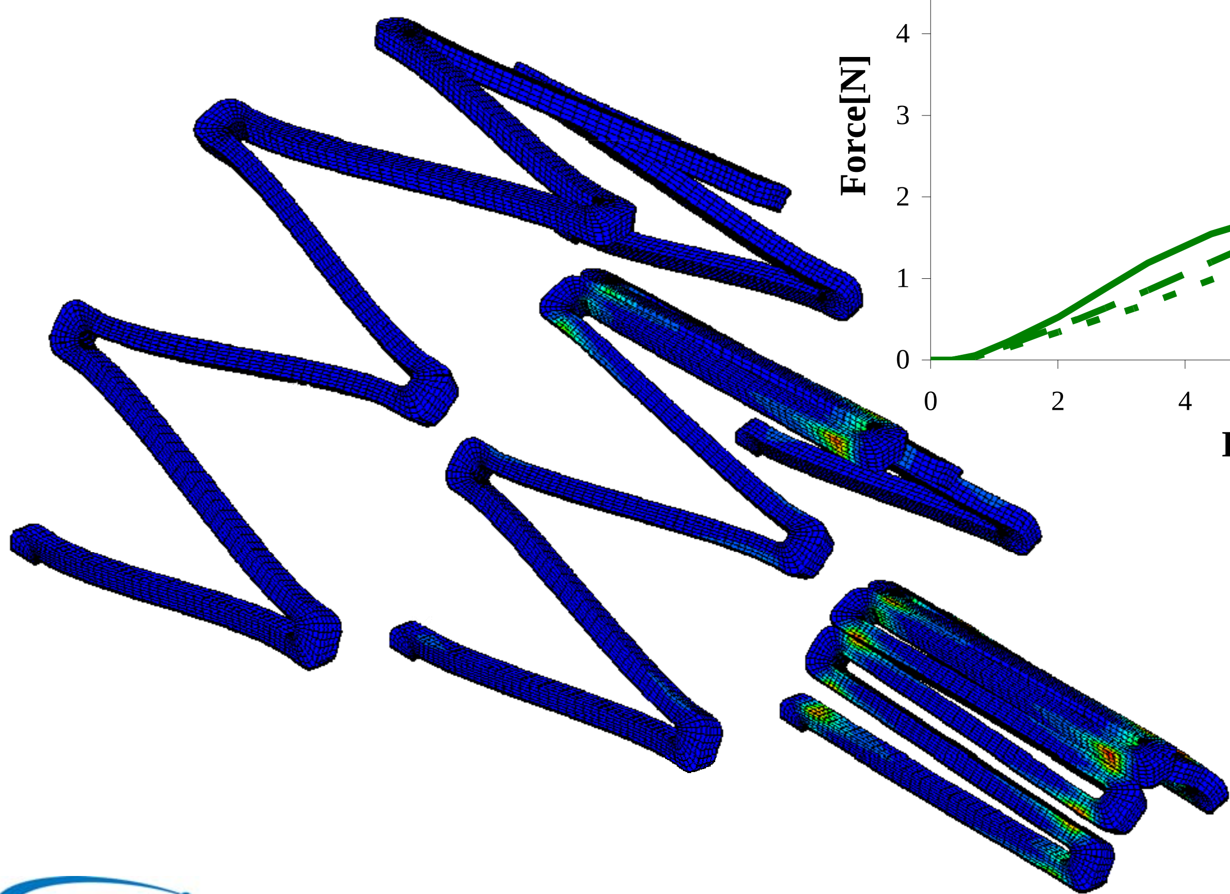


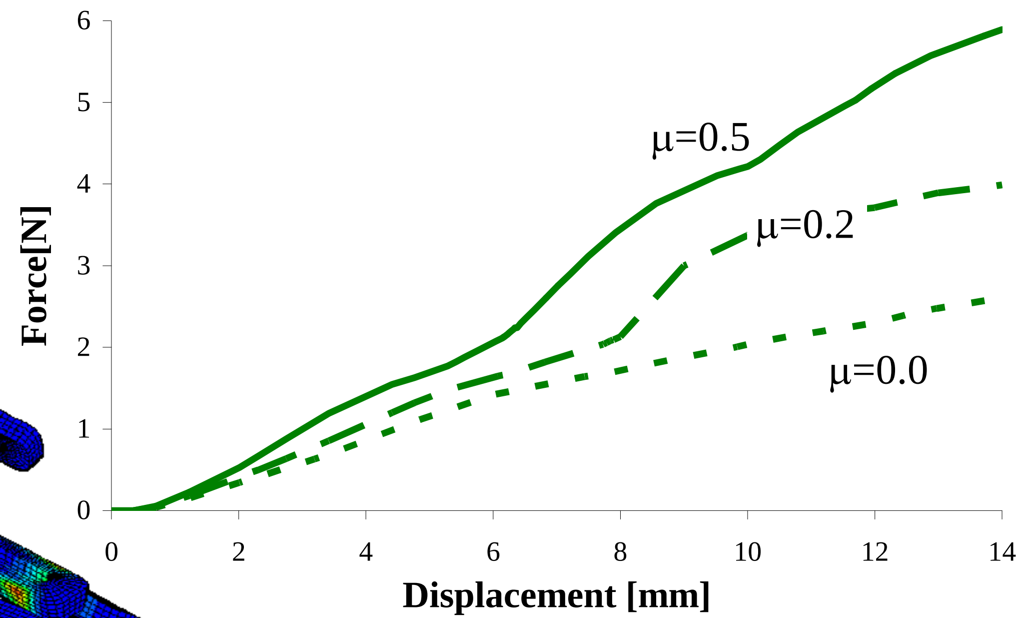




Clam Shell Test Simulation

Friction Effects



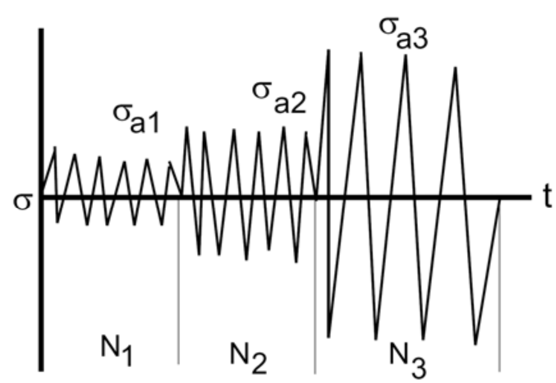


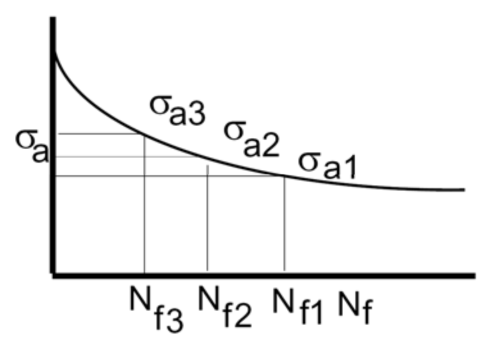
Humps caused
by struts piling-up

echobio

Fatigue and Reliability

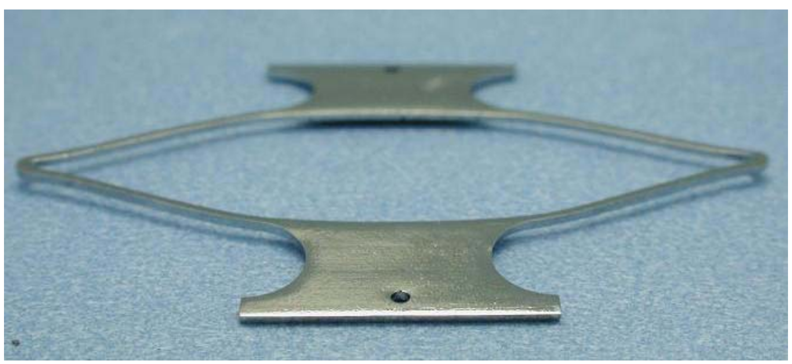
- For medical devices, success comes down to reliability with failure due to fatigue
- In-vitro Fatigue testing
  - Test-to-success versus Test-to-failure
- In-vitro fatigue model verification
- Results interpretation



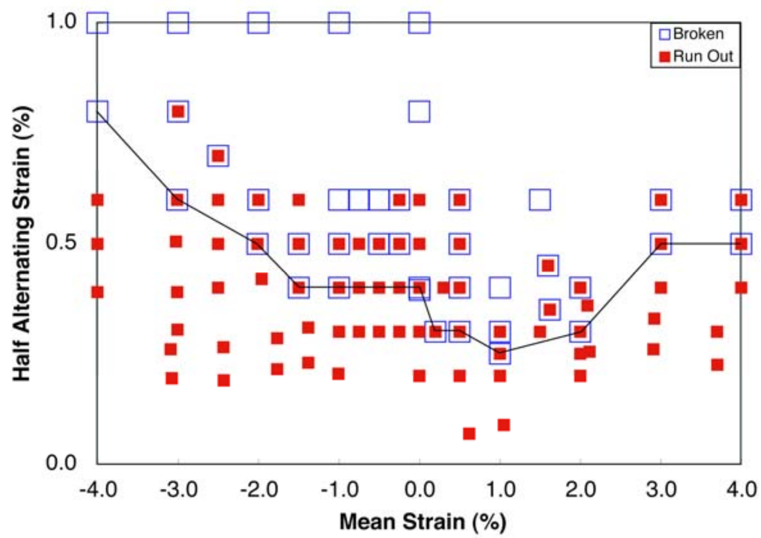


Fatigue Limit Data

- What physical properties are needed for making failure/risk-of-failure decisions?
  - Experimental fatigue limit data with a consistent (and appropriate) fatigue coupon design
  - Borrow “typical” limit properties of NiTi



X-Y Gong, T. Duerig, A. Mehta, V. Imbeni, B. Berg, Presented at Society for Experimental Mechanics 2004 Annual Meeting



Endurance Limit Modifying Factors

$$S_e = K_a\ K_b\ K_c\ K_d\ K_e\ K_f\ S_e`$$

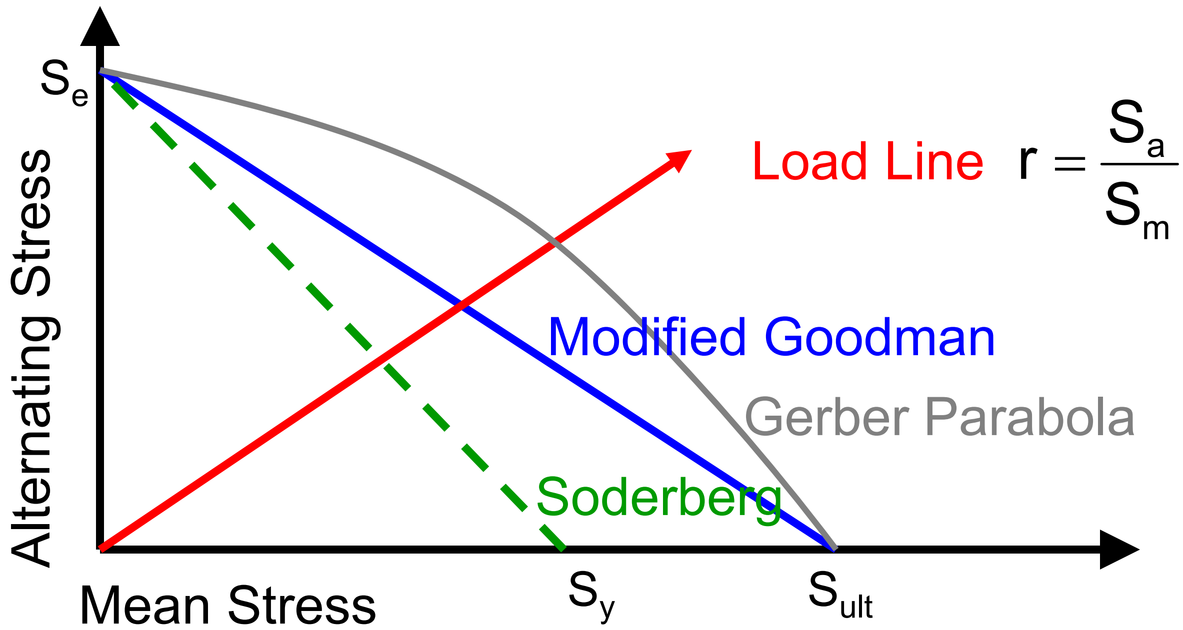
- K_a surface condition factor
- K_b size factor
- K_c load factor
- K_d temperature factor
- K_e reliability factor
- K_f miscellaneous effects factor

Ex.

Reliability	Reliability Factor K_e
.50	1
0.90	.897
0.95	.868
0.99	.814
0.999	.753

Shigley, Mechanical Engineering Design, 1963

Traditional Stress-Based Approach



- Modified Goodman

Intersection

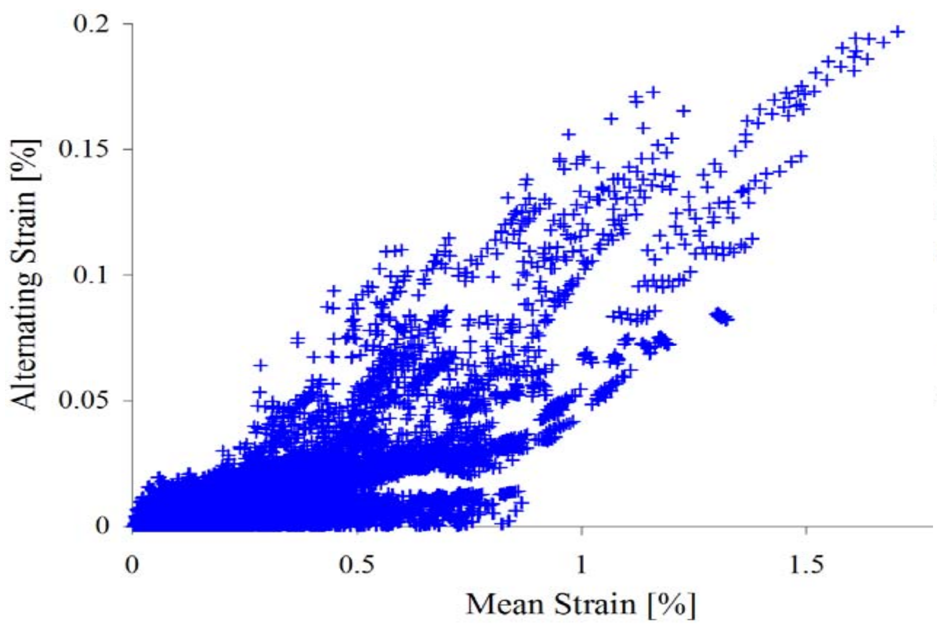
$$\frac{S_a}{S_e} + \frac{S_m}{S_{ult}} = 1$$

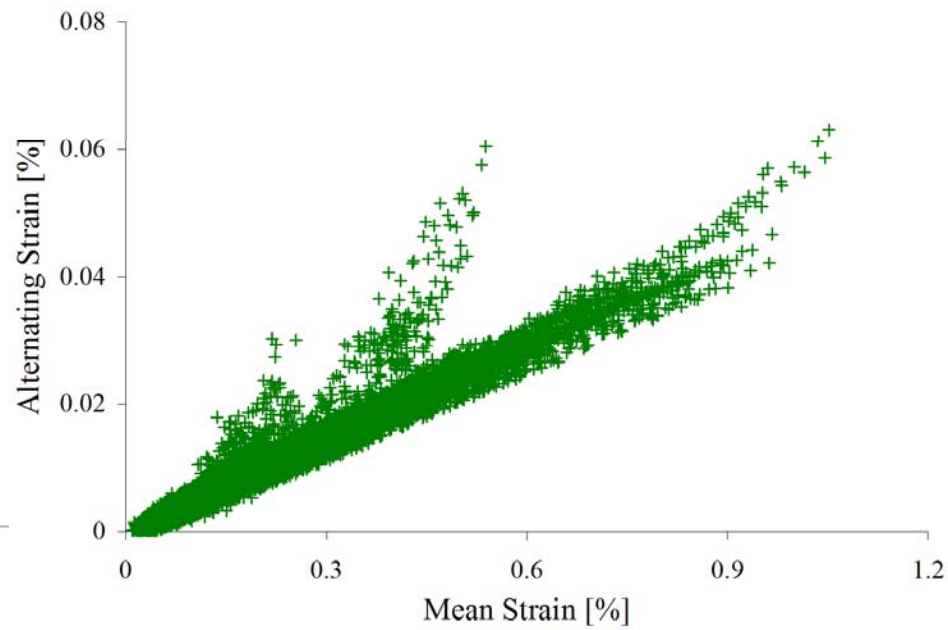
Safety Factor

$$n_f = 1 \bigg/ \left(\frac{S_a}{S_e} + \frac{S_m}{S_{ult}} \right)$$

Mean vs. Alternating Strain Data

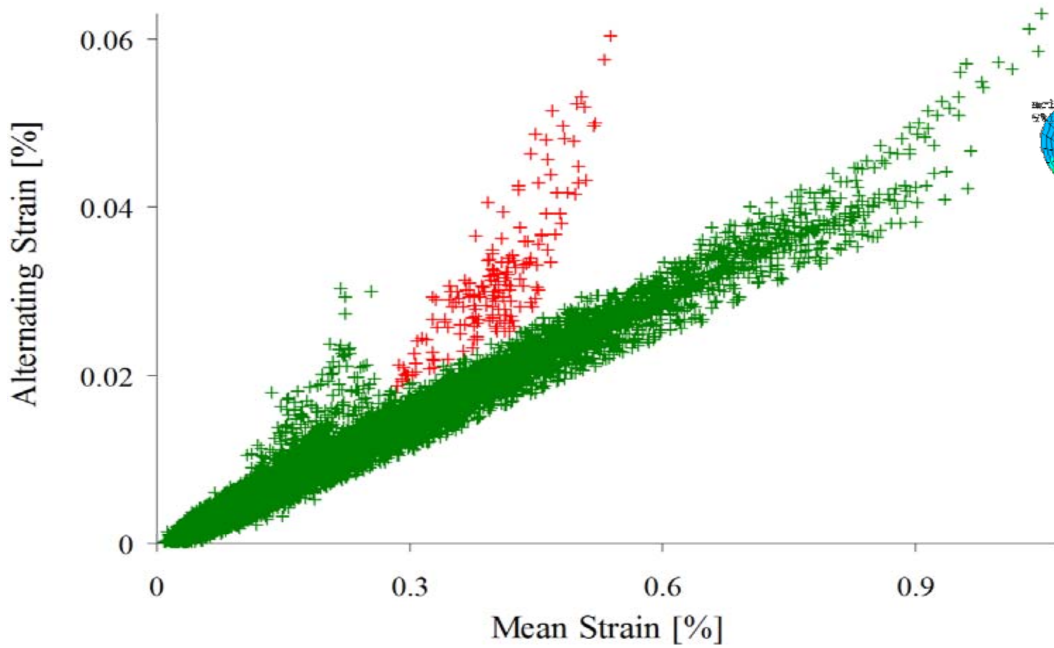
- Goodman-type plot of Integration point data
- Interpretation: quantitative and qualitative "hotspots" point to locations of concern

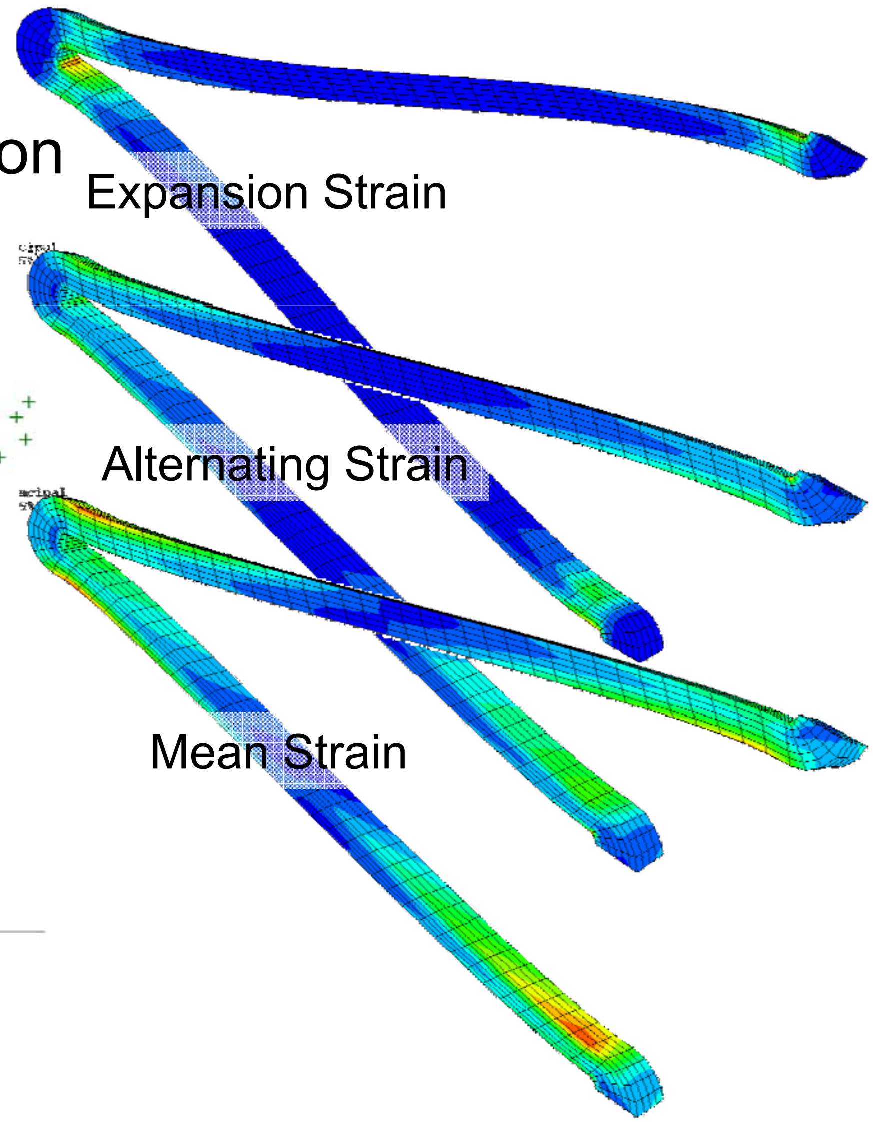




Possible OverStrain Damage

– Red zones are areas of previous severe over-expansion strain (> 10%)





Summary of Good FEA Practices

Calibrate your model

Validate your methodology

and Verify your results