Introduction to Vehicle Crashworthiness
Lecture -1

CE 264
Non-linear Finite Element Modeling and Simulation

Objective

- What is Non-Linear FEM and why study it?
  - FEM is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems for which an analytical solution does not exist
- Non-linearities
  - Material
    - Stress-strain behavior
  - Geometry
    - Change in geometry have a significant effect on the load deformation behavior

Safety Standards

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Federal Motor Vehicle Safety Standards (Part 571)

- **“Active Safety / Crash Avoidance”** - 100 Series
  - Pre-Crash Phase
    - Crash Avoidance & security
      - Braking (ABS), electronic stability control (ESC), lighting and signalling

- **“Passive Safety / Crashworthiness”** - 200 Series
  - Crash Phase
    - Minimize risk of injury to occupants, combines the reciprocal aims of absorbing impact and ensuring a survival space
      - 208 – Occupant Crash Protection
      - 214 – Side Impact Protection
      - 216 – Roof Crush Resistance

- **“Fire-related”** - 300 Series
  - Post-Crash Phase
    - Interior Trim Flammability and fuel system integrity
      - 301 – Fuel System Integrity

Frontal Impact – Regulatory Requirements

- **Federal Motor Vehicle Safety Standard (FMVSS) 208 – old**
  - 30 mph (48 kph) into a fixed barrier
  - 50th percentile Hybrid III dummy in front driver and passenger seats
  - Uses dummy injury measures for regulation
    - Chest G’s <= 60
    - HIC <= 1000
    - Femur Loads <= 10 KN
  - Protection must be automatic

- **Purpose of this test is to evaluate the performance of the occupant restraint systems (seat belts, airbags, etc.)**

FMVSS 208 – New Regulation

- The first stage phase-in, 9/1/03-8/31/06, requires vehicles to be certified as passing:
  - Unbelted test requirements for both the 5th percentile adult female and 50th percentile adult male dummies in a 40 km/h (25 mph) rigid barrier crash
  - Belted test requirements for the same two dummies in a rigid barrier crash with a maximum test speed of 48km/h (30 mph)
  - Include technologies that will minimize risk for young children and small adults
    - De-powered Airbags
    - Occupant sensing system

- The second stage phase-in, 9/1/2007-8/31/2010, requires vehicles to be certified as passing:
  - Maximum test speed for the belted rigid barrier test will increase from 48 km/h (30 mph) to 56km/h (35 mph) in tests with the 50th percentile adult male dummy only
**FMVSS 208 – New Regulation**

- Test requirements to improve occupant protection for different size occupants, belted and unbelted.

  - **50th percentile adult male dummies**
    - Rigid Barrier Test
    - 50% offset frontal deformable barrier test
  - **5th percentile adult female dummy**
    - Left Side Impact
  - **Unbelted Driver and Passenger 20-25 mph**
  - **Belted Driver and Passenger 0-25 mph**
    - Oblique and up to 30 degrees

**FMVSS 208 – Advanced occupant protection**

- FMVSS 208 drove design changes to adjust the deployment of the front airbags to enhance protection for front-seat occupants using:
  - Crash severity sensors
  - Seat belt usage sensors
  - Dual-stage driver and front-passenger airbags
  - Driver’s seat position sensor
  - Front outboard safety belt pre-tensioners etc.

**Frontal Impact – Consumer Tests**

- New Car Assessment Program, NCAP
  - 35 mph (56 kph) into a fixed rigid barrier
  - 50th percentile Hybrid III dummy in front driver and passenger seats
  - Star rating used to assess probability of serious injury
  - Head and chest injury data are combined into a single rating and reflected by the number of stars

- NCAP Frontal Impact Rating System
  - 0-5 stars
  - Corresponding probability of serious injury

- 0 stars = 10% or less chance of serious injury
- 1 to 2 stars = 11% to 20% chance of serious injury
- 3 stars = 21% to 35% chance of serious injury
- 4 stars = 36% to 45% chance of serious injury
- 5 stars = 46% or greater chance of serious injury
Frontal Impact - Consumer Tests

- Insurance Institute for Highway Safety (IIHS)
  - 40% offset 40 mph (64 kph) into a deformable barrier
  - 50th percentile male Hybrid III dummy in front driver seat
  - Good, Acceptable, Marginal and Poor ratings to assess vehicle’s overall crashworthiness
  - Rating based on:
    - Dummy injury measures
    - Structural performance
    - Restraints/dummy kinematics

- Evaluates the structural performance of the vehicle

Side Impact - Regulatory Requirements

- Federal Motor Vehicle Safety Standard (FMVSS) 214
  - 33.5 mph (54 kph) crabbed impact
  - Impactor mass - 3015 lb
  - US SID dummy in front and rear seats
  - Uses dummy injury measures for regulation
  - TTI(d) <= 85g for LTV’s and 4 door passenger cars
  - TTI(d) <= 90g for 2 door passenger cars
  - Pelvic Acceleration <= 130g
  - TTI(d) = 0.5 X (Gr + Gs)
    - Gr = Max. Rib Acc.
    - Gs = Lower spine Acc

Side Impact - Consumer Tests

- Lateral/Side Impact New Car Assessment Program (LINCAP or SINCAP)
  - 38.5 mph (62kph) crabbed impact
  - 3015 lb (1370 Kg) impactor mass
  - SID dummy in front and rear seats (SID/HIII for vehicles with side airbags)
  - Star rating based on TTI
  - Pelvic Acceleration <= 130g

- NHTSA issued an NPRM for side impact on May 19, 2004
  - 59% of fatalities in side impact had a brain injury
  - Promote head protection for all vehicle classes
  - 20mph closing speed at 75° anticlockwise angle of approach into a rigid pole*
  - SID-IIs will be tested with the moving barrier and the oblique pole*
  - ES-2re to replace US DOT SID

- Thoracic Trauma Index
  - 5 Stars <=52
  - 4 Stars 57-72
  - 3 Stars 72-91
  - 2 Stars 91-98
  - 1 Star >=98

Side Impact - Consumer Tests

- Insurance Institute for Highway Safety
  - New test implemented in Fall 2003
  - Impactor mass - 1,500 Kg
  - Impactor shape derived from Ford F150 front profile
  - 50 km/h perpendicular impact
  - SIDII’s driver and rear passenger dummies
  - Seated using UMTRI seating position
Side Impact - Consumer Tests

- Purpose is to represent crash condition that poses greatest risk to occupants (Pick-up/SUV as striking vehicle)
- Promote head protection

Rear Impact – Regulatory Requirements

- Federal Motor Vehicle Safety Standard (FMVSS) 301
  - The purpose of this standard is to reduce deaths and injuries occurring from fires that result from fuel spillage during and after motor vehicle crashes
  - 30 mph (48 kph) with a rigid rear moving barrier
  - 50th percentile Hybrid III dummy in front driver and passenger seats
  - Vehicle is rotated on its longitudinal axis to each successive increment of 90° and fuel spill is measured

Brief Introduction to Finite Element Methods

- Many problems in engineering and applied science are governed by differential or integral equations.
- The solutions to these equations would provide an exact, closed-form solution to the particular problem being studied.
- However, complexities in the geometry, properties and in the boundary conditions that are seen in most real-world problems usually means that an exact solution cannot be obtained or obtained in a reasonable amount of time.
Current product design cycle times imply that engineers must obtain design solutions in a 'short' amount of time.

They are content to obtain approximate solutions that can be readily obtained in a reasonable time frame, and with reasonable effort. The FEM is one such approximate solution technique.

The FEM is a numerical procedure for obtaining approximate solutions to many of the problems encountered in engineering analysis.

In the FEM, a complex region defining a continuum is discretized into simple geometric shapes called elements.

The properties and the governing relationships are assumed over these elements and expressed mathematically in terms of unknown values at specific points in the elements called nodes.

An assembly process is used to link the individual elements to the given system. When the effects of loads and boundary conditions are considered, a set of linear or nonlinear algebraic equations is usually obtained.

Solution of these equations gives the approximate behavior of the continuum or system.

The continuum has an infinite number of degrees-of-freedom (DOF), while the discretized model has a finite number of DOF. This is the origin of the name, finite element method.

The number of equations is usually rather large for most real-world applications of the FEM, and requires the computational power of a super computer. The FEM has little practical value if super computers were not available.

Advances in and ready availability of computers and software has brought the FEM within reach of engineers working in small industries, and even students.

Two features of the finite element method are worth noting.

The piecewise approximation of the physical field (continuum) on finite elements provides good precision even with simple approximating functions. Simply increasing the number of elements can achieve increasing precision.

The locality of the approximation leads to sparse equation systems for a discretized problem. This helps to ease the solution of problems having very large numbers of nodal unknowns. It is not uncommon today to solve systems containing a million primary unknowns.
Origin of FEM

- It is difficult to document the exact origin of the FEM, because the basic concepts have evolved over a period of 150 or more years.
- The term finite element was first coined by Clough in 1960. In the early 1960s, engineers used the method for approximate solution of problems in stress analysis, fluid flow, heat transfer, and other areas.
- The first book on the FEM by Zienkiewicz and Chung was published in 1967.
- In the late 1960s and early 1970s, the FEM was applied to a wide variety of engineering problems.

Advantages of FEM

- The FEM offers many important advantages to the design engineer:
- Easily applied to complex, irregular-shaped objects composed of several different materials and having complex boundary conditions.
- Applicable to steady-state, time dependent and eigenvalue problems.
- Applicable to linear and nonlinear problems.
- One method can solve a wide variety of problems, including problems in solid mechanics, fluid mechanics, chemical reactions, electromagnetics, biomechanics, heat transfer and acoustics, to name a few.

Sources of Error in FEM

- The three main sources of error in a typical FEM solution are discretization errors, formulation errors and numerical errors.
  - Discretization error results from transforming the physical system (continuum) into a finite element model, and can be related to modeling the boundary shape, the boundary conditions, etc.
  - Formulation error results from the use of elements that don't precisely describe the behavior of the physical problem.
  - Numerical error occurs as a result of numerical calculation procedures, and includes truncation errors and round off errors.
General FEA Process

- Model Development - Pre-processing
  - Discretize Geometry: Nodes/Elements
  - Geometry properties: Thickness/Cross-section
  - Material properties
  - Loading conditions
  - Constraints
  - Boundary conditions
- Solver - Solution processing
  - Numerical solution of equations of motion

Background and History of LS-DYNA

- 1976
  - DYNA3D developed at Lawrence Livermore National Laboratory by John Hallquist
  - Low velocity impact of heavy, solid structures, military applications
- 1979
  - DYNA3D ported on Cray-1
  - Improved sliding interface
  - Order of magnitude faster
- 1981
  - New material models - Explosive-structure, Soil-structure
  - Impacts of penetration projectiles
Background and History of LS-DYNA

- 1986
  - Beams, Shells, Rigid Bodies
  - Single Surface Contact
  - Support for Multiple Computer Platforms
- 1988
  - Automotive Applications Support
  - LS-DYNA
- 1989
  - Full Commercial Version
  - LSTC

General Capabilities

- Transient dynamics
- Quasi-static simulations
- Flexible and rigid bodies
- Nonlinear material behavior
- More than 80 constitutive relationships
- More than 40 element formulation
- Finite strain and finite rotation
- General contact algorithm
- Thermal Analysis
- Explicit and implicit analyses

Applications

- Automotive, train, ship, and aerospace crashworthiness
- Sheet and bulk forming process simulation
- Engine blade containment and bird strike analysis
- Seismic safety simulation
- Weapons design and explosive detonation simulation
- Biomechanics simulation
- Industrial accidents simulation
- Drop and impact analysis of consumer product
- Roadside Hardware Analysis
- Virtual proving ground simulation
**LS-DYNA Input File Format**

- **Structured Input Format**
  - Original Format
  - Organized by Entities
  - Fixed Format
- **Keyword Input Format**
  - Started 1993
  - More Flexible
  - Easy to Modify Input Deck

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**Keyword Format Input File**

- **Sections**
  - Control, Material, Equation of State, Element, Parts, etc.
- The "*" followed by keyword indicate beginning of a section block.
- The "$" used for Comment Cards
- Data blocks begin with keyword followed by data pertaining to the keyword
- Multiple Blocks with the same keyword are permissible
- Material and Contact types are defined by name
- Keywords are alphabetically organized in manual
**LS-DYNA Execution**

- **Command Line**

  LS-DYNA:
  
  - LS-DYNA  i=inputfile
  - LS-DYNA  r=d3dump01 memory=1200000
  - LS-DYNA  i= inputfile

- **Example**

  ls-dyna  i=inputfile
  ls940  r=d3dump01 memory=1200000
  ls971s  i= inputfile

**LS-DYNA Output Files**

- d3hsp
- message
- d3plot,d3plot01,...
- d3thdt,d3thdt01, ...
- d3dump01, ...
- runrsf
- Ascii files (glstat, nodout, deforc, ..etc)

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**CAE Influence on Vehicle Development Process (VDP)**

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NCAC
THE GEORGE WASHINGTON UNIVERSITY
**History of Numerical Simulations**

- Explicit FE codes were developed in the 60's and 70's at the Defense Labs in the US
- First full vehicle car crash models were built and analyzed in the mid 80's as a research project
- Introduction of supercomputers (cray) made it possible to run a full vehicle crash model
- Development of the codes continue to make numerical solutions stable and accurate
- Numerical simulation has become a fully integrated tool in the vehicle development process in the last decade

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**Evolution of CAE in Crashworthiness**

<table>
<thead>
<tr>
<th>Year</th>
<th>Regulatory Requirements</th>
<th>FE Model Size (elem)</th>
<th>Prototypes reqd. for crash testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>1</td>
<td>10000</td>
<td>150</td>
</tr>
<tr>
<td>1990</td>
<td>5 (Reduce Injuries &amp; Fatalities)</td>
<td>20000</td>
<td>120</td>
</tr>
<tr>
<td>1995</td>
<td>5</td>
<td>80000</td>
<td>100</td>
</tr>
<tr>
<td>2000</td>
<td>5</td>
<td>0.5M</td>
<td>50</td>
</tr>
<tr>
<td>Today</td>
<td>&gt;20</td>
<td>&gt;1M</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

All numbers shown here are estimates only, and should be treated as such.

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**Engineering Analysis Methods**

- **CAE**: Uses Engineering analysis tools primarily FE, BE and FD methods
- Linear / Non-Linear: based on material, loading
- Static / Dynamic: Temporal variation in loading, boundary conditions
- Quasi Static / Transient are sub-cases of above
**FE Crashworthiness**

- FE crashworthiness analysis of vehicles in particular, is among the most challenging nonlinear problems in structural mechanics
- Vehicle structures are typically manufactured from many stamped thin shell parts and subsequently assembled by various welding and fastening techniques
- The body-in-white may contain steel of various strength grades, aluminum and/or composite materials

**Automotive CAE requirements**

- Validation of Structure: Component, Subsystem and System
- Ride Comfort: NVH, Cabin Acoustics, Passenger Efforts (eg: Door opening)
- Handling: Vehicle Dynamics Analysis, Kinematics
- Safety: Crash (Front, Rear, Side, Roof)
- Durability: Life of components during real-life vehicle loading of variable severity, Fatigue life-cycle analysis
- Fuel Economy, Aerodynamics
- Cross-functional as well as individual optimizations for cost, weight and investment (CWI)

**Automotive CAE Tools**

**Pre-processing (FE modeling):**
- Hypermesh: Standard for Automotive CAE modeling (good for solid modeling, auto/manual meshing edits and all quality checks)
- ANSA: Superior to HM for Shell meshing and assembly but inferior for solid models
- Others: Easi-Crash, LS-Pre, Oasys, I-DEAS, PATRAN

**Solvers:**
- MSC NASTRAN: Best in class for Linear, dynamic and optimization type analyses (best for NVH, Durability)
- LS-DYNA: Non-Linear, large deformation, Crash type analysis
- ADAMS: Vehicle dynamics
- MADYMO: Occupant simulation
- Other: ANSYS (multi-physics problems)

**Post-processing:**
- LS-POST, Hyperview, Easi-Crash etc.,

**48 month VDP**

Program name (sample): 02LH

- Pre-Program Phase
- Main window for Digital/Virtual Vehicle development
- 1st physical Validation prototype

Week 0: Pre-Program Start
Week 150: Concept Selection Approval
Week 80: Theme Confirmation Prototype
Week 208: WBVP
48 month VDP

- Design Alternatives
- Minor Architectural Changes
- High Design Freedom
- High CAE contributions
- Limited Vehicle specific data

Clay model complete

- Design specs available
- Minor modifications to design
- Lower design freedom
- More of optimization following redesign to targets
- Full Design specs available
- Tuning with prototype testing
- Proving ground data
- CAE in reactive and correlation mode

Influence on Vehicle Safety

- Changes
  - High Design Freedom
  - High CAE contributions
  - Limited Vehicle specific data
  - Full Design specs available
  - Tuning with prototype testing
  - Proving ground data
  - CAE in reactive and correlation mode

Crashworthiness Model Requirements

- The models should satisfy at a minimum the following overall requirements:
  - Accuracy – the model should be able to yield reasonably accurate predictions of the essential features being sought
  - Speed – the model should be executable with a reasonable turnaround time, not to exceed 12 hours regardless of its size, to allow for iterations and parameter studies
  - Robustness – small variations in model parameters should not yield large variations in model responses
  - Development time – the model should be built in a reasonably short period of time, not to exceed two weeks

Structure Design for Crashworthiness
Automotive Body

- Two types of body structures (Body-In-White)
  - Unibody (passenger car)
  - Ladder frame (trucks/SUV)

Automotive Structure - Unibody
- Unit-body structures comprise most passenger cars introduced in the U.S. since the early 1980's
- Body, frame, and front sheet metal combined into a single unit constructed from stamped sheet metal and assembled by spot welding or other fastening methods
- Enhance whole vehicle rigidity and provide for weight reduction

Automotive Structure - Ladder Frame
- The ladder frame supports the engine, transmission, powertrain, suspension and accessories
- In frontal impact, the frame and front sheet metal absorb most of the crash energy by plastic deformation
- Structural modules are bolted together to form the vehicle structure
- The vehicle body is attached to the frame by shock absorbing body mounts, designed to isolate high frequency vibrations
**Body-In-White (BWI)**

**Occupant Compartment**
- Firewall – separates engine from compartment
- Center Tunnel – accommodates the exhaust pipes and drive-shaft
- Sills – Profiled longitudinal beams designed in two shell construction
- Side Frame – A,B,C and D pillars
- Side Panel – External side panels
- Floor Assembly – forms the back-bone for the entire body
- Roof

**Front End**
- Underframe/Cradle
  - Used as an engine and/or suspension mount
  - Provides torsional stiffness to the structure
  - Bolted through vibration dampers to the front rails
- Cross member
  - Strong welded steel or magnesium structure (or single cast piece)
  - Transfers energy to the opposite side in the event of a severe side or angular collision

**Wheel Houses**
- Extremely strong by virtue of their shape
- Incorporate strengtheners, beads, and offsets
- Upper side member
  - Positioned along the entire length of the wheel house
  - Absorbs additional energy during severe frontal collisions
  - Incorporate reinforcements
**Body-In-White (BIW)**

**Rear End**
- Simpler design compared to front
- Based on a closed box design
- Rails are incorporated to dissipate energy
- Panels around the wheelhouse provide additional support

**Side Protection**
- Strong B-pillars
- Door beams positioned to engage the barrier
- Door trims have foam padding to minimize hard contact points on impact