Recent Developments in LS-DYNA

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Fall, 2005
Livermore Software Technology Corporation

Outline of talk

- Introduction
- New features in version 971
- Recent developments in ALE and EFG
- Implicit
- LS-Prepost
- Future versions 971 and 980
- Conclusion

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Development goals LS-DYNA

- Combine multi-physics capabilities in a scalable code for solving highly nonlinear transient problems
  - Full 2D & 3D capabilities
  - Explicit Solver
  - Implicit Solver
  - Coupled Heat Transfer
  - ALE, EFG, SPH
  - Navier-Stokes Fluids
  - Radiation transport
  - Electromagnetics
- Enable the solution of coupled multi-physics and multi-stage problems in one run

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Development of one code has advantages

- Huge cost savings relative to developing an array of software applications.
  - Explicit elements only need added stiffness matrix
  - Features needed for implicit applications are available for explicit
    - Double precision
    - 2nd order stress updates
  - Implicit MPP utilizes all prior efforts for explicit solver
  - Pre and post-processing software development supports one interface.
  - QA is performed on one code.

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LSTC's vision

- In automotive, one model for crash, durability, NVH shared and maintained across analysis groups
- One scalable multi-physics code, LS-DYNA, enables complete modeling of crash including airbags, occupants, and fuel tank.
- Compatibility with MSC/NASTRAN to enable model sharing between analysis groups
  - Solution 700: LS-DYNA in the NASTRAN environment
- Manufacturing simulation results from LS-DYNA used in crash, durability, and NVH modeling
- Improvements in code accuracy will eliminate the need for physical testing

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LSTC's vision

- No optional added cost LSTC developed features in LS-DYNA
- LS-DYNA specific pre-processing, post-processing, LS-PrePost, and optimization, LS-OPT, with no added charges.
- Focus on large distributed memory low-cost clusters
- As processor cost decrease and cluster sizes increase, our 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

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Release of version 971

- Version 971 was intended to be an update to version 970 to include parallel implicit
- Implementation of implicit parallel has taken years longer than expected
- A formal release is planned by November 1, 2005.
- Due to the delays, many features added to 971 were also implemented in version 970.

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Version 971 developments

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*Control_spotweld_beam

- Failure is sensitive to the:
  - location of the spotweld on the contact segment
  - physical size of the segment
- This new control card provides a means of scaling the failure force resultants to compensate for these sensitivities

$$\left(\frac{s_T s_O \sigma_{rr}}{\sigma_{rr}^F\left(\dot{\varepsilon}_{eff}\right)}\right)^2+\left(\frac{s_S s_O \tau}{\tau^F\left(\dot{\varepsilon}_{eff}\right)}\right)^2-1=0$$

- Also, in next release of version 970

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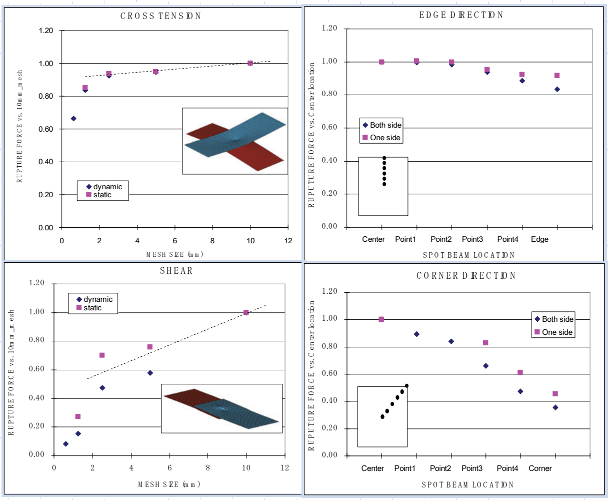
*Control_spotweld_beam



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*Define_set_adaptive

- Sets adaptive refinement level by element or part set ID
- Minimum element size is specified in addition to the adaptive level
- Also, added to version 970

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*Include_path

- The "path" option defines a directory where the include files can be found
- Multiple *Include_path" definitions may be given
  - When a file name is specified the local directory is searched first
  - If the file is not found in the local directory then all directories specified in the *Include_path definitions are searched until the file is found
- Added to version 970

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*Parameter_expression

- Define numerical values of parameter names referenced throughout the input file.
- Like the *PARAMETER keyword, but allows for general algebraic expressions, not simply fixed values.
- Available functions: *sin, cos, tan, csc, sec, ctn, asin, acos, atan, atan2, sinh, cosh, tanh, asinh, acosh, atanh, min, max, sqrt, mod, abs, sign, int, aint, nint, anint, float, exp, log, log10, float*
- General arithmetic expressions involving +, -, *, /, and **

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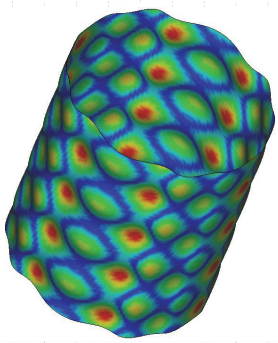
*Perturbation

- *PERTURBATION_SHELL_THICKNESS
- *PERTURBATION_NODE
- Defined using:
  - Sine series expansion
  - Scaled displacements/modes



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Monte Carlo radiative heat transfer

- Available for the calculation of exchange factors for heat transfer analysis.
  - Arbitrarily complex geometries
  - Arbitrary number of material properties
  - Arbitrary number of energy (wavelength) bands
  - Mixed specular and weighted diffuse material model

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Monte Carlo radiative heat transfer

- Emission capabilities
  - Directional emission based upon material properties
  - Weighted diffuse emission
  - Collimated (beam) emission
- Guaranteed to converge
- Simulates rarefied molecular gas dynamics
- Runs on single processor during input phase

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*Part_composite

- Provides a simplified method of defining a composite material model for shell elements
- Eliminates the need for user defined integration rules
- For each integration points the user defines:
  - Material ID-not part ID's.,
  - Thickness
  - Material angle referenced to local shell coordinate system.

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*Part_composite

- Integration point data is given sequentially starting with the bottom
- Number of integration points is determined by the total number of entries
- The total thickness of the composite shell is the sum of the integration point thickness
- With *PART_COMPOSITE, the keywords *SECTION_SHELL and *INTEGRATION_ SHELL, are unnecessary.

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*Case

- Provides a way of running multiple load cases sequentially in a single run
- Within each case, the input parameters, which include loads, boundary conditions, control cards, contact definitions, initial conditions, etc., can change.
- Results from a previous case can be used during initialization.
- Each case creates unique filenames for all results files by appending the prefix "*IDn.*" to the default name where n is the case ID for the active case.

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*Constrained_spline

- A cubic spline interpolation element
  - Displacements and slopes are matched at endpoints
    - Based on beam theory
    - Widely used in NASTRAN
  - Provides a way of connecting regions of different mesh density
  - Works explicitly and implicitly
  - Implemented for NASTRAN compatibility
  - A linear capability

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*Control_implicit_inertia_relief

- New feature for implicit computations to allow analyses of models with rigid body modes, e.g., aircraft in flight
- Computes the rigid body modes and uses these rigid modes to constrain the motion
- Works for linear statics, both single and multi-step
- Works well for nonlinear springback in metalforming applications. Eliminates need to choose nodes for constraints.
- Input requires threshold eigenvalue for identifying the rigid body modes. Default=0.001hz

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*Define_curve_function

- Can be referenced just like any other curve
- Arbitrary analytic expressions of any complexity
  - Read in as ASCII FORTRAN expression
- Can reference other curves, either tabulated or analytic
  - For complete generality, a dependency tree is created so curves can reference curves that reference curves, etc.
- Examples of analytic expressions:
  - 42.5*sin(time*pi/20.)
  - Max(LC10,sqrt(LC122*5.))
    - LC10 and LC122 are load curve ID's
- Expressions can be functions of time, displacements, velocities, etc.

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*Node_transform

- Perform a transformation on a node set based on a transformation defined by *DEFINE_TRANSFORMATION.
- Requires as input the transformation ID and the node set ID.
- Allows the node set to be translated and rotated as a rigid body
- More general than *Part_move
- Also, in version 970

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*Define_transformation

- POINT option
  - Requested for dummy positioning
  - The POINT option in ROTATE provides a means of defining rotations about axes that have been reoriented by previous transformations in the *Define_transformation definition
  - The coordinates of the two POINTs are transformed by all the transformations up to the transformation where they are referenced.
  - The POINTs must be defined before they are referenced, and their identification numbers are local to each *Define_transformation.
  - The coordinates of a POINT are transformed using all the transformations before it is referenced, not just the transformations between its definition and its reference. To put it another way, while the ordering of the transformations is important, the ordering between the POINTs and the transformations is not important.
- LS-DYNA versions 970 & 971

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Mass property output

- *Database_glstat_mass_properties: This is an option for the glstat file to include global mass and inertial properties in the output for each output state.
  - Mass center, mass, inertia tensor, principle inertias
  - Computed from nodal point and rigid body mass and inertia.
  - Excludes failed nodes and elements
- *Database_ssstat_mass_properties: This is an option for the ssstat file to include mass and inertial properties for the subsystems.
- LS-DYNA versions 970 & 971

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*Termination_deleted_shells

- NFAIL1 and NFAIL4, which are defined on *CONTROL_SHELL, checks for negative jacobians and deletes any shells where one is found
- If the NFAIL1/NFAIL4 option is set, the calculation can be terminated based on the number of elements that have failed within a given part ID. The number of failed shells is specified by this *Termination option.
- SMP and MPP implementation
- LS-DYNA versions 970 & 971

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*Hourglass

- A new hourglass control option, type 7, has been added for hyperelastic materials
  - Implemented for modeling tires undergoing extreme loading conditions
    - Also, extremely useful for foam materials
  - Implemented in the Belytschko-Bindeman solid element
    - Uses an exact elastic hourglass stiffness if the hourglass coefficient is unity. Original geometry is always recovered upon unloading
  - Combines hourglass viscous and stiffness forces together for tire applications
    - Hyperelastic materials frequently require additional damping for stability
- LS-DYNA versions 970 (type 6) & 971

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*Hourglass

- A new hourglass control option, type 9, is now available for solid elements.
- This hourglass control is an implementation of the solid element by Puso published in paper entitled: "A highly efficient enhanced assumed strain physically stabilized hexahedral element" IJNME, 49, 2000.
- Implemented in version 971 is for both implicit and explicit applications.
- Tests so far seem to show that Puso's hourglass control is marginally less sensitive to solid element distortion than type 6, the Belytschko-Bindeman solid element.

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*Contact_guided_cable

- A sliding contact that guides 1D elements, such as springs, trusses, and beams, through a list of nodes
- Ordering of the nodal points and 1D elements in the input is arbitrary
- Defined by a set of guide nodes and a part set of one-dimensional elements
- Explicit, implicit, and MPP implementation
- LS-DYNA versions 970 & 971

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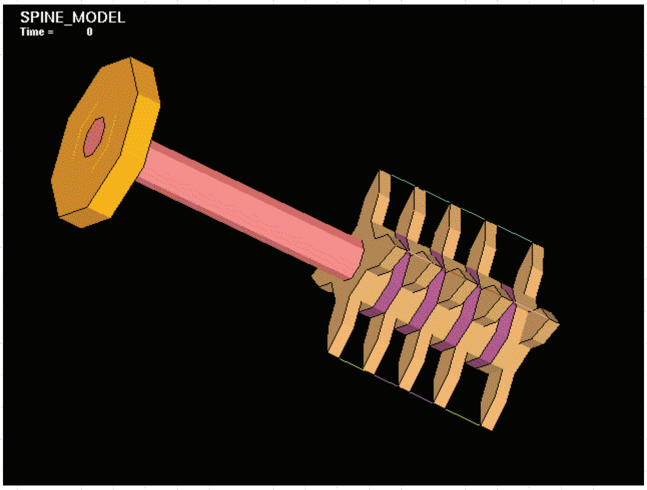
*Contact_guided_cable



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*Define_friction

- Define friction coefficients between parts for use in the contact options:
  - SINGLE_SURFACE,
  - AUTOMATIC_GENERAL,
  - AUTOMATIC_SINGLE_SURFACE,
  - AUTOMATIC_NODES_TO_SURFACE,
  - AUTOMATIC_SURFACE_TO_SUFACE,
  - AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE,
  - ERODING_SINGLE_SURFACE.

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*Define_friction

- One *DEFINE_FRICTION input permitted
- Friction values are given for each pair of parts, if n parts exist in the model, then up to n(n+1)/2 unique pairs are possible
- Default friction constants are used if a pair of contacting parts have no defined friction values
- The coefficients are stored using sparse matrix storage. A fast look-up is used to get the friction coefficients for each contact pair. Every contact segment has an associated part ID

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*Mat_muscle

- A Hill-type muscle model with activation and a parallel damper.
- Extension of *MAT_SPRING_MUSCLE to truss elements.
- Mass density is defined so lumped nodal masses are not required
- Implicit/explicit implementations
- LS-DYNA versions 970 & 971

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*Mat_add_thermal_expansion

- Adds thermal expansion to all non-thermal material models
  - Elastic and hyperelastic
- Applies to all nonlinear solid, shell, thick shell, and beam elements
- Thermal expansion coefficient with 2 options:
  - Constant for all temperatures
  - Load curve defines coefficient as a function of temperature

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*Mat_simplified_rubber/foam_with_failure

- Failure criterion is defined in terms of the invariants of the right Cauchy-Green deformation tensor:

$$f(I_1, I_2, I_3) = (I_1 - 3) + \Gamma_1 (I_1 - 3)^2 + \Gamma_2 (I_2 - 3) = K$$

where *K* is a material parameter which controls the size enclosed by the failure surface

- Works with shell and solid elements
- LS-DYNA versions 970 & 971

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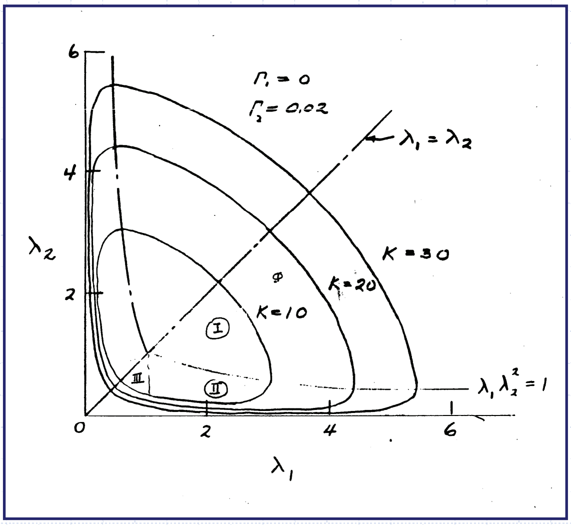
*Mat_simplified_rubber/foam_with_failure



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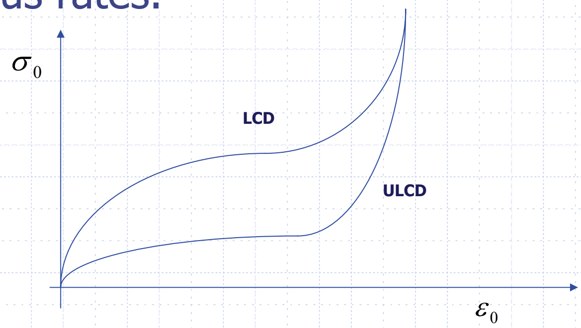
*Mat_simplified_rubber_with_damage

A rate independent unloading curve is defined. Rate effects are included by a table definition for stress vs. strain at various rates.



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*Mat_simplified_rubber_with_damage

- Simulates the rubber behaviour under cyclic loading. The implementation uses incompressible Ogden functional
- LS-DYNA versions 970 & 971, shells and solids

$$W = \left(1 - d\left(\frac{W_0}{W_{0,\max}}\right)\right)\sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{*\alpha_j} - 1\right) + U(J)$$

$$W_0 = \sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{*\alpha_j} - 1\right)$$

$$W_{0,\max} = \max\left(W_0, W_{0,\max}\right) \Rightarrow 0 \le \frac{W_0}{W_{0,\max}} \le 1$$

$$0 \le d \le 1$$

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*Mat_simplified_rubber_ with_damage

The principal true stresses that account for damage are easily computed:

$$W = \left(1 - d\left(\frac{W_0}{W_{0,\max}}\right)\right)\sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{*\alpha_j} - 1\right) + U(J)$$

$$\sigma_i \neq \frac{1}{\lambda_j \lambda_k}\frac{\partial W}{\partial \lambda_i}$$

$$\sigma_i = (1-d)\frac{1}{\lambda_j \lambda_k}\frac{\partial W_0}{\partial \lambda_i} + \frac{1}{\lambda_j \lambda_k}\frac{\partial U}{\partial \lambda_i}$$

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Rubber and shells

- Shell types 1, 2, 4, 7, 11, and 16 can now be used with rubber materials
- Improved stability at large stretch ratios
  - Implemented in version 971 and the next 970 release
- Ogden model can now be fit with up to 8 terms for improved accuracy in version 971

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*Mat_viscoelastic_thermal

- Viscoelastic model with up to 12 terms in the prony series expansion
- The Arrhenius and Williams-Landau-Ferry shift functions account for the effects of the temperature on the stress relaxation

$$\Phi(T) = \exp(-A\{\frac{1}{T} - \frac{1}{T_{REF}}\}) \qquad \Phi(T) = \exp(-A\frac{T - T_{REF}}{B + T - T_{REF}})$$

- Material type 175

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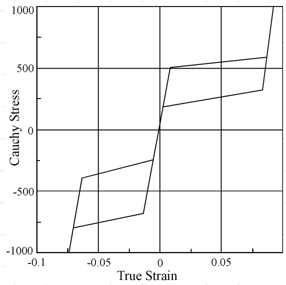
*Mat_shape_memory

- Shape-memory alloys undergo large deformations with a full recovery in loading-unloading cycles
- Now implemented for shell elements for use in new European side impact dummy



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Orthotropic viscoplastic & damage

- Now available for solid elements:
  - *MAT_SIMPLIFIED_JOHNSON_COOK
  - *MAT_PLASTICITY_WITH_DAMAGE
- Damage evolves monotonically in principle strain directions in tension only. Orthotropic behavior after failure (prior to rupture).
  - Better correlation with experimental data
  - Failure occurs in tensile regions, not compressive regions
  - Consistent results with minor input changes

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*Mat_3-parameter_barlat

- Three new hardening options have been added
  - The Voce equation

$$\sigma_Y(\varepsilon_p) = a - be^{-c\varepsilon_p}$$

  - The Gosh equation

$$\sigma_Y(\varepsilon_p) = k(\varepsilon_0 + \varepsilon_p)^n - p$$

  - The Hocket-Sherby equation

$$\sigma_Y(\varepsilon_p) = a - be^{-c\varepsilon_p^n}$$

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*Eos_gasket

- For modeling the response of thick shells where the through thickness, normal stress is nonlinear under compression and tension.
- The normal stress is completely decoupled from the shell material in the local coordinate system of the shell, this model defines the normal stress, σ_{zz}
- In plane stress components are determined from the shell constitutive model
- Use with the thick shell with selective-reduced integration (ELFORM=2 on SECTION_TSHELL)
- May also be used with solid elements as an equation-of-state to determine pressure

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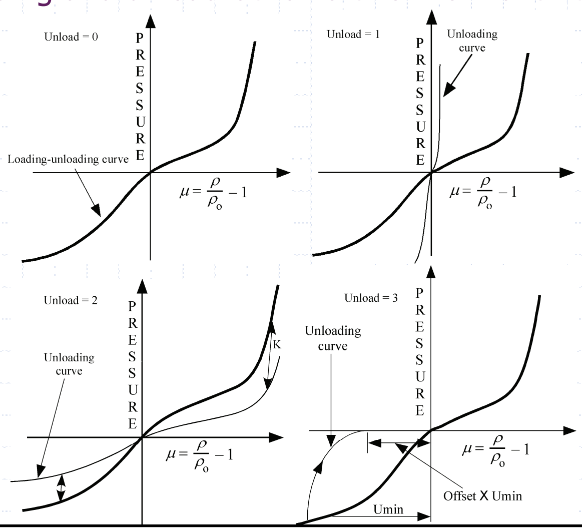
*Eos_gasket

Loading and unload behaviors for normal stress



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*Section_beam

- Additional built in sections are now available

Type01: I-shape	Type12: Cross
Type02: Channel	Type13: H-shape
Type03: L-shape	Type14: T-shape1
Type04: T-shape	Type15: I-shape2
Type05: Tubular box	Type16: Channel1
Type06: Z-shape	Type17: Channel2
Type07: Trapezoidal	Type18: T-shape2
Type08: Circular	Type19: Box-shape1
Type09: Tubular	Type20: Hexagon
Type10: I-shape1	Type21: Hat-shape
Type11: Solid box	Type22: Hat-shape1

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*Integration_beam

- Built-in integration rules are also available for all 22 sections. Before, the first 7 were supported.

Type 01: I-shape	Type 12: Cross
Type 02: Channel	Type 13: H-shape
Type 03: L-shape	Type 14: T-shape1
Type 04: T-shape	Type 15: I-shape2
Type 05: Tubular box	Type 16: Channel1
Type 06: Z-shape	Type 17: Channel2
Type 07: Trapezoidal	Type 18: T-shape2
Type 08: Circular	Type 19: Box-shape1
Type 09: Tubular	Type 20: Hexagon
Type 10: I-shape1	Type 21: Hat-shape
Type 11: Solid box	Type 22: Hat-shape1

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Warped beam type 11

- An integrated beam element with warpage
- Explicit and implicit
- Based on Vlasov theory of thin-walled beams with open cross sections.
- Seven degrees-of-freedom where the seventh degree-of-freedom represents the warping of the cross section.
- Behaves more realistically than beams without warpage.
- Beam type 11

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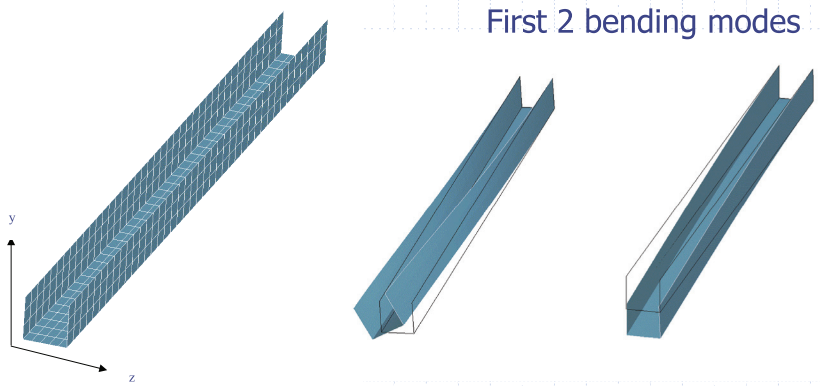
Example

First 2 bending modes



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Eigenvalue analysis

Shell	$t_f = t_w = 0.1$	$t_f = t_w = 0.05$
Bending about y	264.2	246.1
Bending about z	592.2	587.2
Twist/Bend	1290/1313	851.5
Double twist	1867	975.7
Triple twist	-	1053
Warped beam		
Bending about y	438.6	429.1
Bending about z	544.9	547.3
Twist	1142/1168	897.5/929.2
Double twist	1292	1040
Triple twist	1431	1162
Hughes-Liu		
Bending about y	718.9	724.1
Bending about z	544.9	547.4

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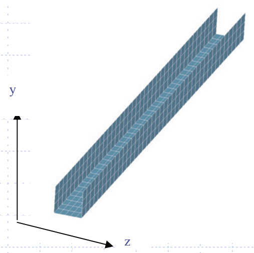
Static loading



Load direction	Shell structure	Warped beam	Hughes-Liu beam
Z	0.32	0.32	0.14
Y	0.22	0.25	0.25

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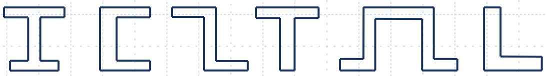
Warped beam type 12

Based on Battini's doctoral thesis titled "Co-rotational beam elements in instability problems," Department of Mechanics, Royal Institute of Technology, Stockholm, Sweden, 2002

- Resultant beam that uses LS-DYNA co-rotational frame.
- Linear elastic material. Seven DOF per node. Wagner effects considered.
- Reference frame located at centroid with e_2 and e_3 directed along principal axes.
- Centroid and shear center can be at arbitrary points of the cross-section.
- All cross-sectional properties computed numerically from user-defined dimensions.
- Currently twenty-two beam cross-sections available, e.g.



Application: Static, pseudo-static, or dynamic analysis of frame structures.

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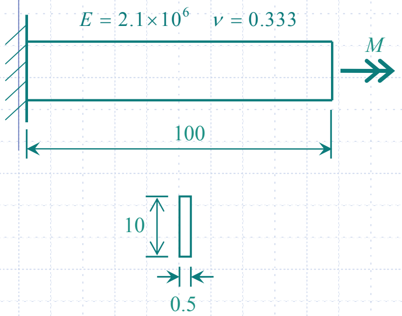
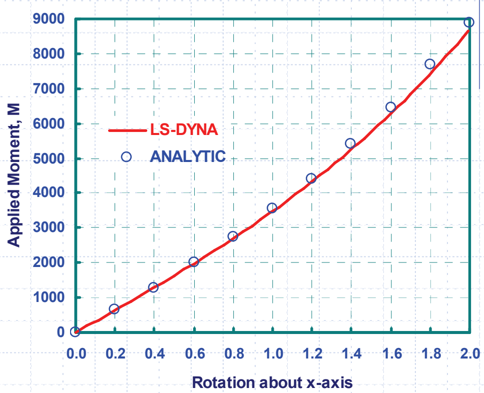
Warped beam

1. Non-linear Torsion (Goyet)





# of Elements	Explicit Elapsed Time	Implicit Elapsed Time
20	121 seconds	2 seconds

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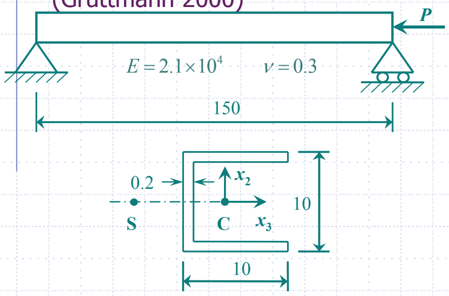
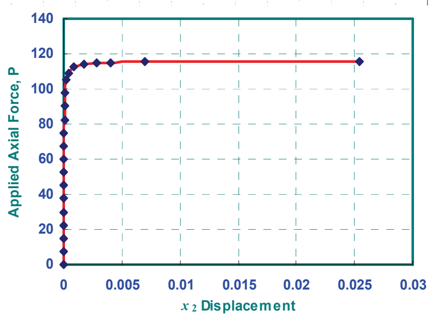
Warped beam

- 2. Lateral Torsional Buckling (Gruttmann 2000)





Buckling is initialized by a small tip torque $10^{-5}P$

Lateral Torsional Buckling Load		Flexural Buckling Load (For Comparison)	Pure Torsional Buckling Load (For Comparison)
LS-DYNA	Theory		
115.50	115.54	594.06	125.1

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*Section_shell

- The shell thickness offset, which is specified by NLOC in the user's manual, now applies to all shell elements, not just the Hughes-Liu element.
- NLOC.EQ. 1.0: top surface,
- NLOC.EQ. 0.0: mid-surface (default),
- NLOC.EQ.-1.0: bottom surface.
- Note that values of NLOC <-1 and >+1 are permissible. If NLOC is defined, the mid-surface is offset along the shell's normal vector an amount given by:

$$-0.50 \times NLOC \times (average\ shell\ thickness)$$

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*Element_shell_..._offset

- "Offset" option has been added for all shell elements.
- The offset is included when defining the connectivity of the shell element
- The mid-surface is projected along its normal vector
  - Offsets greater than the shell thickness are permitted
  - Overrides the offset specified in the *SECTION_SHELL input
- Nodal inertia is modified to account of the offset and provide a stable time step of explicit computations
- Explicit and implicit implementation
- Offsets will be considered in contact in near future

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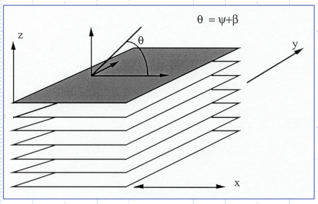
*Integration_shell

- Material types can change from integration point to integration point through the shell thickness.
  - Mix orthotropic, elastic-plastic, and viscoelastic materials
  - New input option to control failure when material types are mixed
    - EQ.0: Element is deleted when the layers which include failure, fail.
    - EQ.1: Element failure cannot occur since some layers do not have a failure option.



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*Integration_shell

- Contact stiffness is now based on a weighted average of through thickness values
- Time step size is based on a weighted average of though thickness sound speeds

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Nonlinear shell element with thickness stretch

- Belytschko-Tsay, type 2, and the assumed strain, fully integrated, type 16, shell elements has been extended to account for a linear strain through the thickness
  - Now implemented and available in version 971, but LSTC will not recommend their application to production problems
- An 8-parameter theory accounts for thickness changes leading to a 32 DOF shell
  - Nodal connectivity uses 4 nodes and 4 scalar nodes where each scalar node has 2 DOF
    - Scalar nodes can be user defined or generated automatically
- Full 3D constitutive routines employed – not necessarily zero stress through thickness. Constitutive models for solid elements are used.
- Obvious applications are in manufacturing simulations, not crash

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Nonlinear shell element with thickness stretch

- Surface loading is better captured – more accurate solutions as thinning is not predicted solely from membrane straining but also from the normal tractions
- Responds to double sided contact situations, for instance in the situation with a sheet squeezed between dies in metal forming applications
- May be useful for predicting delamination in composite materials since a meaningful normal stress is available for the failure calculations.
  - 3D composite subroutines will need to be recoded if they are used by both solids and shells.
- There are obvious applications in crash analysis, but much additional development will be required
  - Spotweld constraints will need to consider the normal degrees of freedom
  - Automatic contact subroutines used for crash must provide nodal normal forces for thickness updates
  - Intersecting shells are permitted
- Possible that 971 may allow use of thickness updated shell for crash

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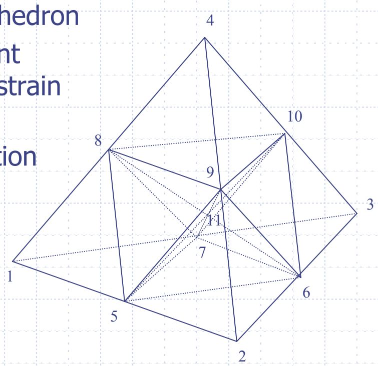
Composite tetrahedron

- Based on Belytschko-Guo unpublished paper (1997)
- Ten-node tetrahedron divided into 12 sub-tetrahedrons
- Linear displacement in sub-tetrahedron
- Assumed linear strain, or constant volumetric and linear deviatoric strain over entire tetrahedron
- Implicit and explicit implementation
- SMP-MPP
- Speed ~ fully integrated solid



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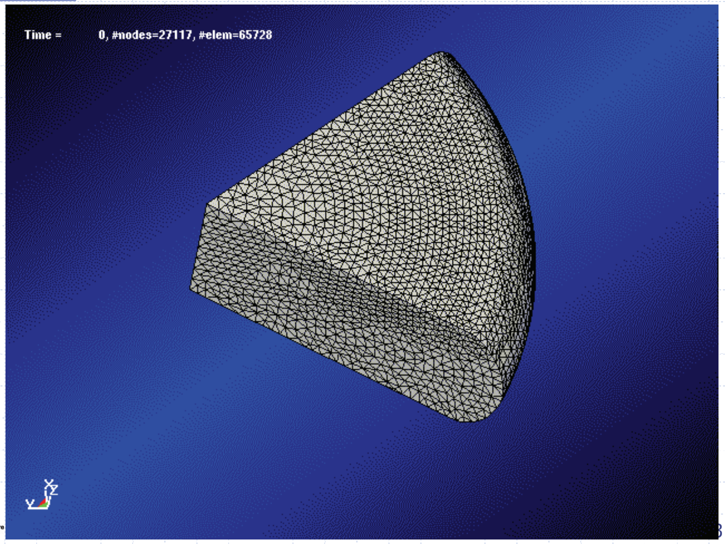
Type 13 tetrahedron now works implicitly



Cohesive elements

- Used to predict interface failure.
  - Glued surfaces
- Two new constitutive models are available
  - *MAT_COHESIVE_ELASTIC
  - *MAT_COHESIVE_TH
    - Tvergaard and Hutchinson theory
- User subroutine is also available
- Solid element type 19 for connecting solid elements and type 20 for connecting shells at their mid-sufaces
  - Type 20 transmits moments, 19 does not
  - Four planar integration points
  - Hexahedron shape

64

Seatbelt shell element

- Seatbelt shell elements can now be used in place of 2-node belt elements.
  - Provides a better distribution of forces to dummy
  - It is an extension of existing capabilities
- Combines fabric quadrilateral membrane element with belt elements capabilities such as sliprings and retractors.
- Needs a logically regular mesh

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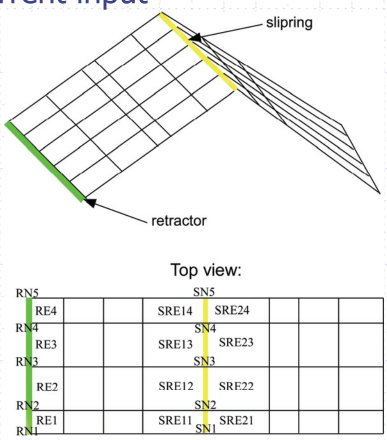
Seatbelt shell element

Definition of slipring and retractor is simple extension of current input



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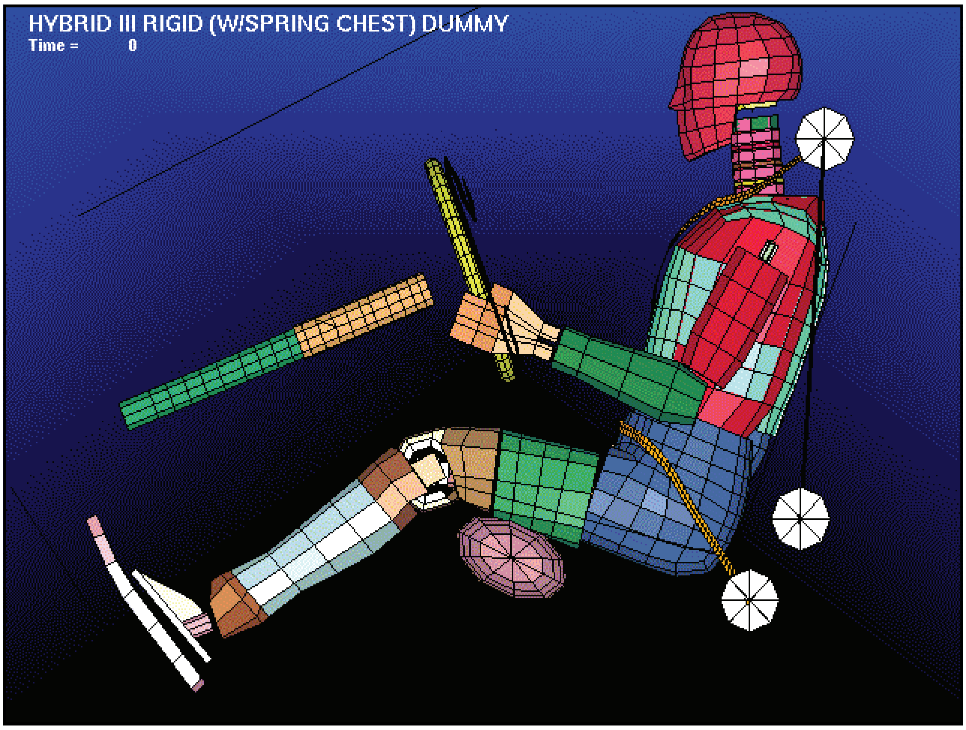

*Element_direct_matrix_input

- Option for reading and using superelements
  - Explicit or Implicit
  - Allows multiple superelements connecting into the LS-DYNA model at overlapping attachment nodes.
    - Note: in version 970 overlapping attachment nodes are not allowed.
  - Demonstrated in a vehicle driving simulation with superelements for body and frame and detailed modeling of tires and suspension system.
  - MPP explicit implementation is working in version 971

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User defined element interface

- User defined element interface is now implemented that works for both implicit and explicit elements
  - Simple to use. For integrated elements the user only supplies the
    - Gradient-displacement matrix
    - Jacobian matrix
  - LS-DYNA computes the stiffness matrix
  - LS-DYNA constitutive models may be used
  - Arbitrary numbr of degrees-of-freedom can be used per node to accommodate more complicated theories
- Implemented for solid and shell elements
- Example implementations include a constant stress solid, the Belytschko-Tsay shell, and the Hughes-Liu shell
- User elements are types 101-105

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User defined equations-of-state

- Permits 10 additional EOS, EOS 21-30 inclusive.
- Similar in implementation to user defined materials.
  - Scalar (ueosXXs) or vectorized (ueosXXv) implementation.
  - Permits history variables.
  - Up to 48 EOS constants.
- Can be called by user defined material models.

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Recent developments for ALE, and EFG

71

OOP capabilities

- Modeling out-of-position occupants requires the ability to compute the early time evolution of the airbag deployment before the uniform pressure, control volume, approach is valid. An approach using Arbitrary Lagrangian Eulerian techniques, ALE, is used in LS-DYNA.

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OOP capabilities

- Gas mixture
- Moving point sources
- Automatic expansion of the ALE mesh
- Moving ALE mesh with vehicle
- Robust contact algorithm for mulit-layer airbags
- Fabric porosity for ALE
- Discrete venting for ALE
- Blockage considered for porosity and venting
- ALE supported in Serial, SMP, and MPP

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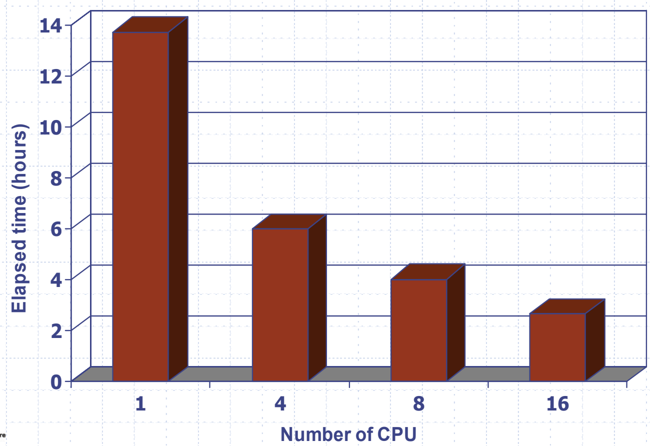
MPI scalability for ALE model



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*AIRBAG_ALE

- In current 970 release
  - Simplified input
  - Smooth transition from control volume to ale for users currently using control volume method
  - Options
    - Run control volume only
    - Run ALE only
    - Start with ALE and switch to control volume

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*AIRBAG_ALE

- Fabric porosity in ALE and CV phase
- Venting in ALE and CV phase
- Blockage considered for porosity and vents during ALE and CV phase
- ALE mesh movement with vehicle
- ALE mesh automatic expansion for folded airbags

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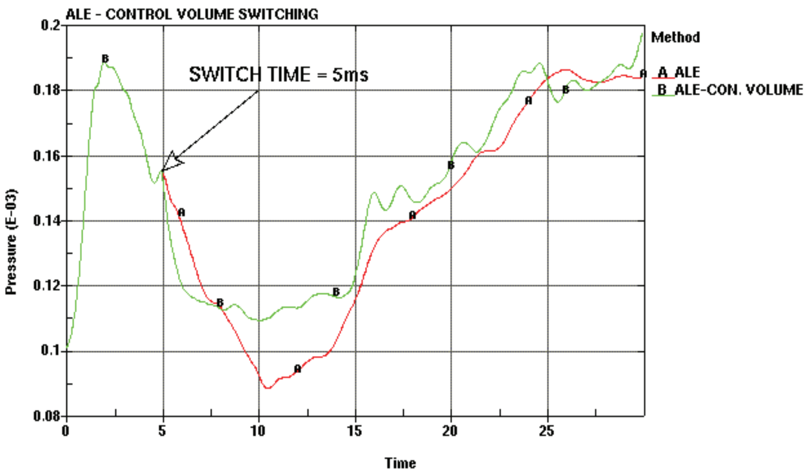
ALE-control volume switching



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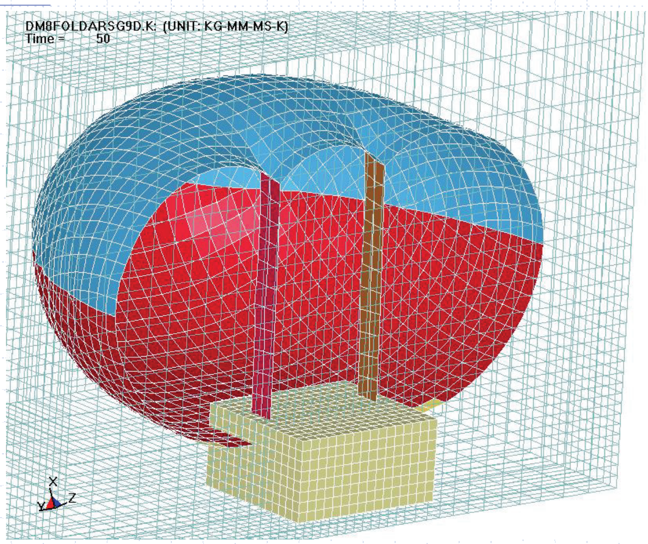
ALE fixed mesh for inflator



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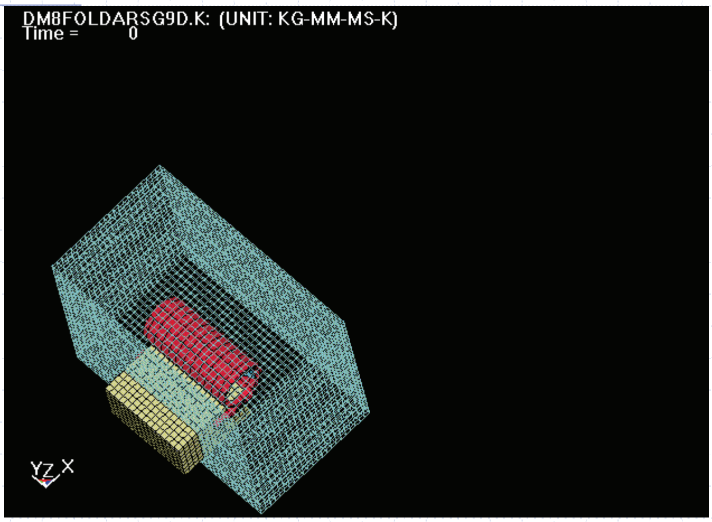
ALE rotation



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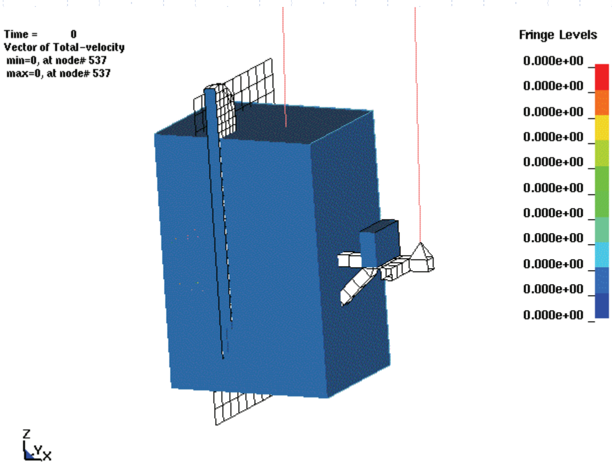
ALE-pendulum test validation



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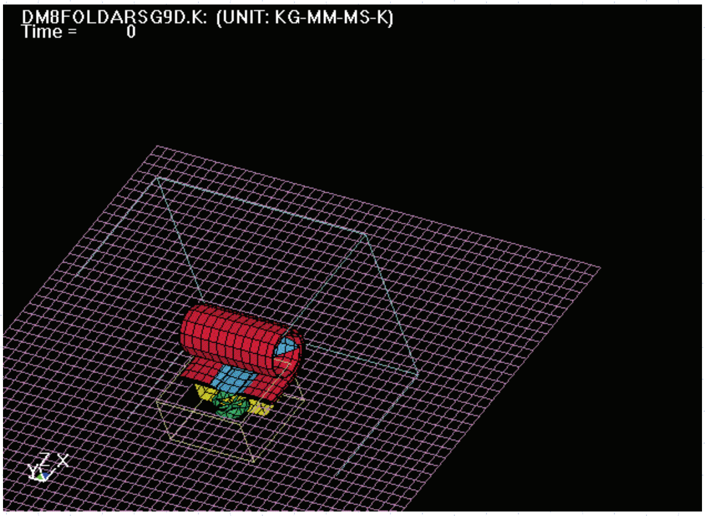
ALE physical venting



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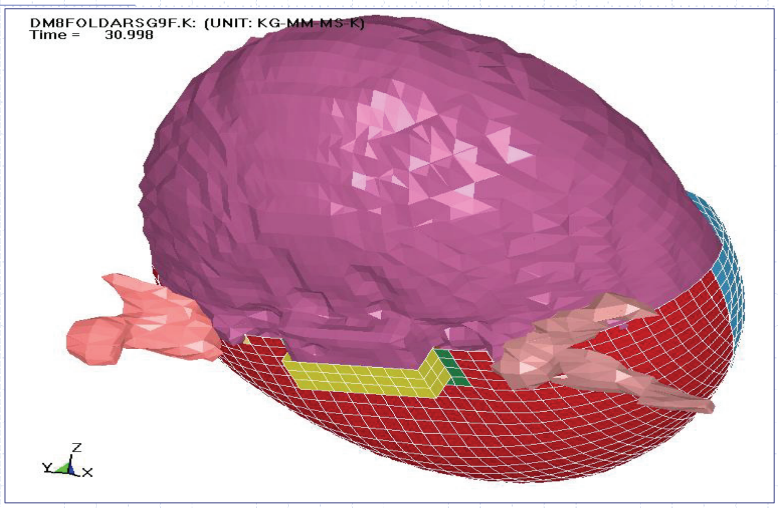
ALE part ID switching for venting gas



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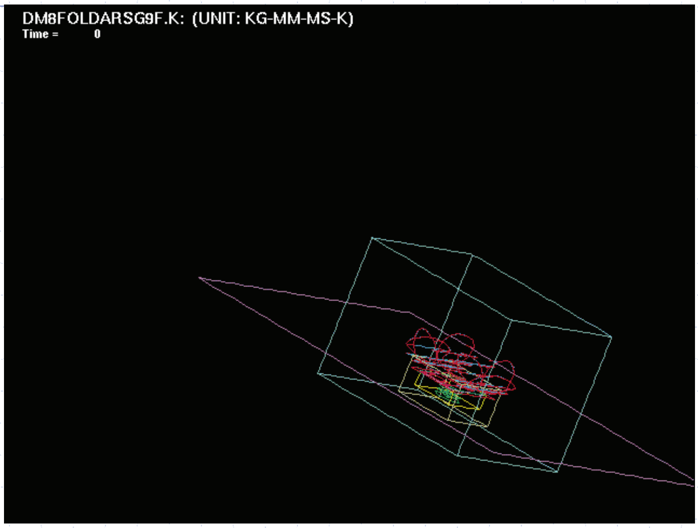
ALE part ID switching for venting gas



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Mesh-free developments

- Reaching production level in version 971
- Scalable MPI implementation in 971
- Main applications:
  - Barrier crushable foams
  - Dummy foam materials
  - Seat foams
- Advantages:
  - Improved stability with fewer problems with negative volumes
  - No hourglass energy dissipation

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Current LS-DYNA EFG formulations

EFG Basics

1. Smoother stress and strain
2. Less sensitive to the discretization
3. No hourglass control
4. Higher resolution
5. Higher CPU
6. More memory
7. More difficult in theory
8. More developments and refinements on theory are required

- Solid (ls970 &ls971)

  EFG Plane strain #43
  EFG Axisymmetric #44
  EFG 3D solid #41
  (including 4/6/8-node elements)

  - Rubber industry
  - Highly compressible foam
  - Dummy
  - Forging simulation

- Shell (ls971)

  EFG shell #41
  EFG shell #42
  (including 3/4-node elements)

  - Metal Forming
  - Crashworthiness

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Coupled fem/mesh-free

A is the transformation matrix between the general (EFG) and nodal (FEM) displacements

$$\mathbf{d}_{\text{FEM}} = \mathbf{A}\mathbf{d}_{\text{EFG}}$$

$$\mathbf{M}_{\text{FEM}} = \mathbf{A}^{-T}\mathbf{M}_{\text{EFG}}\mathbf{A}^{-1}, \quad \mathbf{K}_{\text{FEM}} = \mathbf{A}^{-T}\mathbf{K}_{\text{EFG}}\mathbf{A}^{-1}, \quad \mathbf{R}_{\text{FEM}} = \mathbf{A}^{-T}\mathbf{R}_{\text{EFG}}$$

$$\mathbf{d}_{\text{EFG}} = \mathbf{A}^{-1}\mathbf{d}_{\text{FEM}}$$

The fast transformation method eliminates **A**!

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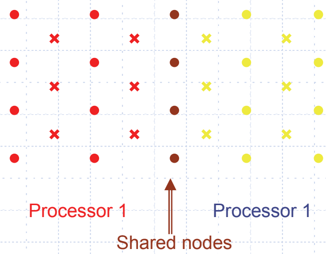
Parallel mesh-free

- SMP
  - Scalability depends on the efficiency of the matrix multiplication with the transformation matrix
- MPP
  - Parallel assembly and factorization of A required. Parallel triangular solves may affect scaling-should be in core for efficiency
  - More communication in an EFG region among processors
    - ✓ More neighbors involve in nodal force computation
    - ✓ Another set of neighbors in transformation



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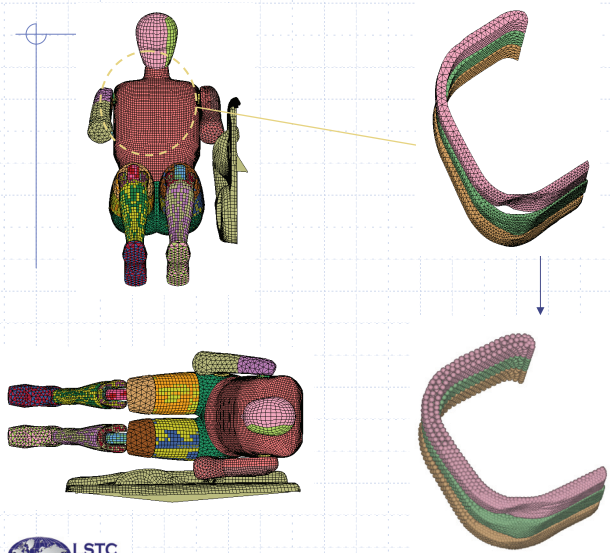
Dummy with Side Impact



Three EFG Foam Ribs
Total 7698 EFG nodes
(4-node background element)

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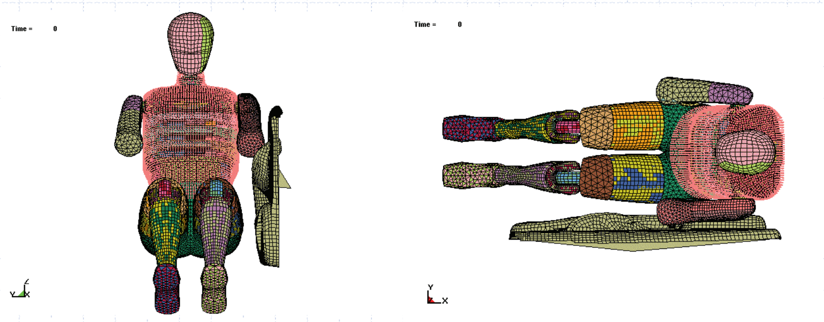
Dummy with Side Impact



FEM/EFG (AVI)

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IMPLICIT
Serial and MPP

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Implicit development

- Implicit analyses require that a stiffness matrix be assembled and factorized
- Implicit is fully integrated in the explicit solver and shares elements, contact, constraints, etc.
- Implicit must perform well in the MPP environment

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Parallel implicit is more difficult than parallel explicit

- Explicit analysis does not require the following operations, which are very difficult to parallelize and load balance:
  - Finite element matrix assembly
  - Constraint matrix generation
  - Generation of the reduced equation set
  - Second domain decomposition for sparse solver
  - Factorization, both in and out-of-core
  - Triangular solves both in and out-of-core

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Implicit development

- LSTC's MPP linear sparse solver, DMF, is giving good scalability
- The BCSLIB-EXT eigensolver is now extended to use the DMF linear solver and is operational under MPI
- LCPACK constraint package is working in parallel
- Heat transfer is working in parallel with a parallel CG solver
- Many automotive specific options are already implemented for implicit solutions, e.g., spot welds, foam materials, etc.
- An AMG iterative solver is under development --- possibly for later 971 releases

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Implicit development

- Most features used in crash analysis are implemented for static initialization and springback of vehicle models
- Seatbelts
  - Nearly completed
- Airbags
  - Fabric material forms 0 and 1 are implemented
  - Inflator models 3, 5, 10, and 11 are implemented
- Airbag contact
  - Soft=2 option is critical
- Additional QA problem are being developed to ensure that MPP implicit works at least as well as SMP implicit

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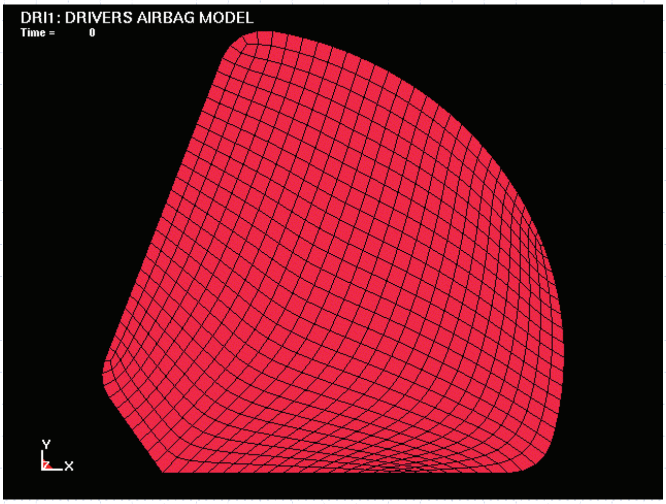
Implicit airbags



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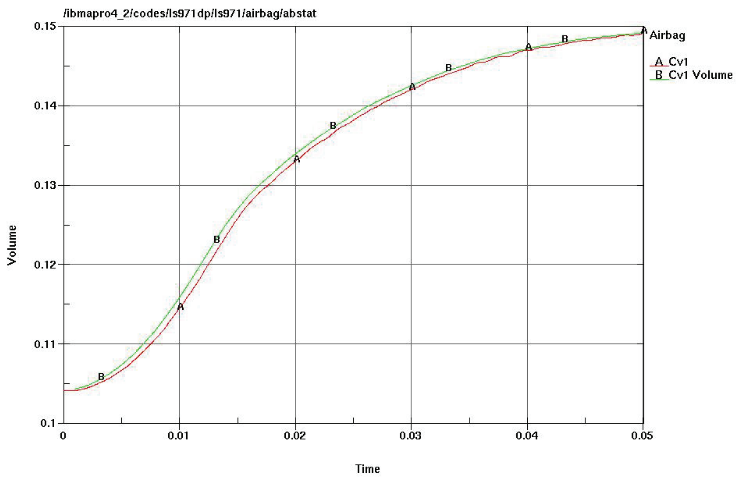
Implicit airbags



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MPP Eigensolver

(Preliminary Results-April 2004)

- CPU times for problem with 390K rows and 10 modes (from car model)

# Proc	Time
1	509
2	319
4	190
8	123

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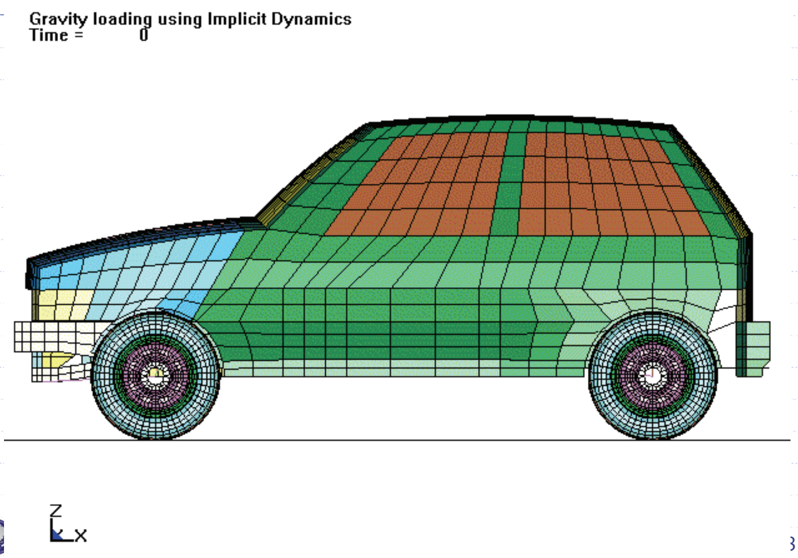
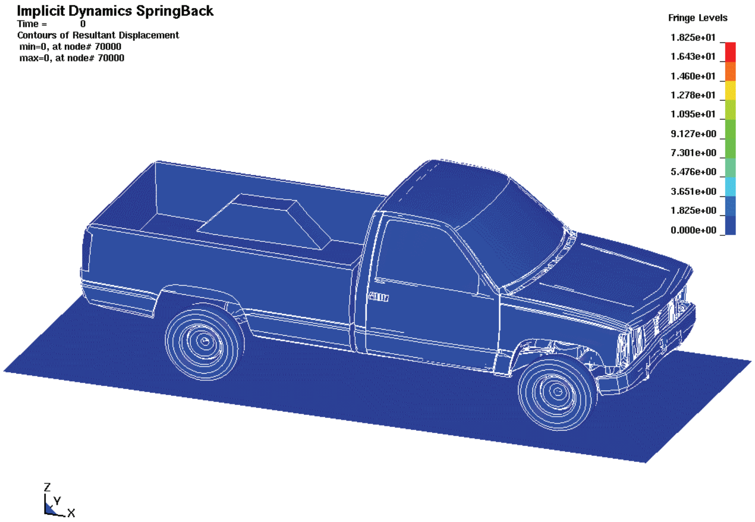
Gravity loading



Deformation after crash



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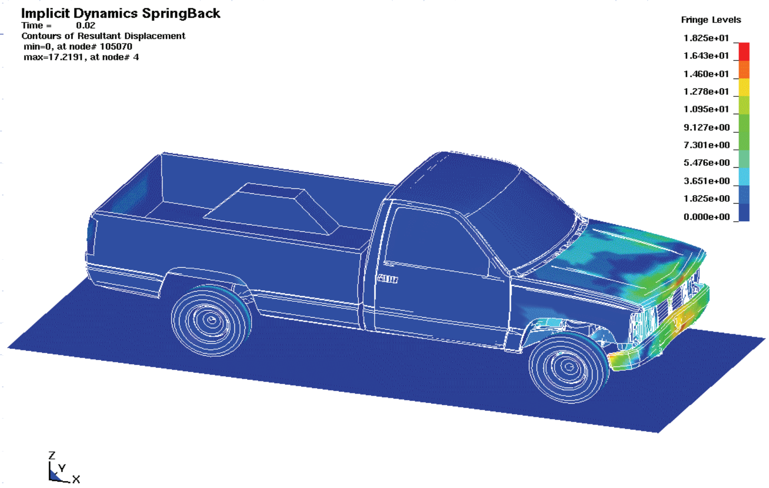
Spring-back using implicit dynamics



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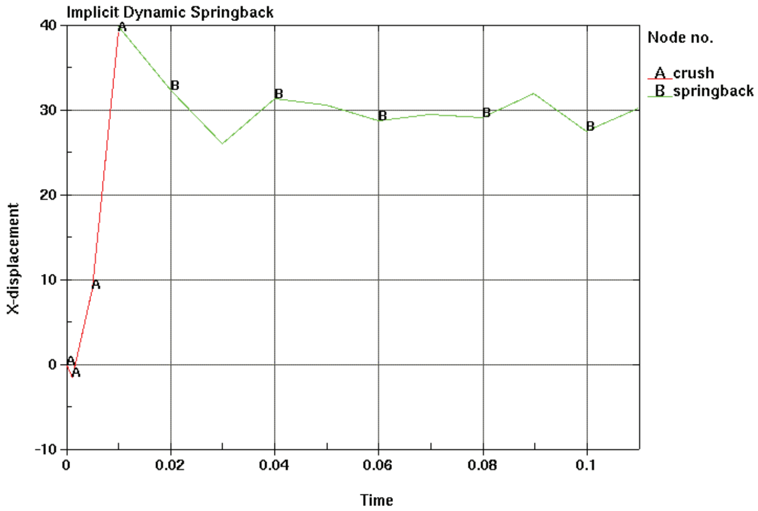
Implicit springback



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Development goals LS-PrePost

- Provide Pre- and Post-processing for LS-DYNA
  - Full LS-DYNA 970/971 keyword support
    - All LS-DYNA keywords can be read, modified and output
    - Keyword data modified by form with field name definitions and descriptions shown interactively
  - Extensive model manipulation features
    - Mesh generation including Tool Mesher for Metal stamping and Topology Mesher for crash and other applications
    - Mesh quality check and repair
    - LS-DYNA data creation, setup and display
    - Multiple models can be merged into a single model
    - Project file save/load for model editing

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Development goals LS-PrePost

- Full post-processing support for all LS-DYNA analyses
    - State results animation
    - Fringe component plots
    - ALE fluid data processing and visualization
    - Extensive model visualization and time history plotting
    - History data manipulation using command file without graphics
    - Use command macro for repeated operations
    - Save DB file with partial model, and selected states
    - Chaining multiple models (forming, trimming, springback) into single sequence

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Development goals LS-PrePost

- Special applications
    - Metal forming process setup and post-processing
    - Airbag folding with mesh generation
    - Occupant positioning
    - Seatbelt fitting and pre-tensioning
    - 201 Head impact positioning and data setup
    - IIHS intrusion computation
- No extra cost with LS-DYNA
- Can be downloaded from
    - ftp://ftp.lstc.com/outgoing/lsprepost2/
    - No license keys required

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Current and Future Developments LS-PrePost

- Use industrial standard GUI interface for both Windows and Unix/Linux (WxWidget)
- Multi-Physics solver post-processing support
- 64-Bit support for very large dataset
- Very large model rendering using parallel processing
- 3D solid meshing using index space mapping
- User defined interface Builder
  - Allows user to group LS-Prepost commands together into a simplified interface
  - Allow user to build their own applications

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Future versions of 971

- Improved robustness and speed of nonlinear implicit options
- Faster ALE for airbag deployment
- User requested options that are considered urgent
- 8 parameter shells for crash analysis
- Improved scalability to 1000+ processors
  - Most crash job today use 8, 12,24, or 32 processors.
  - In the near future we expect 64 to 128 to be typical as models approach 10 million elements (2mm elements)
  - Scaling improvements will be achieved by improved modeling techniques, better algorithms, and hardware communication speeds

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IBM BlueGene/L computer

- 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 crash 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

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Cray XD1 with RapidArray interconnects AMD Dual Core Opteron 2.2 GHz

3 Car crash simulation run to completion (750K nodes) timings posted on *www.topcrunch.org*

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

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Version 980

- Version 980 introduces four new packages and significant enhancements to the incompressible flow solver
  - LSPLOT is a new highly flexible output database that allows for unlimited flexibility
  - A new explicit compressible flow solver based upon the Conservation Element/Solution Element (CE/SE) Method
  - Solid-fluid heat flow coupling for the incompressible flow solver
  - Radiative heat transport through participating media, as well as using exchange factors Initially coupled to the incompressible flow solver
  - Electromagnetic solver
- A new code framework, including new meshes, has been created for these physics packages
  - Largest rewrite of LS-DYNA ever attempted.

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CE/SE method

- CE/SE Method:
  - CS/SE ----- Conservation Element and Solution Element
  - Originally proposed by Dr. Chang (NASA GRC, 1991)
  - Explicit Eulerian MPP solver
  - Some non-traditional features:
    - ***Space-time*** conservation (locally & globally)
    - Accurate
    - Novel & simple shock-capturing strategy
  - Some of the applications
    - High-speed compressible flows (with complex shock patterns)
    - Acoustics (resolve both strong shocks & acoustic waves)
    - Detonation
    - Cavitation

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CE/SE fluid-structure interactions

- Structure and fluid solvers
  - Structure ---- FEM
  - Fluid ---- CESE
- Interface boundary treatments for fluid
  - A variant of ghost-fluid method
  - Moving reflective BC (other boundary points)
- Test cases that work currently:
  - Rigid body / fluid interactions
  - Shell / fluid interactions

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Incompressible flow solver

- Incompressible flow solver active development projects:
  - Immersed Interface Method. This couples to explicit structural dynamics for viscous fluid-structure applications (shells and beams)
  - Coupling to participating medium radiative heat transfer solver
  - k-ε Reynolds-averaged Navier Stokes turbulence models coupled with the immersed interface method
- Future Incompressible flow solver:
  - Lagrangian
  - Naturally adapts to the flow
  - Multifluid

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LS-DYNA electromagnetism

- Introduction of electrical currents in solid conductors.
- These currents generate magnetic fields, electric fields, as well as induced currents.
- The magnetic fields coupled with the currents generate Lorentz forces on the conductors.
- The forces induce motion and deformation of the conductors.
- This motion has an effect on the fields and the currents.
- The currents generate Joule heating in the conductors, changing the temperature, and thus some mechanical as well as electromagnetic properties (conductivity for example).

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Development Progress

- A Finite Element Method (FEM) is used to solve the electromagnetism (EM) equations in the solid conductors.
- The FEM is implemented on solid hexahedral elements at this time, soon on tetrahedra and wedges.
- A Boundary Element Method (BEM) is used to solve the EM equations in the air (no air mesh needed).
- The user can choose between:
  - 1- a full coupling between the FEM (solid) and the BEM (air) to completely solve the problem.
  - 2- a BEM only, approximate solution, where approximations are made on the diffusion of the magnetic fields in the conductors.
- The solution of type 2 will be introduced on shells in the next few months.
- Both solutions 1 and 2 are fully coupled with the mechanics
- Solution 1 is coupled with the thermal solver (solution 2 soon)

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Development Progress

- Some EOS can be introduced for the conductivity vs temperature (at this time, Burgess model).
- The electromagnetism related fields can be plotted using LS-PREPOST :
  - Current density
  - Magnetic field
  - Electric field
  - Lorentz force
  - Vector potential
  - Joule heating power
- All these development are in serial (no parallelization yet).

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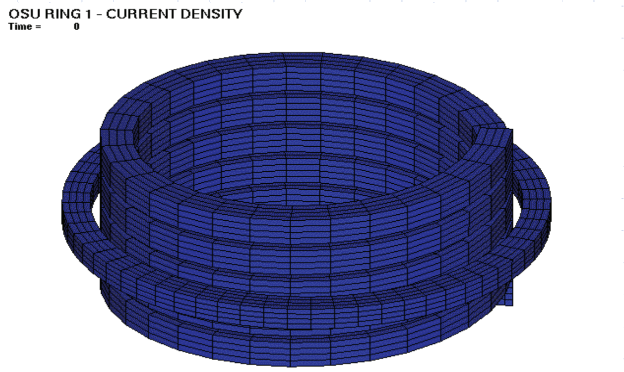
Ring expansion (based on OSU experiments)

A copper coil induces a current in an aluminum ring, and the EM forces drive the expansion of the ring.



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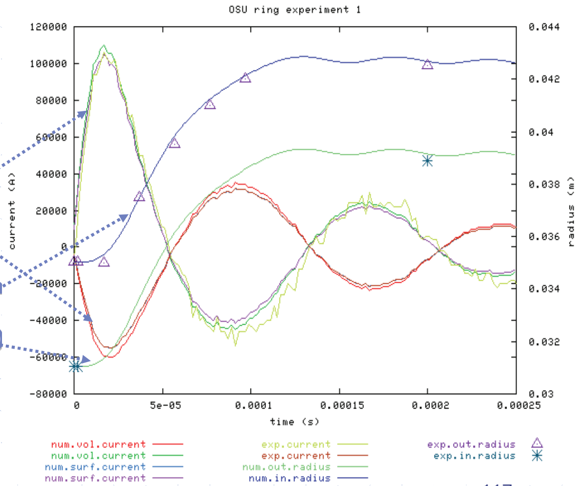
Ring expansion

Comparisons experimental/numerical: induced current, ring radius vs time

- ring current (exp and num)
- coil current (exp and num)
- ring out radius (exp and num)
- ring in radius (exp and num)



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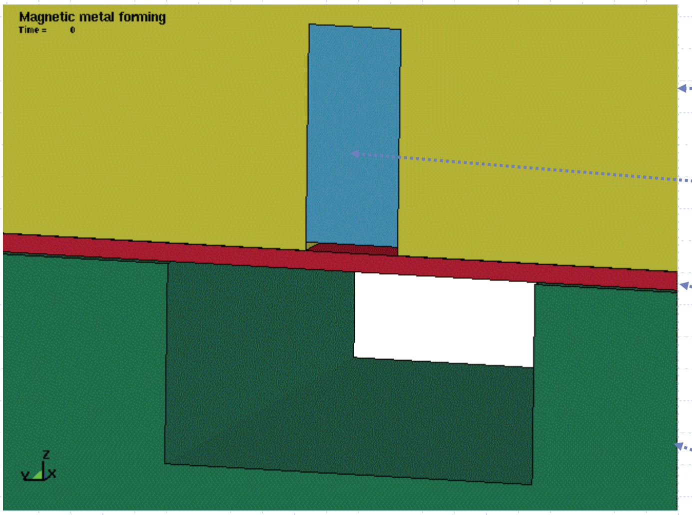
Magnetic Metal Forming



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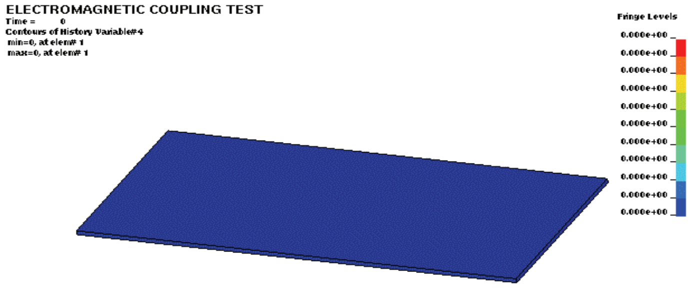
Magnetic Metal Forming

Current density in the workpiece



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Conclusions

- Version 971 has become a major release with many new capabilities that focus on the automotive industry
  - MPP implicit
  - ALE is at production level for out-of-position occupant analysis
  - EFG is implemented for scalable MPP applications
- Significant progress has been made to include most crash capabilities within the implicit solver
- LSTC's software development goal continues to be the implementation within one scalable code of all capabilities required to solve problems that involve, multi-physics, requiring multiple-stages, running on large clusters of processors.
- Nearing full compatibility with structure models used in MSC/NASTRAN

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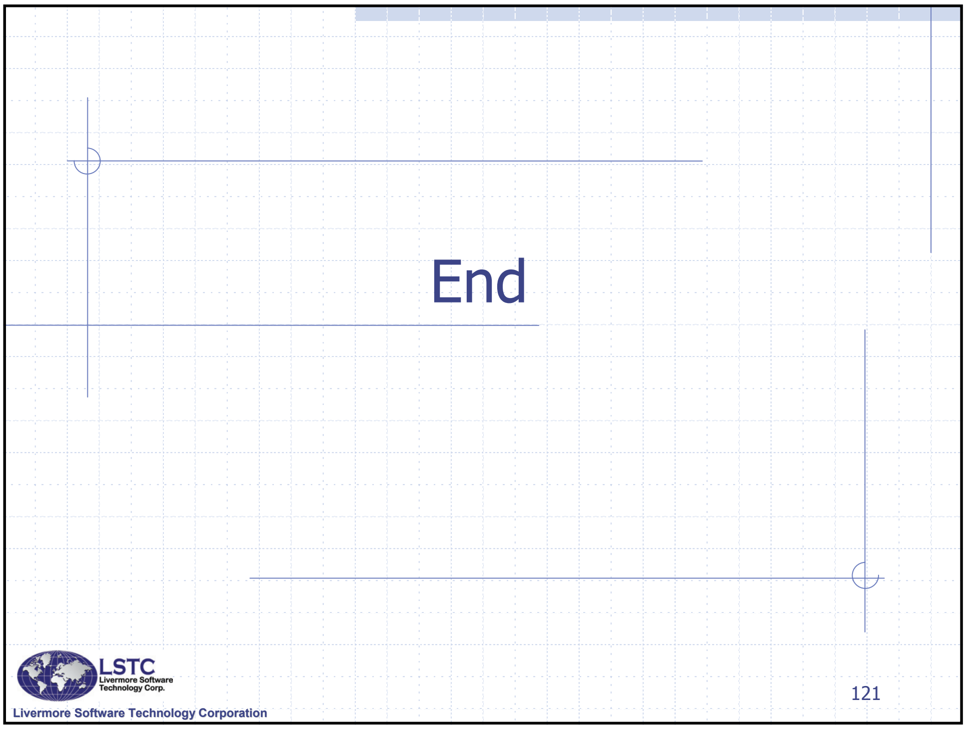
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