Explicit FEM Applied to Impact Biomechanics Problems

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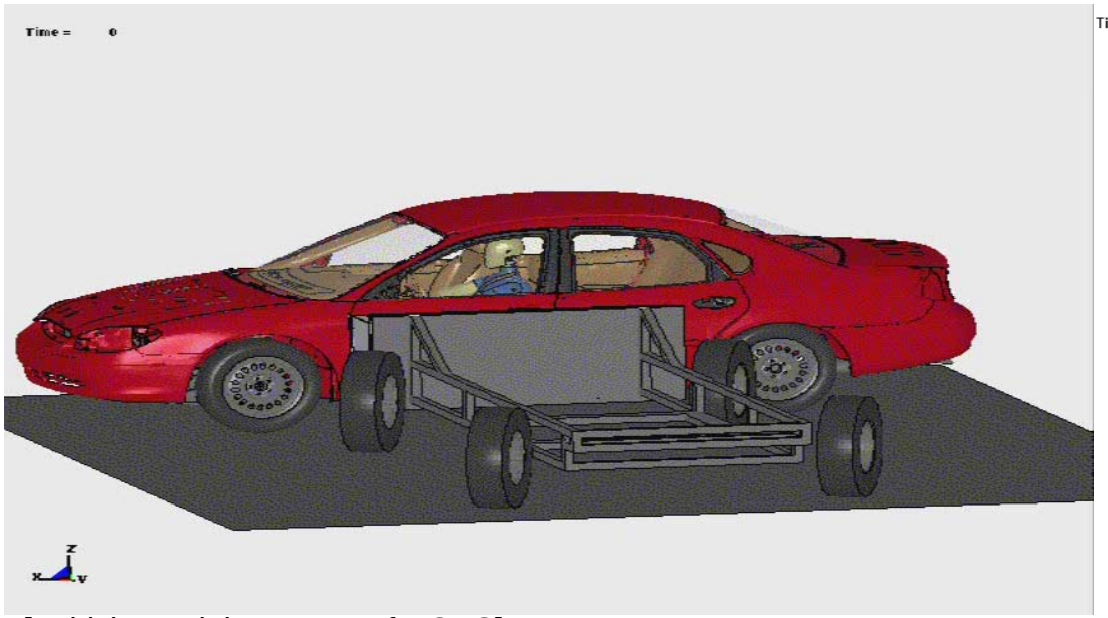
IRCOBI 2011

Introduction

93,986 solid elements
20,903 shell elements
1,129 beam elements
256 material definitions.

[Yuen 2010]

- Impact Biomechanics
  - Is the study of human body response to impact loading, and injury resulting from mechanical interaction [Schmitt 2010]
- Explicit FE allows us to consider complex geometry, nonlinear materials and contact in transient problems



[Vehicle model courtesy of NCAC]

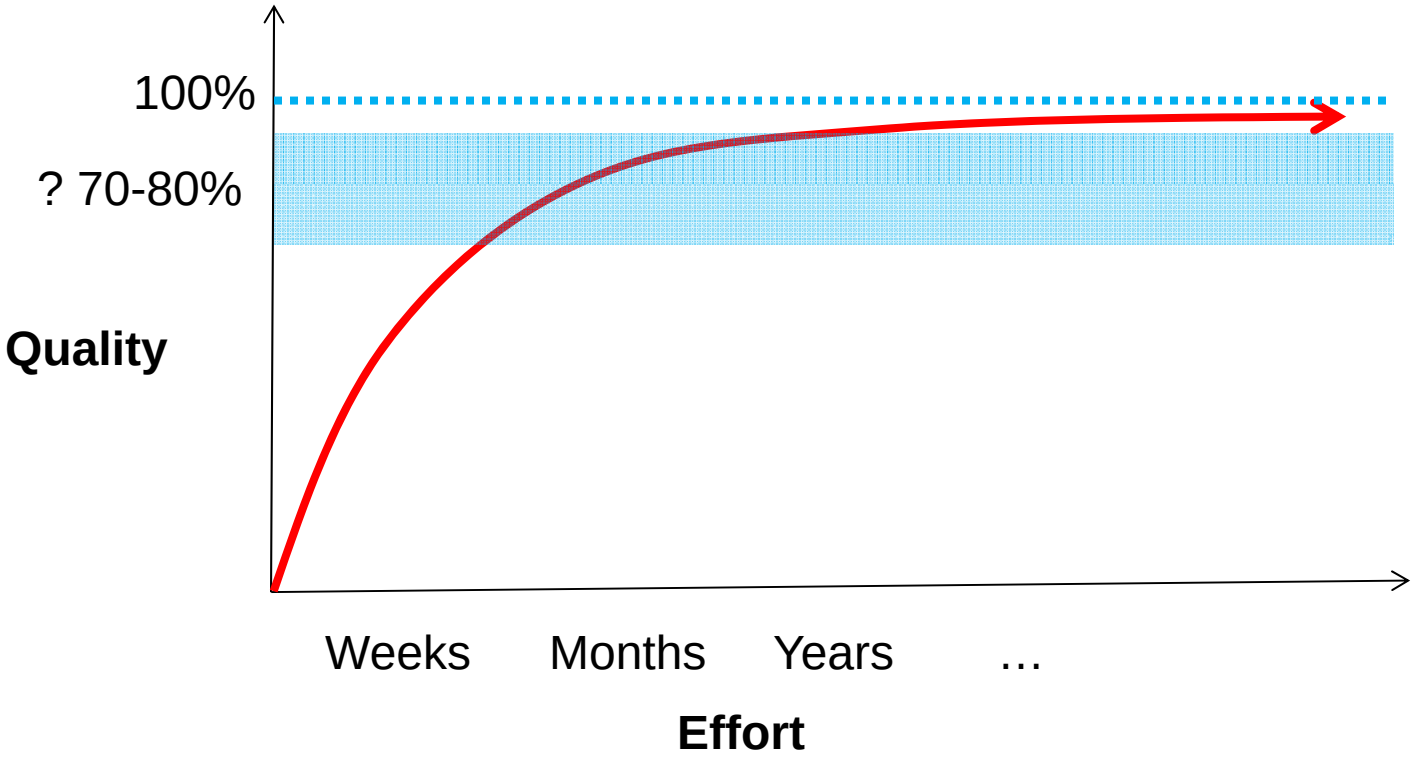
FMVSS 214 (54 kph) side impact test [Watson 2010]

Conclusion

- Nobody believes the model, except the modeler…
- Everybody believes the experiment, except the experimentalist…

What's the answer?

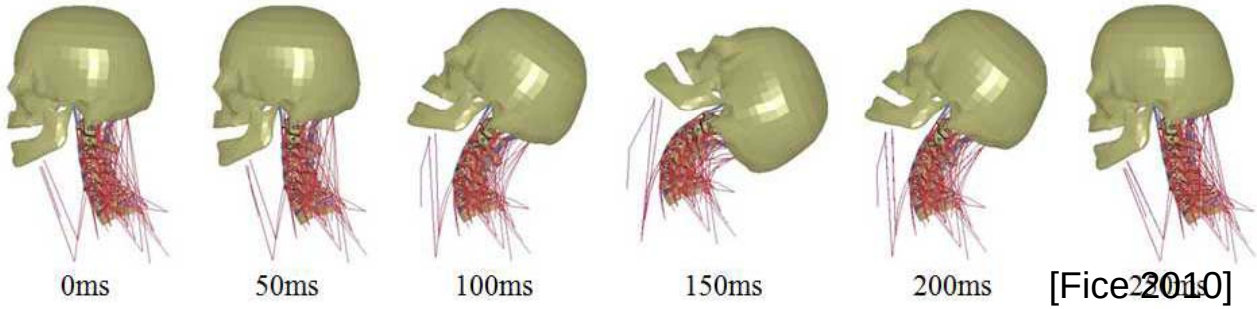
- What do we really need?
  - Understanding or a design tool
- Diminishing returns for effort



Introduction - Why pursue modeling?

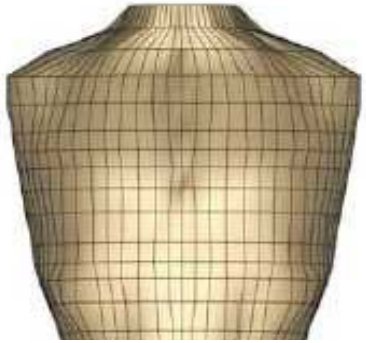
- Models can allow us to:
  - Interpret experimental results
  - Investigate response to impact (sensitivity studies)
  - Consider new designs for protection and safety

- **Models must be developed with a specific intent or hypothesis in mind.**
  - Models are an approximate representation of a physical phenomenon, bounded by their assumptions and have a finite life.



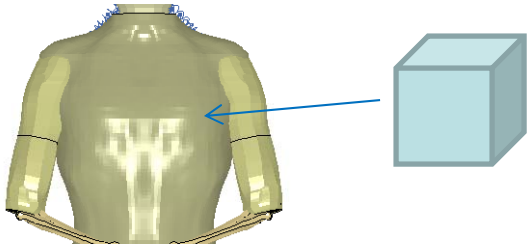
[Fice 2010]

Model Construction



Pre-processing → Solver → Post-processing

Geometry -> Mesh

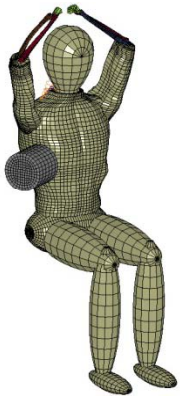


Material properties

$$\sigma = f(\varepsilon', \dot{\varepsilon})$$

$$p = f(\varepsilon_V)$$

Boundary conditions



Validation

Convergence (Verification)

Response

(93,986 solid elements)

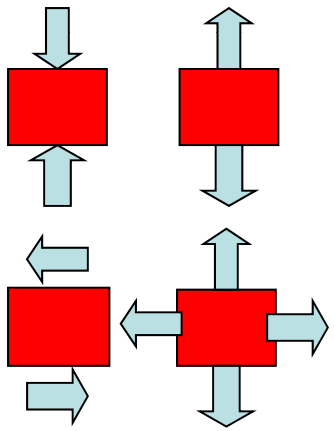
(301,800 solid elements)

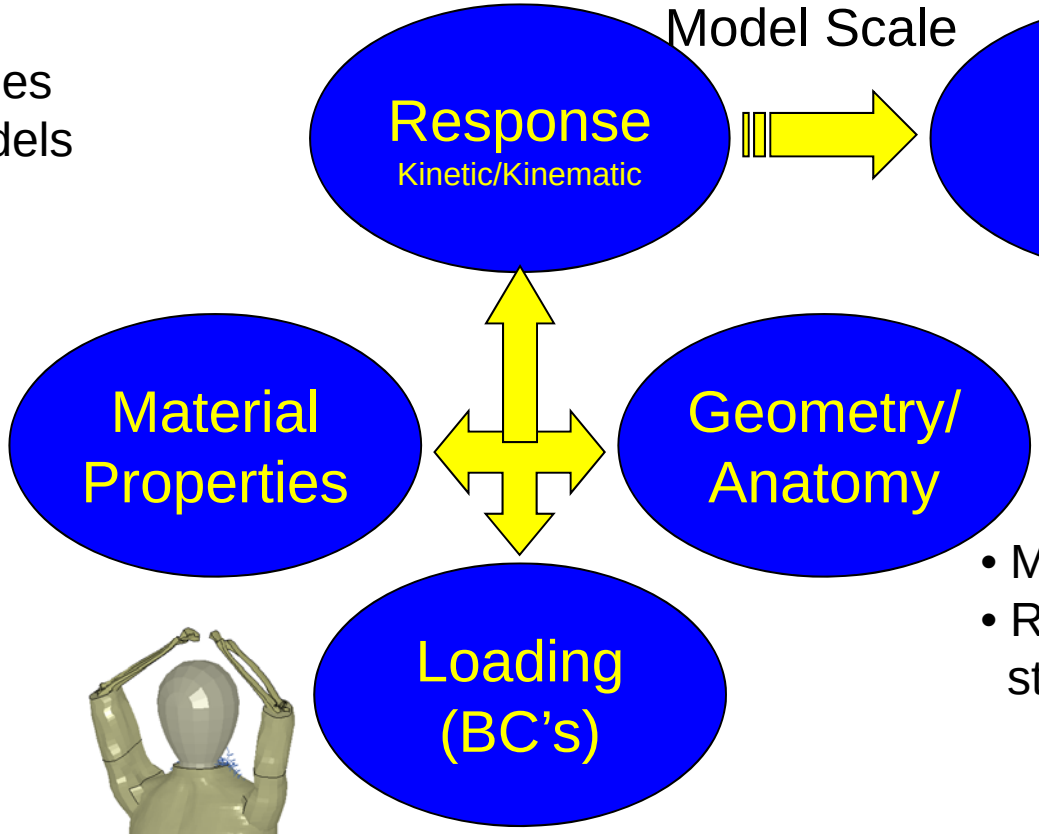
Model Requirements

A balanced approach is required!

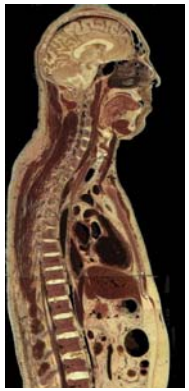
Model Scale

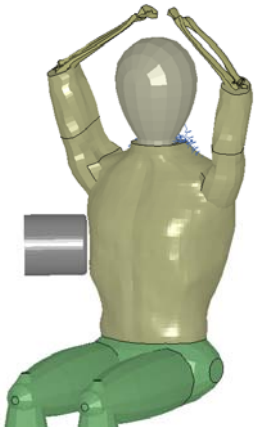
- Material properties
- Constitutive models





- Model refinement
- Relevant anatomical structures





- Force, Deformation or related quantities
- Representative
- Coupling

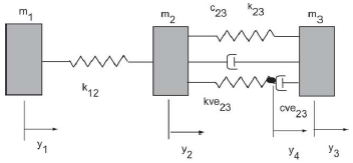
Model Requirements - Geometry

- Model design must be reasonable, and meet requirements:
  - Prediction goals
  - Relevant material properties
  - Continuum-based approach
  - Computation cost

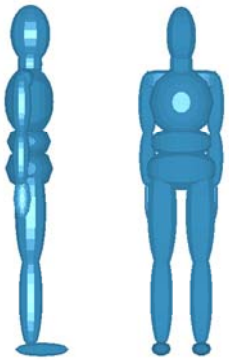
http://www.nlm.nih.gov/research/visible/visible_human.html

Detailed (3-D) local model

Mathematical Model

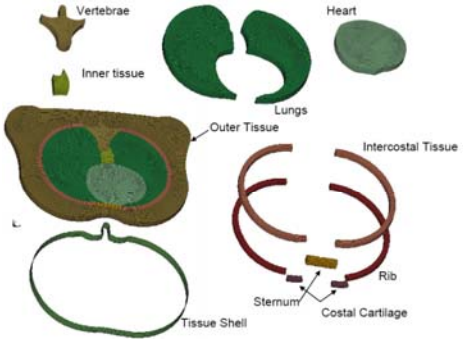


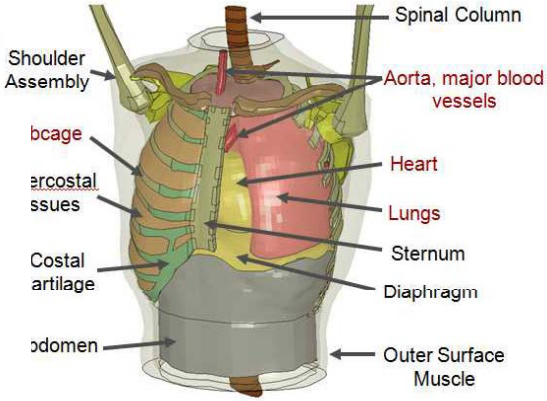
Lobdell lumped mass model



Multibody model

Detailed 2-D blast model



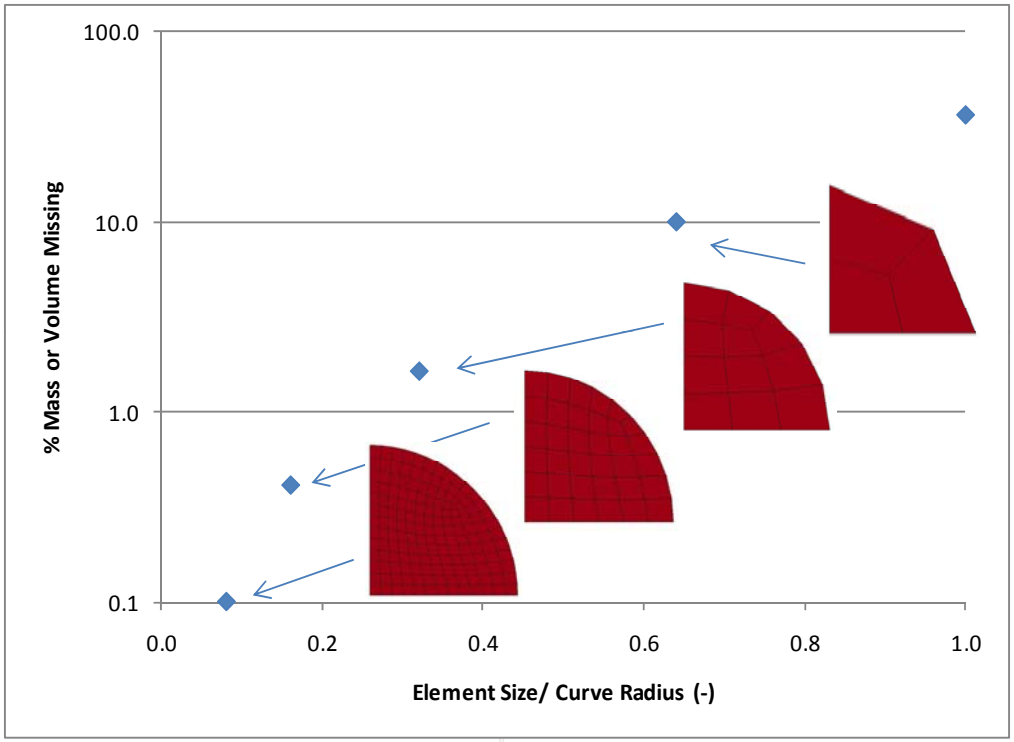


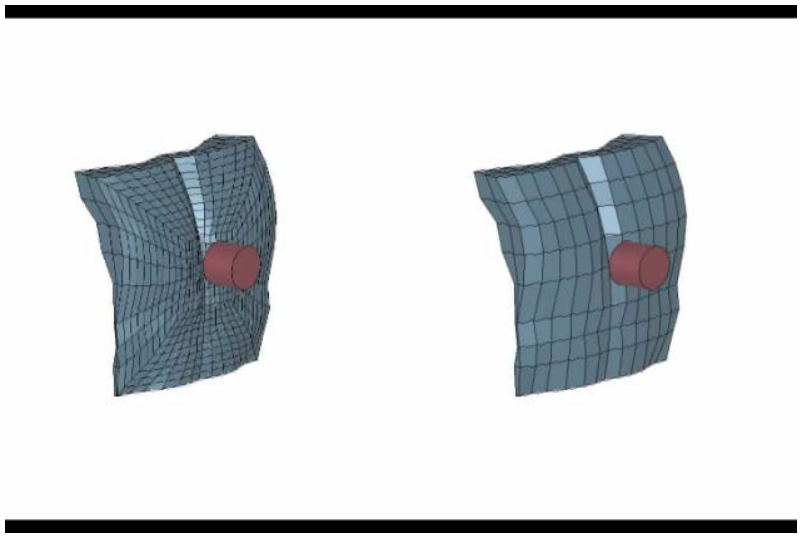
[Yuen 2010]

Model Requirements - Geometry

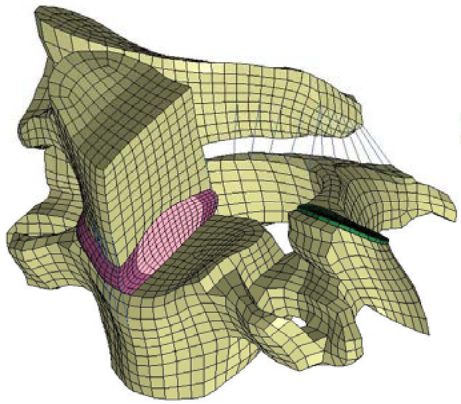
Meshing

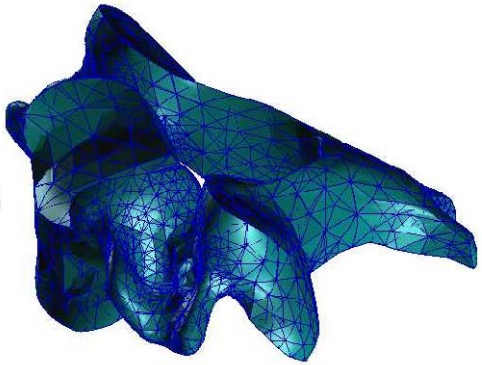
- Discretization:
  - 1D, 2D shell, 3D solid
- Element size and quality
- Strain rate
- Element formulation





Forbes 2005

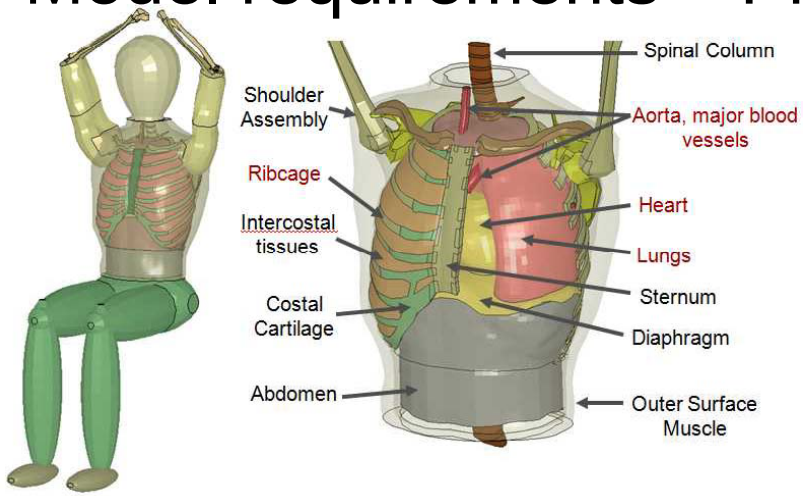




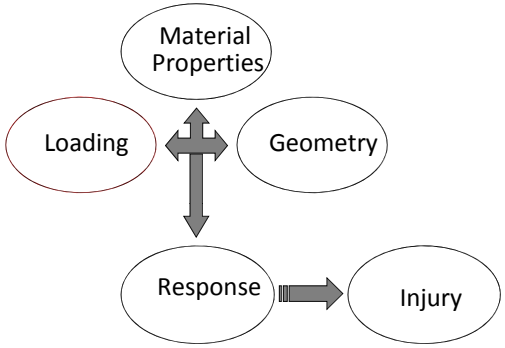
Tetrahedral elements – limitations

Model Requirements – Loading (BCs)

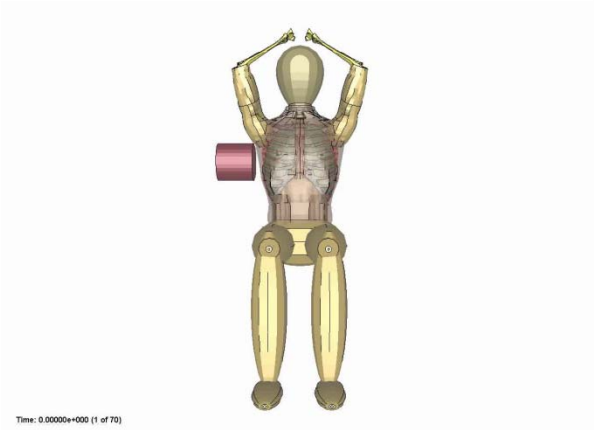
- Model requirements – Progressive complexity



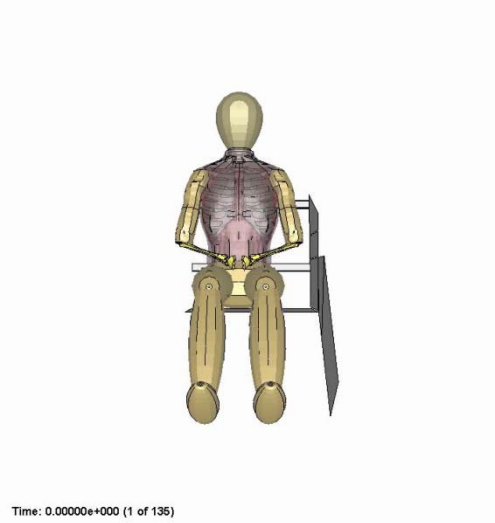
Watson, IJCR 2011
Yuen, WCB 2010
Campbell, ESV 2009
Yuen, IRCOBI 2008
Forbes, IJC 2006
Forbes, WCB 2006
Forbes, IUTAM 2005



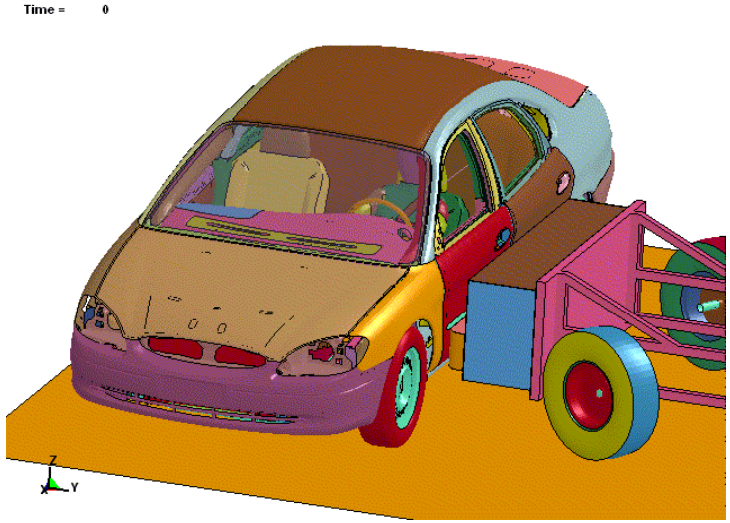
Pendulum impact



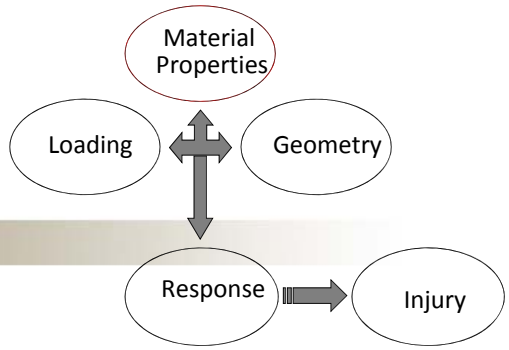
Side sled test



Side impact vehicle test

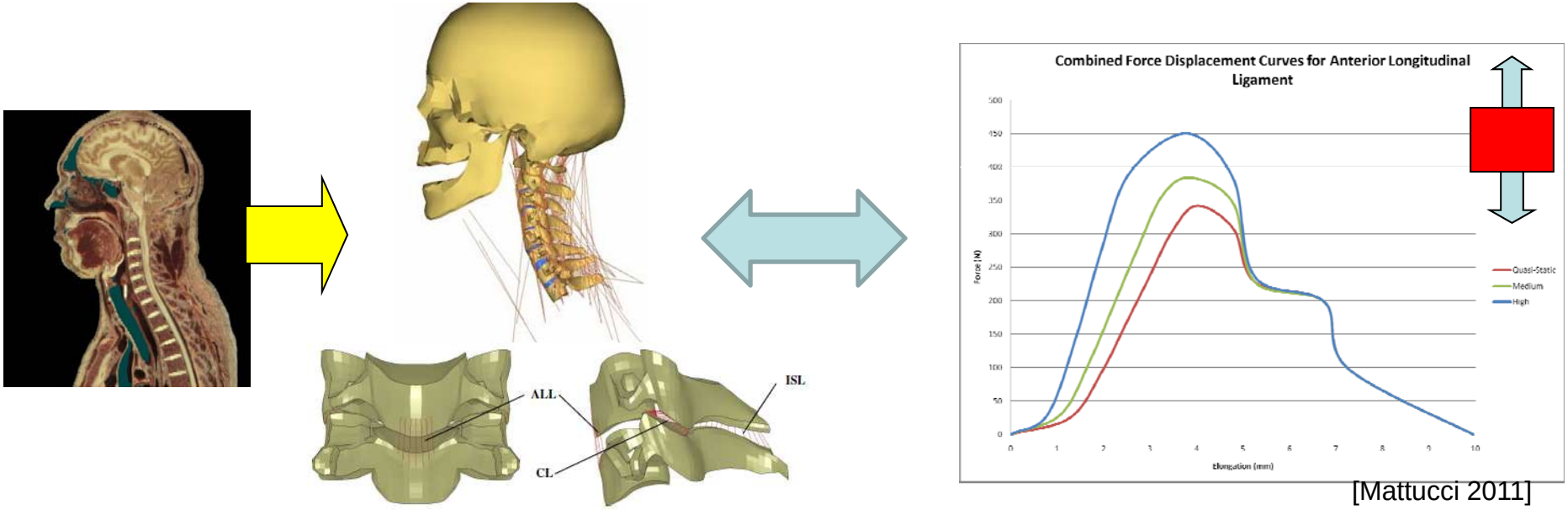


Material Properties



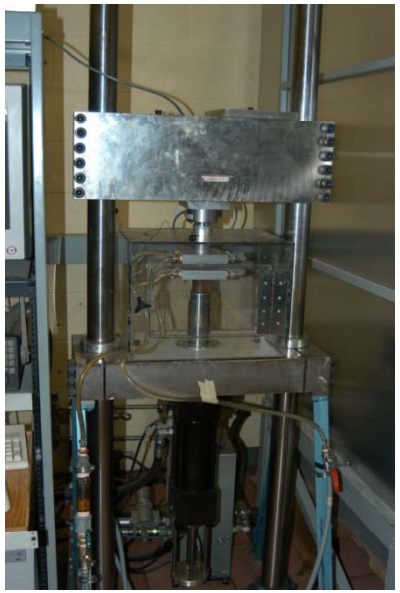
- Generally regarded as the most challenging area with the highest degree of uncertainty
- Most biological materials exhibit non-linear response and are sensitive to strain rate.

** Need to know the expected strain and strain rate

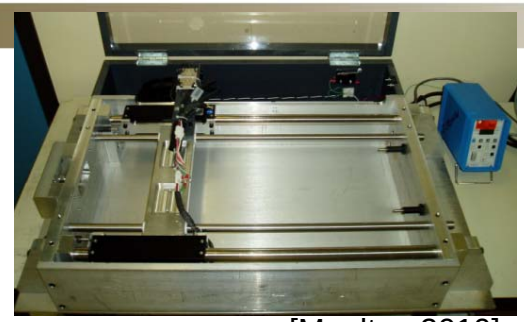


[Mattucci 2011]

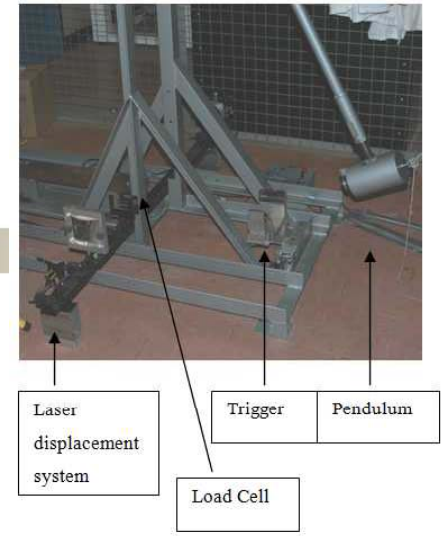
Model Requirements – Materials (Macro)



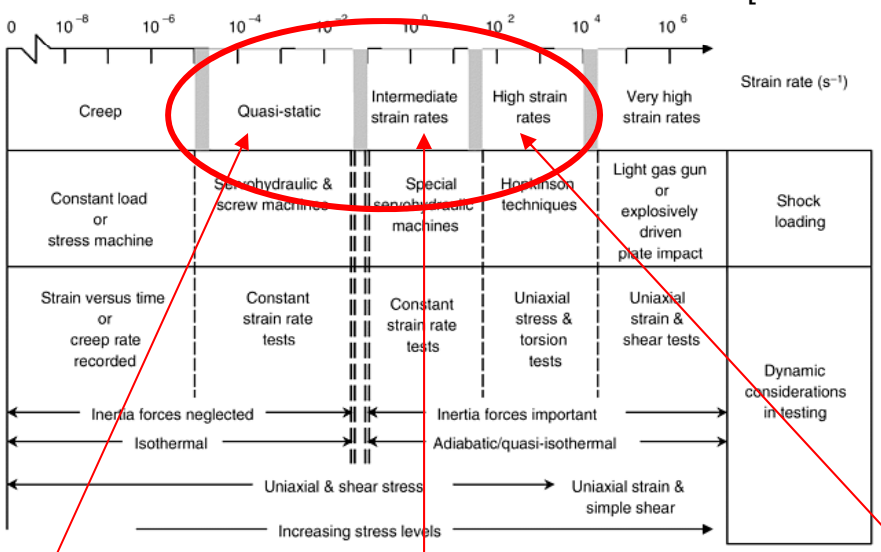
(~0.01-10 1/s)



[Moulton 2010]



(~100-500 1/s)



From ASM, Volume 8, Mechanical Testing and Evaluation

(~300-3000 1/s)

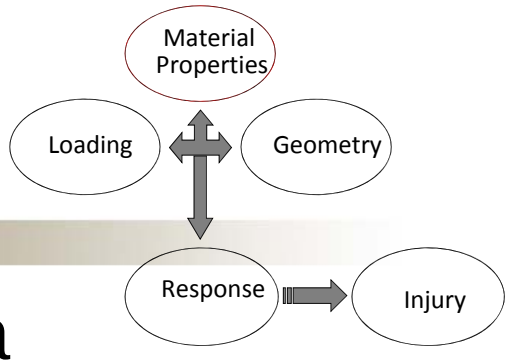
Cronin SEM 2011
Cronin SEM 2010
Campbell, SEM 2007
Ouellet, Exp Mech 2006
Doman, Exp Mech 2006
VanSligtenhorst, JoB 2006
Ouellet, PASS 2004
Motuz, SAV 2003
VanSligtenhorst, ASME BED 2003
Salisbury, Plasticity 2002

Servohydraulic

Pendulum Impact
Drop Tower
EM Test Frame

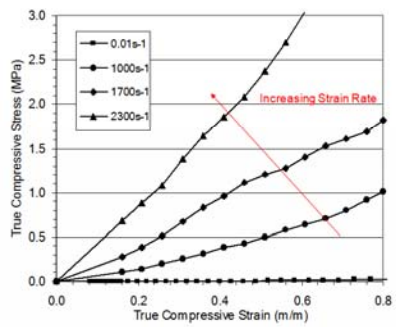
Split Hopkinson
Pressure Bar Apparatus

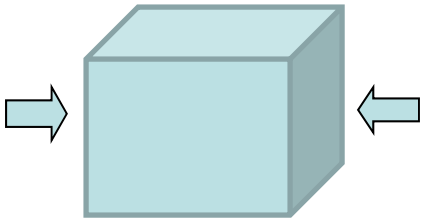
Material Properties



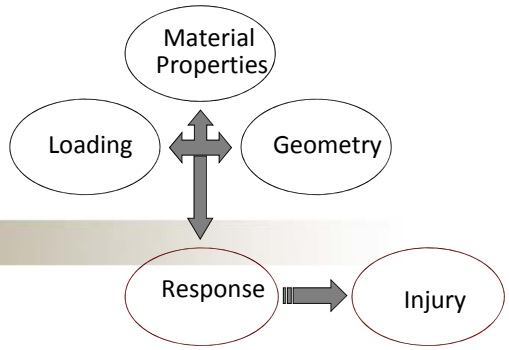
- Properties need to be expressed in a mathematical / numerical form (~200 models in LS-Dyna)
- Experimental method should be directed towards the model requirements.
- A constitutive equation relates stress and strain, accounting for:
  - Deviatoric stress $\sigma = f(\varepsilon', \dot{\varepsilon})$
  - Volumetric response $p = f(\varepsilon_V)$

Bovine muscle tissue (1500s^{-1})

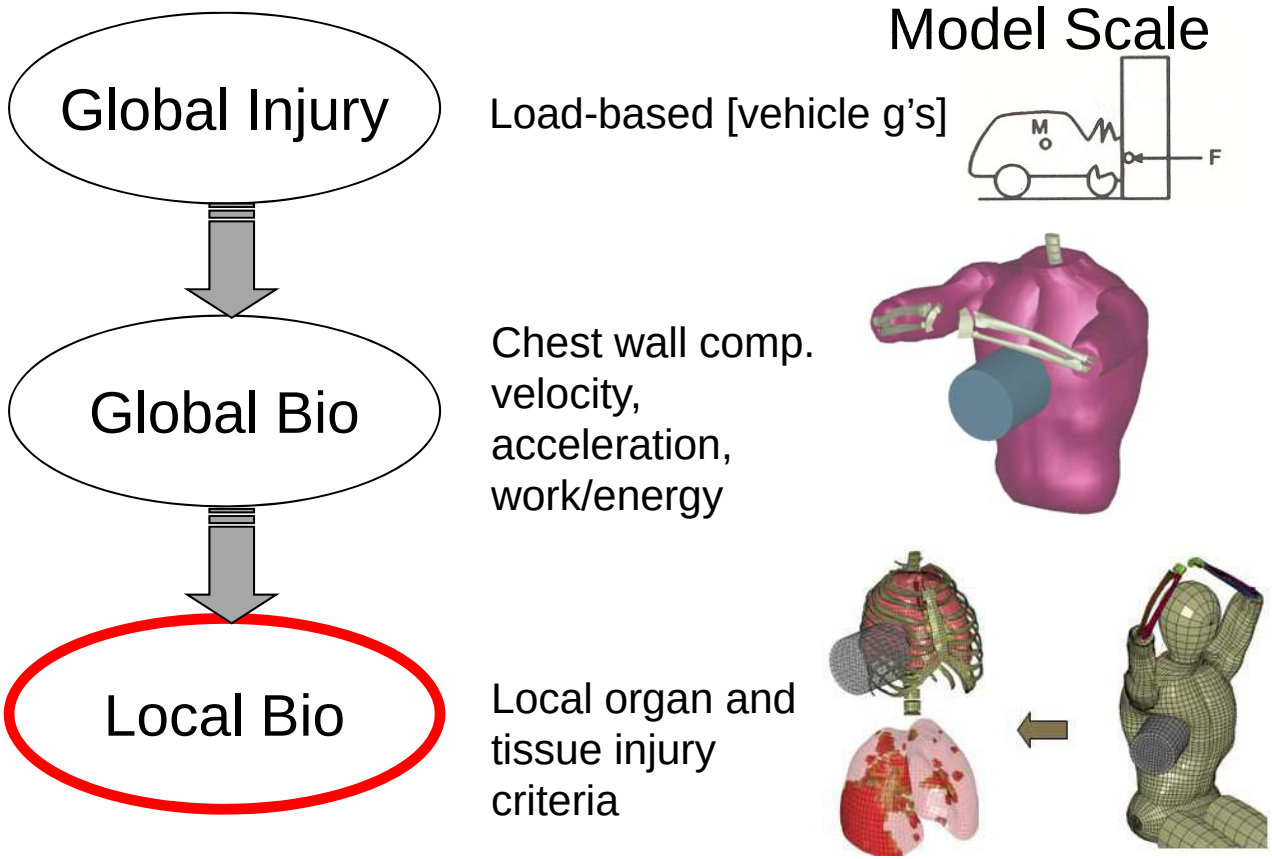


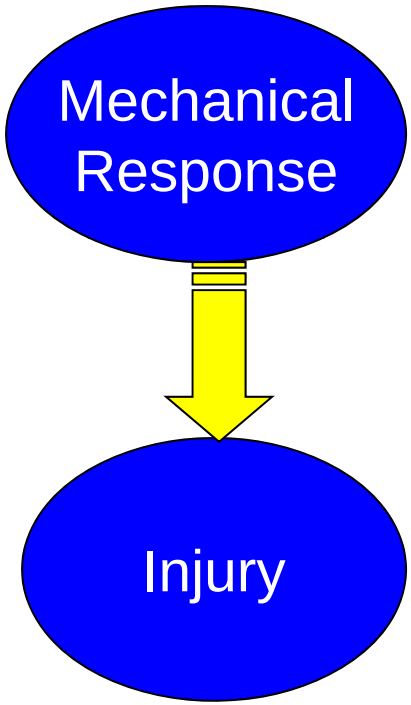


Prediction of injury



- A question of scale…
- Requires model **calibration**





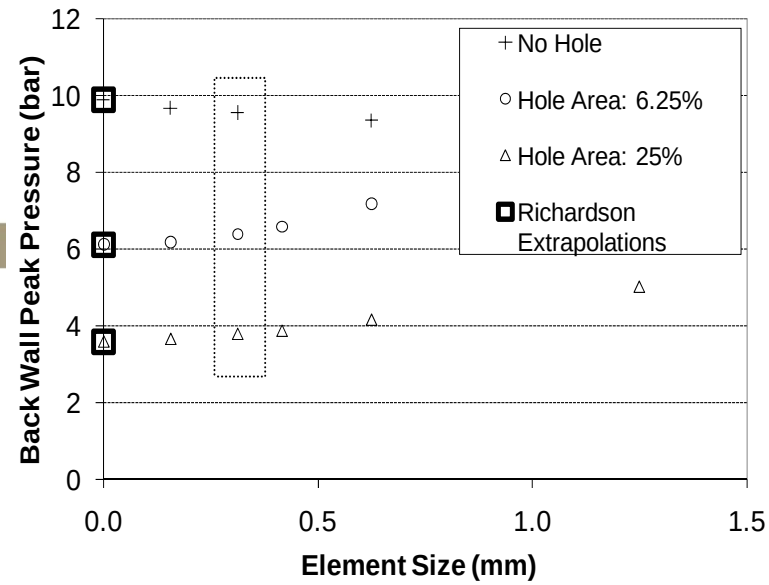
Experimentalists
Epidemiologists
Scientists
Medical
Engineers
…

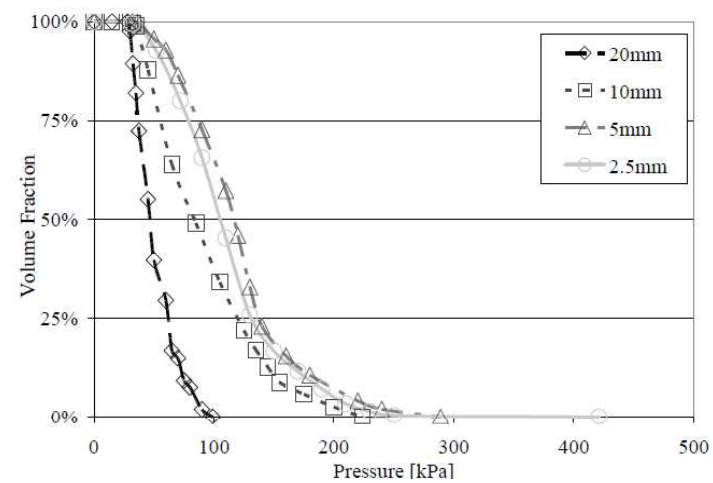
Model Response

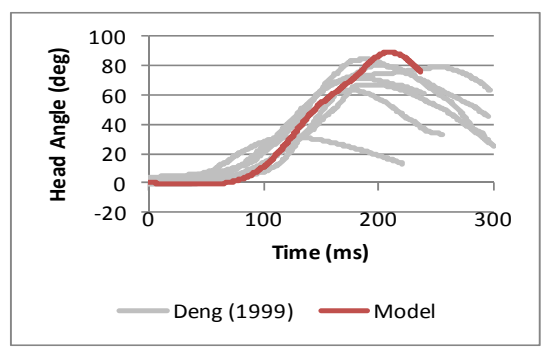
Model convergence

- Mesh size depends on:
  - Loading and Boundary Conditions
  - Material properties and failure
  - Contact models
  - Assessment metric

- Evaluation Methods
  - Single/multiple parameter
  - Corridor (ISO)
  - Cross-correlation (CORA)





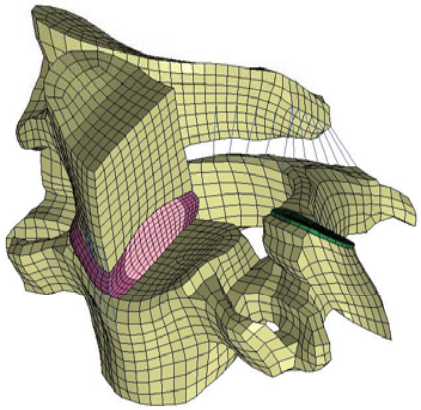


ASME V&V 10-2006, “Guide for Verification and Validation in Computational Solid Mechanics”

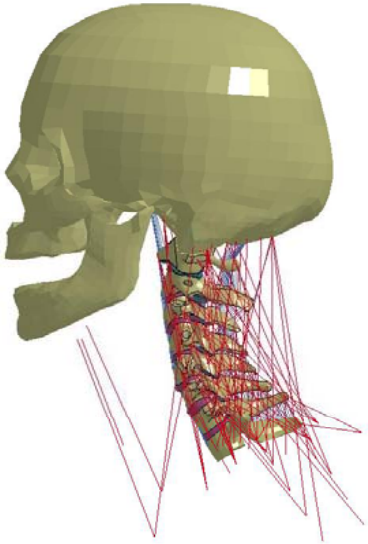
Response - V&V

- Verification and Validation (V&V) forms the basis for model development

  …a continuous process



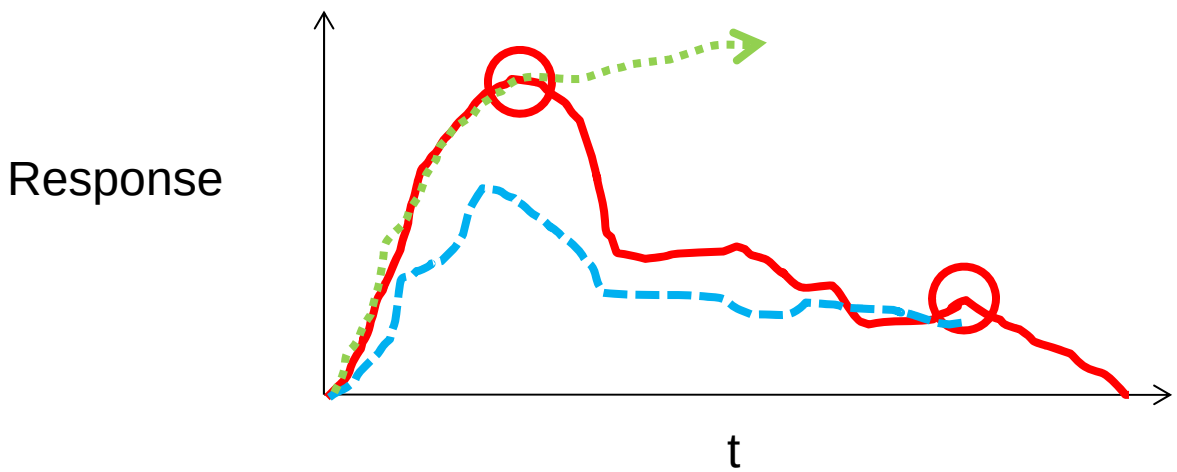
- Key principles:
  - Verification (assess code and numerical errors) must precede validation (comparison of model to experiments)
  - Validation should be pursued in a hierarchical fashion (simple to complex)
  - Validation is specific to a particular model and application
  - Uncertainty assessment



Fice, 2010

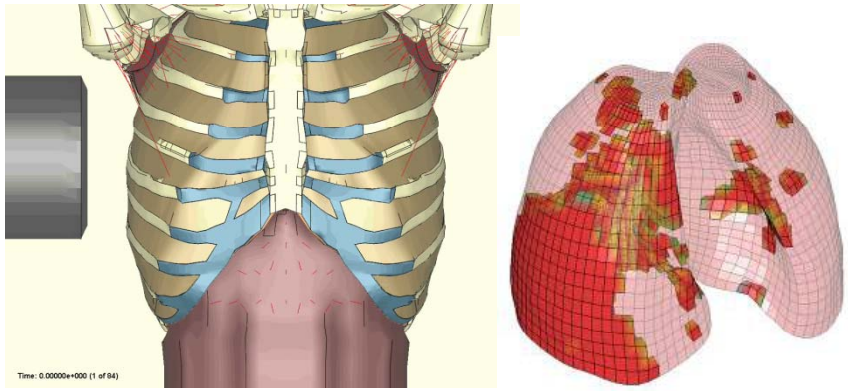
Solution uniqueness

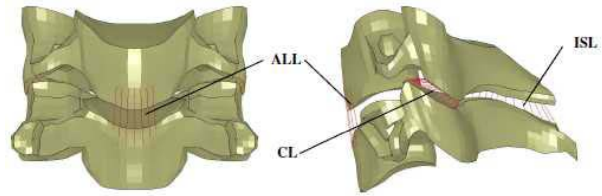
- The problem follows a unique time-response path
- It is possible for the solution to diverge from this path
  - Numerical round-off
  - Material failure / Contact failure
  - Parameter estimation for non-linear materials

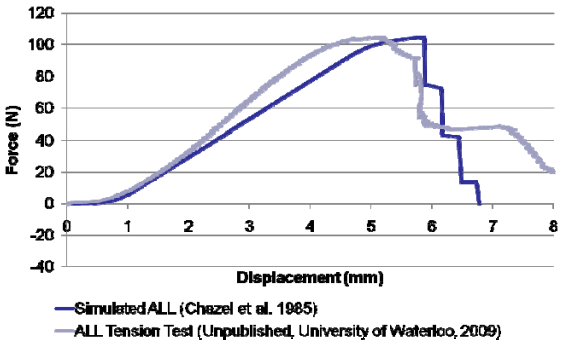


Material Failure and Damage

- We are often interested in response to impact, and the subsequent damage
  - Hard tissue damage and failure
    - Often addressed using elastic-plastic material model with element erosion
  - Damage and/or failure of soft tissues
    - CDM for structural (gross) failure
    - Developing area for physiological response

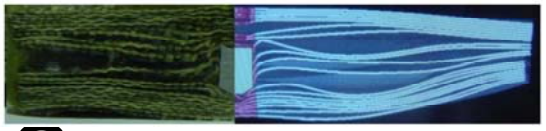


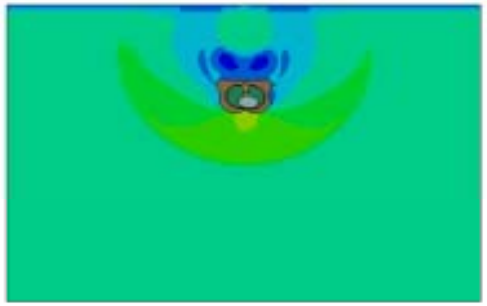




[DeWitt 2010]

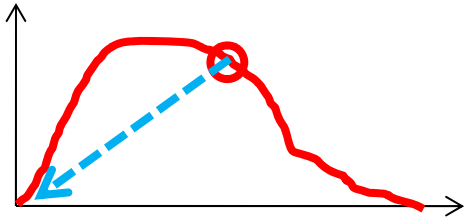
What's current and next?





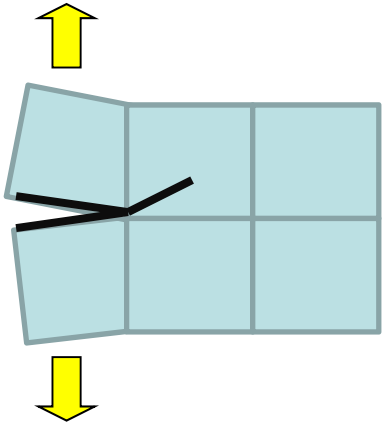
Current

- Multi-physics (Fluid/gas-structure)
- Continuum Damage Mechanics
- Meshless and other (EFG, SPH)



Next

- Crack propagation (XFEM)
- Improved CDM approaches
- Material properties and constitutive modeling



Summary

- A model should be developed based on a hypothesis, with appropriate specifications.
- Focus on balance (geometry, materials, bc's)
- ! Mesh refinement must be sufficient !
- V&V is an ongoing process (multiple scales).

- Modeling is a technique that can give us insight.

- Take small steps and ask simple questions to get reasonable answers.