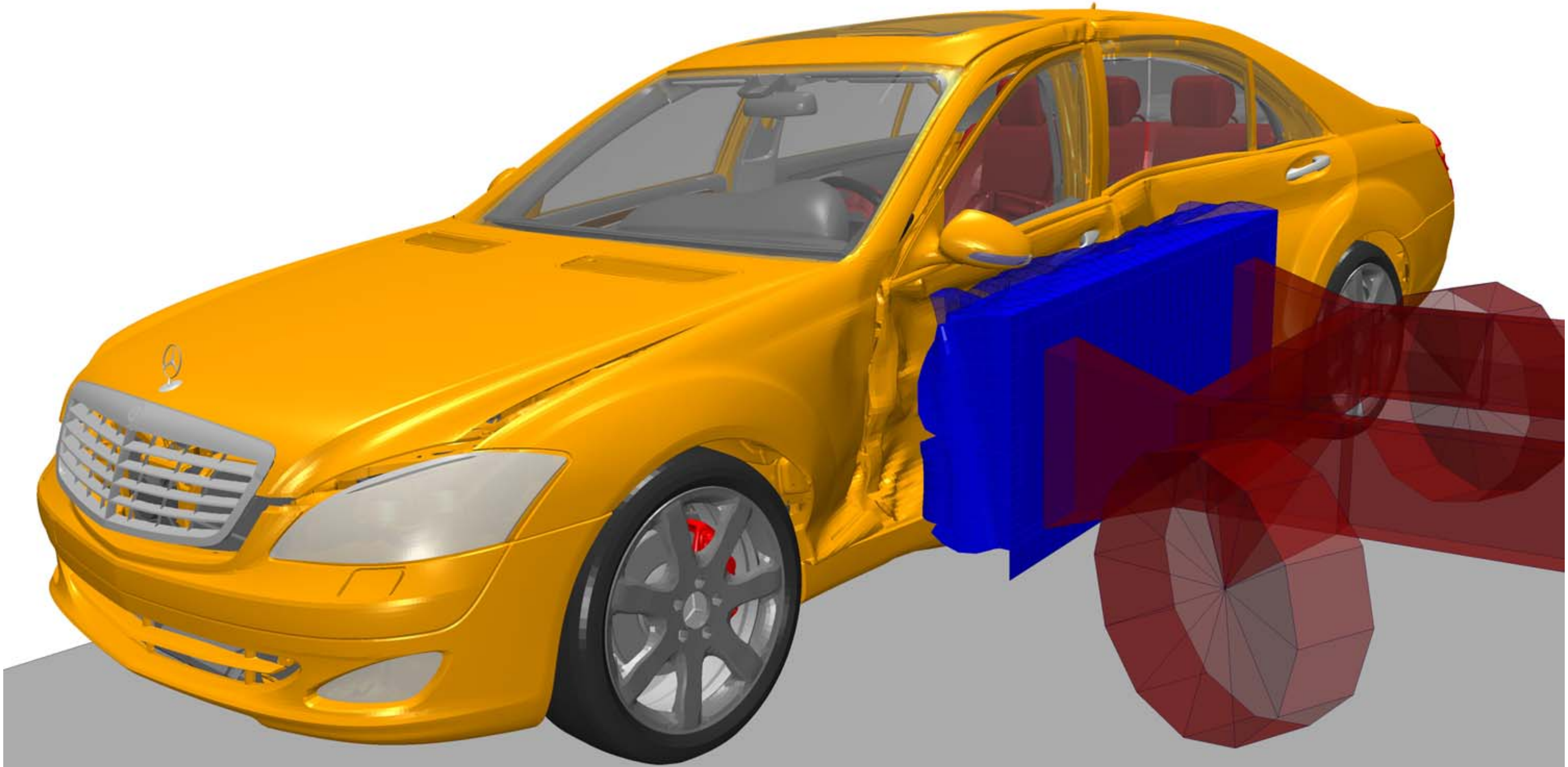

The History of LS-DYNA®

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Outline of talk

- Origins of DYNA3D at LLNL.
- Current LSTC development philosophy for LS-DYNA.

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Origins of DYNA3D

- LLNL was developing the FUFO bomb for low altitude release from bomber.
  - Impact velocity ~40m/s
- No 3D software available for simulating impact
- 2D software inadequate
  - HEMP, HONDO
  - HEMP3D was under development
    - Restricted to IJK logically regular meshes not useful for engineers

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Origins of DYNA3D

- Manual released in August, 1976, for public distribution
  - John Hallquist was the “development team”.
  - FUFO bomb cancelled
- Development of DYNA2D and NIKE2D, NIKE3D started (also with Hallquist as the development team).
- Request for DYNA3D source code from France. DYNA3D released into the public domain (1978) without restrictions.

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Origins of DYNA3D

- In 1978 LLNL received funding from BMD to continue 3D software development
- New version released in 1979 for CRAY-1 supercomputer
  - Two element formulations
    - One point integrated finite element
    - HEMP3D finite difference option with FE mesh
  - General tied contact and surface-to-surface contact with unlimited sliding
  - Material and EOS library including explosives
  - Coding extremely vectorized to obtain 10x over CDC7600
  - Commercial codes were neither vectorized nor explicit.

Origins of DYNA3D

- The 1979-1981 versions and their revisions created interest in Japan and Europe. BCS in London had several large users including Rolls-Royce Jet engines.
- User seminars started in Japan and Europe in 1982
- Lab started to get inquires from several companies for permission to commercialize the code.
  - At the request of Hallquist, permission was always granted by a letter from a lab attorney (Technically, permission was not needed.)
  - Two companies begin sales and marketing activities for DYNA3D based software, creating even more interest in the free public domain version.

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Origins of DYNA3D

- DYNA3D leveraged the developments from finite difference (FD) and finite element (FE) literature.
  - Clean efficient vector coding with no extra operations for speed.
  - FD: Radial return plasticity, bulk viscosity, equations-of-state.
  - FE: Professors Belytschko and Hughes:
    - Huge advances in element technology, stabilization, constitutive modeling, and contact.
    - Supportive of research from outside of academia.

Origins of DYNA3D

- In 1984 David J. Benson joined LLNL.
  - Doubled the size of the development team.
  - Single surface, automatic, contact added
    - First in FEA.
    - Critical capability for buckling in crash.
  - Rigid body dynamics coupled to FEA.
    - Reduced cost of calculations.
    - Used in both crash and metal forming. Metal forming results now mapped to crash model for accurate material response.
  - Improved element technology.
  - Many other developments.
  - Left in 1987 for UCSD, but continues to consult extensively with LSTC to the present.

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Single Surface Contact

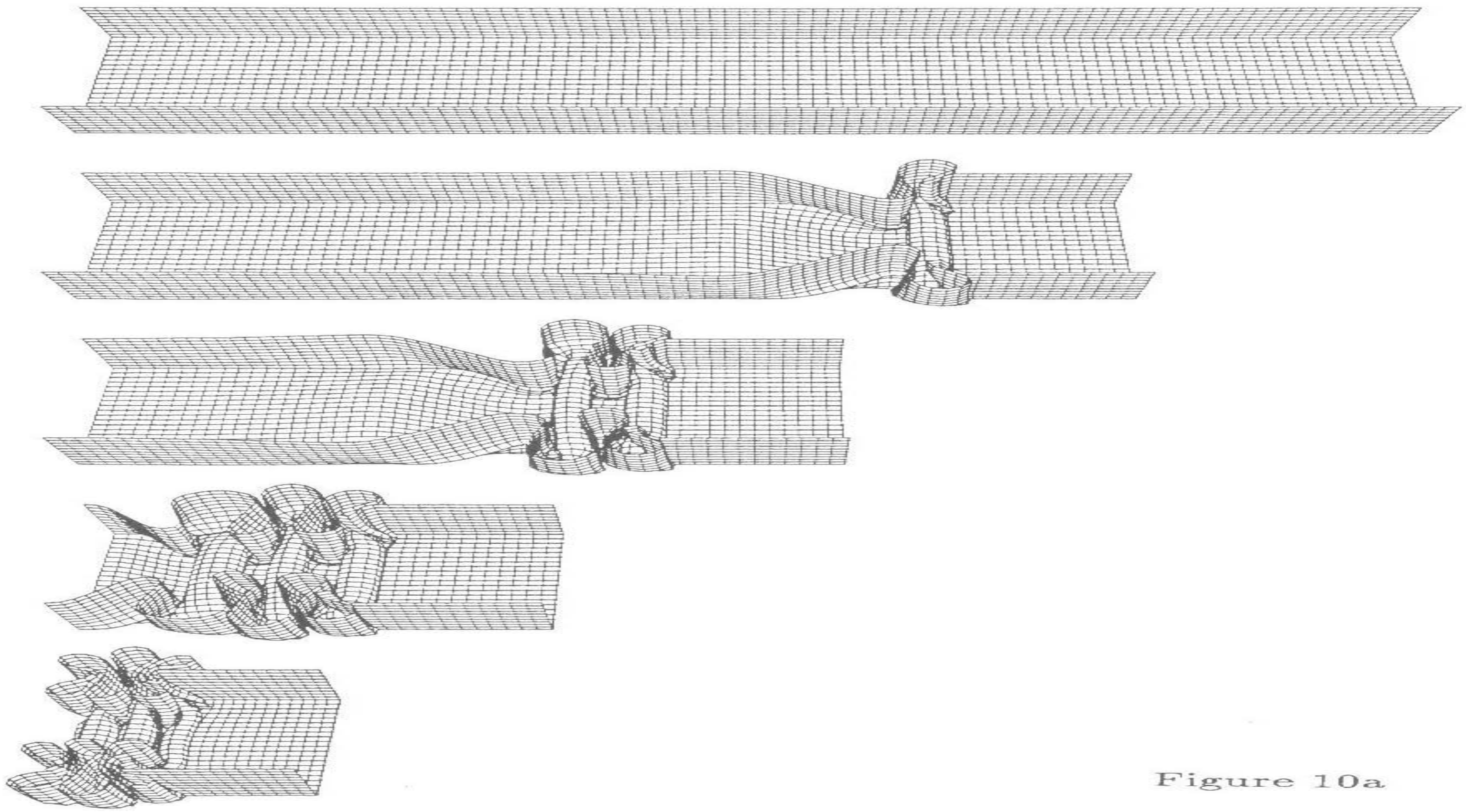


Figure 10a

Rigid Bodies

Originally used for metal forming

SIMPLE RIGID BODY ALGORITHM

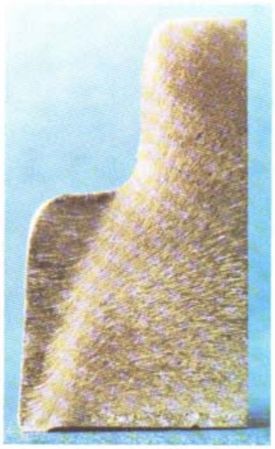
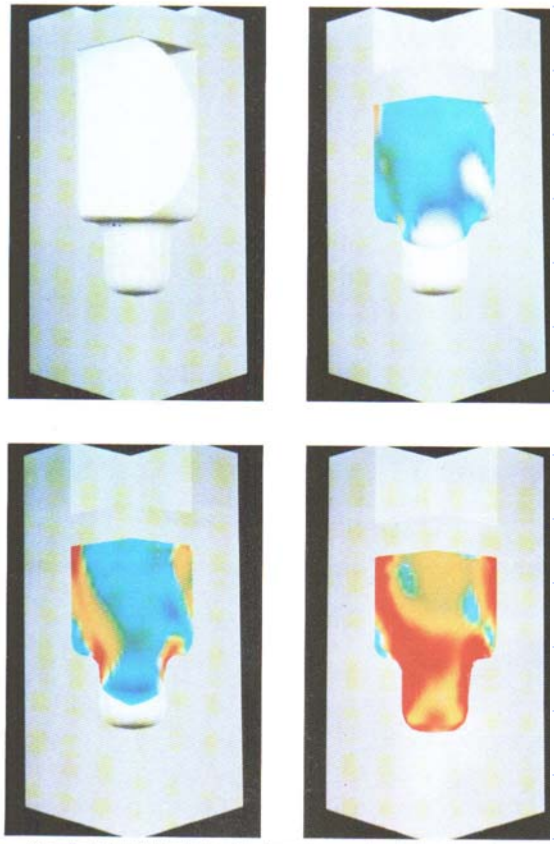


Plate 1. Cross-section of valve body forging showing shear band

Plate 2. Shear bands are evident on the plane normal to the ram along the axis of the bar-stock



Origins of DYNA3D

- By 1988 approximately 600 tapes containing DYNA3D, DYNA2D, NIKE2D, NIKE3D, TAURUS, and INGRID had been sent to requestors from LLNL.
- By 1988 Hallquist consulted for ~60 companies and organizations on the use of DYNA3D.
  - In the 80's, it was official DOE policy to encourage consulting by DOE employees to transfer technology to industry.
  - In contrast, today engineers at LLNL are not allowed to consult with LSTC due to potential conflicts of interest.

Origins of DYNA3D

- By 1989 the commercial market for explicit software in automotive and aerospace was growing quickly
- Hallquist left LLNL at the beginning of 1989 to start LSTC.
  - DOE policy to encourage technology transfer by employee consulting ceased.
  - ME Dept. slowed approval of outside consulting.
  - Spent last years at LLNL in K-Division (Geophysics).
  - LLNL stopped the release of new versions of DYNA3D into the public domain after Hallquist left.

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Origins of DYNA3D

- By 1989 DYNA3D was the most advanced FEA code available for transient dynamics.
- A user base of several hundred companies, which needed support.
- Hallquist had connections to the user base due to contacts while at LLNL.
  - This customer base provided a starting point for LSTC.
  - Industry started purchasing supercomputers.

LLNL Development Environment

- Developers (both) worked directly with users.
- Development agenda set by developers and users. Management was not involved.
- Theory and implementation were done by the same people.
- There were no milestones to meet.
  - Allowed unproductive developments to be abandoned without penalty (e.g., first shell element was unsuccessful).
- Funding (although small) was guaranteed from overhead.
- This environment was not the usual one at LLNL and isn't the current one for most software development.

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LLNL Development Environment

- Computer science background:
  - John Hallquist: 1 class in Fortran 66.
  - David Benson: 1 class in Fortran 66.
- All DYNA3D development in Fortran.
- Developed on Crays.
- Execution speed was always a concern.
- Support of 1 computer scientist for graphics and postprocessing in later years.

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Adoption by Industry and Government

- Government regulations mandate increasingly higher levels of safety.
- Prototypes are extremely expensive.
- They are made with different manufacturing processes than the production models, therefore *crash experiments have limited accuracy*.
- Industry has no alternative to analysis.
- Government forced to accept analysis for the same reasons as industry.

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Cost-Benefit Analysis

- Example of Ford-Mondeo (data provided by Paul DuBois, 1999).
  - 150 prototypes crashed in Europe & USA.
  - Development cycle of 5 years: 30 prototypes per year.
  - Average cost of prototype: $0.25 M
  - Conservative estimate: 30% of prototypes can be replaced by simulations.
  - Roughly 10 prototypes per year = $2.5M
- Today:
  - Prototype costs up.
  - Computing costs down.

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Major Stumbling Blocks (Paul Dubois, 1999)

- "The major stumbling block for predictive simulations today is the structural use of non-steel materials."
- "*Lack of suitable material models (plastics, foams,...)*"
- "Discontinuous cell structures..."
- "Inhomogeneous composites..."
- "Brittle failure..."
- Many of these problems remain today.
- Spot weld and fastener failure are current issues.
- Would like to replace dummies with models of humans, therefore need better bio-material models.

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Crash Model Size Trends

- 1986: First model had 3439 elements.
- 1990: 15-20,000 elements.
- 1995: 50-100,000 elements.
- 2000: 100-250,000 elements.
- 2005: 1-1.5x10^6 elements.
- Near future: 10x10^6 elements.
- All current simulations performed on clusters.

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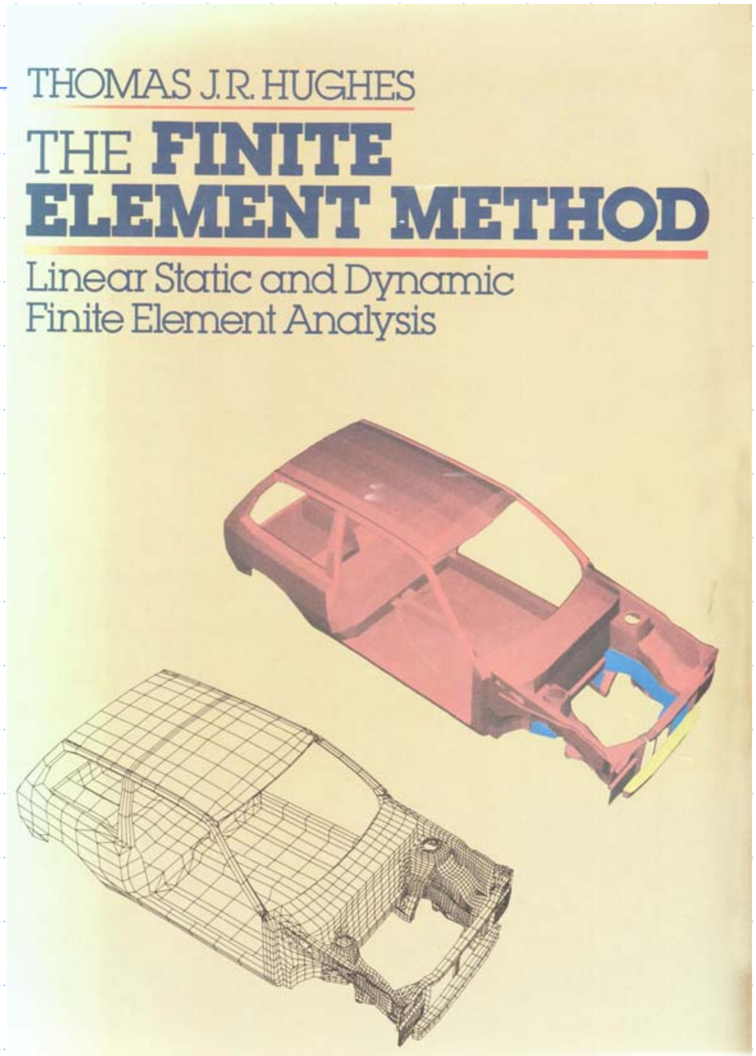
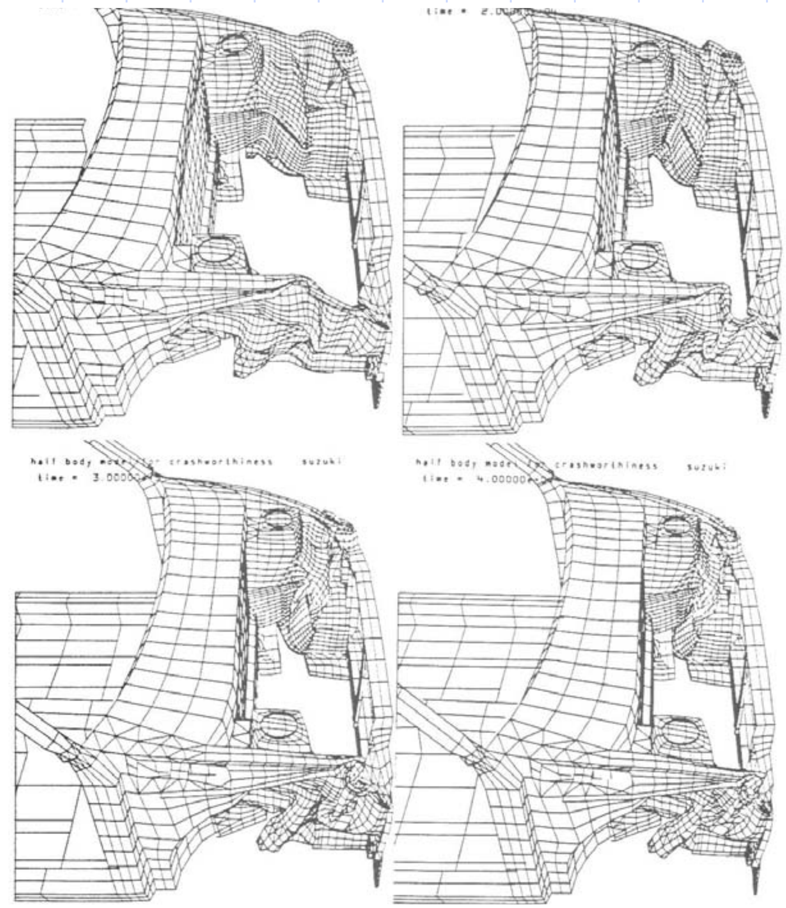
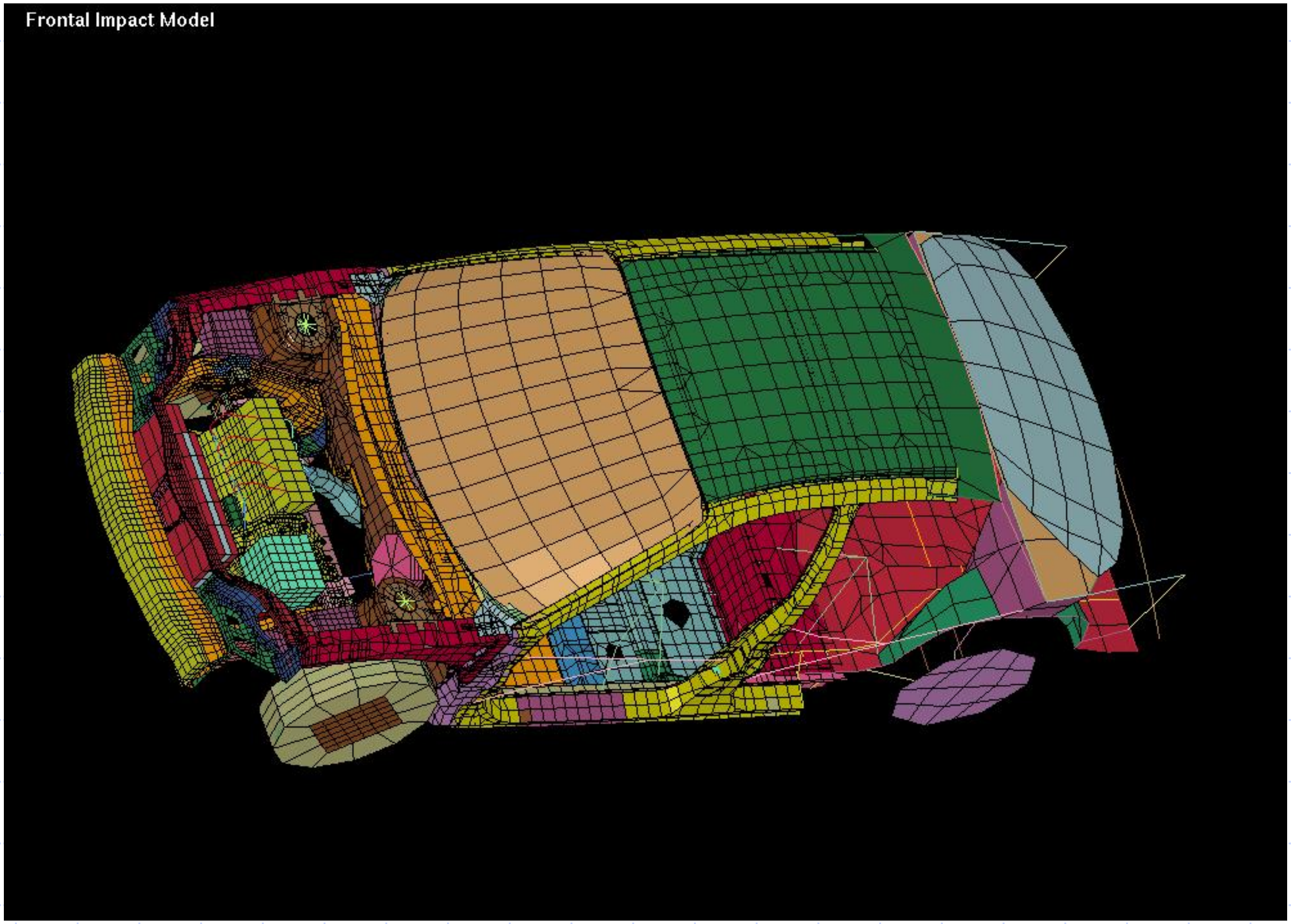
First DYNA3D Full Vehicle Crash Simulation





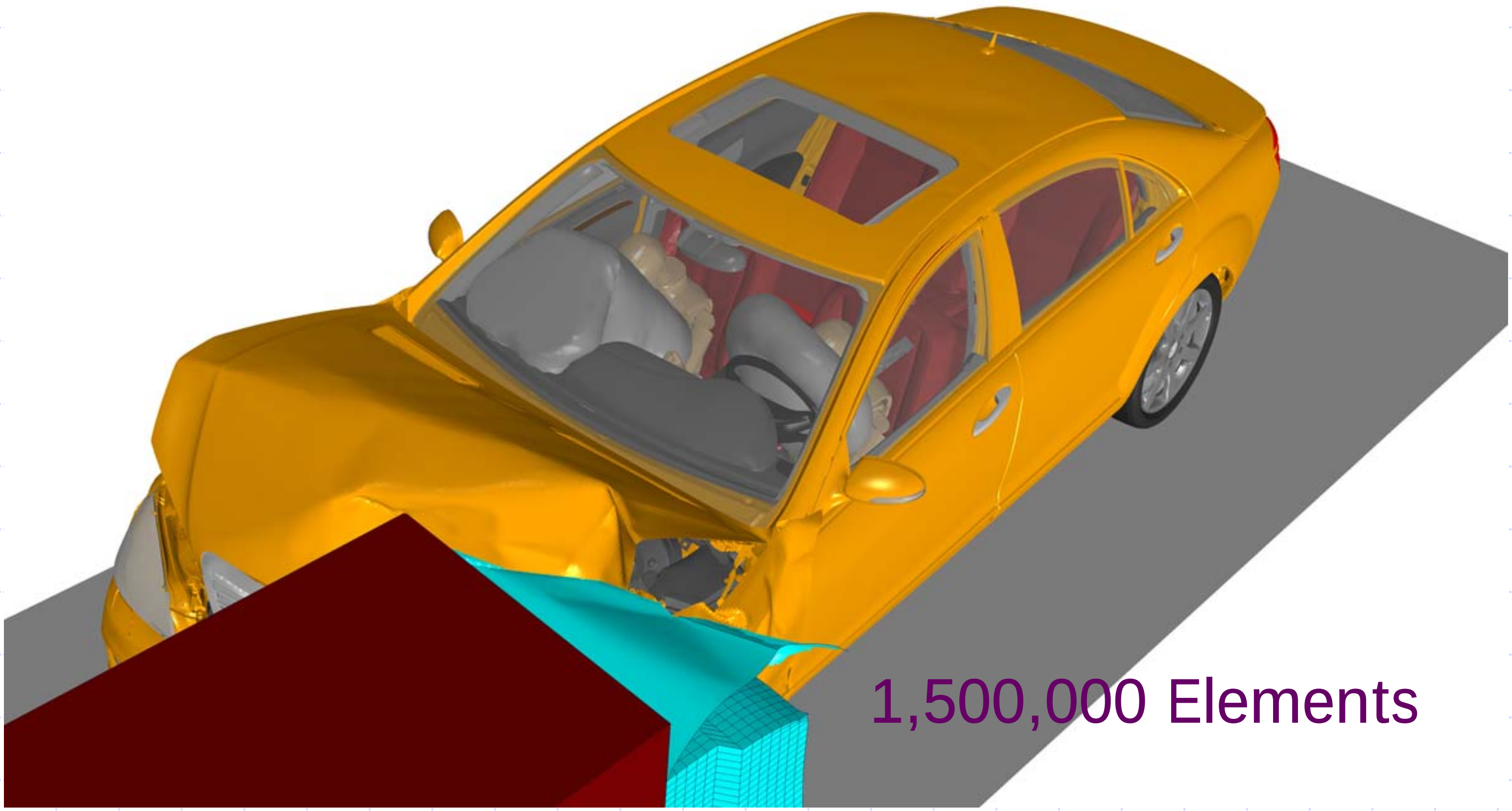
3439 Elements

Early Crash Calculation ~1994



36000 Elements

Current Crash Calculation 2005



1,500,000 Elements

LSTC LS-DYNA Development

- LSTC developments are concentrated on three products:
  - LS-Dyna
  - LS-Opt
  - LS-PrePost
- LS-PrePost and LS-Opt are part of the LS-Dyna distribution and do not require license keys.

Development Goals

- Combine multi-physics capabilities in a scalable code for solving highly nonlinear transient problems to enable the solution of coupled multi-physics and multi-stage problems in one run
  - Full 2D & 3D capabilities
  - Explicit Solver
  - Implicit Solver
  - Heat Transfer
  - ALE, EFG, SPH, particle methods
  - Navier-Stokes Fluids (version 980)
  - Radiation transport (version 980)
  - Electromagnetics (version 980)
  - Acoustics
  - Interfaces for users, i.e., elements, materials, loads, etc.
  - Interfaces with other software, Madymo, USA, etc.

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LS-DYNA Development

- Advantages of the one code strategy
  - A combined solver for multi-physics applications focuses the entire development team on one comprehensive analysis code.
  - A large cost savings relative to developing an array of uncoupled multi-physics solvers and then coupling them.
  - Large and diverse user base covering many industries means low licensing costs
  - Features needed for implicit applications are available for explicit
    - Double precision, 2^{nd} order stress update, Global constraint matrix, etc.

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LS-DYNA Development

- Advantages of the one code strategy
  - Implicit MPP utilizes all prior efforts for explicit solver
  - More freedom for developers, who can work on multiple developments governed by different field equations
  - LS-PrePost/LS-Opt software development supports one interface.
  - QA is performed on one code
  - No costly add-ons for customers who require multi-physics solutions.

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LS-DYNA Development

- We recognize that no single method is superior in all applications.
- New developments and methodologies take time before gaining general acceptance and robustness.
- Requests for developments from users are given the highest development priority.
- Accuracy, speed, and scalability are the critical considerations for large scale simulations.
- New releases must accept and run all input files from all previous releases without translation.
- Developers and users talk directly.

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Development Goals-Implicit

- Springback for sheet metal stamping.
- Static initialization of crash models.
- Dynamic springback simulation after crash simulation
  - Reliable measurements between numerical and physical results can be more easily obtained.
- An embedded linear capability to automatically solve for normal modes, attachment modes, and constraint modes.
  - Include infinitesimal motions superimposed on rigid bodies for NVH and durability modeling.
- Eigenvalue analysis to check the rigid body modes in the crash models.
  - Identify inadvertent constraints.

LSTC's Vision

- In automotive, one model for crash, durability, NVH shared and maintained across analysis groups.
- One scalable multi-physics code, LS-DYNA, to enable the complete modeling of crash including airbags, occupants, and fuel tank.
- Manufacturing simulation results from LS-DYNA used in crash, durability, and NVH modeling.
- Explicit durability and NVH modeling go mainstream in MD Nastran.
- No optional added cost LSTC developed features in LS-DYNA.

LSTC's Vision

- LS-DYNA specific pre-processing, post-processing, LS-PrePost, and optimization, LS-OPT, with no added charges.
- Unrestricted open databases.
- Focus on large distributed memory low-cost clusters running large simulations.
- As processor costs decrease and cluster sizes increase, LS-DYNA software prices per processor will proportionally decrease to keep simulation costs affordable.
- Optimization technology will automate engineering design calculations. LS-OPT is considered a critical enabling technology.

Current State of Explicit

- Currently, typical large simulation models typically contain 1,000000 to 4,000,000 elements.
- FEA dummies are preferred over rigid body dummies in crash simulations.
- 12-32 processors are used in runs that complete within 12-24 hours.
- Calculations give digit-to-digit repeatability for a fixed domain decomposition.
- MPP version is recommended if more than 4 processors are used per run.
- Model sizes continue to grow faster than Processor speed.

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Near Future for Explicit

- Model sizes of 10,000,000 elements.
- 128-512 processors in overnight runs.
- Human dummy models, such as THUMS, will increase model sizes even further.
- Honeycomb barriers will be modeled by shell elements.
- Number of processors will increase 5-10 times.
- Optimization software use in crash analysis will become widespread.

Final Goal for Explicit Simulations

- Simulation results accepted in place of prototype testing.
  - What is required?
    - Strict modeling guidelines for analysts, and a single comprehensive model for crash, NVH, Durability, etc.
    - Continued software improvements:
      - Constitutive models
      - Contact
      - FSI with SPH, ALE, Particle methods
      - Sensors and control systems
      - Complete compatibility with NASTRAN
    - Manufacturing simulations (in LS-DYNA, Moldflow, etc.) providing the initial conditions for crash simulations.

Parallel Computing

- In less than one decade from 1998-2006 the use of explicit codes has undergone a radical transformation.
  - From 100% serial and SMP licensed CPU's for crash to 90% MPP with the remaining 10% of CPU's typically running smaller models on 1-8 processors.
  - Today serial and SMP explicit codes are becoming obsolete and will eventually be phased out.
- What about implicit?
  - More difficult to create an MPP version.
  - Requires more expensive hardware so there is less customer pressure to create MPP versions.
  - However, it is safe to predict that serial and SMP implicit solvers *used in large scale nonlinear simulations* will also become obsolete within the next 5 years.

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Scalability on Large Clusters

- IBM BlueGene/L computer is based on low cost PowerPC processors with modest clock speed, low power consumption, high speed network
- 2**16 (65000+) parallel processors
- Scalability of LS-DYNA on 1,048,576 element customer model run to completion:
  - 128 -Elapsed time 5 hours 27min. 437564 cycles
  - 256 -Elapsed time 2 hours 44min. 437564 cycles
  - 512 -Elapsed time 1 hour 27min. 437564 cycles
  - 1024 -Elapsed time 50min. 437564 cycles
  - 2048 -Elapsed time 32min. 437564 cycles

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Scalability on Large Clusters

- Cray XD1 with RapidArray interconnects AMD Dual Core Opteron 2.2 GHz
- 3 Car crash simulation run to completion (750K nodes)

Nodes x (processors/node) x (cores/processor)

64 x 2 x 2 = 256	1696 sec	
32 x 2 x 2 = 128	2416	
24 x 2 x 2 = 96	2981	single core 2.2 GHz
16 x 2 x 2 = 64	3846	32 x 2 x 1 = 64 4619
12 x 2 x 2 = 48	5226	
8 x 2 x 2 = 32	7591	
4 x 2 x 2 = 16	14078	
2 x 2 x 2 = 8	26230	4 x 2 x 1 = 8 24681
1 x 2 x 2 = 4	49460	2 x 2 x 1 = 4 47611

THANK YOU

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