Explicit FEM Applied to Impact Biomechanics Problems

D. Cronin
IRCOBI 2011
93,986 solid elements
20,903 shell elements
1,129 beam elements
256 material definitions.

• 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

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)
A balanced approach is required!

- Material properties
- Constitutive models

Model Scale
- Response
  - Kinetic/Kinematic
- Injury

Material Properties

Geometry/Anatomy
- Model refinement
- Relevant anatomical structures

Loading (BC's)
- 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

Mathematical Model
- Lobdell lumped mass model
- Multibody model

Detailed 2-D blast model

Detailed (3-D) local model

Visible Human Project (TM)
Human-Computer Interaction Lab
Univ. of Maryland at College Park


[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

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)

- Materials

- (~100-500 1/s)
  - Moulton 2010

- (~0.01-10 1/s)
  - Cronin SEM 2011
  - Campbell, SEM 2007
  - Ouellet, Exp Mech 2006
  - Domanski, Exp Mech 2006
  - VanSligtenhorst, JoB 2006
  - Ouellet, PASS 2004
  - Motuz, SAV 2003
  - VanSligtenhorst, ASME BED 2003
  - Salisbury, Plasticity 2002

- (~300-3000 1/s)
  - Cronin SEM 2010
  - Ca m p b e , S E M 2 0 0 7
  - Doman, Exp Mech 2006
  - Ouellet, Exp Mech 2006
  - VanSligtenhorst, JoB 2006
  - Ouellet, PASS 2004
  - Motuz, SAV 2003
  - VanSligtenhorst, ASME BED 2003
  - Salisbury, Plasticity 2002

From ASM, Volume 8, Mechanical Testing and Evaluation

- 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**

**Global Injury**

- Load-based [vehicle g’s]

**Global Bio**

- Chest wall comp.
  - velocity,
  - acceleration,
  - work/energy

**Local Bio**

- Local organ and tissue injury criteria

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**Model Scale**

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**Mechanical Response**

**Injury**

- 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)
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
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.