Recent developments in LS-DYNA®

German LS-DYNA Forum
10/13/2011

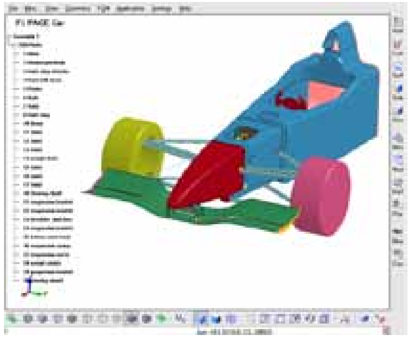
Presented by
John O. Hallquist

LSTC
Livermore Software
Technology Corp.

Outline of talk

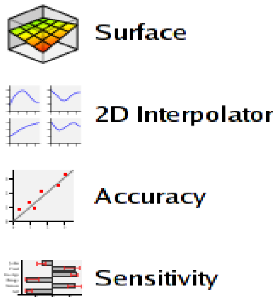
- Introduction
  - Version 980
- Current Developments
  - LSTC dummy/barrier
  - Implicit update
  - Frequency domain
  - Isogeometric elements
  - LS-DYNA 971 R5 & R6
- Conclusions

LSTC Products



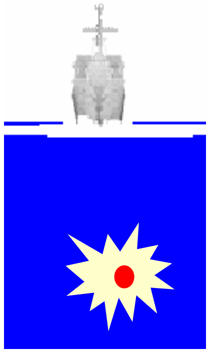
LS-PrePost

LS-DYNA



LS-OPT
LS-TaSC

DUMMIES & BARRIERS



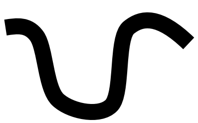
USA

No additional license cost

LS-DYNA Applications

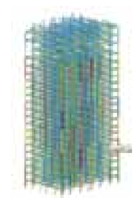
Automotive
- Crash and safety
- NVH
- Durability

Aerospace
- Bird strike
- Containment
- Crash



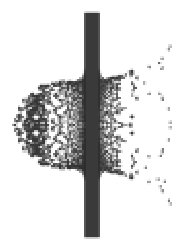
Manufacturing
- Stamping
- Forging

Consumer Products



Structural
- Earthquake safety
- Concrete structures
- Homeland security

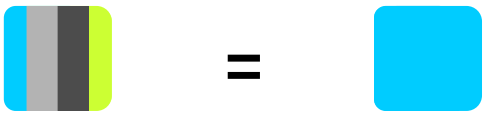
Electronics
- Drop analysis
- Package analysis
- Thermal



Defense
- Weapons design
- Blast response
- Penetration
- Underwater Shock Analysis

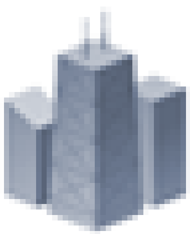
Development goals

- Reduce customer costs to encourage and enable massively parallel processing for large scale numerical simulations
- Approaches used by LSTC to help reduce costs

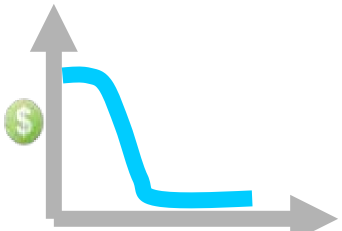


4 jobs/1 core = 1 job/4 core

Flexibility with 4 core license
1 job running 4 cores or 4 jobs running 1 core



Unlimited Site wide license



Steeply reduced license costs
As # of cores increase

- Expand analysis capabilities in all areas of physics to provide scalable, accurate, and robust solutions to the coupled multi-physics problems faced every day by development engineers worldwide

LS-DYNA

One code strategy

"Combine the multi-physics capabilities into one scalable code for solving highly nonlinear transient problems to enable the solution of coupled multi-physics and multi-stage problems"

Explicit/Implicit	✓		
Heat Transfer	✓	Incompressible Fluids	980
Mesh Free EFG,SPH,Airbag Particle	✓	CESE Compressible Fluid Solver	980
User Interface Elements, Materials, Loads	✓	Electromagnetism	980
Acoustics Frequency Response, Modal Methods	✓		
Discrete Element Method	✓		

Extensions in LS-DYNA 980

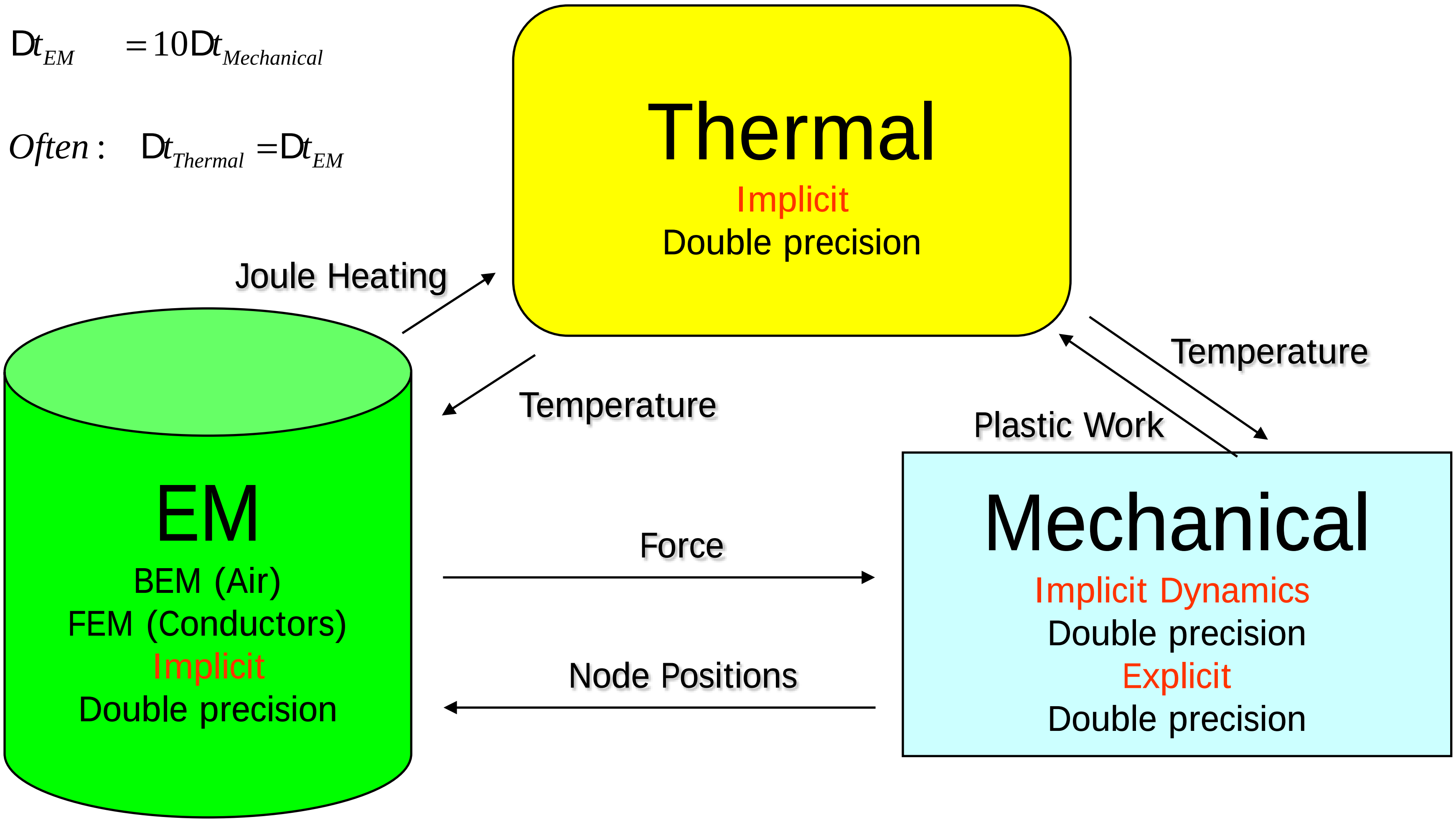
- EM solver involves an eddy-current approximation to the electromagnetics equations and couples to both the thermal and structural solvers.
- iCFD incompressible CFD solver handles low Mach number single and two-fluid flows; it also couples with both the structural and thermal solvers for FSI and conjugate heat transfer.
- CESE compressible CFD solver performs high-accuracy explicit space-time solutions to the Euler and Navier-Stokes equations, with coupling to a chemical reactions module and a stochastic particle capability for sprays and other applications. It also solves for FSI coupling.

Coupled mechanical/thermal/electromagnetic simulations

- Different solvers can be used in one model:

$$Dt_{EM} = 10Dt_{Mechanical}$$

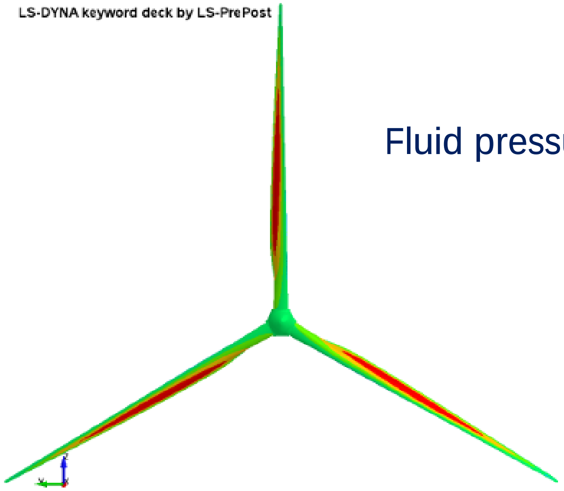
$$Often: \quad Dt_{Thermal} = Dt_{EM}$$



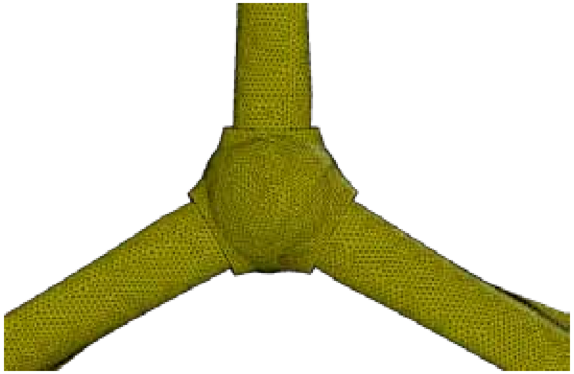
Incompressible CFD solver

Wind Turbine Simulation

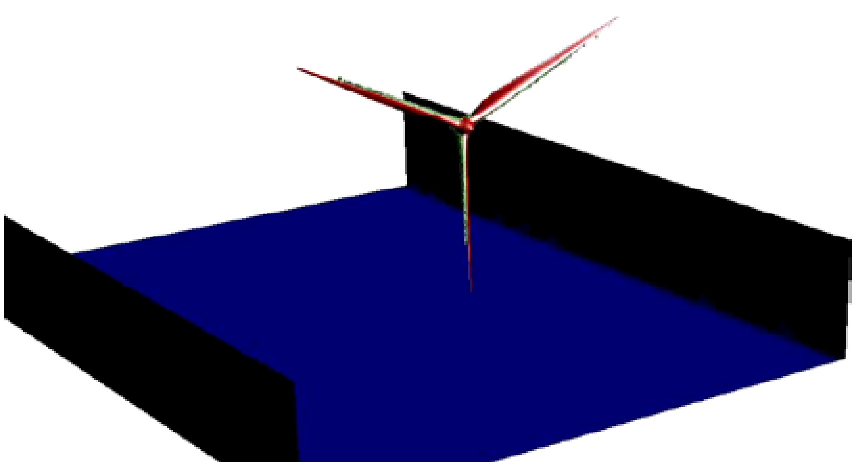
- Horizontal wind turbine.
- Blade span: 44.5m.
- Wind speed: 11.4 m/sec.
- Rotation speed: 1.26 rad/sec.
- Fluid mesh: 15.2M tet elements
- Solid mesh: 67.4K tri shells.
- Parallel run: 20 CPUs.



Fluid pressure field



Hub



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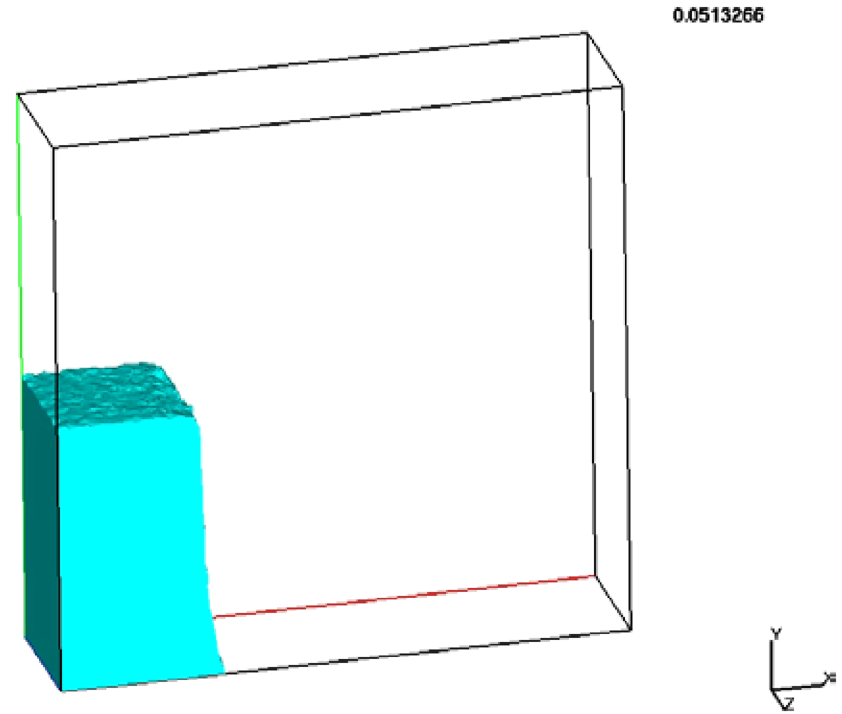
Incompressible CFD solver

Free Surface Simulation

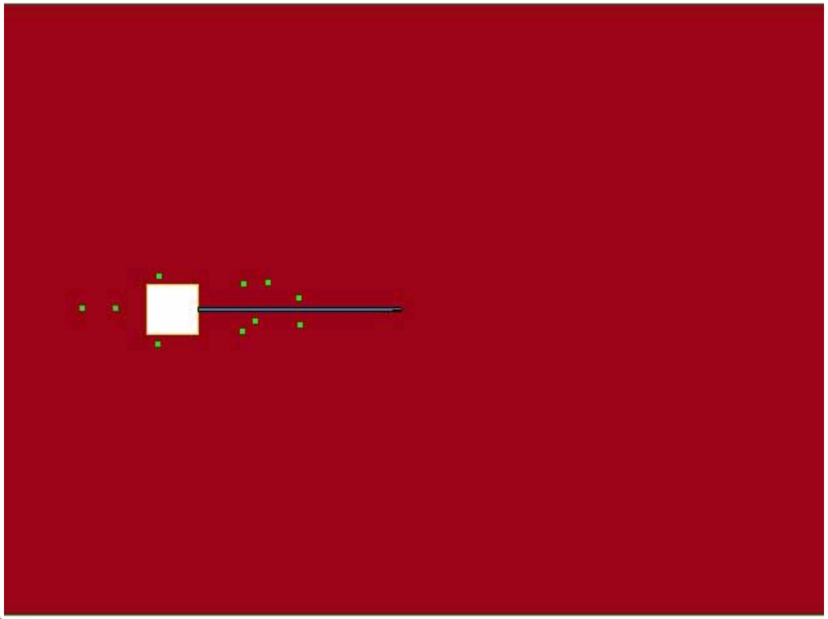
- The free surface is implemented using a Level Set.
- It allows the simulation of free surface flows using a single phase model.
- The Level Set allows large time steps with CFL=>1.



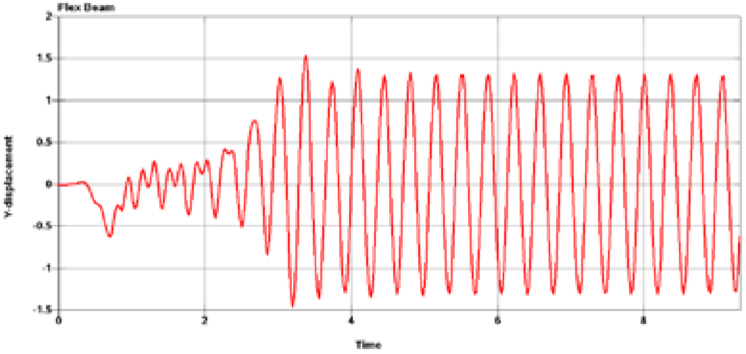
Incompressible CFD solver

Streamlines Visualization

- New feature in LSPP. Under the “Trace” button.
- It allows the user to easily identify fluid features.
- The example shows an FSI problem where the green dots are the source for the streamlines. The recirculation areas on the flag are shown.



Flag tip vertical displacement



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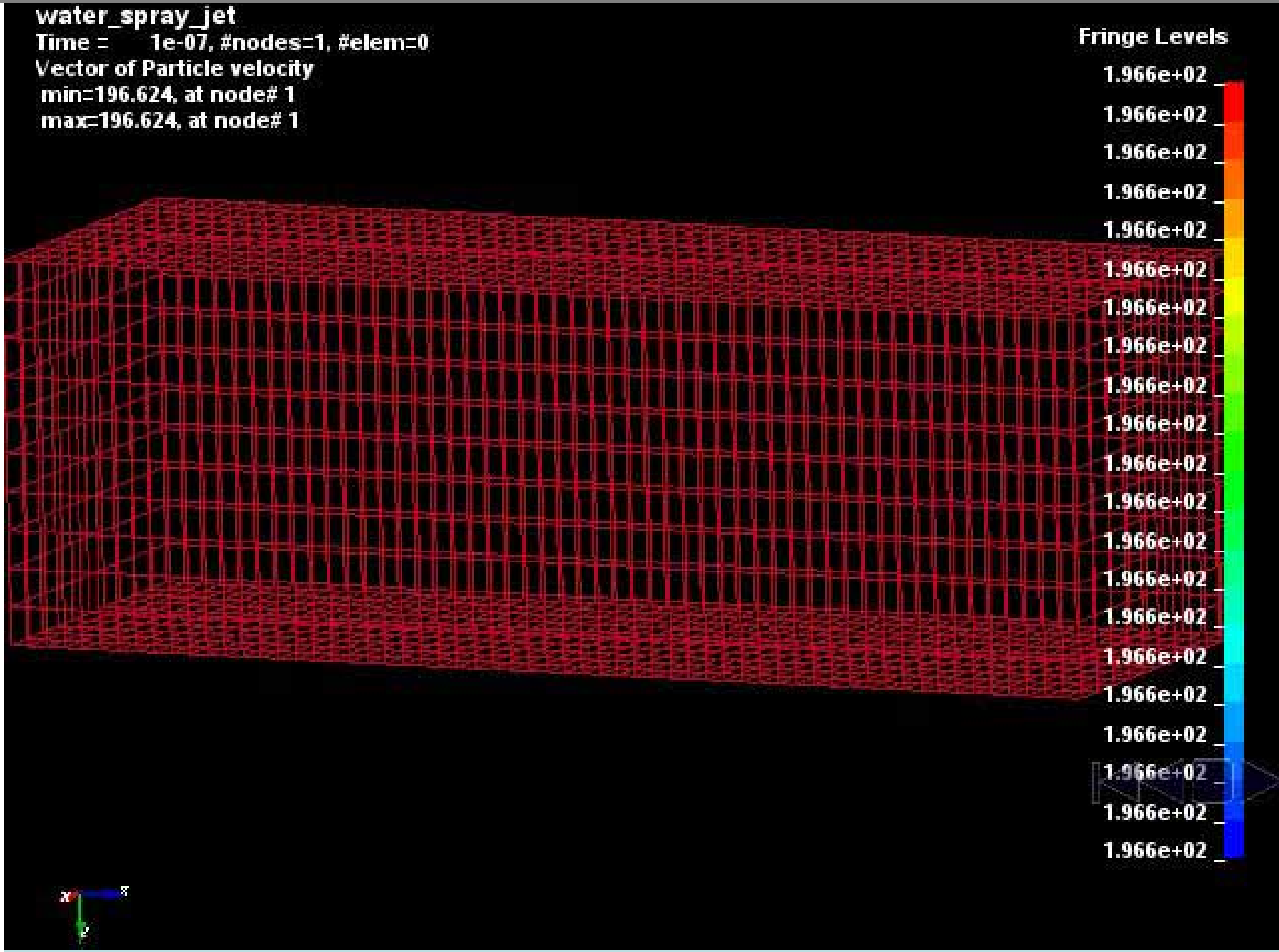
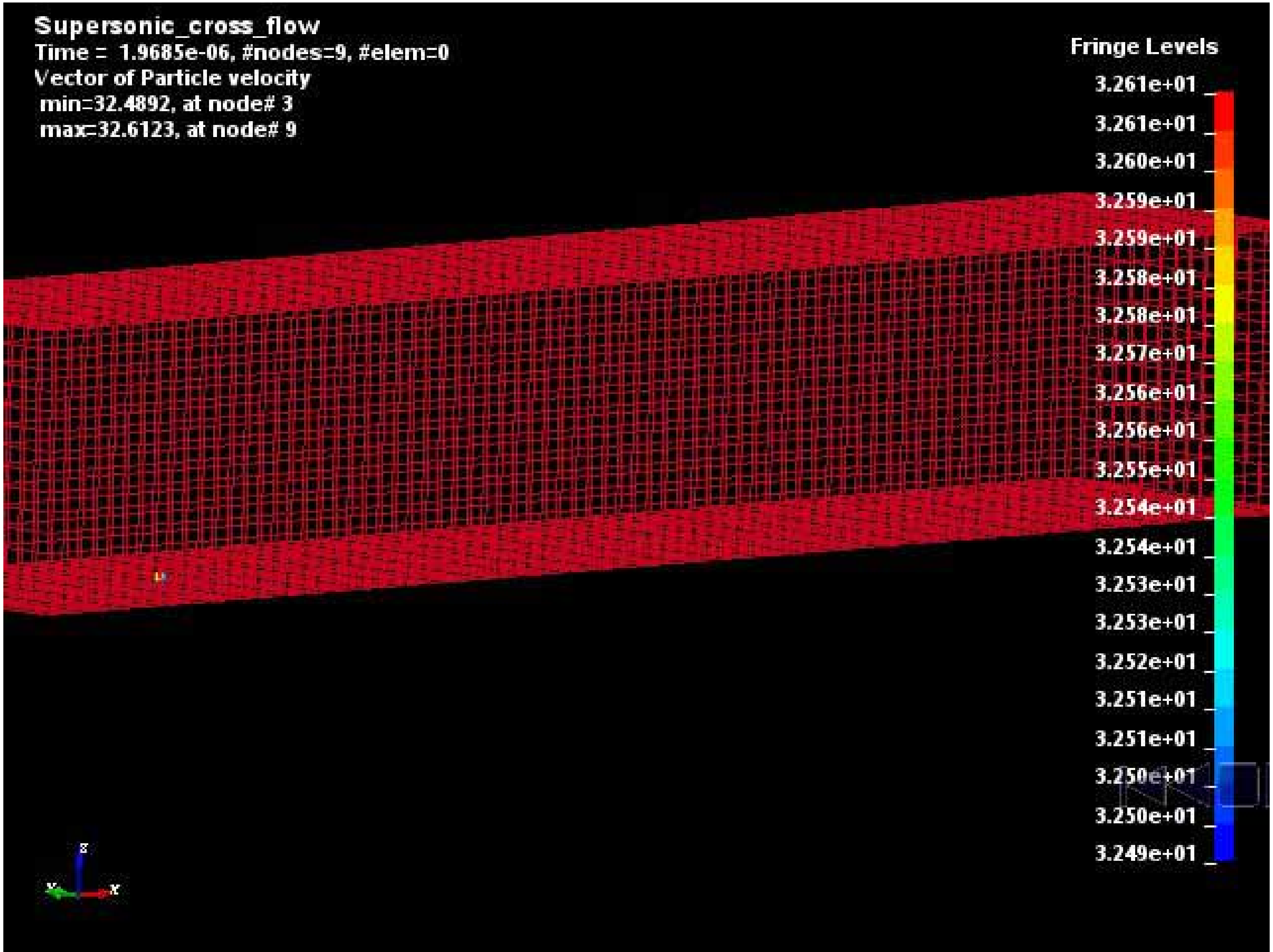
Compressible CFD solver



Water Spray Jet (coupled to CESE)

Compressible CFD solver

Spray Particles Injected into a Supersonic flow (CESE)



Dummies

Dummies & barriers

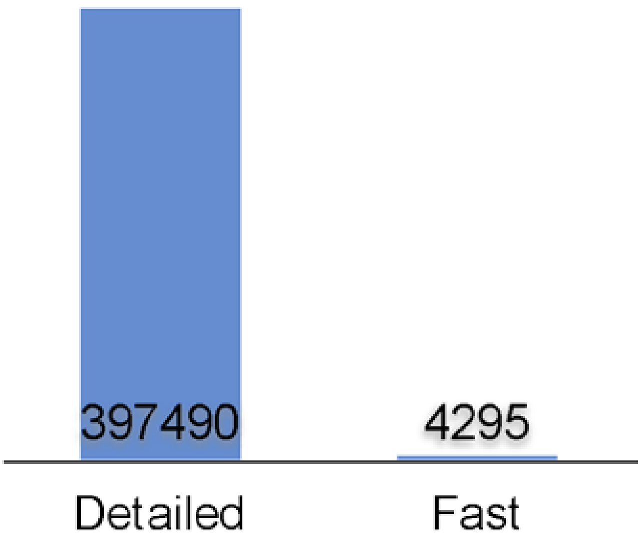
- For licensed LS-DYNA users
  - No separate licensing from LS-DYNA.
- Continuous updates and support from LSTC and distributors
- Companies may improve models and keep the improvements proprietary
- Companies may redistribute their improved models to their suppliers and subsidiaries for LS-DYNA simulations
- Dummy development partners include DYNAmore, NCAC, a major automotive supplier, and several OEM’s.

LSTC Hybrid III Adult Release Dates

	Fast	Standing 	Detailed 
5%	●		●
50%	●	●	●
95%	●		
			NCAC

● **Released**

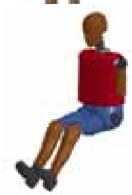
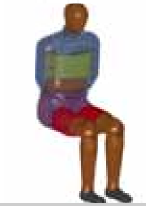
LSTC Hybrid III Adult Element Count



LSTC Hybrid III Child Models

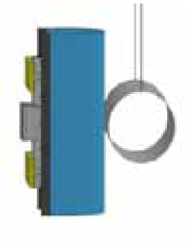
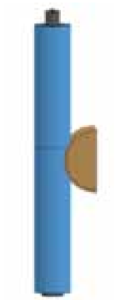
	Status	Next Steps	Release Date
3yr Old	Calibration tests	Calibration tests, Model clean-up, Documentation	November, 2011
6yr Old	Calibration tests	Calibration tests, Model clean-up, Documentation	October, 2011

LSTC Side Impact Dummies Release Dates

		Detailed	Fast	Status
	EuroSID 2	●	TBD	
	EuroSID 2re	●	TBD	
	SID IIs D	●	●	
	USSID	●		

● **Released**

LSTC LegForm and Headform

		Detailed	Released
	Upper Legform	✔	●
	Lower Legform	✔	●
	Headform	✔	●

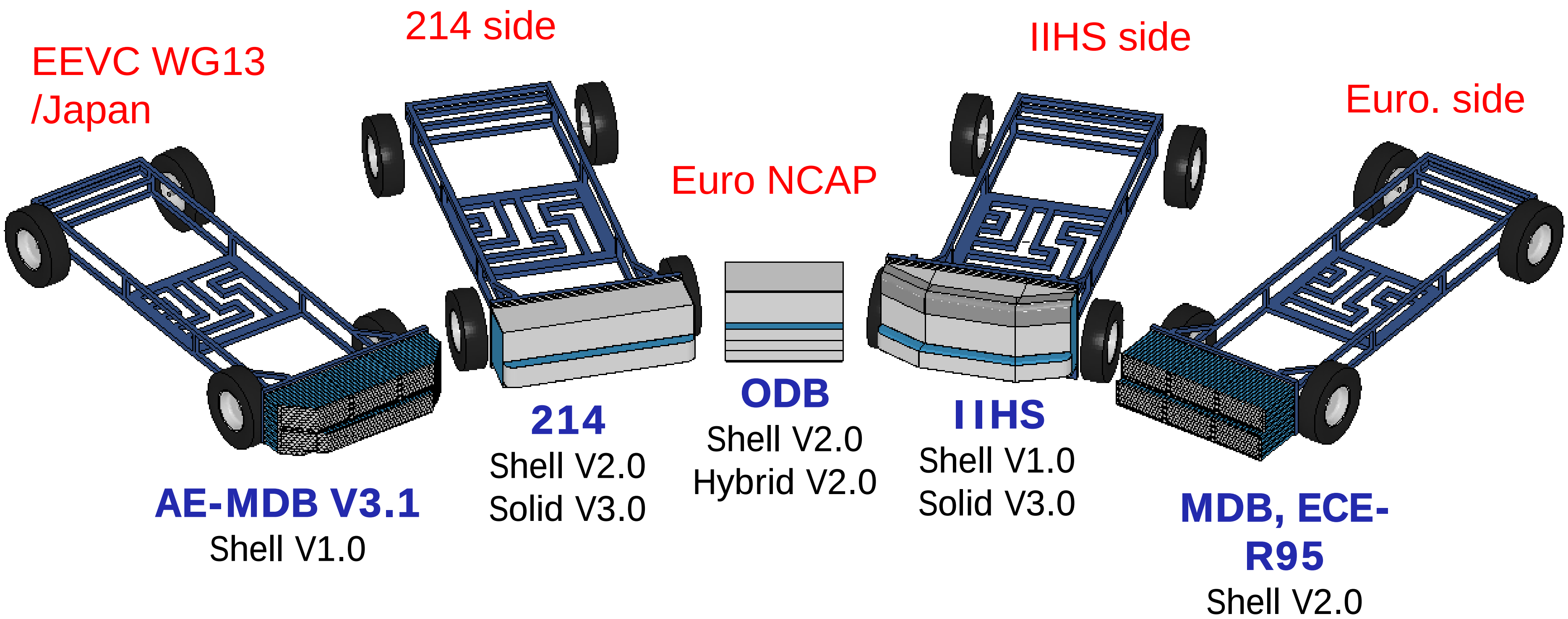
● **Released**

LSTC Upcoming. Models

	Partner	Detailed	Status	Release Date
World SID		✓	Model Assembly	Summer 2012
Bio RID	Dynamore	✓	Certification Testing	Dec, 2011
Q-series child dummies				TBD
Flex PLI Flexible Pedestrian Legform Impactor				TBD
THOR-NT		✓	Meshing	TBD

LSTC Barrier Models Update

LSTC family of barriers



Solid barriers were sponsored by Honda USA
Shell barriers were first pioneered by Toyota

Implicit Update

Implicit update

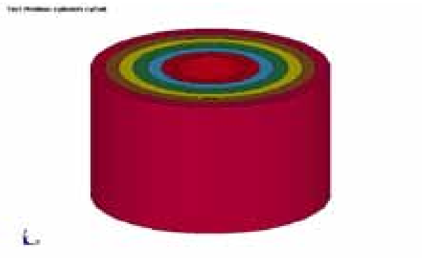
- MPP implicit and hybrid implicit are scaling to hundreds of processors.
- The global stiffness matrix, not an issue for explicit, is necessary for implicit
  - Processing time is dominated by the numeric factorization
  - Memory and disk storage is dominated by storing the factorization
- Memory management is very important.
- Symbolic Processing is the current bottleneck.
  - Improvements are being researched at LSTC

GPU Implementation for Implicit

- Advantage
  - Cheap, fast, and scalable with multiple CPU’s
- Limitation
  - Less memory than CPU side
  - Communication between the CPU and GPU is slow
  - Currently Fortran does not port to the GPU.
  - GPU’s hundreds of cores only work at the promised speed for specialized applications with carefully programmed software.
- Current implementation uses one GPU per processor, which will be automatically detected and applied without special licensing or pricing

GPU Performance in Implicit

- Test Environment
  - PC with a dual quad core Xeon 5560 processors and 2 Nvidia Tesla boards. The host has 96 Gbytes of memory while each GPU has 2 Gbytes of memory.
- Benchmark problem: AWE 1M nodes



No. of MPI Ranks	Factor WCT w/out GPU	Factor WCT w/ GPU	Elapsed WCT w/out GPU	Elapsed WCT w/ GPU
1	10111	2885	25359	9163
2	9682	2251	23986	8387

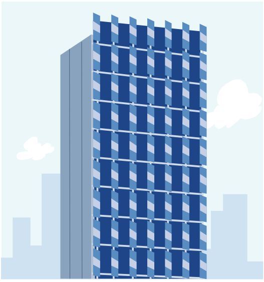
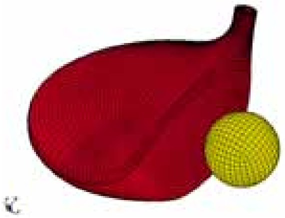
Frequency Domain Developments

Frequency domain analysis

- Random vibration
- Random fatigue
- Frequency response function
- Steady state dynamics
- Response spectrum analysis
- BEM Acoustics
- FEM Acoustics

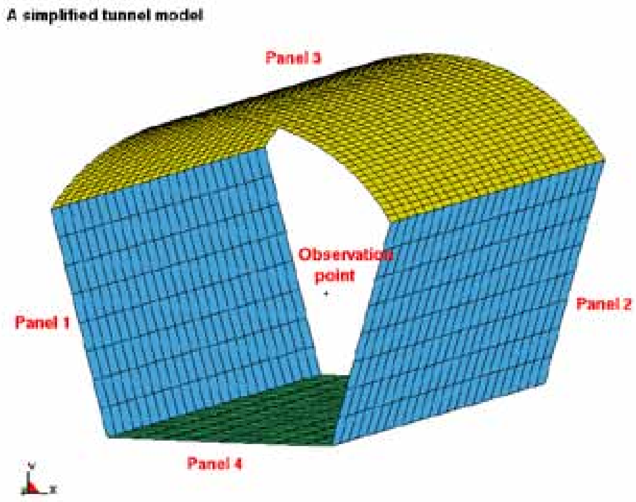
Applications

- NVH of automotive and air plane
- Golf club design
- Defense industry
- Fatigue of mechanical structures
- Civil Engineering

BEM acoustics

- Keyword
  - *FREQUENCY_DOMAIN_ACOUSTIC_BEM
- A wide choice of methods
  - Rayleigh method
  - Kirchhoff method
  - Indirect variational BEM
  - Collocation BEM
  - Dual BEM with Burton-Miller formulation

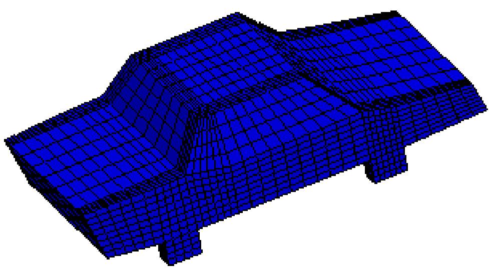


- Boundary conditions given by
  - Direct load curve input
  - Time domain dynamic analysis followed by FFT conversion
  - Frequency domain steady state dynamic analysis
- Acoustic panel contribution analysis

BEM acoustics

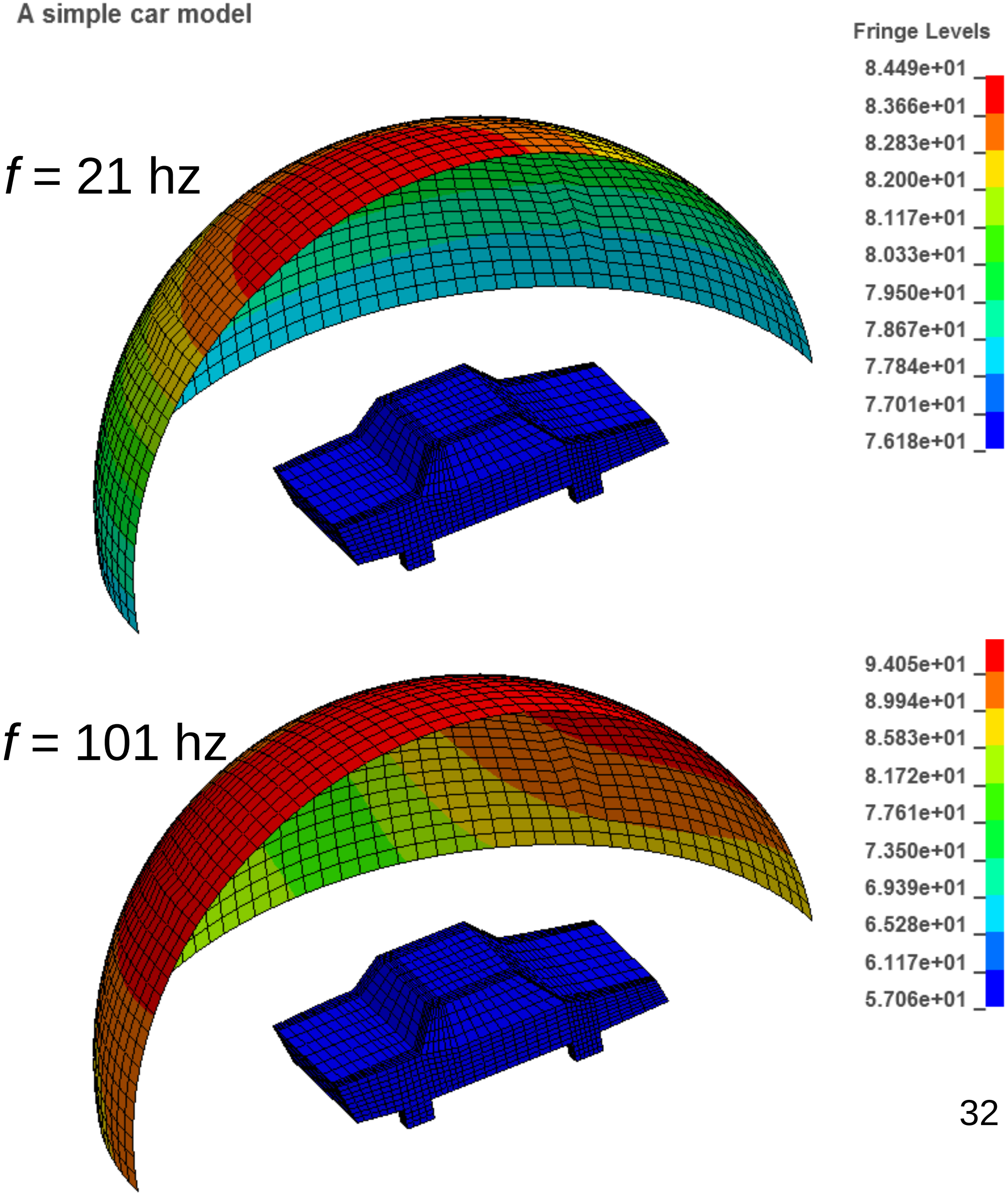
Radiated noise by a car

Harmonic nodal force applied at the top



f = 21 hz

f = 101 hz



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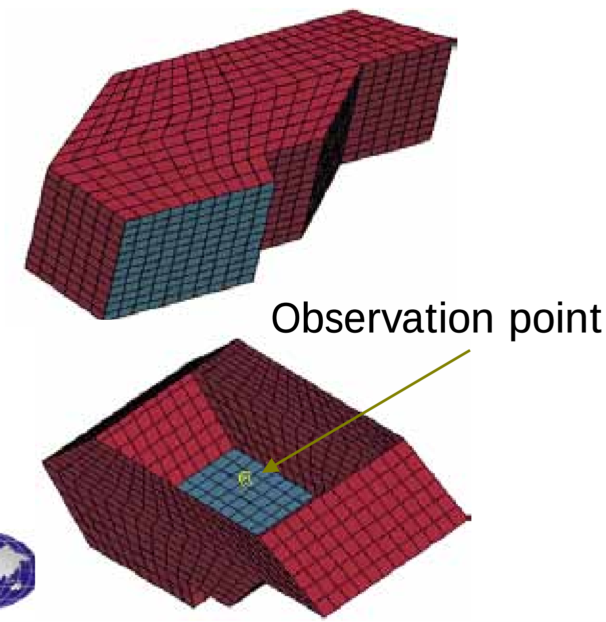
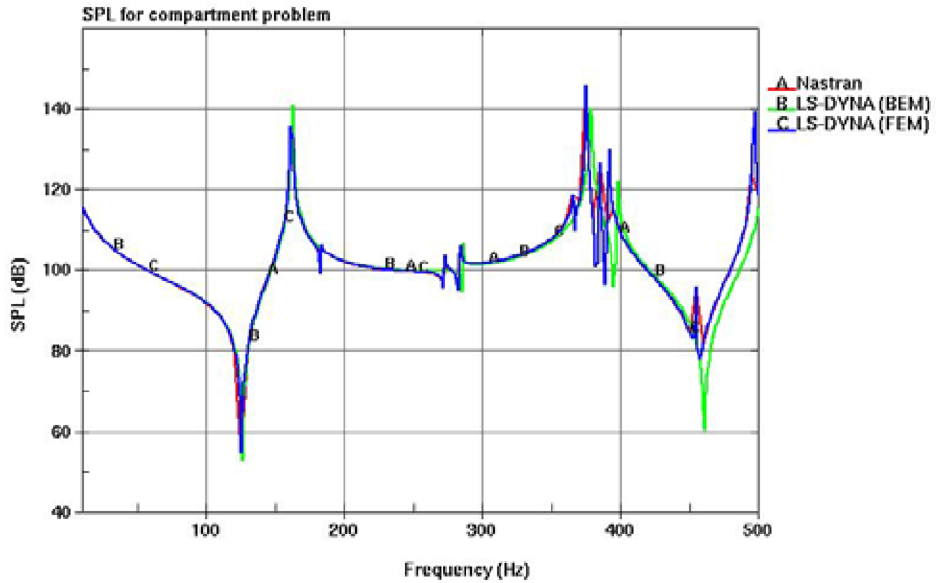
FEM acoustics

- Keyword
  - *FREQUENCY_DOMAIN_ACOUSTIC_FEM
- Solve interior acoustic problem
- Tetrahedron and Hexahedron elements are available
- Very fast since only 1 unknown at each node

A simplified compartment example





New database files

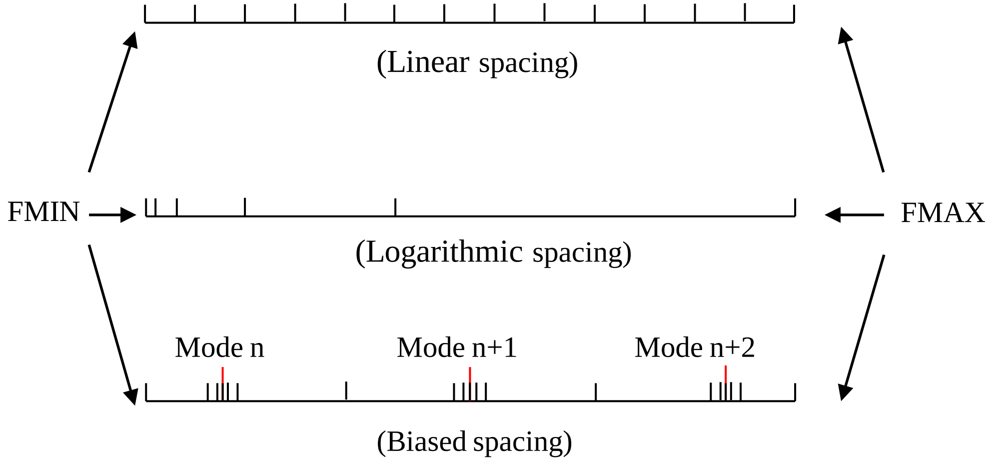
- Keyword
  - *DATABASE_FREQUENCY_BINARY_OPTION

Available options

D3ACS, D3FTG, D3PSD, D3RMS, D3SPCM and D3SSD

Card 1	1	2	3	4	5	6	7	8
Variable	BINARY							
Type	I							
Default	1							

Card 2	1	2	3	4	5	6	7	8
Variable	FMIN	FMAX	NFREQ	FSPACE	LCFREQ			
Type	F	F	I	I	I			
Default	0.0	0.0	0	0	0			



Isogeometric analysis

NURBS-based finite elements

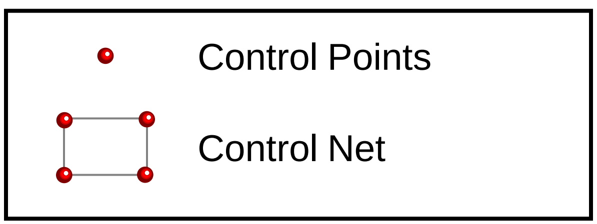
- ISOGEOMETRIC-Analysis
  - research since 2003
  - many promising features (CAD-to-FEA, accuracy, …)
- GENERALIZED-Elements in LS-DYNA (User defined)
  - possible to try different shape functions …
  - good results (accuracy, …)
  - difficult to use, huge input-decks with lots of data à slow to read …
- Decision to implement NURBS-based finite elements in LS-DYNA
  - NURBS: most widely used geometric description
  - first step into ISOGEOMETRIC-Analysis
- Very first implementations …
  - 2D-NURBS for shell analysis
  - Boundary conditions (contact) with interpolation nodes/elements

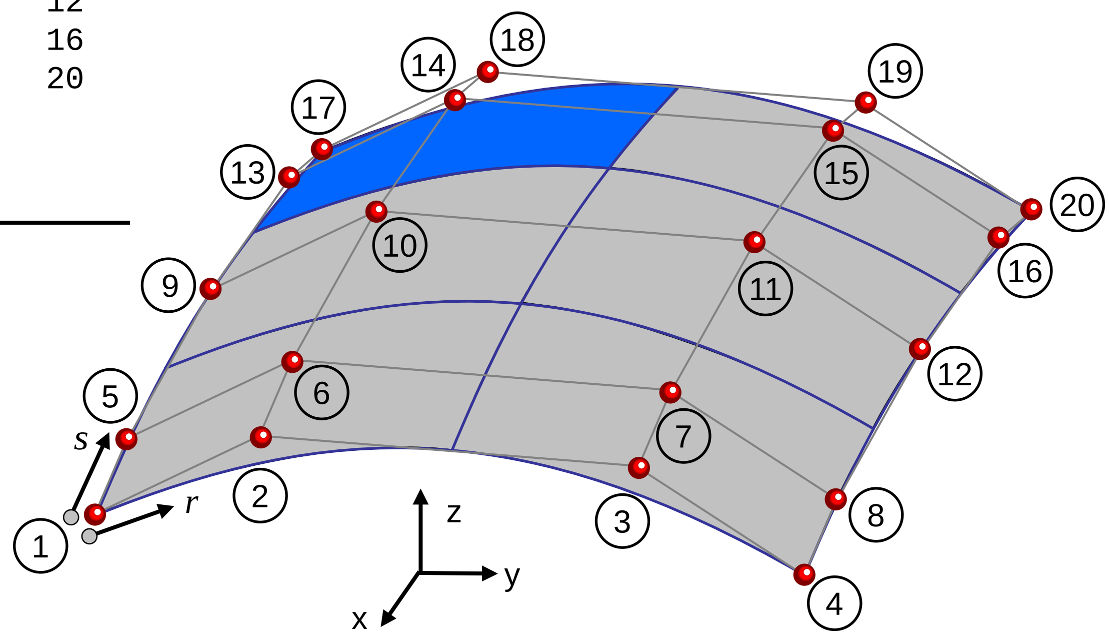
Present Capabilities in LS-Dyna

- New Keyword: *ELEMENT_NURBS_PATCH_2D
  - definition of NURBS-surfaces
  - 4 different shell formulations with/without rotational degrees-of-freedom
- Preprocessing
  - work in progress for LS-PrePost … current status (lspp3.1beta)
    - à Visualization of 2D-NURBS-Patches
    - à import IGES-format and construct *ELEMENT_NURBS_PATCH_2D
    - à Modification of 2D-NURBS geometry
- Postprocessing and boundary conditions (i.e. contact) currently with
  - Interpolation nodes
  - Interpolation elements
- Analysis capabilities
  - implicit and explicit time integration
  - eigenvalue analysis
  - other capabilities (e.g. geometric stiffness for buckling) implemented but not yet tested
- LS-DYNA material library available (including umats)

NURBS-based finite elements

```
*ELEMENT_NURBS_PATCH_2D
$---+--EID----+--PID----+--NPR----+---PR----+--NPS----+---PS----+----7----+----8
        11        12         4         2         5         2
$---+--WFL----+-FORM----+--INT----+-NISR----+-NISS----+IMASS----+----7----+----8
         0         0         1         2         2         0
$rk-+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
       0.0       0.0       0.0       1.0       2.0       2.0       2.0
$sk-+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
       0.0       0.0       0.0       1.0       2.0       3.0       3.0       3.0
$net+---N1----+---N2----+---N3----+---N4----+---N5----+---N6----+---N7----+---N8
         1         2         3         4
         5         6         7         8
         9        10        11        12
        13        14        15        16
        17        18        19        20
```





Summary & Future Directions

- NURBS based elements are stable
- Code optimization necessary to make it faster but already competitive. MPP enabled.
- Perform a lot more studies in different fields à experience
- Encourage customers to test these elements
- Further implementation
  - (selective) mass scaling
  - thickness update of shells
  - use NURBS for contact (instead of interpolation elements)
  - make pre- and post-processing more user-friendly
  - introduce 3D NURBS elements
  - … much more

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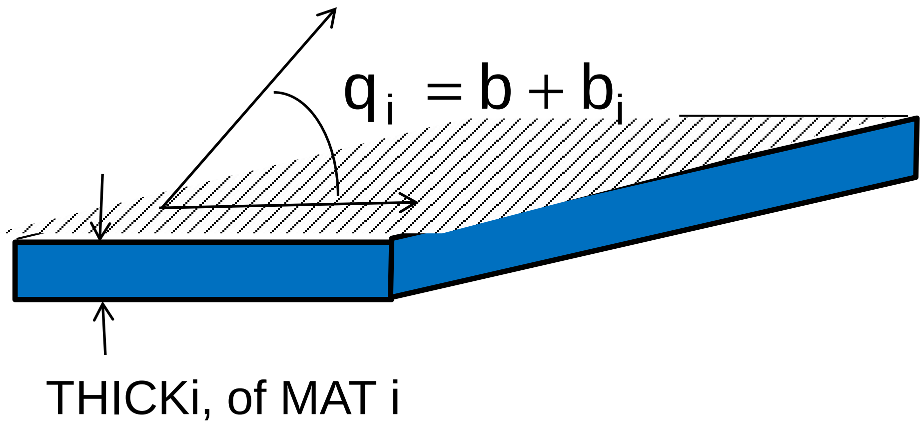
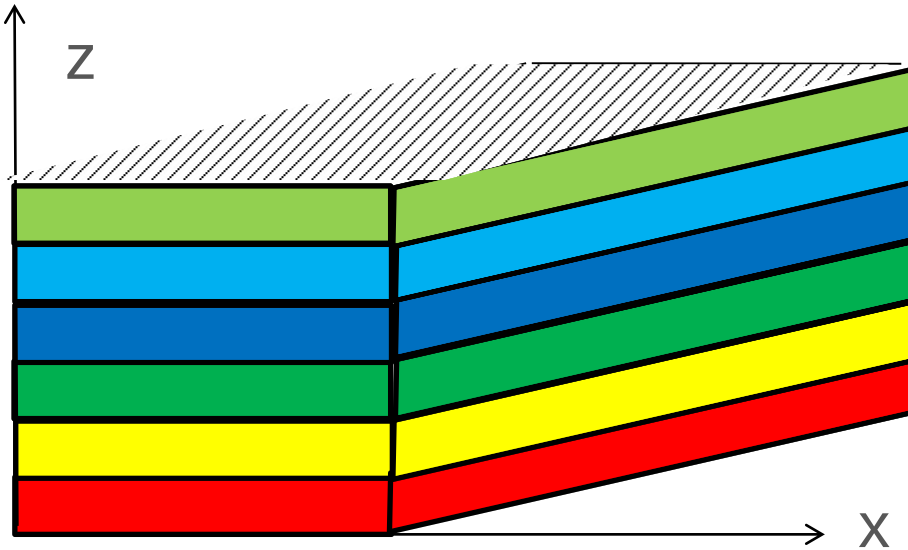
LS-DYNA Version 971 recent developments

LS971R5 & R6

*ELEMENT_SHELL_COMPOSITE
*ELEMENT_TSHELL_COMPOSITE

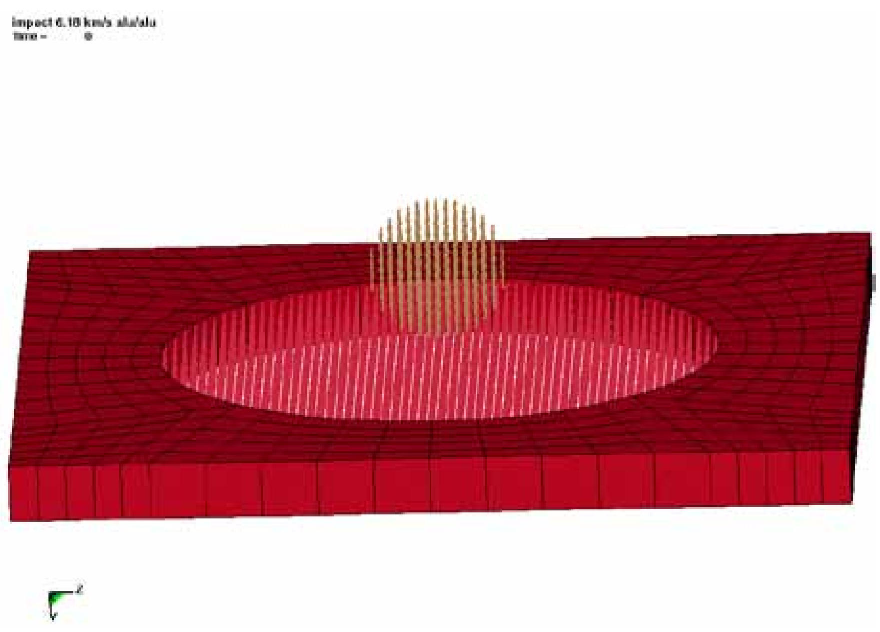
- To define elements for a general composite shell part where the shells within the part can have an arbitrary number of layers
- The material ID, thickness, and material angle are specified for the thickness integration points for each shell in the part

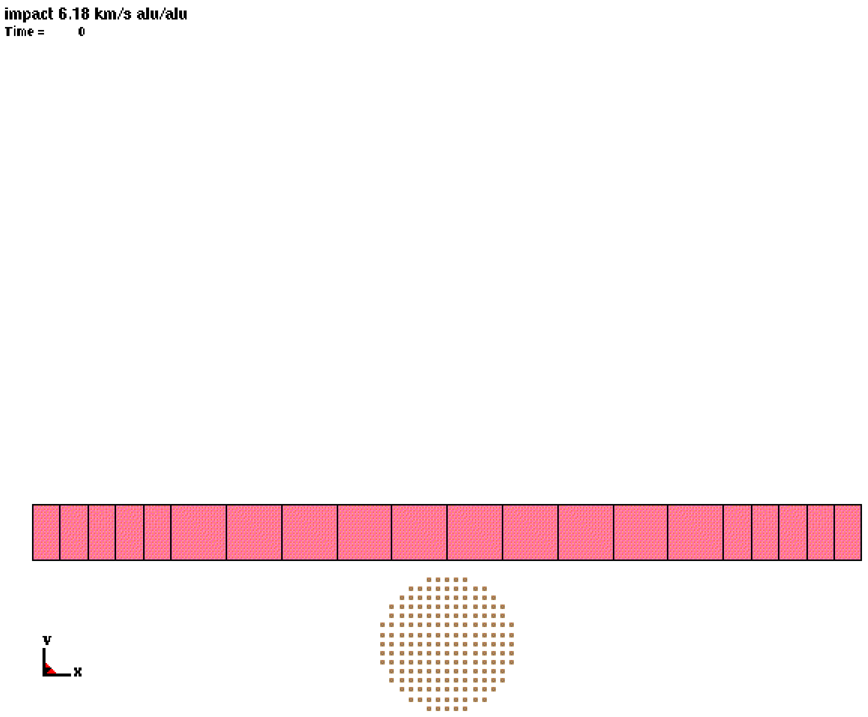




Node-to-node contact for SPH

*DEFINE_SPH_TO_SPH_COUPLING to define penalty-based SPH-to-SPH particle contact

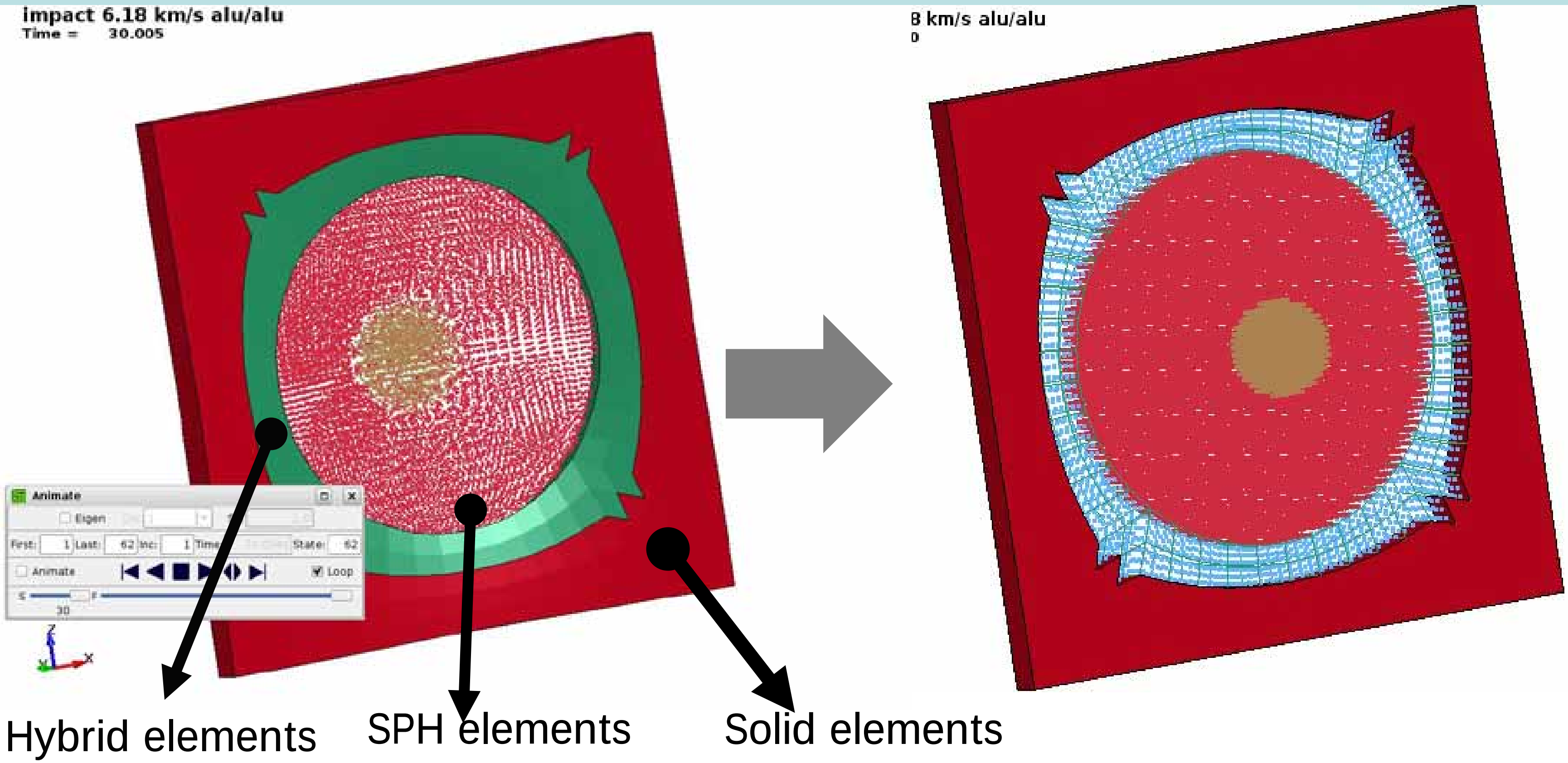




Hybrid element couples SPH to solid

*DEFINE_ADAPTIVE_SOLID_TO_SPH

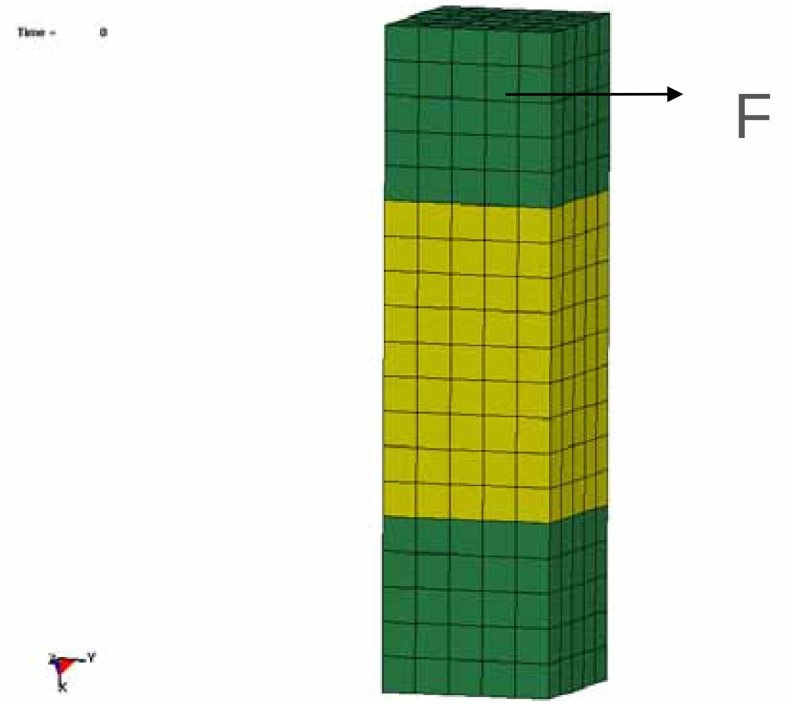
ICPL=1 creates hybrid elements as transit layers between SPH elements and Solid elements. Solid elements constrain SPH nodal locations. SPH elements provide "penalty force“ against solid nodal motion.

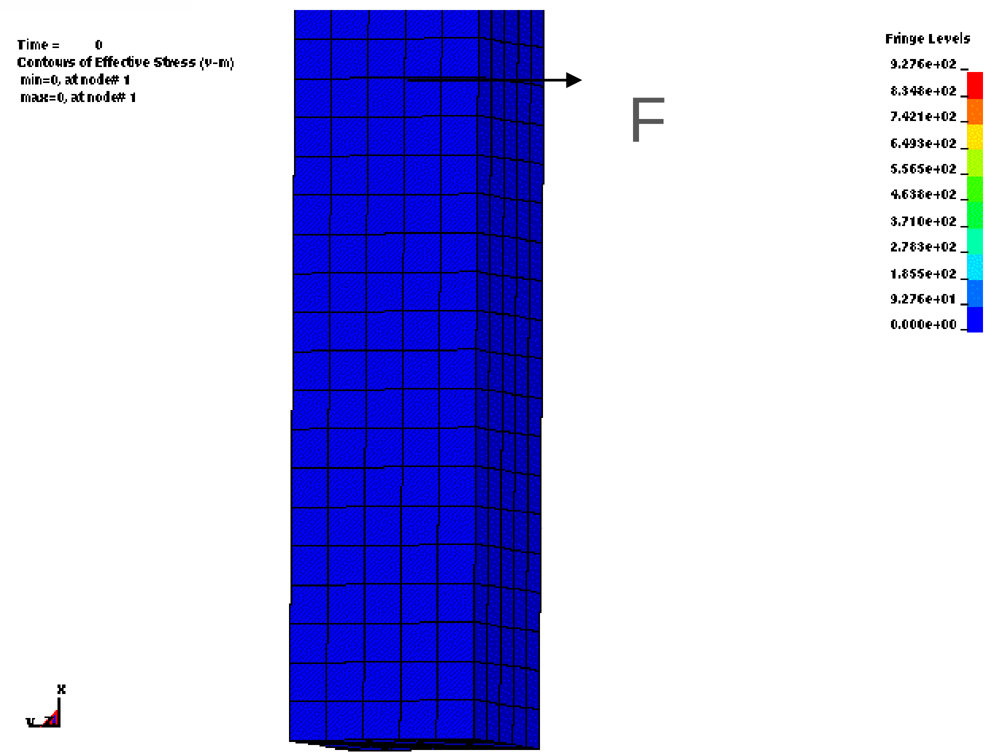


Adaptive solid to SPH

*DEFINE_ADAPTIVE_SOLID_TO_SPH

The SPH particles replacing the failed element inherit all of the properties of failed solid element, e.g. mass, kinematic variables, and constitutive properties. Hybrid transition elements are automatically created.





Stress contour

SPH thermal

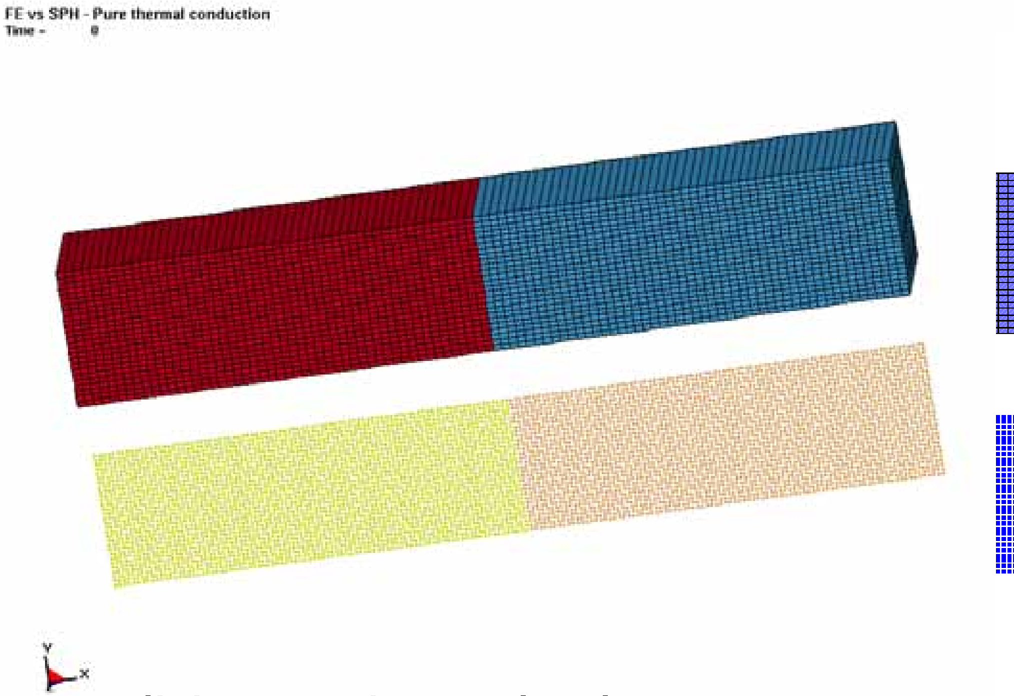
- A new explicit thermal conduction solver is implemented for SPH analysis
- Following keywords are supported
  - *INITIAL_TEMPERATURE_*OPTION*
  - *BOUNDARY_TEMPERATURE_*OPTION*
  - *BOUNDARY_FLUX_*OPTION*
- Thermal coupling with SPH is implemented

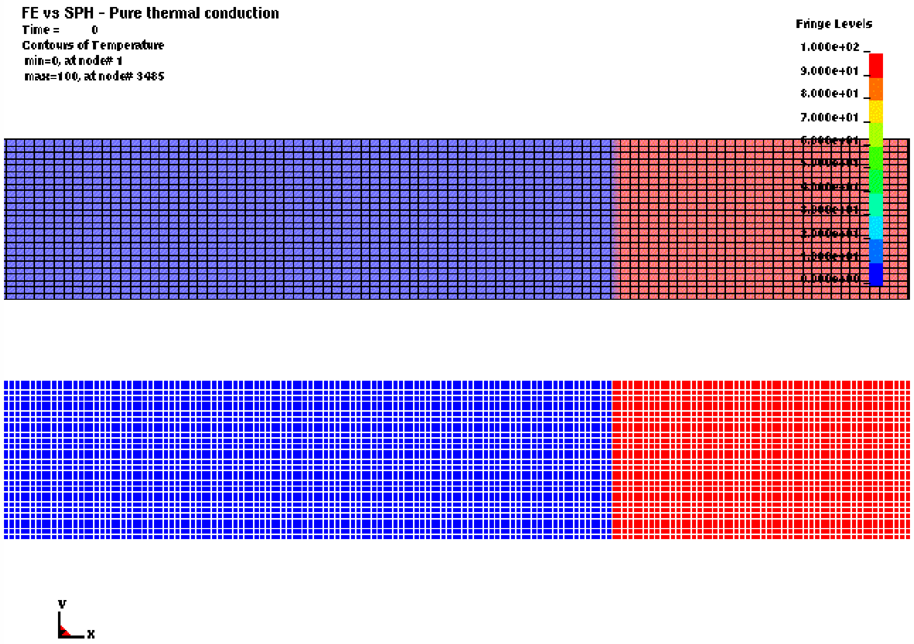
SPH thermal conduction

INITIAL_TEMPERATURE_*OPTION

Lagrangian thermal solver

time step: $\Delta t = \mu \Delta l^2 \rho c / k \quad \mu = 1/12$





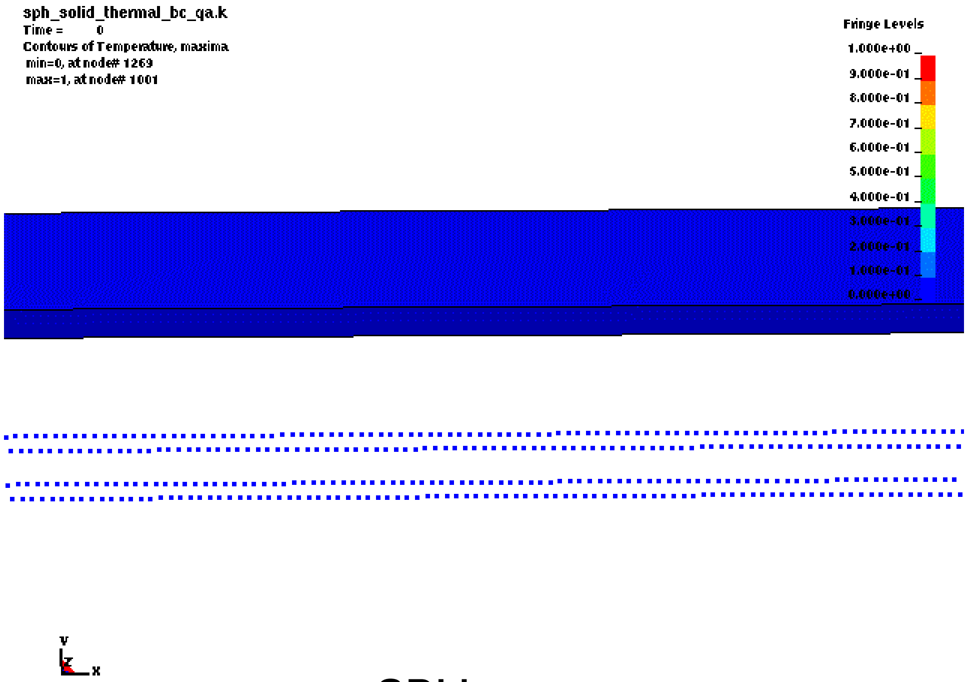
explicit SPH thermal solver

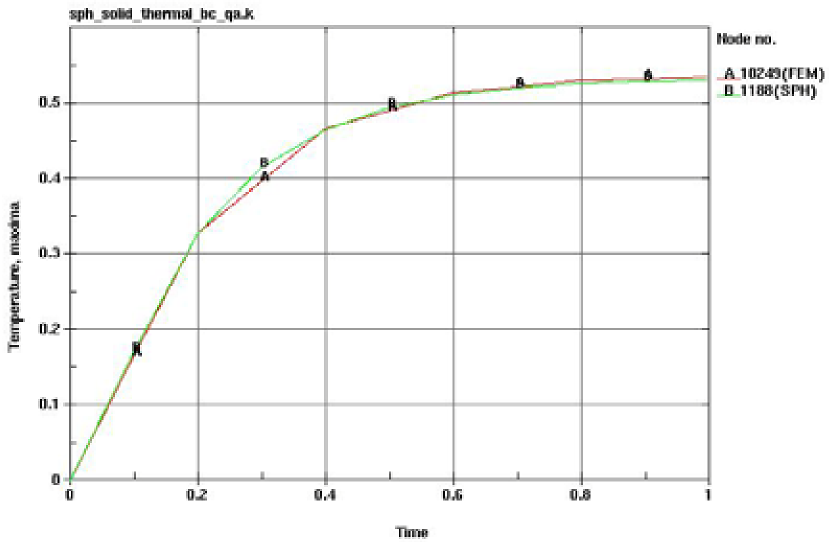
time step: $\Delta t = \zeta \rho c_v h^2 / k \quad \zeta = .1$

Boundary_temperature

BOUNDARY_TEMPERATURE_*OPTION

Solids



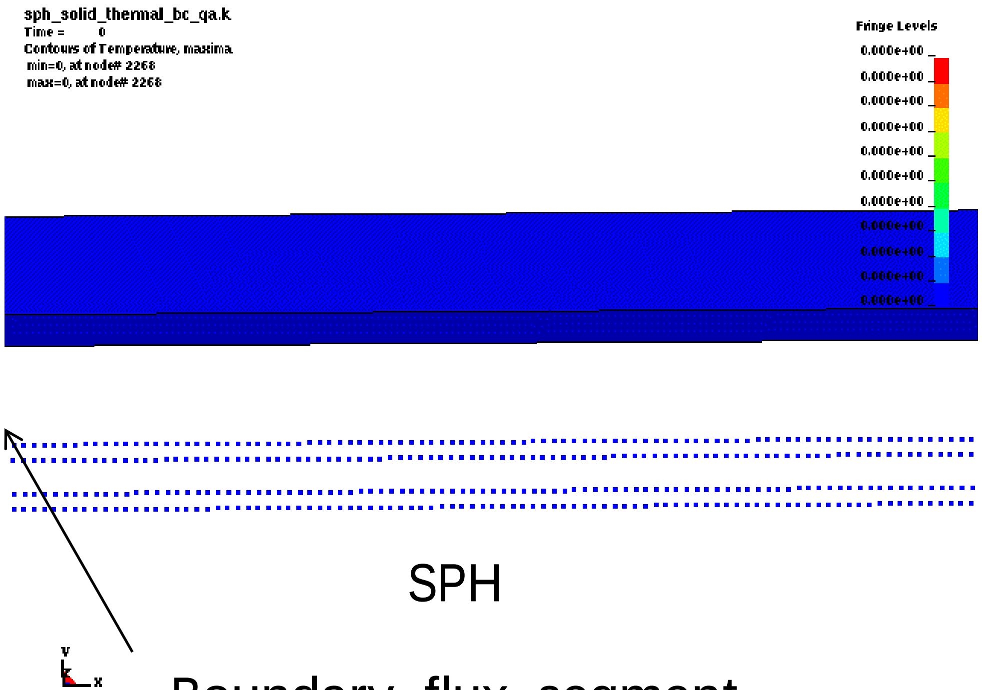


SPH

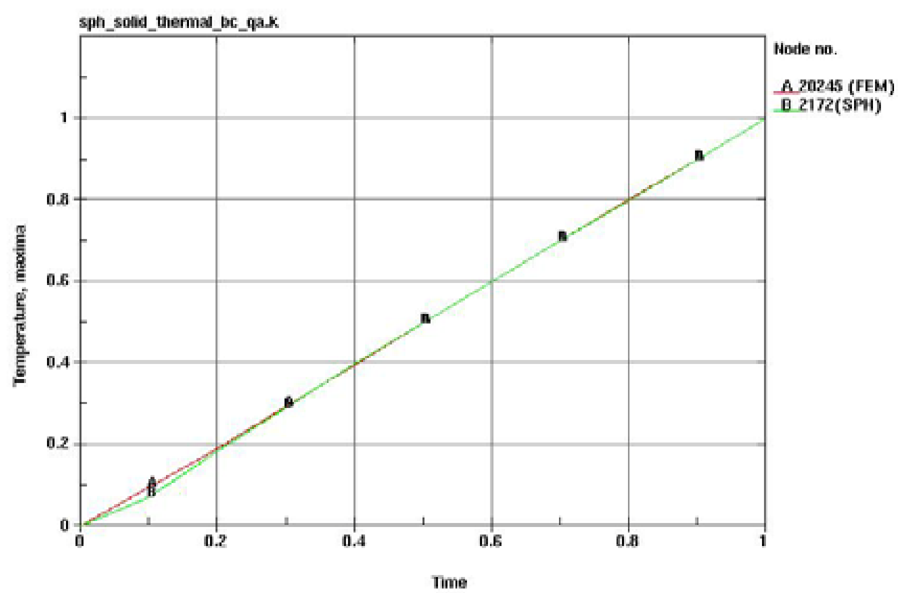
Boundary_temperature

BOUNDARY_FLUX_*OPTION

Solids



SPH

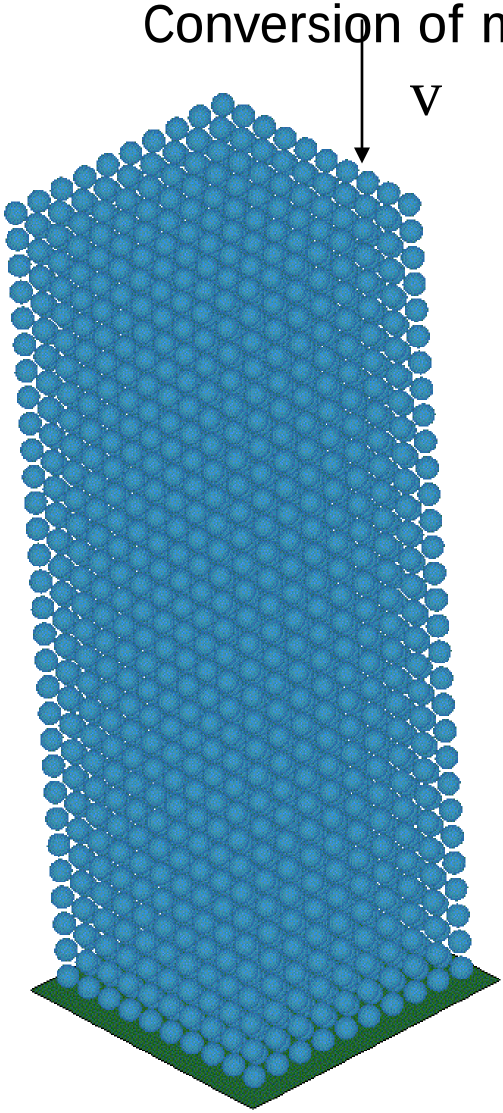


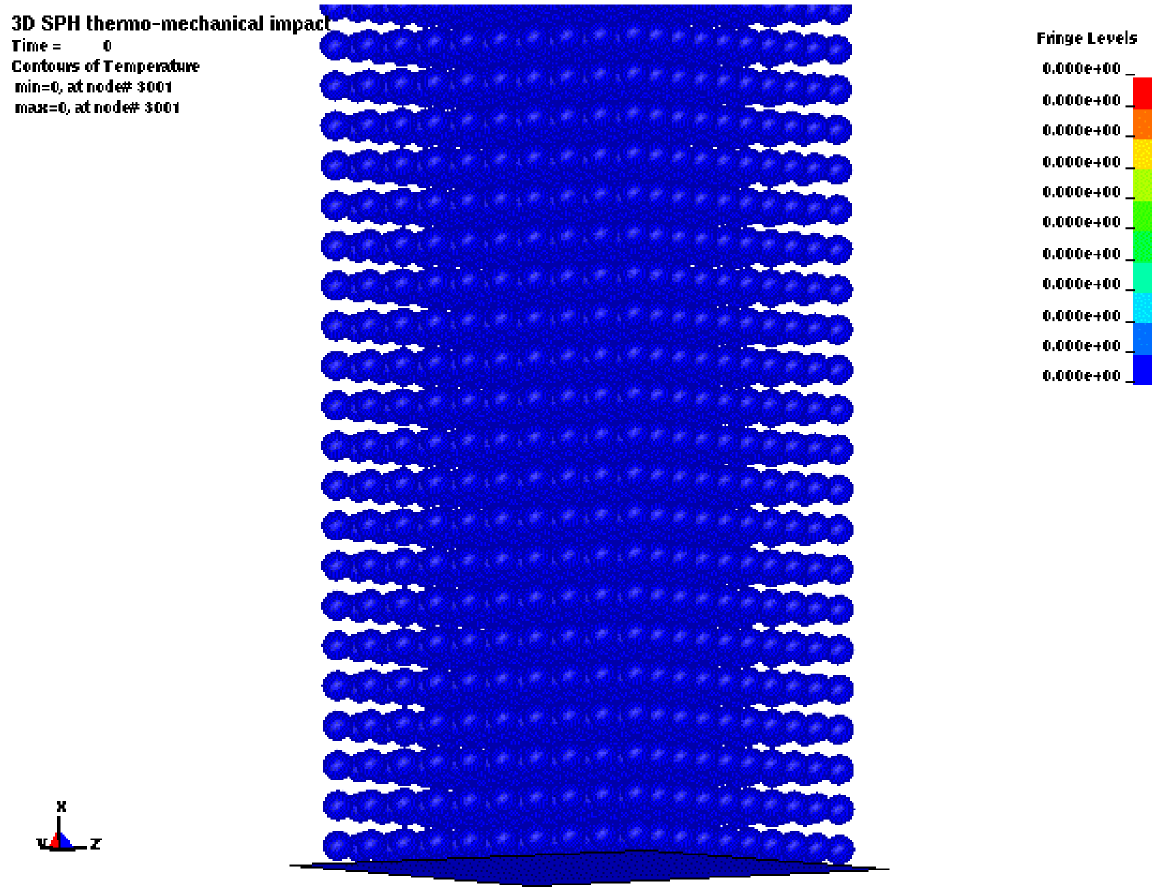
Boundary_flux_segment
Heat flow is negative in the direction of surface normal vector(left hand rule)

Thermal coupling with SPH

Control_thermal_solver: $(eqheat)(fwork)w = r c \mathrm{D} T$

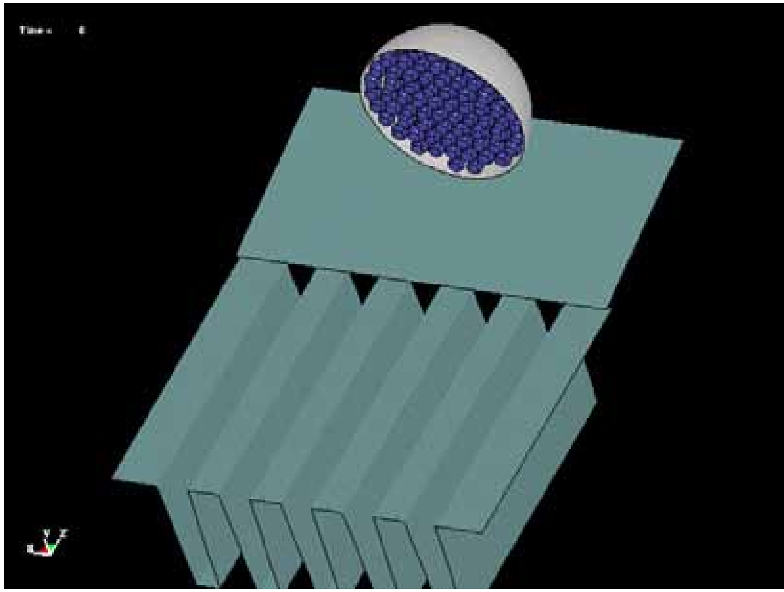
Conversion of mechanical work to heat





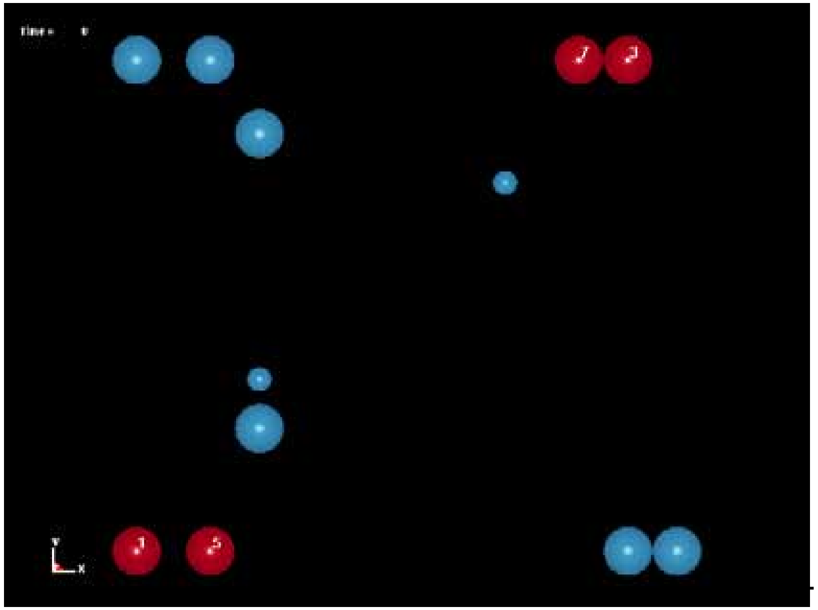
*Mat_rigid_discrete or *Mat_220

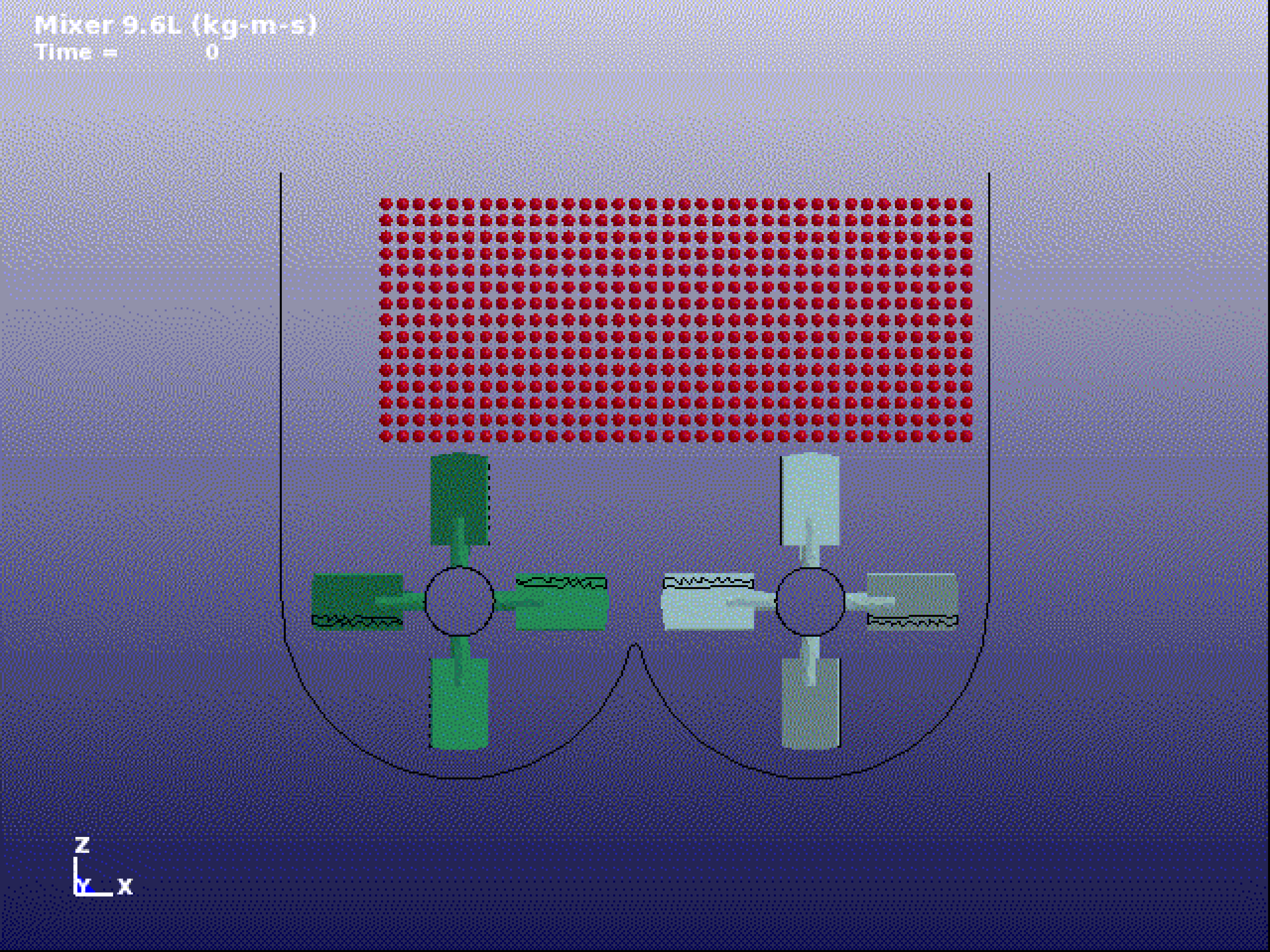
- A single rigid material is defined which contains multiple disjoint pieces.
- Each rigid piece can contain an arbitrary number of solid elements that are arranged in an arbitrary shape.
- reduction in memory and wall clock time over separate rigid bodies
- Can be used to model granular material



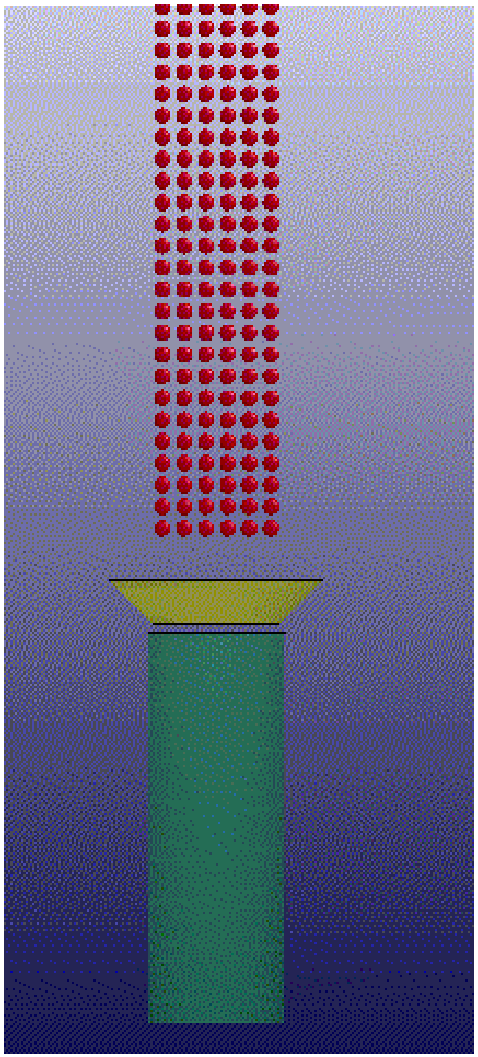
*Element_discrete_sphere

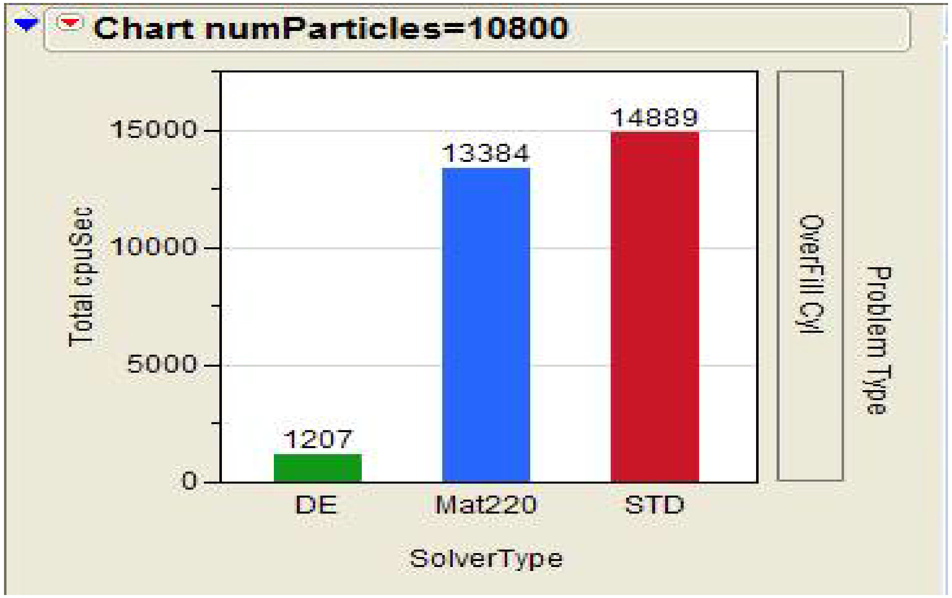
- For cases where the particles can be modeled with geometric shapes, meshing of particles are not needed for solving contact and analytical contact can be used.
- Speed is considerably faster than with arbitrarily shaped particles and general single surface contact
- Spherical particles with arbitrary radii have been implemented for
  - Elastic impact
  - Inelastic impact
  - Combination of elastic and inelastic impacts




Mixer 9.6L (kg-m-s)
Time = 0
Z
X

*Element_discrete_sphere



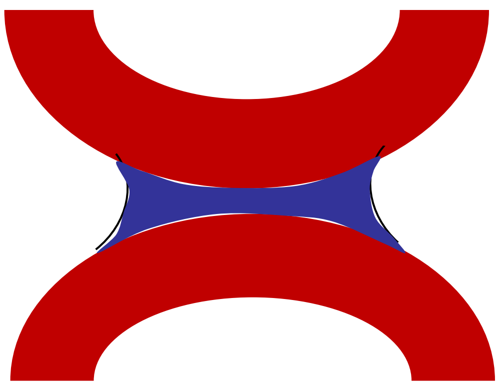


	Porosity
STD mat_20	0.409
Mat_220	0.409
DE sphere	0.399

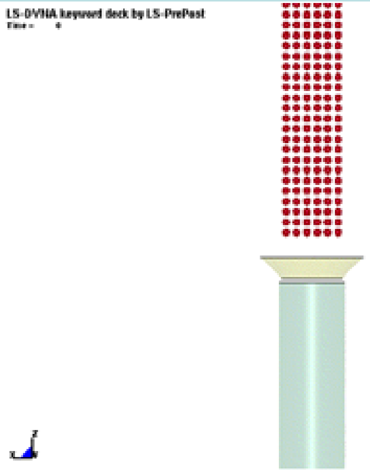
CPU time and porosity comparison between DES and discrete elements based on Mat_220 and Mat_20

*Element_discrete_sphere

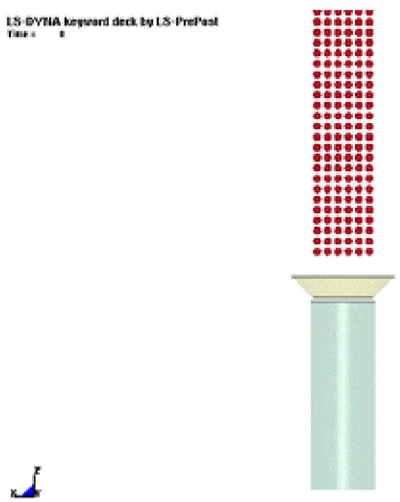
Effects of viscosity on the mechanical response of a liquid bridge is considered.



Dry



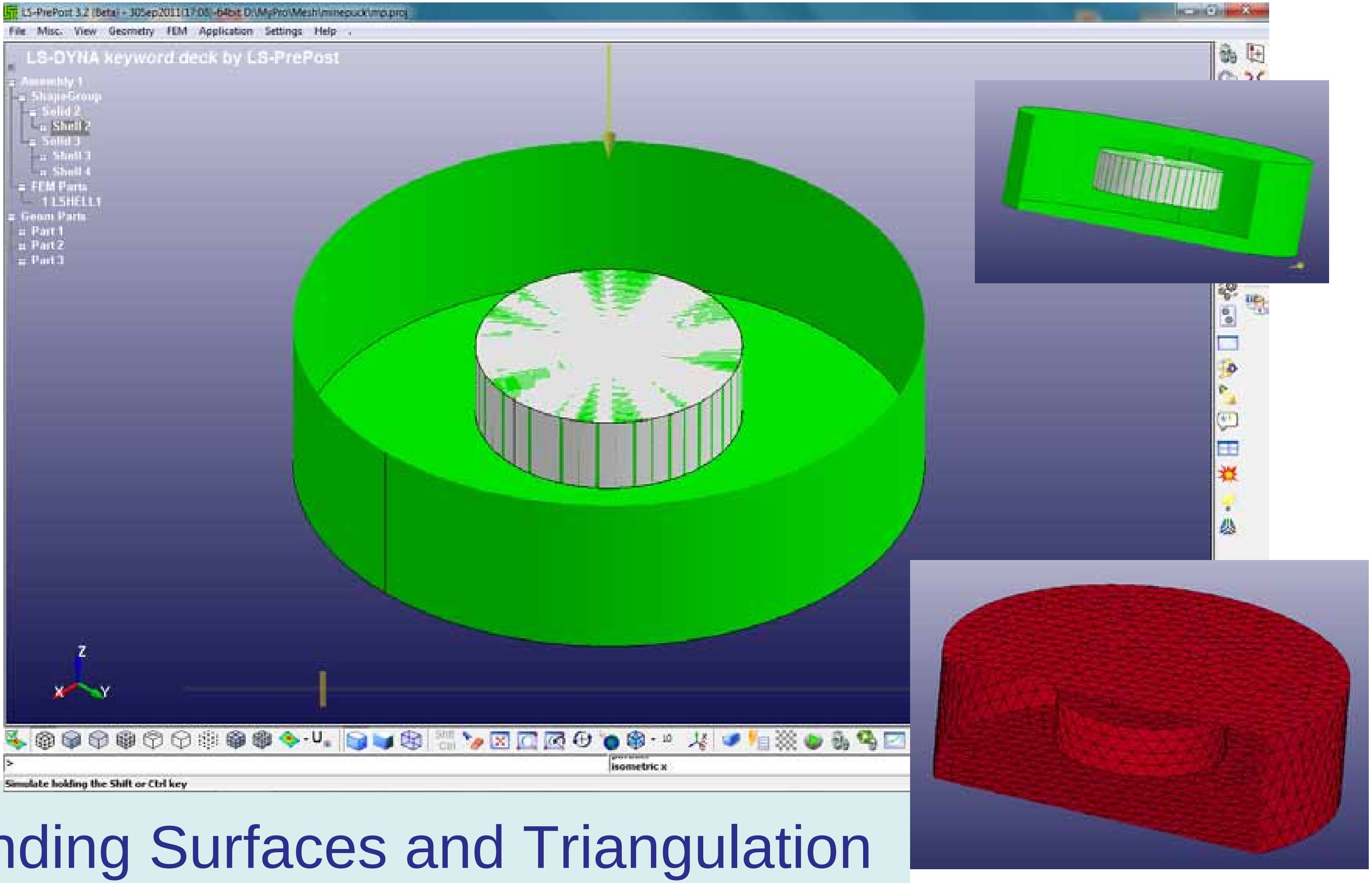
Wet



Discrete element sphere particle filling algorithm

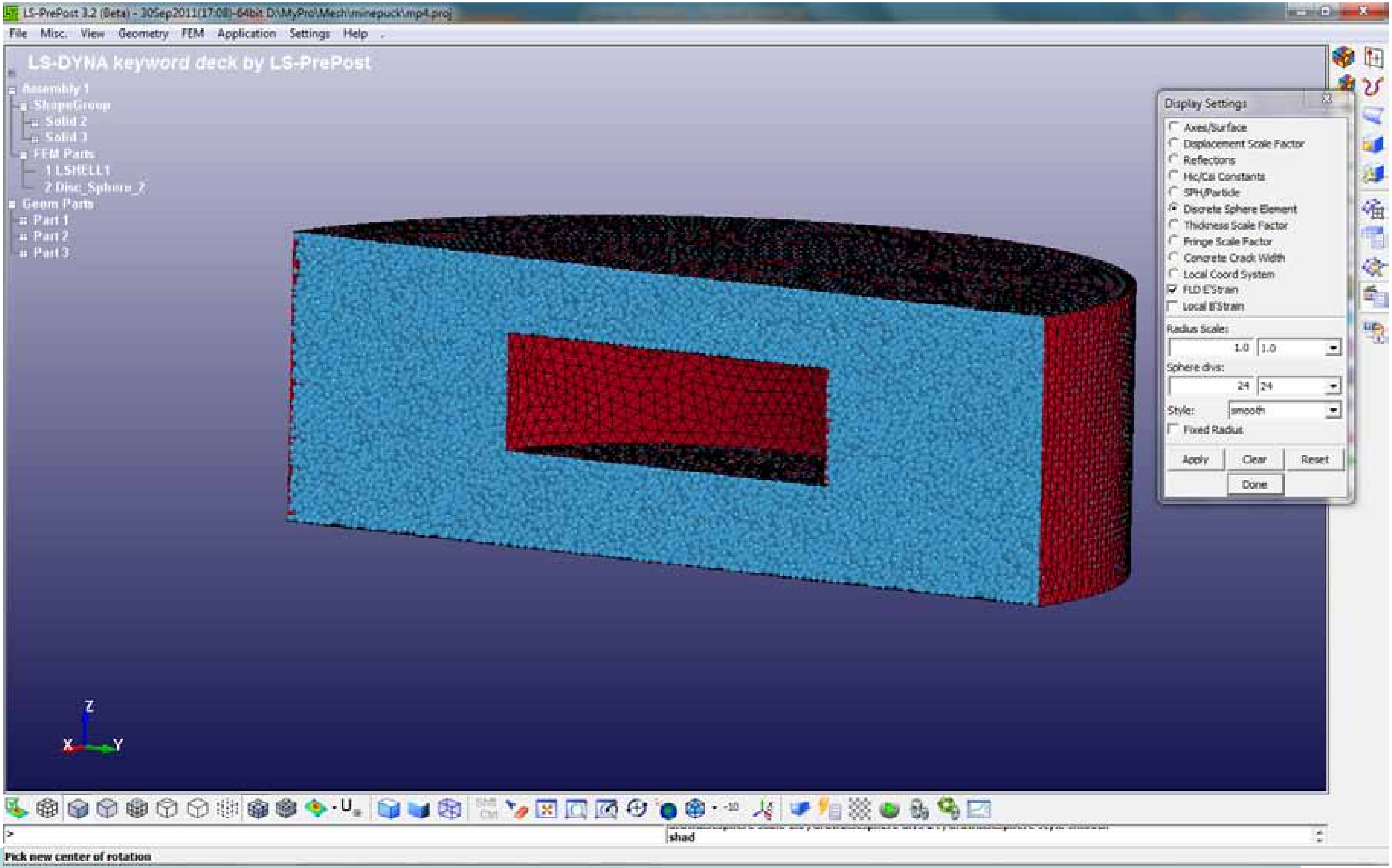
- Linear Packing Speed
  ~8,500 sphere/second, single CPU, including sphere regularization
- Packing Density: ~56.7%
- Direct implemention into LS-PrePost and generate the LS-DYNA keyword input

Discrete element sphere particle filling algorithm



Bounding Surfaces and Triangulation

Particle filling algorithm

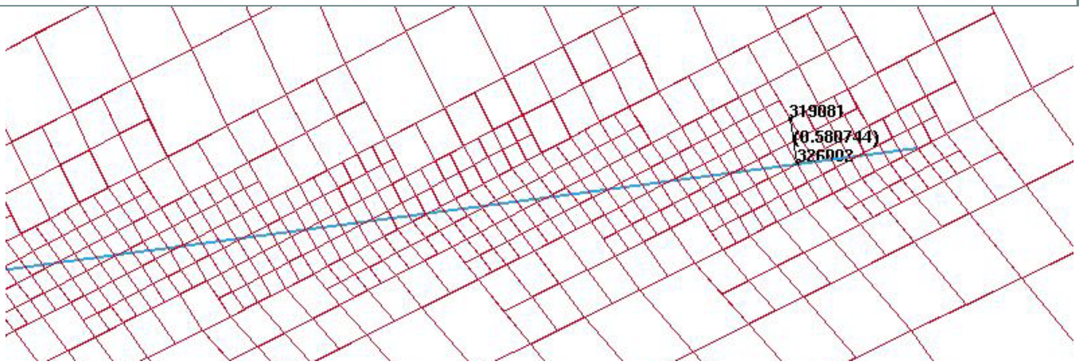


Phase III: Filling the volume

Mesh refinement along a curve

- DEFINE_CURVE_TRIM_NEW
  – Used together with *CONTROL_ADAPTIVE_CURVE

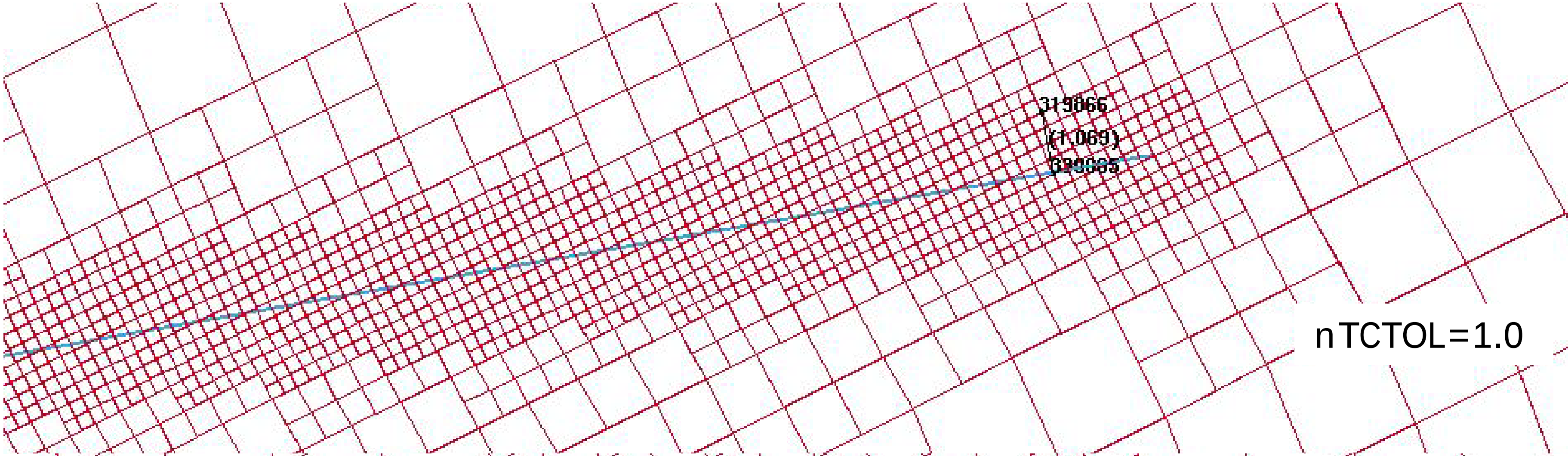
```
*DEFINE_CURVE_TRIM_3D
$       TCID    TCTYPE      TFLG      TDIR     TCTOL     TRDIS
           1         2         0         0     0.500     2.000
adpcurves.iges
*CONTROL_ADAPTIVE_CURVE
           1         2         4       0.3
```

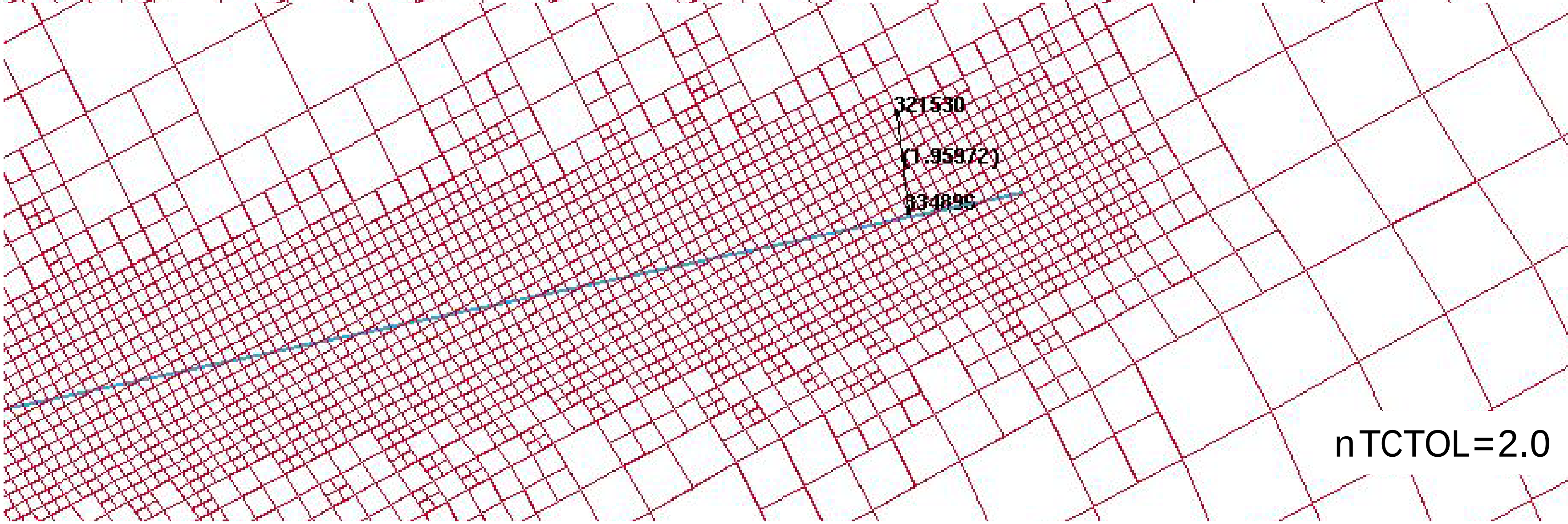


- Purpose
  – Refine elements along curve
  – No further refinement in later simulation
  – Flanging and hemming simulating become more efficient

Mesh refinement along a curve

- New method – Allow specifying distance from the curve to the edge of refinement



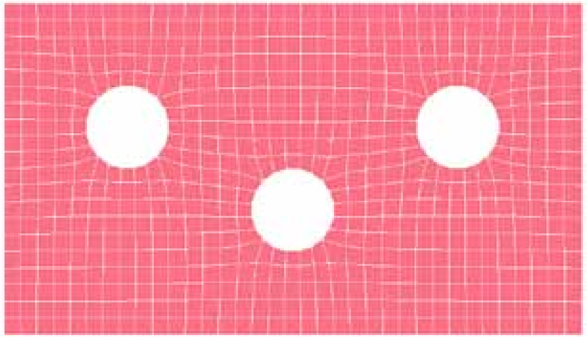


NUMISHEET'02 Fender along hood line

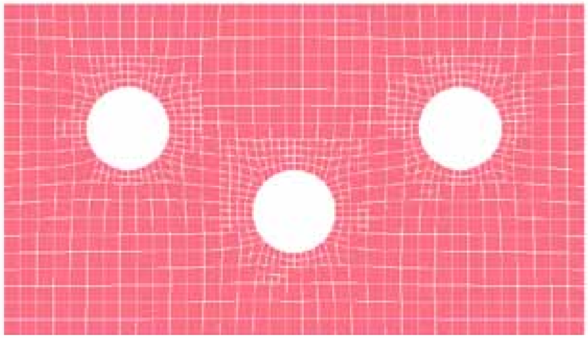
Linear implicit with adaptivity

- Adaptive meshing allows stress concentrations to be automatically resolved in linear static calculations.
- Implementation in LS-DYNA :
  - If 4 levels of adaptive remeshing are specified, then 4 load steps are performed holding the load constant. Error norms are computed each step to determine which elements are refined.
  - Super-convergent Patch Recovery, SPR, is now the default for error estimate

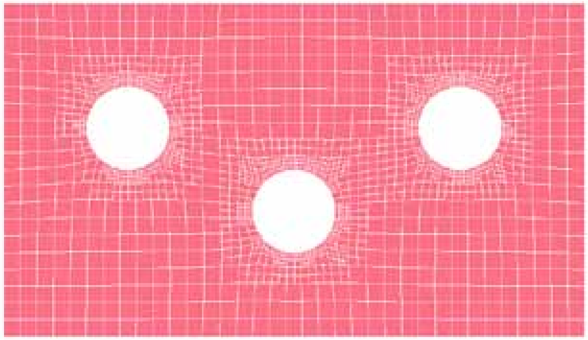
STEP 1
#node 706
#ele 625



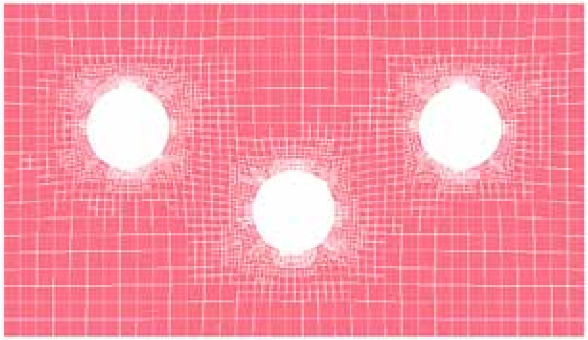
STEP 2
#node 1133
#ele 967

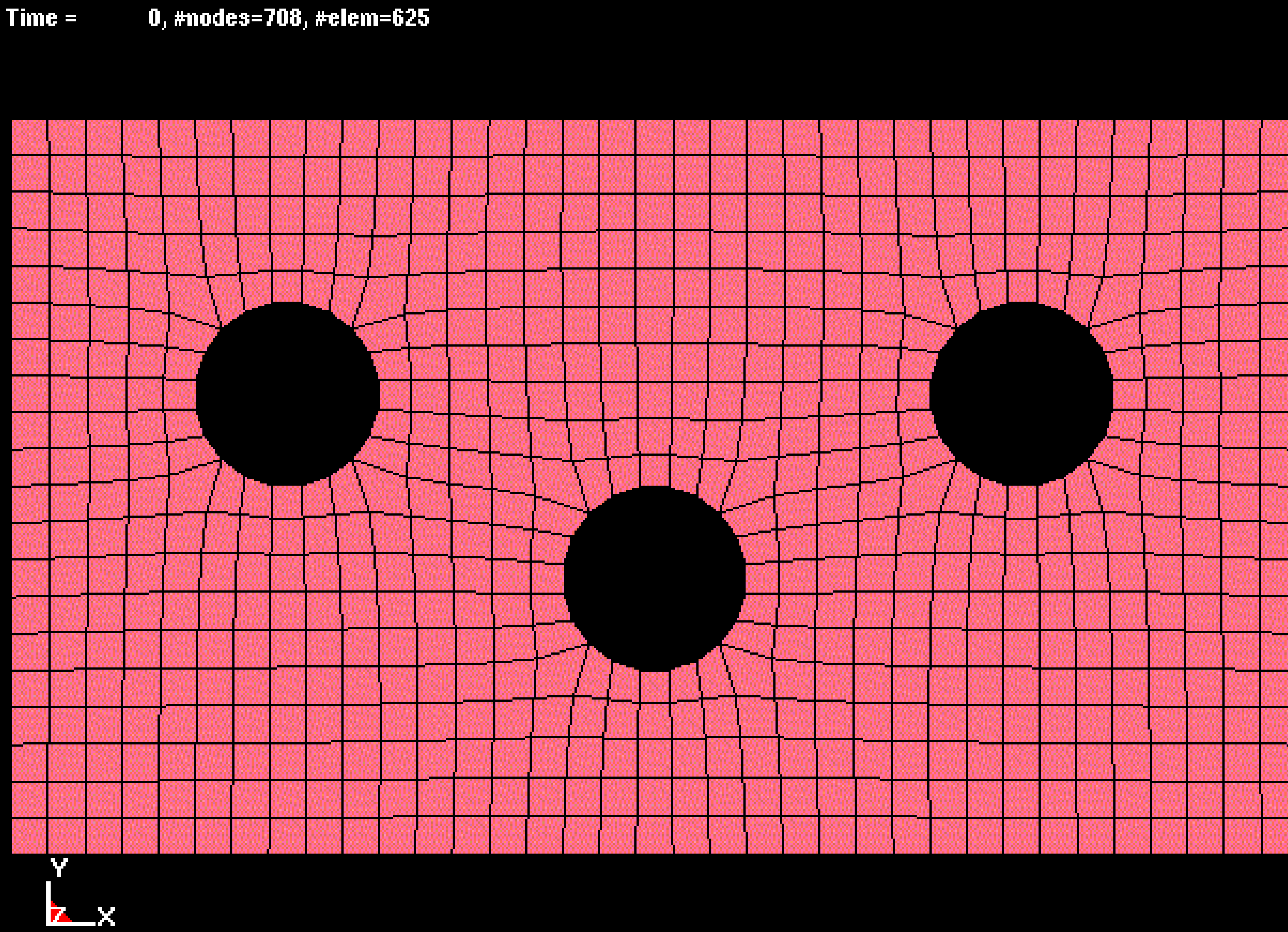


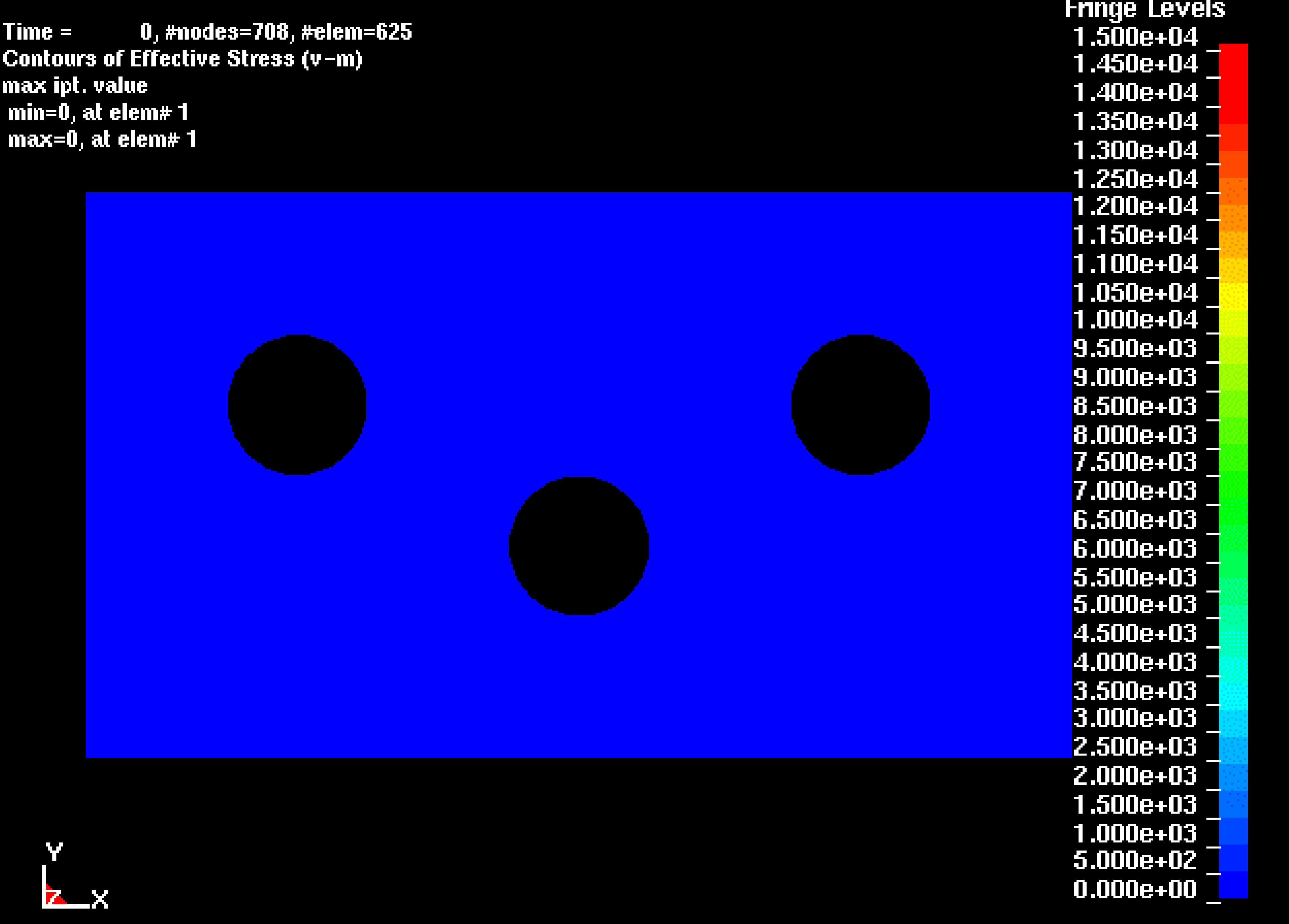
STEP 3
#node 1961
#ele 1675



STEP 4
#node 5203
#ele 4483




Time = 0, #nodes=708, #elem=625
Y
X

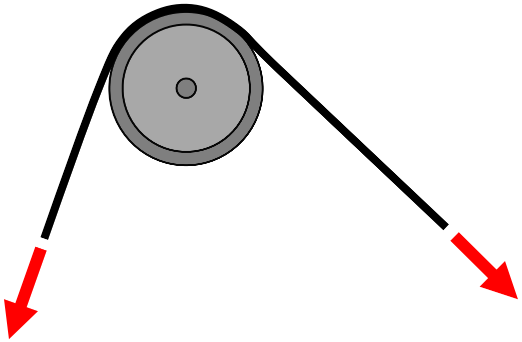

Time = 0, #nodes=708, #elem=625
Contours of Effective Stress (v-m)
max ipt. value
min=0, at elem# 1
max=0, at elem# 1
Fringe Levels
1.500e+04
1.450e+04
1.400e+04
1.350e+04
1.300e+04
1.250e+04
1.200e+04
1.150e+04
1.100e+04
1.050e+04
1.000e+04
9.500e+03
9.000e+03
8.500e+03
8.000e+03
7.500e+03
7.000e+03
6.500e+03
6.000e+03
5.500e+03
5.000e+03
4.500e+03
4.000e+03
3.500e+03
3.000e+03
2.500e+03
2.000e+03
1.500e+03
1.000e+03
5.000e+02
0.000e+00
Y
X

Linear adaptivity

- Superconvergence Patch Recovery (SPR) has been extended for shells and plates.
- The element-centered element patch is used for the SPR with the weighted lease square, to support T-joints and feature lines natively.
- Support various error estimators, within the element, including the energy norm, maximum tension or shear, von Mises stress, etc.
- All error estimation procedures are carried out locally, which is MPP friendly.

*ELEMENT_BEAM_PULLEY

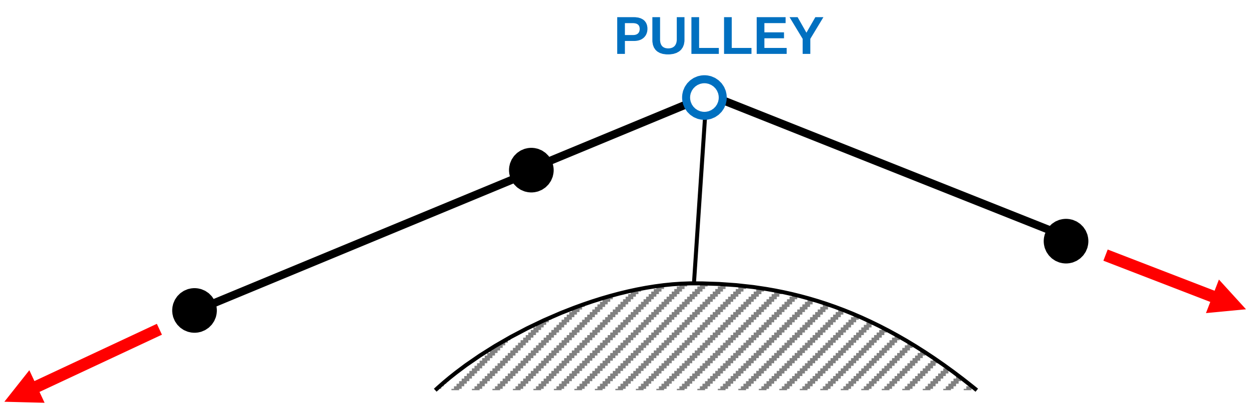
- General framework for **pulley mechanism**: rope / cable / belt / chain runs over a wheel → beam elements run over pulley node



- Adpoted from slipring mechanism for belts

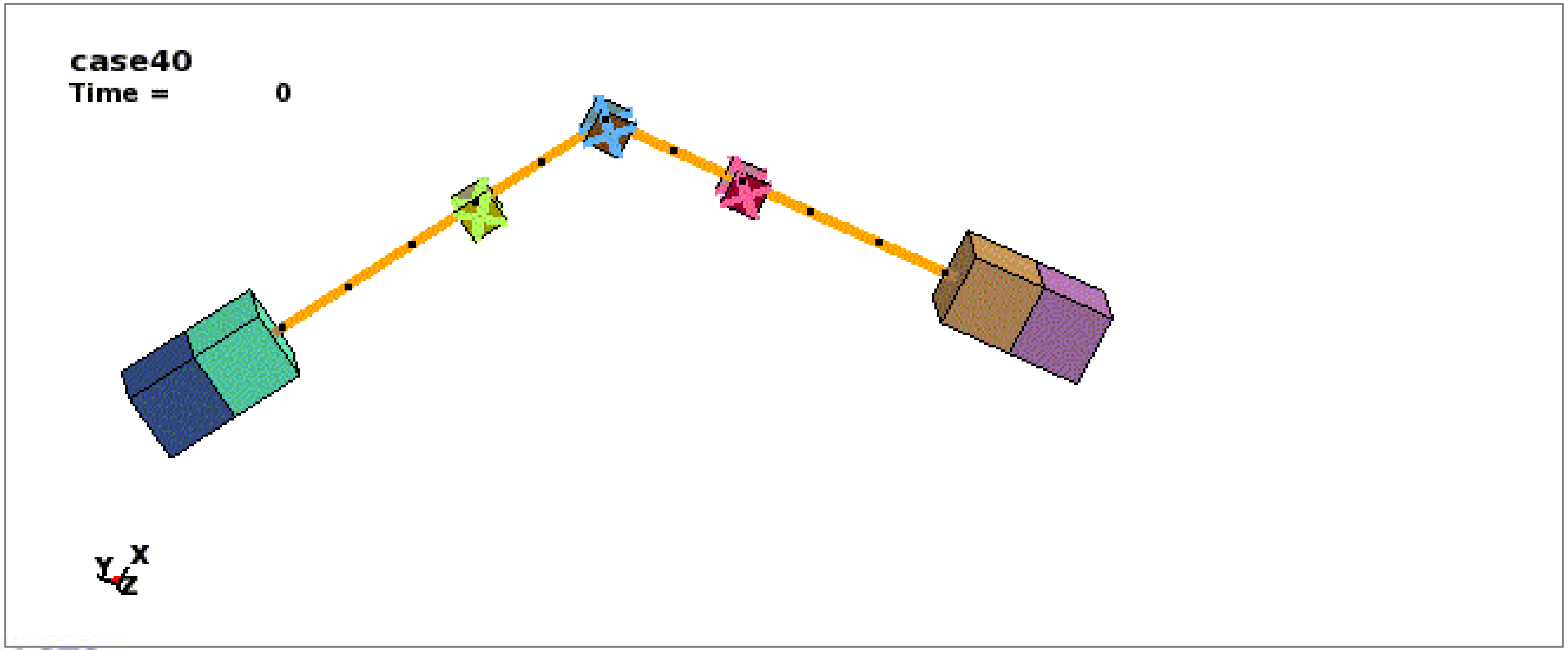
- Available for **truss beam elements**

- Available for ***MAT_ELASTIC** and ***MAT_MUSCLE**, more materials could be implemented



*ELEMENT_BEAM_PULLEY

- Smooth transition of beam material from one side to the other
- Swapping of beam elements if elements get too short
- Static and dynamic friction coefficients can be defined



Simplified Table Definitions

*DEFINE_TABLE_2D

Unlike the *DEFINE_TABLE keyword, a curve ID is specified for each abscissa value defined in the table.

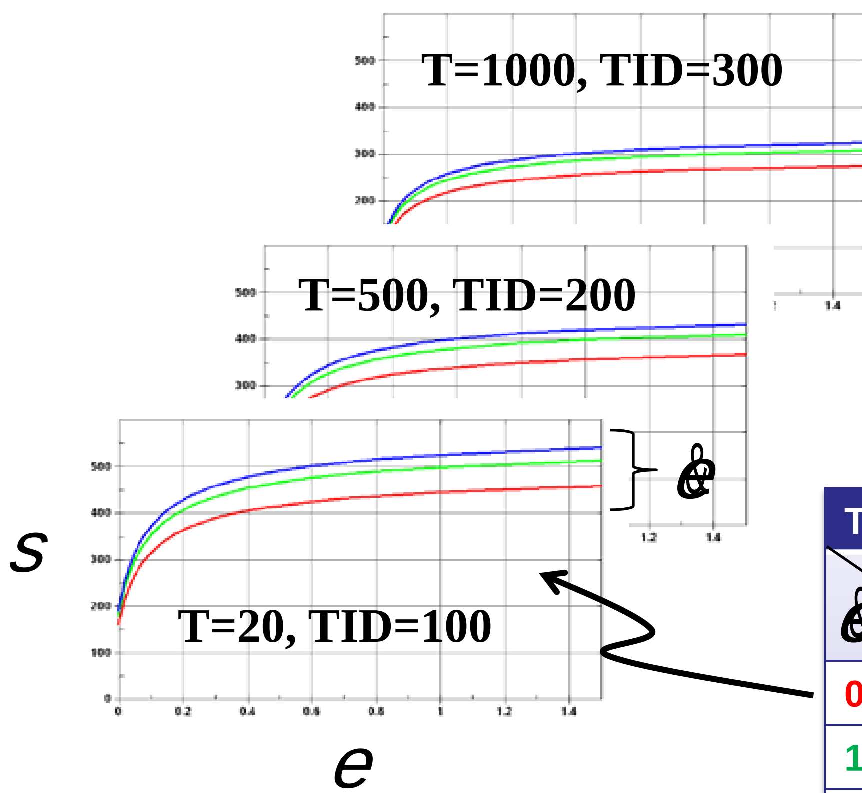
The same curve ID to be referenced by multiple tables, and the curves may be defined anywhere in the input file.

*DEFINE_TABLE_3D

A table ID is specified for each abscissa value defined for the 3d table

*Define_table_3d

Consider a thermal material model. For each temperature, T, we have a table of hardening curves of stress versus strain at 3 strain ε $\dot{\varepsilon}$ rates, i.e, $\sigma = f(\ ,\ , T)$



T=1000

$\dot{\varepsilon}$ \ ε	**0.0**	**0.1**	**0.4**	**1.0**
0.1	98	190	244	268

T=500

$\dot{\varepsilon}$ \ ε	**0.0**	**0.1**	**0.4**	**1.0**
0.1	130	253	325	357

T=20

$\dot{\varepsilon}$ \ ε	**0.0**	**0.1**	**0.4**	**1.0**
0.1	**σ = 162**	**σ = 316**	**σ = 406**	**σ = 446**
1.0	182	354	455	500
10.	192	373	479	527

*DEFINE_TABLE_{2,3}D Example

```
*DEFINE_TABLE_3D
$    tbid
    2000
$       temperature   tbid
               20.    100
               500.    200
              1000.    300
*DEFINE_TABLE_2D
$    tbid
     100
$       strain_rate   lcid
               0.1    101
                1.0    102
               10.0    103
*DEFINE_CURVE
$    lcid
     101
$             strain   stress
               0.0    162
                1.0    446
```

For each temperature, we specify a table with 3 strain rates

For each strain rate, we specify a curve of s vs e

*MAT_ADD_EROSION

- New failure criteria added

  EPSEFF – Effective in-plane strain for cohesive elements

  LCFLD – Forming Limit Diagram curve for shell elements

  EPSTHIN – Thinning strain to failure for shell elements

- New GISSMO features added

  LCSDG – Failure as function of triaxiality and Lode parameter

  LCSRS – Failure as function of plastic strain rate

  SHRF, BIAXF – Reduction factors for regularization

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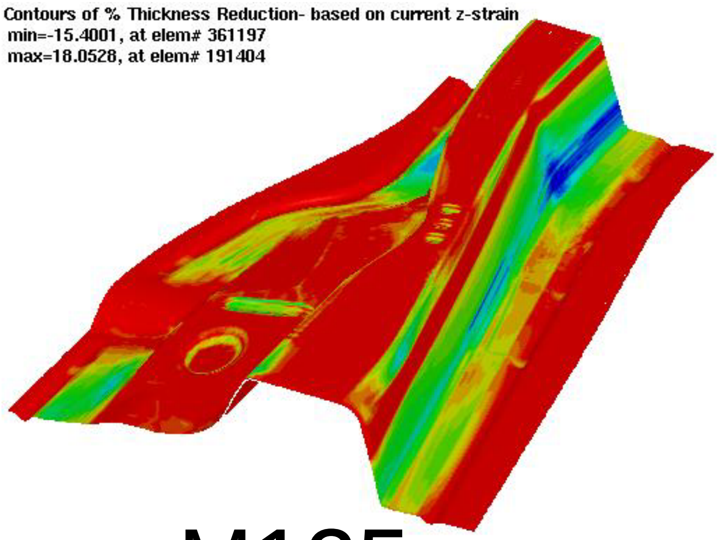
Technology Corp.

*Mat_kinematic_hardening_barlat89 (Mat 226)

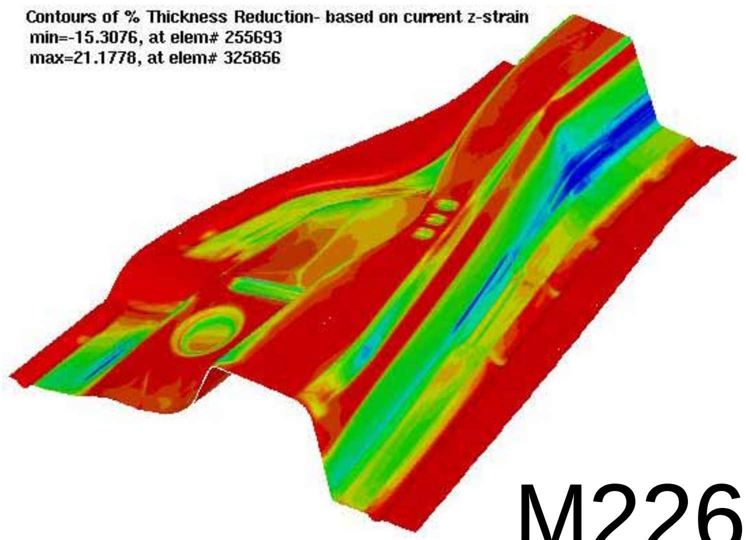
- Background
  - Yoshida's non-linear kinematic hardening has been found to be very important for high-strength steel and aluminum
  - Mat_125 (Yoshida's hardening + Hill's yield surface)
    - Is suitable for many high strength steels
    - Needs improvement for aluminum
  - Barlat 89 yield surface is more suitable for aluminum
    - It is natural to combine Barlat89 yield surface with Yoshida's non-linear kinematic hardening

*Mat_kinematic_hardening_barlat89 (Mat 226)

- M125 and M226 give similar predictions of thickness changes
  - NUMISHEET'05 Xmbr – AL5182



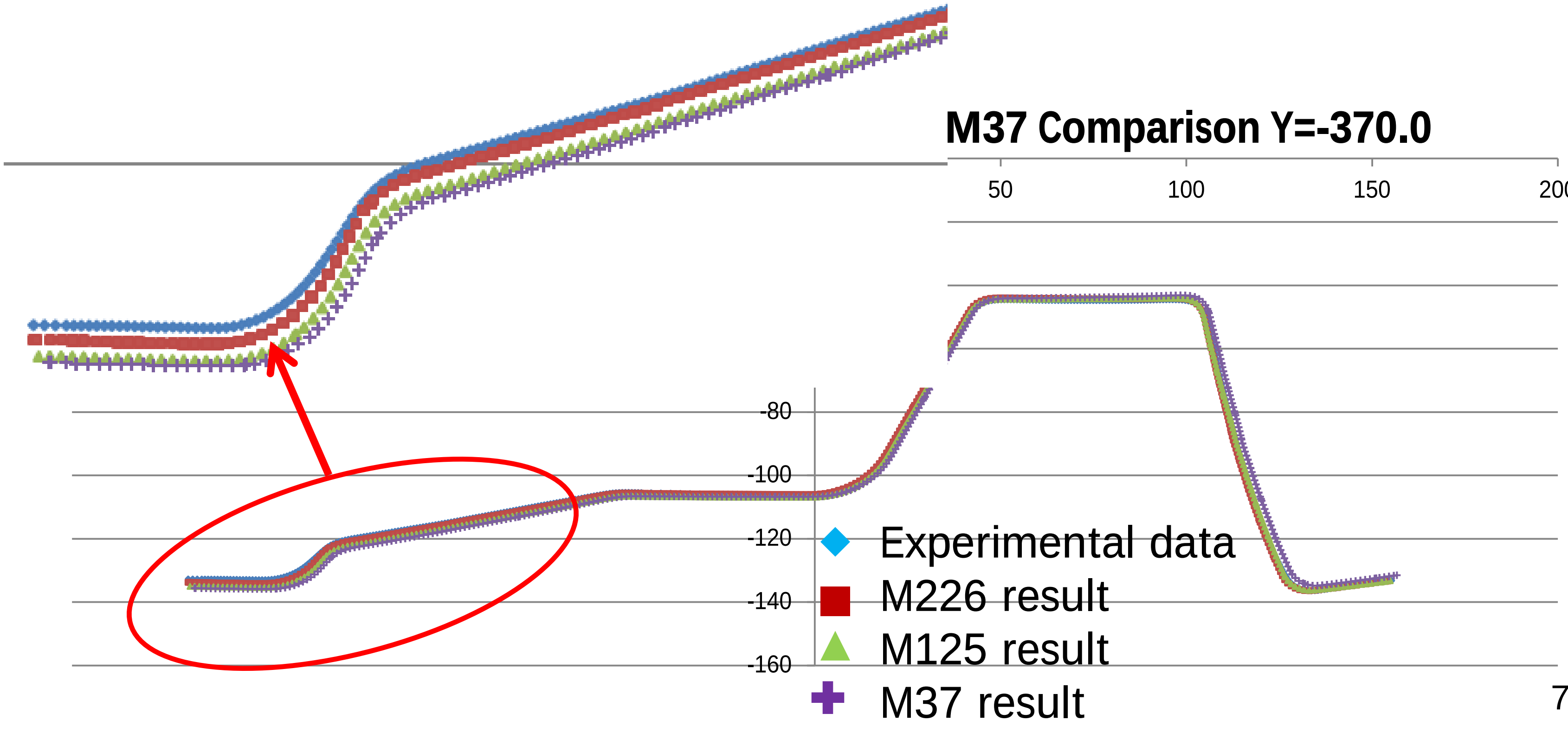
M125



M226

*Mat_kinematic_hardening_barlat89 (Mat 226)

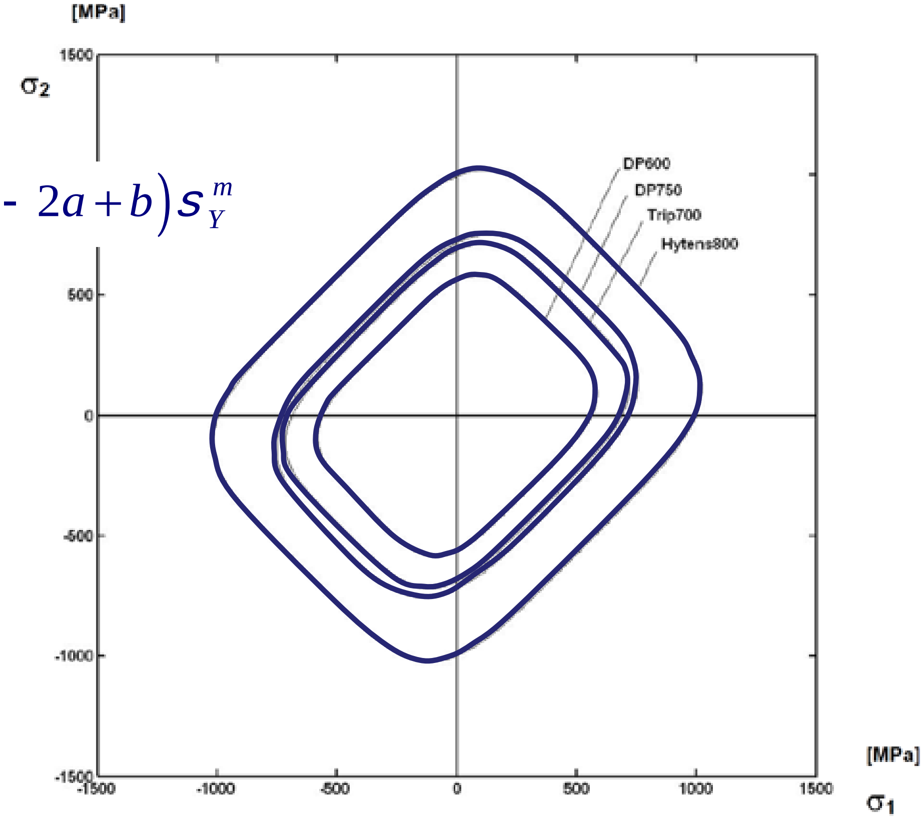
- M226 gives the best springback prediction – AL5182



*MAT_HILL_90

- New material model for forming simulations, e.g. aluminum

- Features **anisotropic yield criterion** of Hill (1990)



$$F = K_1^m + K_3 \cdot K_2^{(m/2)-1} + c^m \cdot K_4^{m/2} = \left(1 + c^m - 2a + b\right)\sigma_Y^m$$

$$K_1 = \left|\sigma_x + \sigma_y\right|$$

$$K_2 = \left|\sigma_x^2 + \sigma_y^2 + 2\sigma_{xy}^2\right|$$

$$K_3 = -2a\left(\sigma_x^2 - \sigma_y^2\right) + b\left(\sigma_x - \sigma_y\right)^2$$

$$K_4 = \left|\left(\sigma_x - \sigma_y\right)^2 + 4\sigma_{xy}^2\right|$$

- Available for **shell elements**

- Supports all options of widely used *MAT_3-PARAMETER_BARLAT

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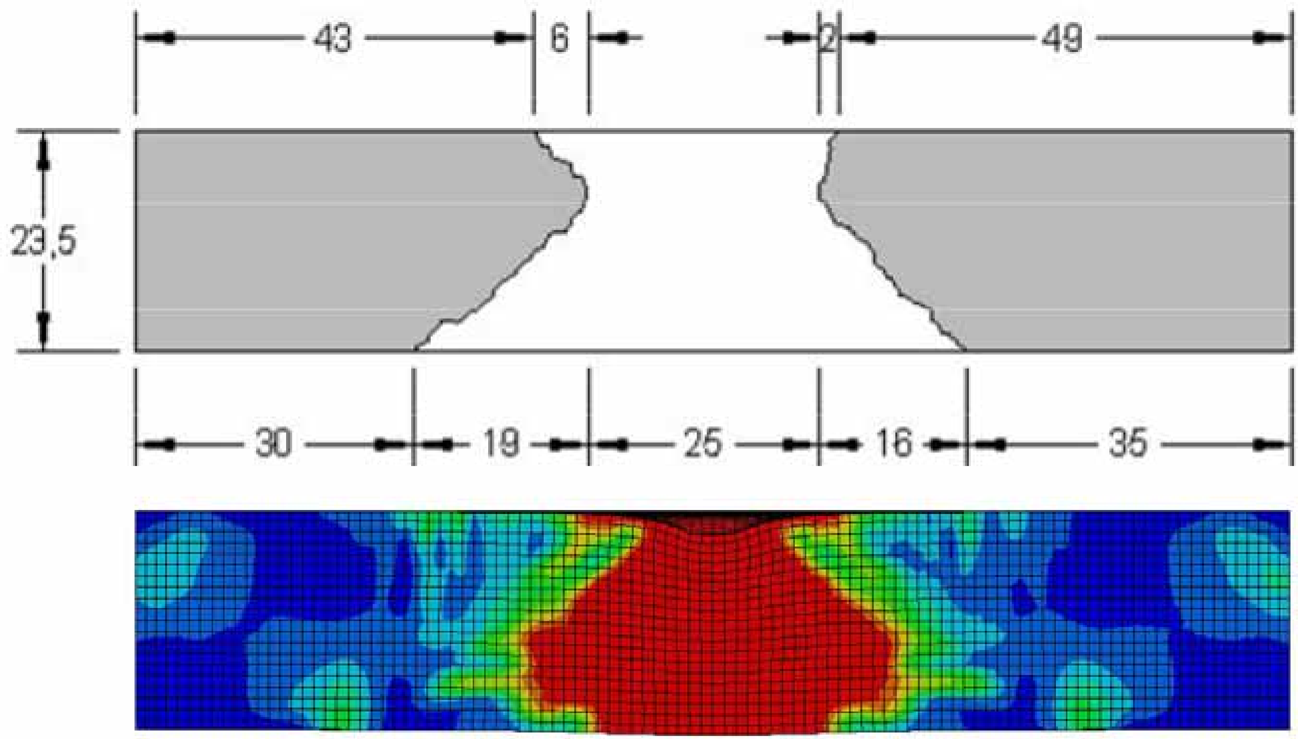
*MAT_RHT (*MAT_272)

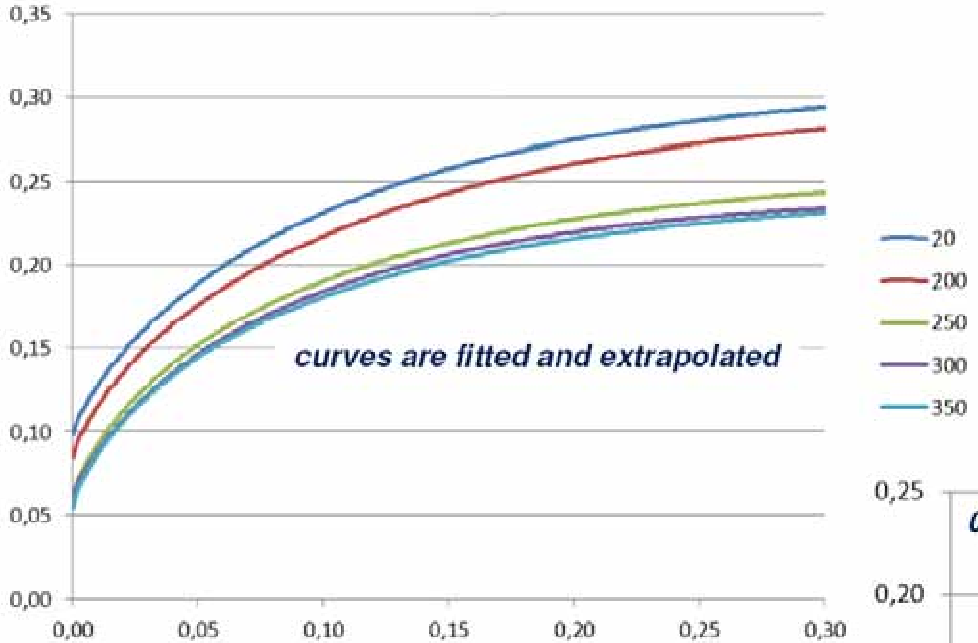
- Based on works of Riedel, Hiermaier and Thoma
- Concrete model featuring
  - Pore crush
  - Meridian dependence
  - Strain rate effects
  - Three curve formulation
    - Yield surface
    - Failure surface
    - Residual surface

Contact detonation

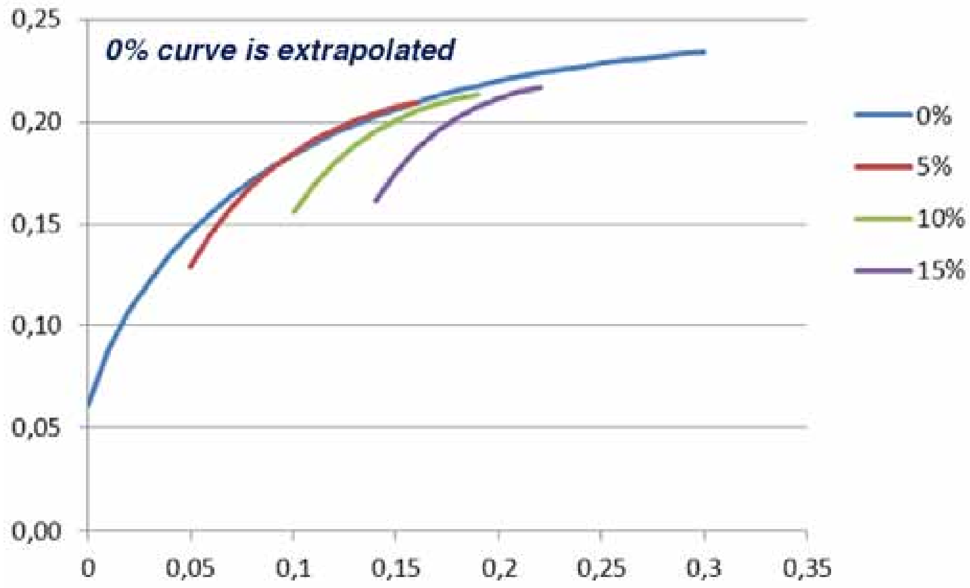


- Cross sectional view of concrete block after subjected to close range detonation
- Damage fringed and compared with experiment

Heat treatment in materials 36 & 133



- Hardening curves at different temperatures
- Component prestrained, heated and cooled



- Yield stress reduced but hardening increased
- Enhanced formability

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Mullins effect in *MAT_077

- For modelling hysteresis in rubber
- Hysteresis controlled via a table *D* giving damage as function of current and peak elastic energy

$$\mathbf{S} = D(W_{\mathrm{dev}}, \overline{W}_{\mathrm{dev}}) \frac{\partial W_{\mathrm{dev}}}{\partial \mathbf{E}} + \frac{\partial W_{\mathrm{vol}}}{\partial \mathbf{E}}$$

- Damage table determined from cyclic compression tests
- Used for accurate estimation of HIC value in pedestrian impact

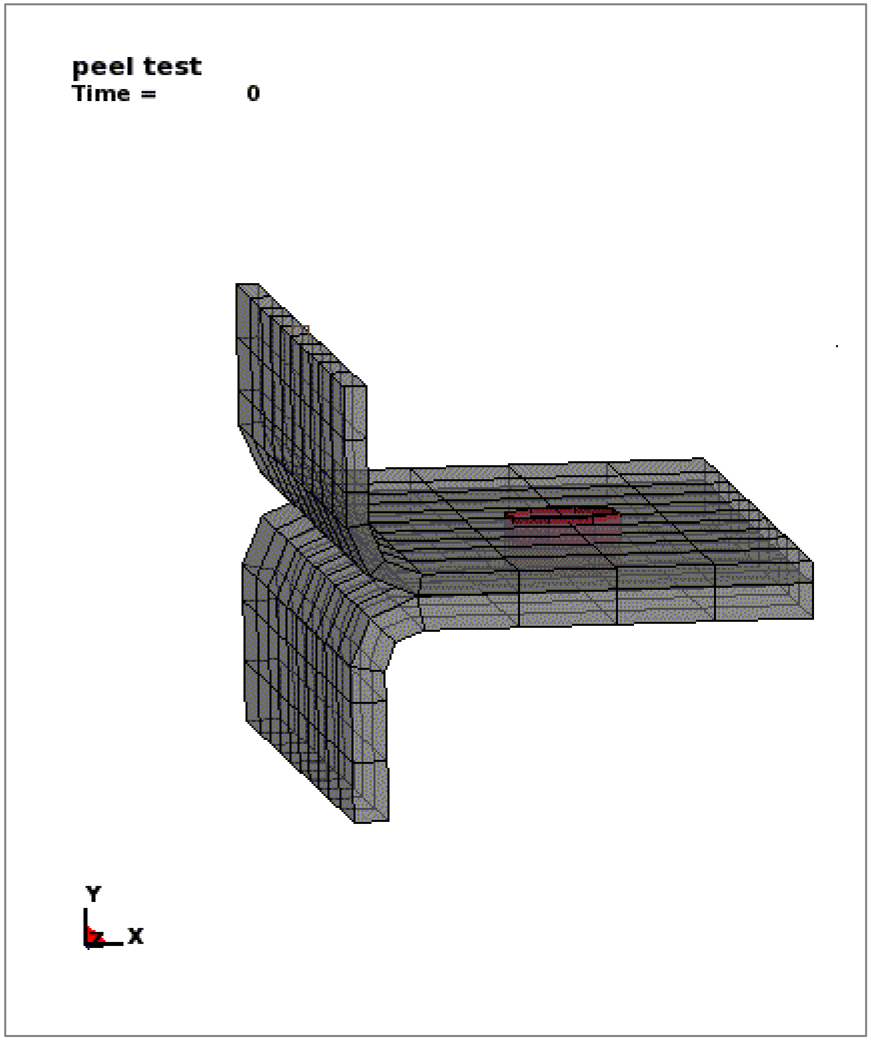
Eight-chain rubber model (*MAT_267)

- A new advanced rubber model is available in LS-DYNA R6.
- Based on the standard (*mat_127) model but enhaced with the following features:
  - For solids and explicit simulations only.
  - Includes general Hill plasticity, Kinematic hardening, Visco-plasticity (4 types), Visco-elasticity (2 types) and Mullin’s effect (2 types).

*CONSTRAINED_SPR3

(or *CONSTRAINED_INTERPOLATION_SPOTWELD)

- Visualization by beam elements
- Output to SWFORC will be implemented soon



*CONSTRAINED_SPR3

§ Two shell element meshes are connected via a constrained model

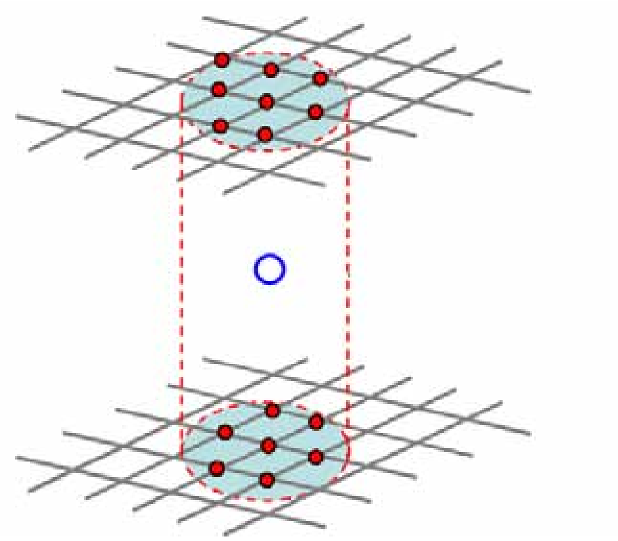
§ Free node between both parts defines center of the connection

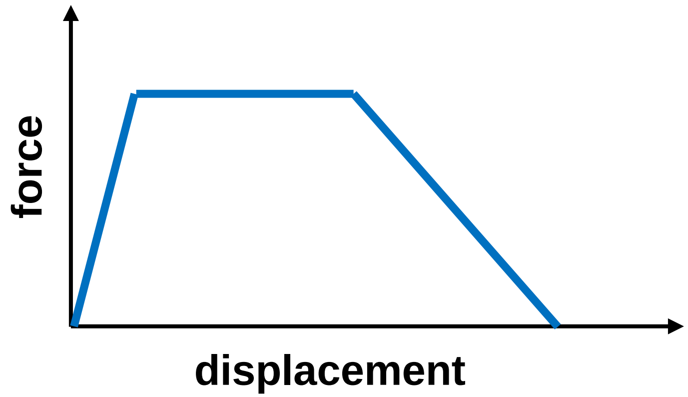
§ Shell nodes inside domain of influence (e.g. spotweld radius) are involved

§ Relative deformation between both parts through interpolation

§ Plasticity-damage model with failure

§ Forces and moments distributed to corresponding shell nodes





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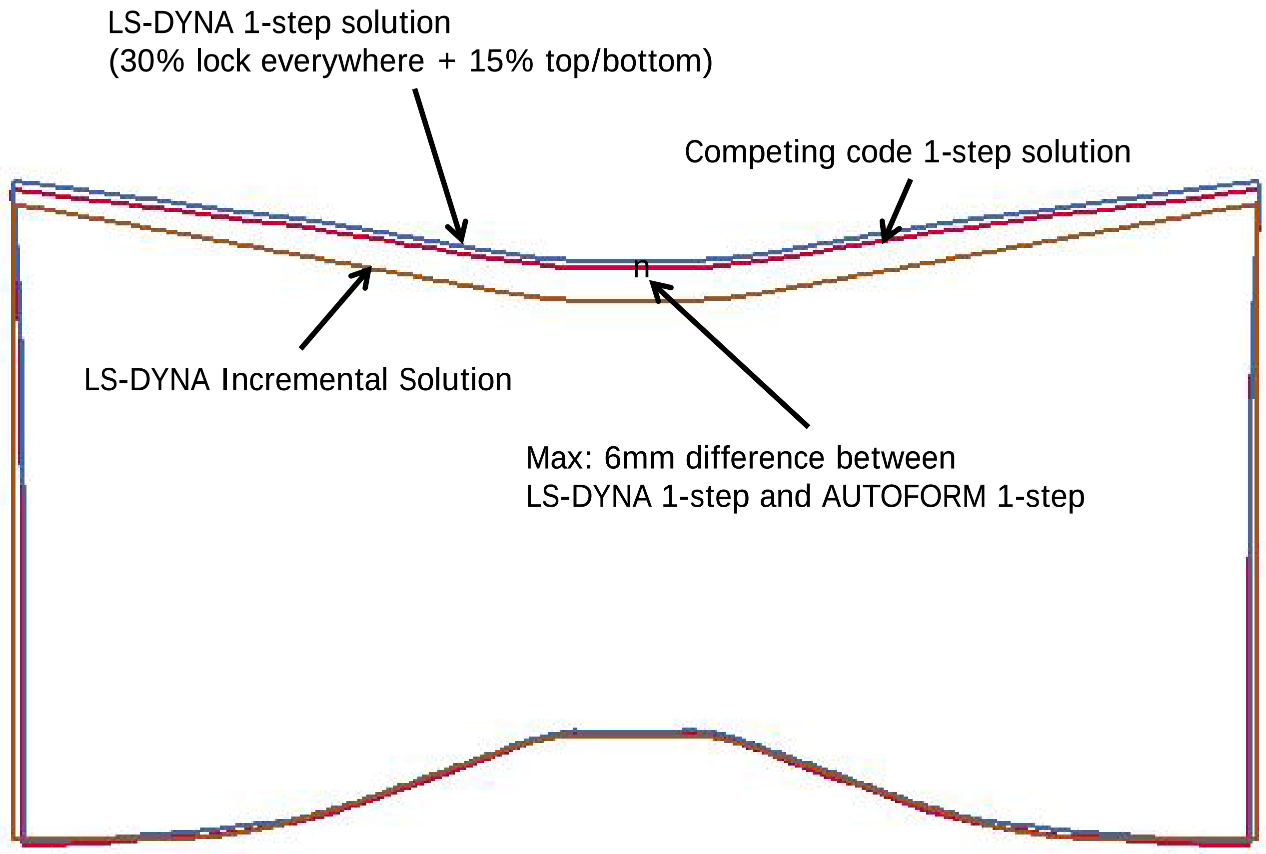
One step solution

- Keyword: ***CONTROL_FORMING_ONE_STEP**
- Purpose:
  - For forming simulations:
    - Determine initial blank size
    - In the feasibility phase, approximately predict the formability
  - For crash simulations:
    - It can provide approximate thickness and plastic strain distributions to improve simulation accuracy
- Characteristics of the one-step solver:
  - Triangular and quadrilateral shell elements are supported
  - Complex parts are handled,
    - including parts with under-cuts
  - Friction and drawbead definitions are considered

One step solution



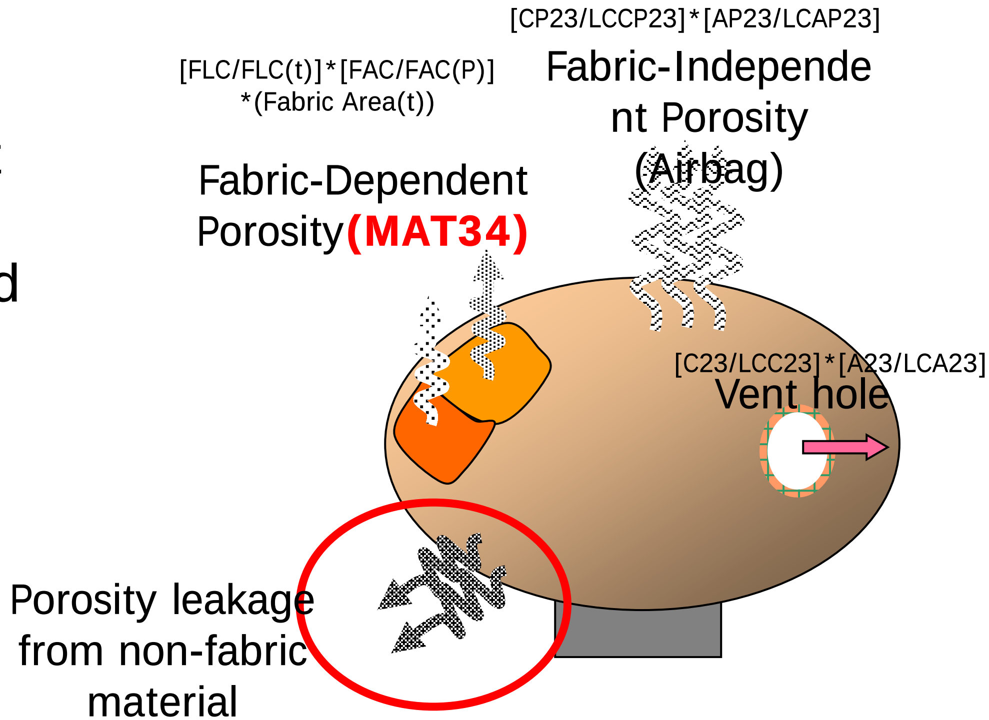
Initial Blank Size Prediction

Porosity leakage for non-fabric

- *MAT_ADD_AIRBAG_POROSITY_LEAKAGE

Variable	MID	FLC/X2	FAC/X3	ELA	FVOPT	X0	X1

- Allows users to model porosity leakage through non-fabric material when such material is used as part of control volume
- Applies to both airbag_hybrid and airbag_Wang_Nefske
- Application includes pyrotechnic device design, where non-fabric material is used to model a control volume and leakage through area-dependent leakage has to be considered.



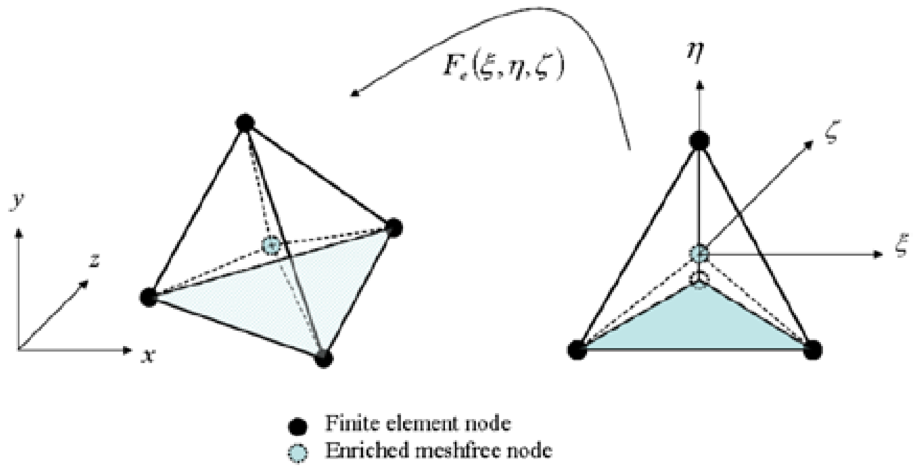
*Set_xxxx_intersect

- Define a set as the intersection, ∩, of a series of specified sets. The new set, SID, contains the common elements of all named sets.
- Applies to:
  - *SET_BEAM
  - *SET_NODE
  - *SET_SEGMENT
  - *SET_SHELL
  - *SET_SOLID

*New element formulation for implicit analysis of rubber-like materials

Meshfree - enriched finite element formulation

- A purely displacement-based finite element formulation.
- Enriched with a meshfree node in tetrahedral element.
- Easy to be incorporated with existing finite element model
  Volumetric locking-free



Isoparametric mapping in the 5-noded meshfree-enriched tetrahedral element

Wu, C. T. and Hu, W. (2011), "Meshfree-enriched Simplex Elements with Strain Smoothing for the Finite Element Analysis of Compressible and Nearly Incompressible Solids", Computer Methods in Applied Mechanics and Engineering, Vol. 200, pp. 2991-3010.

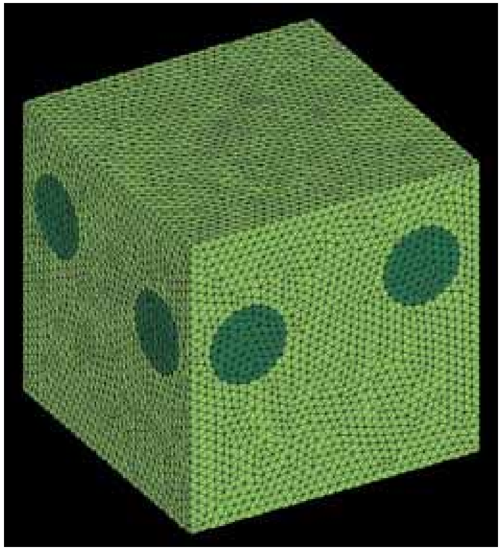
*New element formulation for implicit analysis of rubber-like materials

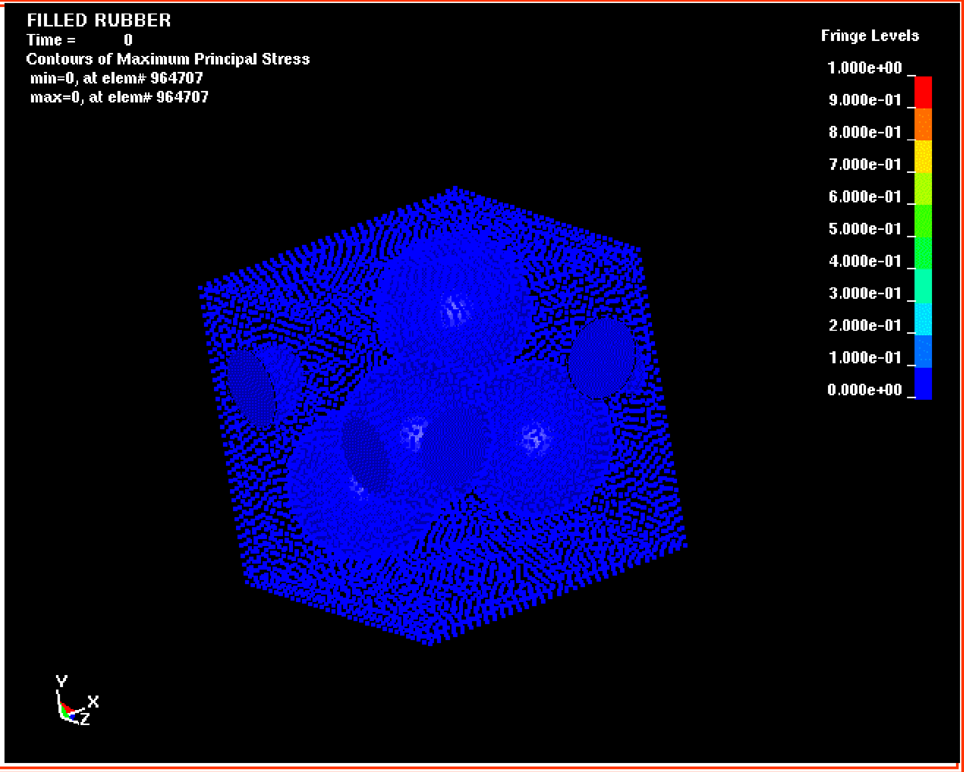
*SECTION_SOLID

Variable	SECID	ELFORM	
Type	I	I	

ELFORM EQ.43: meshfree-enriched finite element formulation

Large deformation analysis of microscopic particle-reinforced rubber compound

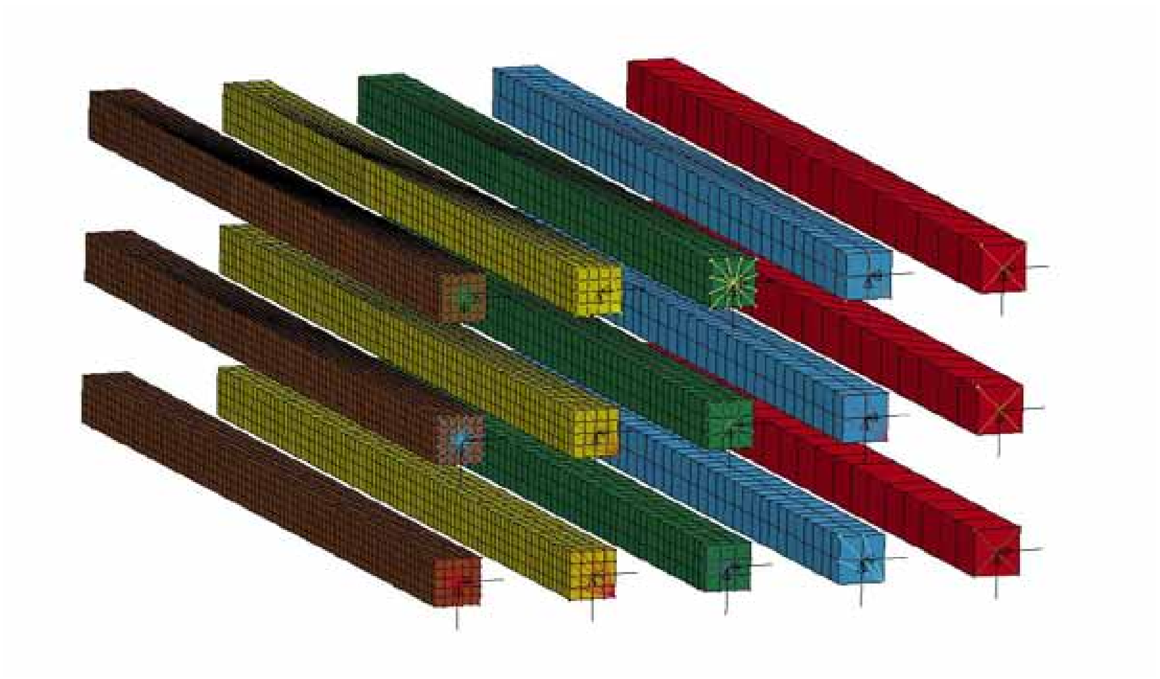




Cosserat point hexahedron

- Brick element using Cosserat Point Theory
- Implemented as solid element type 1 with hourglass type 10
- Hourglass is based on a total strain formulation
- Hourglass constitutive coefficients determined to get correct results for
  - Coupled bending and torsion
  - High order hourglass deformation
  - Skewed elements

Cosserat point hexahedron



- Tip loaded cantilever beam
  - 5 mesh size levels (H=10, 5, 3.33, 2.5, 2 mm)
  - 3 distortion levels (a=-20, 0, 20 mm)
  - 2 load cases (horizontal (H) and vertical (V))
- Analytical tip displacement 0.21310 mm

Cosserat point hexahedron

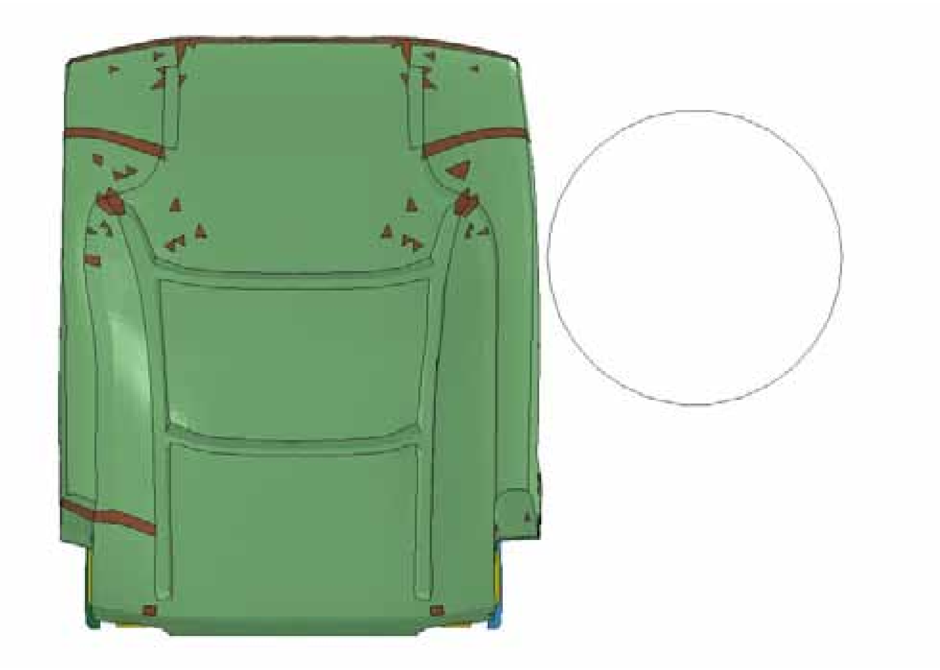
Cosserat	Belytschko-Bindeman	Puso
1.7%	61.8%	24.8%
0.8%	46.8%	14.7%
0.6%	40.0%	14.5%
0.3%	39.8%	9.2%
0.2%	33.9%	8.5%
0.2%	27.0%	6.2%
0.1%	24.6%	5.3%
0.1%	22.3%	3.6%
0.1%	19.0%	0.9%
0.1%	15.4%	0.3%

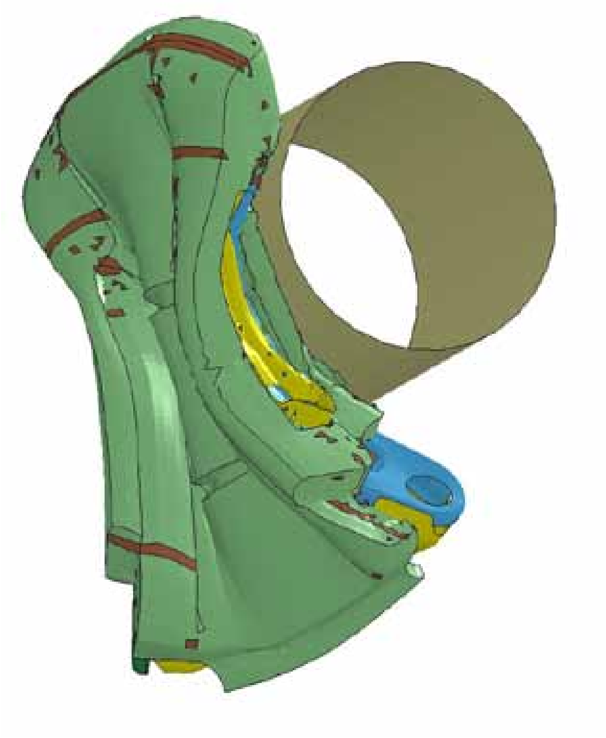
- Worst errors for three hourglass formulations

Single point pentahedron

- Implemented as element type 115
- Supports Flanagan-Belytschko viscous and stiffness hourglass types
- Presumably more robust than the 2 point integrated pentahedron element
- Degenerated single point hexahedron elements are sorted to type 115
- Supported for implicit calculations

Seat impact





Robustness enhanced when pentahedron elements (depicted in brown) are run with element type 115 compared to element type 15

Miscellaneous

- Selective mass scaling now supports
  - Geometric rigid walls
  - Constraint based contacts
- Hardening laws implemented in materials 36 and 133
  - Gosh and Hocket-Sherby hardening
  - TRansformation Induced Plasticity (TRIP) hardening
  - Young’s modulus as function of plastic strain in material 133
- Mortar contact supports
  - Initial penetration check
  - Ignore option
  - Proper edge to edge contact, edges treated as flat surfaces

ALE

Recent developments

- Modified *EOS_JWL to get correct cavitation effect
- Variable FSI friction based on relative interface velocity
- Implemented in 2D and 3D
  - ALE static adaptive
  - ALE dynamic adaptive

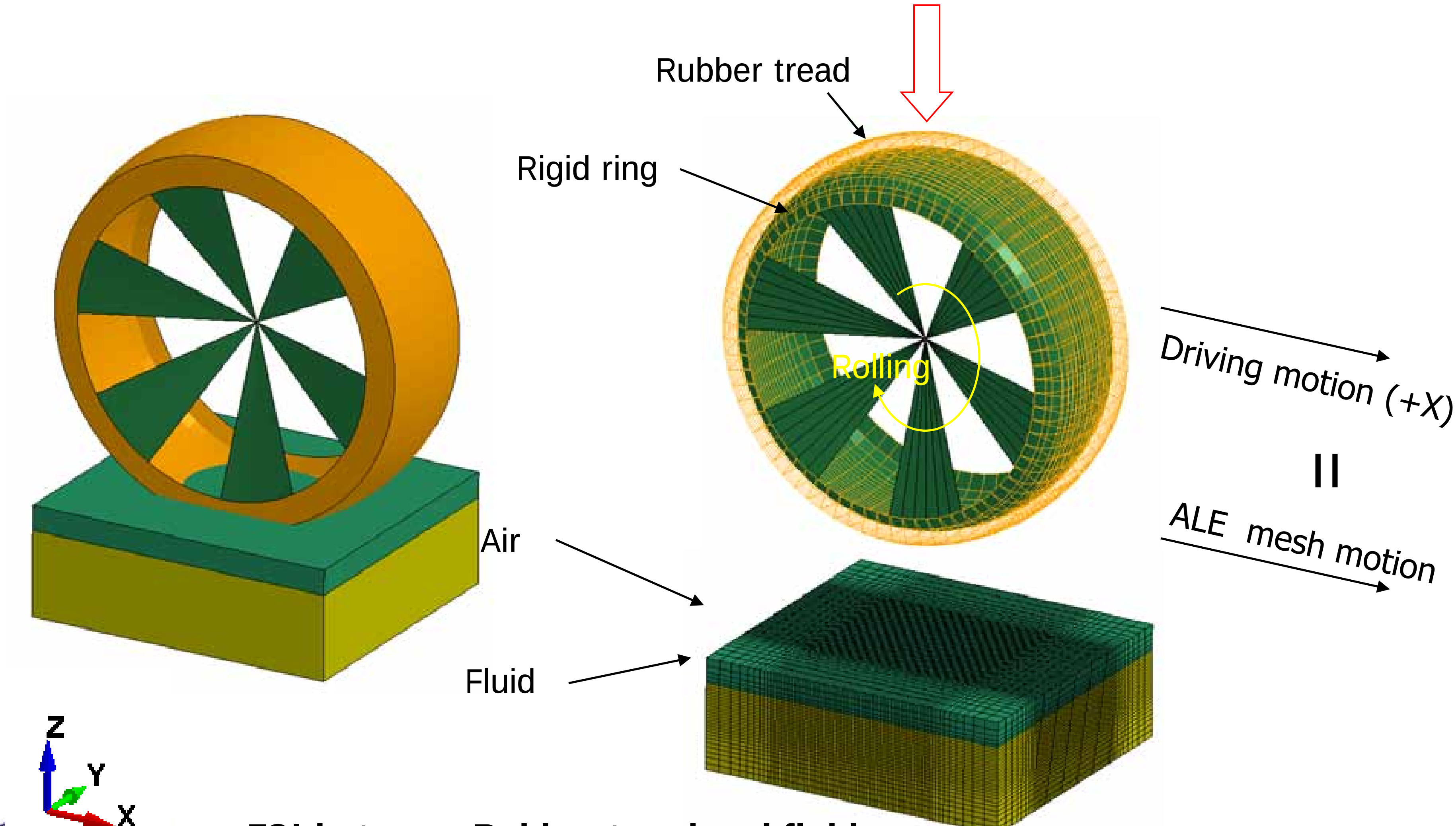
Variable FSI Friction

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
		PFAC	FRIC	FRCMIN	NORM	NORMTYP	
			ILEAK	PLEAK			

- Friction coefficient being a function of relative velocity and pressure.
- FRIC= -N: N the table ID
  - Abscissa: Pressure
  - Ordinate: A load curve ID specifies relative velocity versus friction coefficient.

Variable FSI Friction

*Courtesy of Shoji Oida, Bridgestone



FSI between Rubber tread and fluid

Variable FSI Friction

*Courtesy of Shoji Oida, Bridgestone

Relative interface velocity

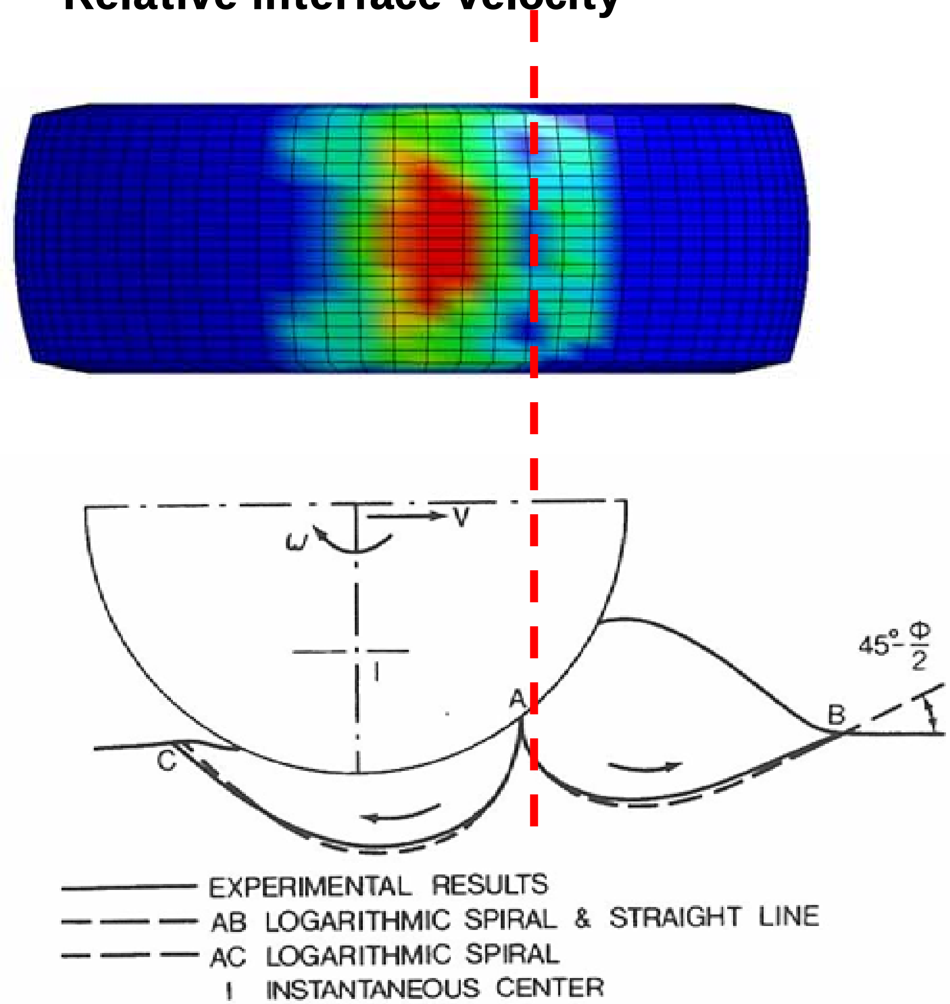
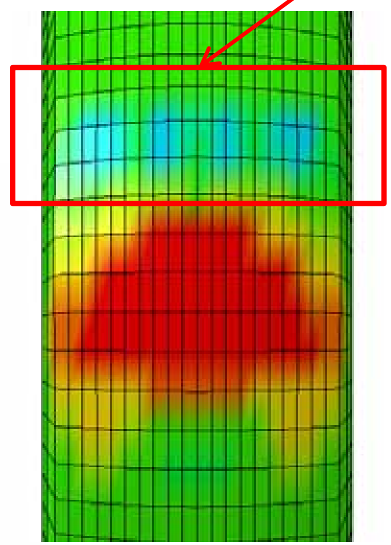


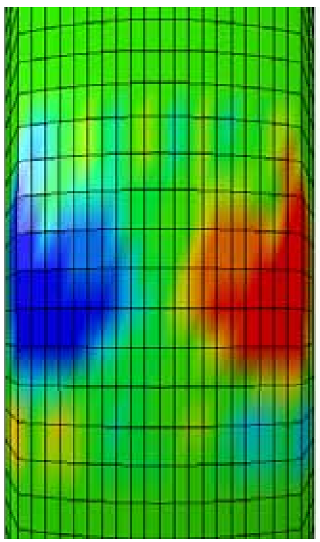
Fig. 2.19 Flow patterns and bow wave under the action of a driven roller in sand.

Ref: Theory of Ground Vehicle, 3rd ed., J. Y. Wong, 2001

Backward flow can be observed as expected.



V_x



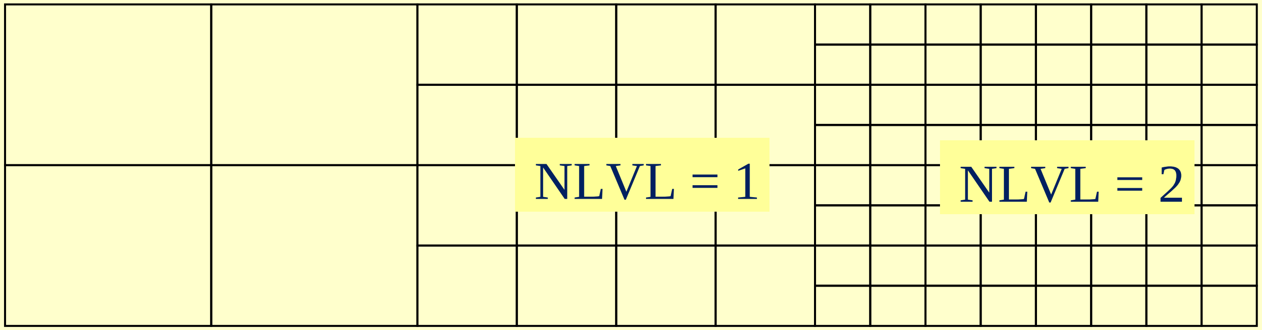
V_y

ALE static adaptive

*ALE_REFINE

Variable	SID	STYPE	MMSID	NLVL
Type	I	I	I	I

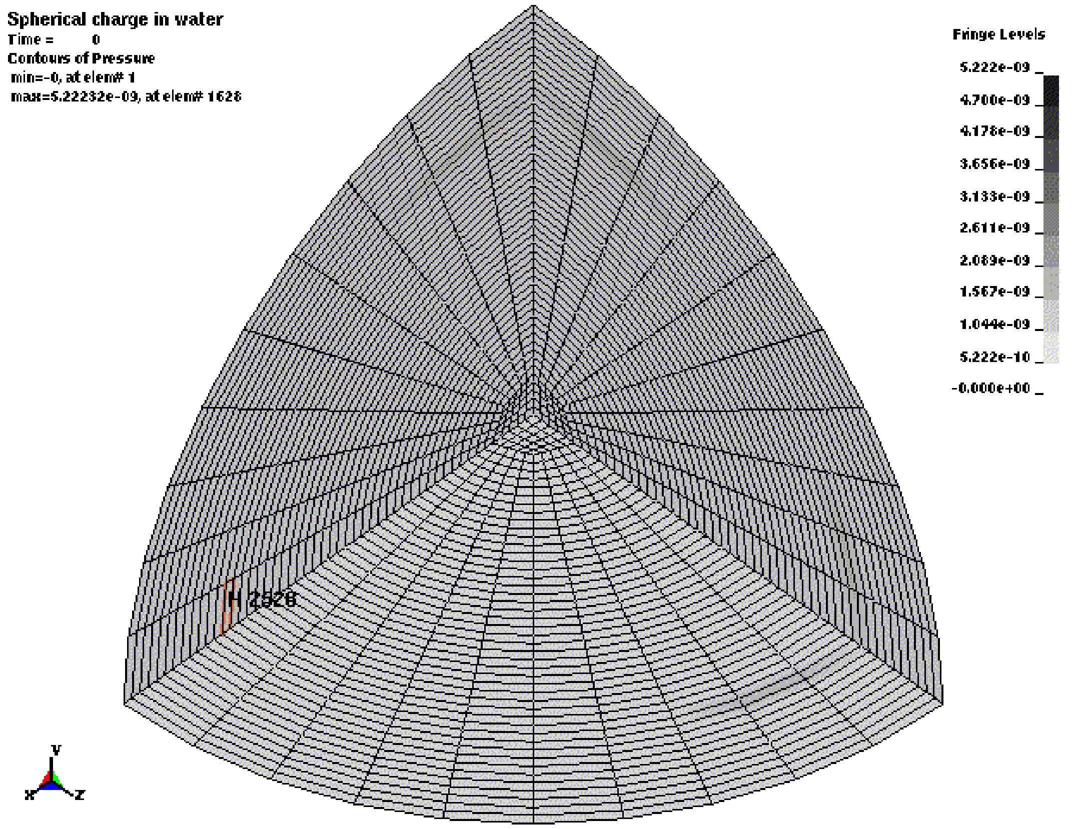
VARIABLE	DESCRIPTION
SID	Set ID. Id of a set defined by SETTYP
STYPE	Set type: ALE part set/ALE part/Part set coupled to ALE/ etc.
MMSID	Multi-Material Group Set Id GT.0: Refine ALE cells having at least one of the ALE MMG LT.0: Refine ALE cells only having mix of the ALE MMG
NLVL	Number of levels of refinement



ALE static adaptive

*ALE_REFINE

Application: Underwater explosion



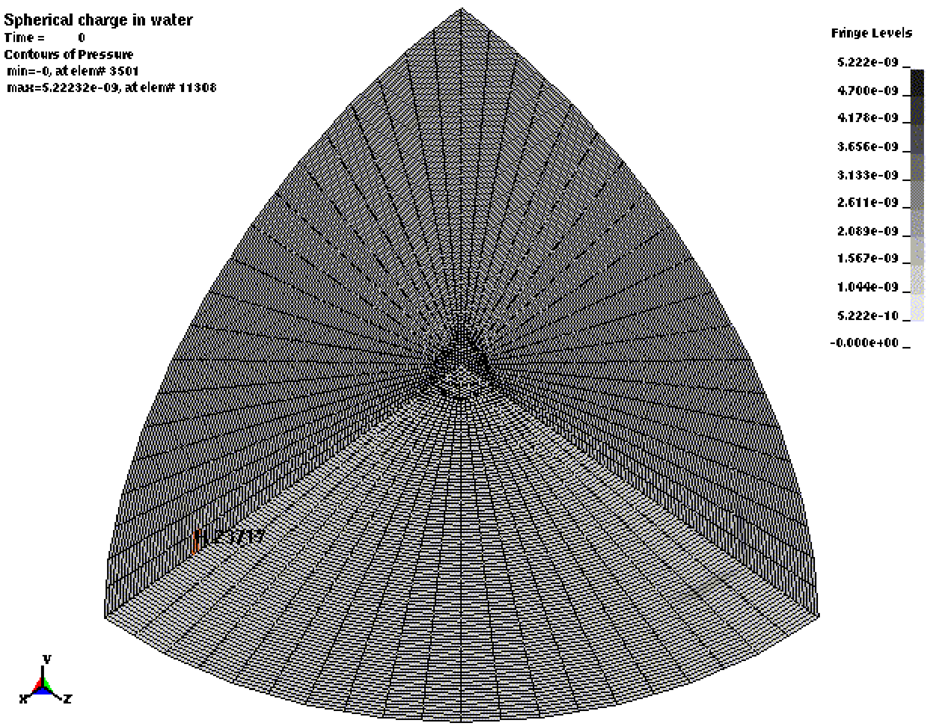
Original mesh: 11 min. 16 sec.

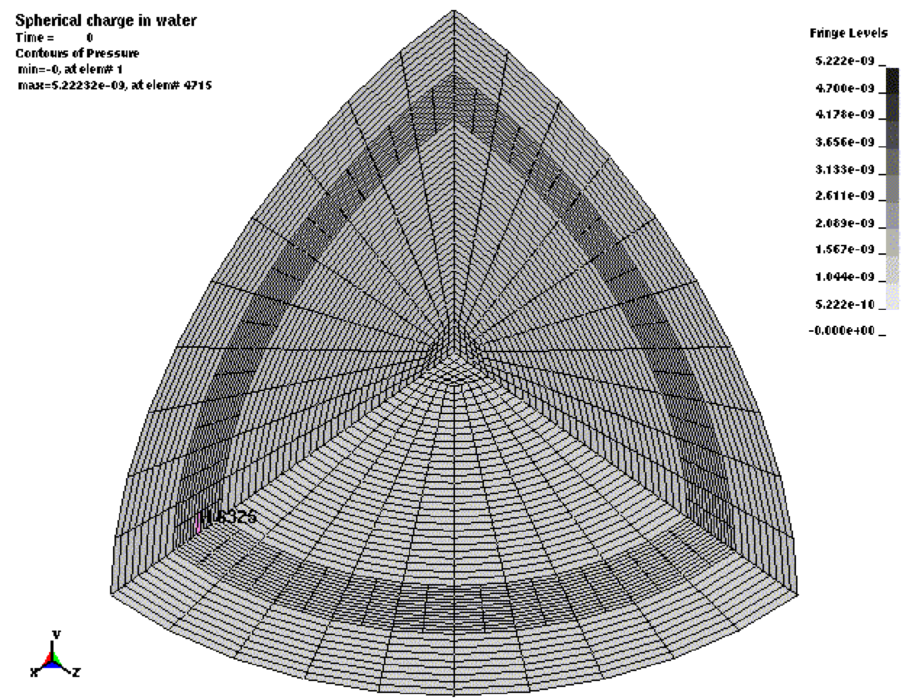
History pressure in h2528

ALE static adaptive

*ALE_REFINE

Catch better pressure front





<u>Globally refined mesh</u>: 53 min. 04 sec.

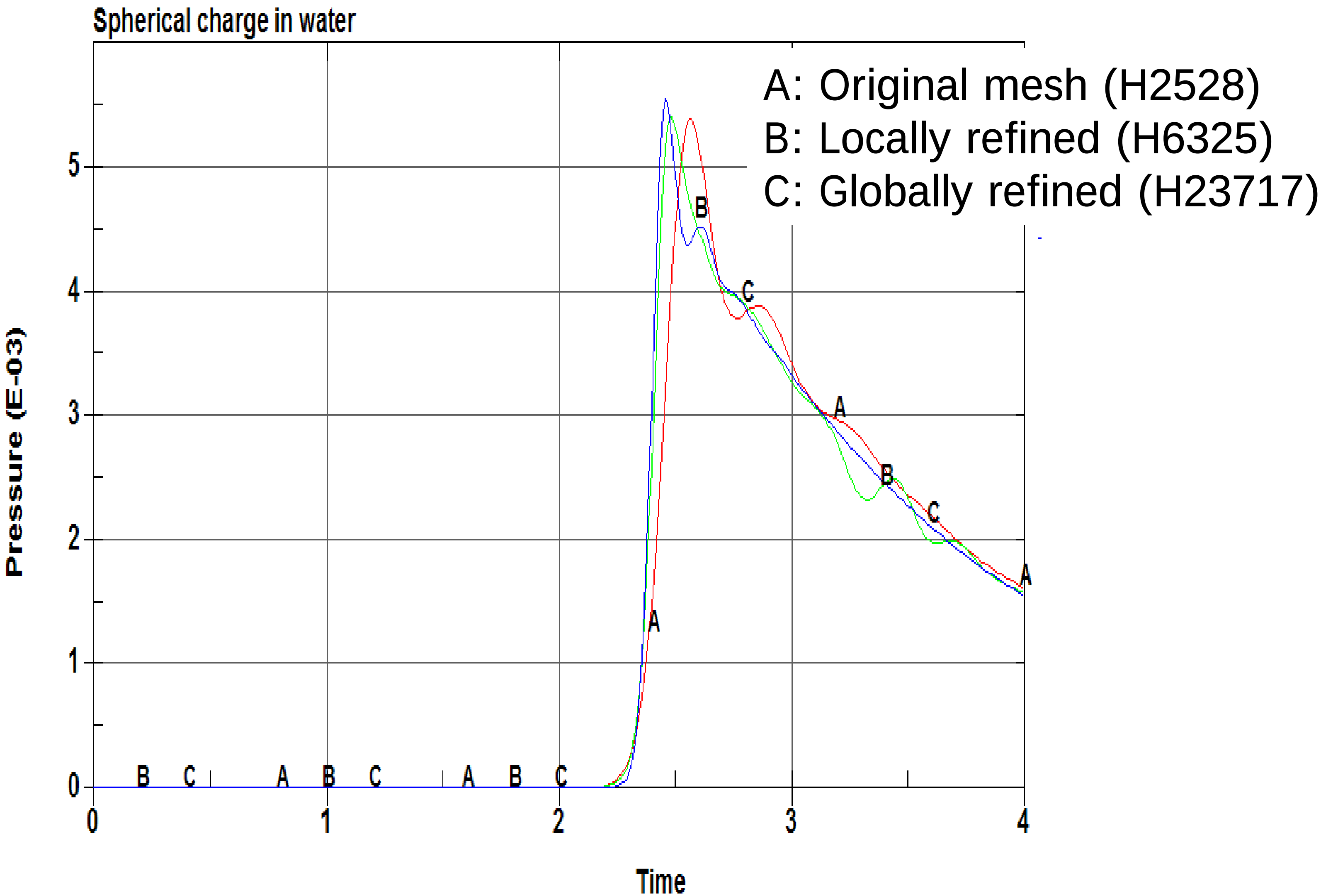
History pressure in h23717

<u>Locally refined mesh</u>: 15 min. 52 sec.

History pressure in h6325

ALE static adaptive

*ALE_REFINE



ALE dynamic adaptive

*ALE_REFINE

Purpose: The 2nd line allows to dynamically refine the ALE mesh

Variable	SID	STYPE	MMSID	NLVL
Type	I	I	I	I

Variable	NELEM	FREQ	CRITERIA	VALUE
Type	I	I	I	F

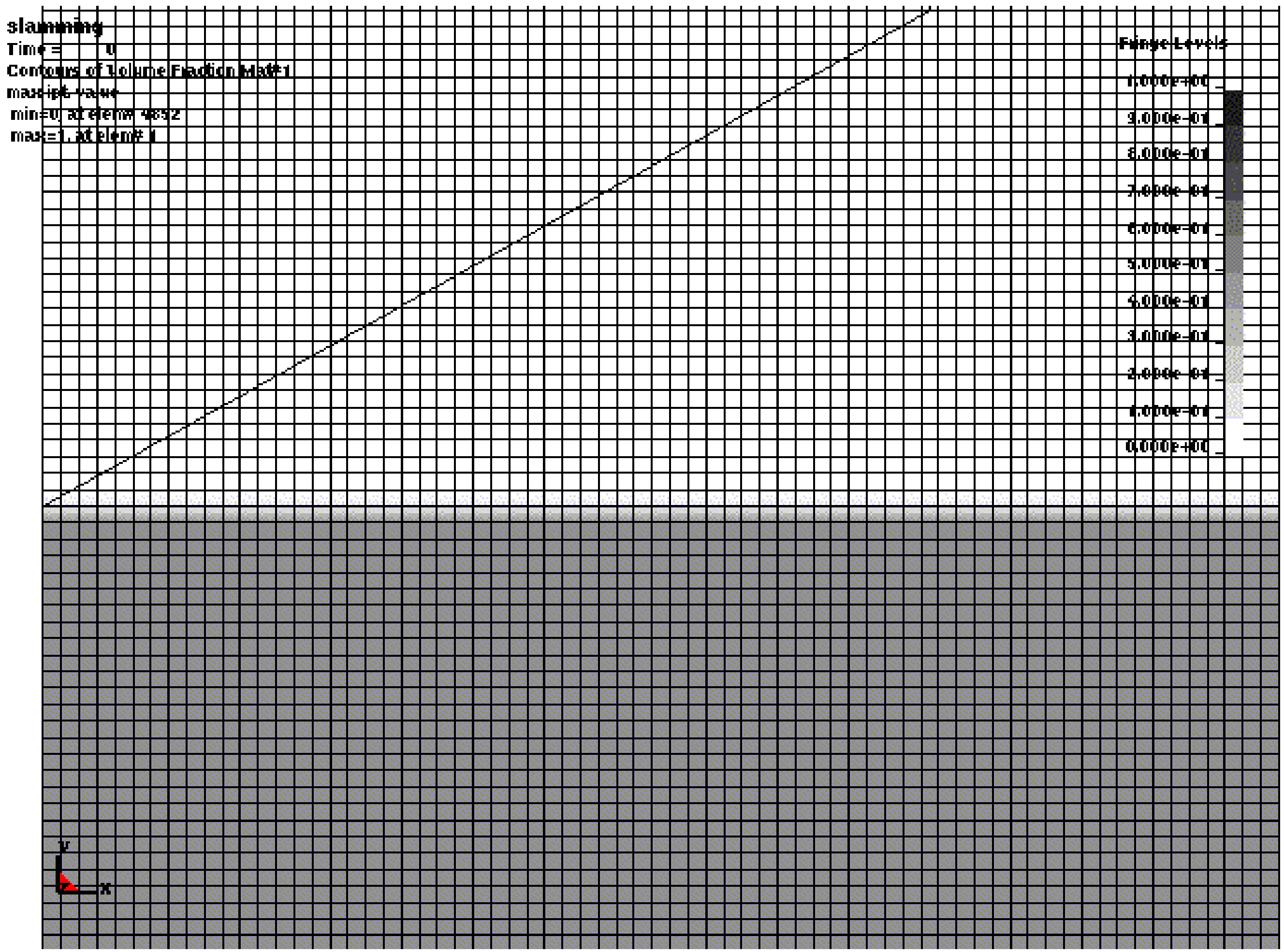
VARIABLE	DESCRIPTION
NELEM	Number of ALE elements to refine
FREQ	Number of cycles between each refinements
CRITERIA	Criteria type for the refinement: EQ.1 : Pressure EQ.2 : Divergence of velocity EQ.3 : Volume fraction
VALUE	Threshold value for mesh fission/fusion

ALE dynamic adaptive

*ALE_REFINE

Every cycle dynamically refine 300 ALE cells that:

1) coupled to the structure
2) mixed with air and water
3) volume fractions > 0.0



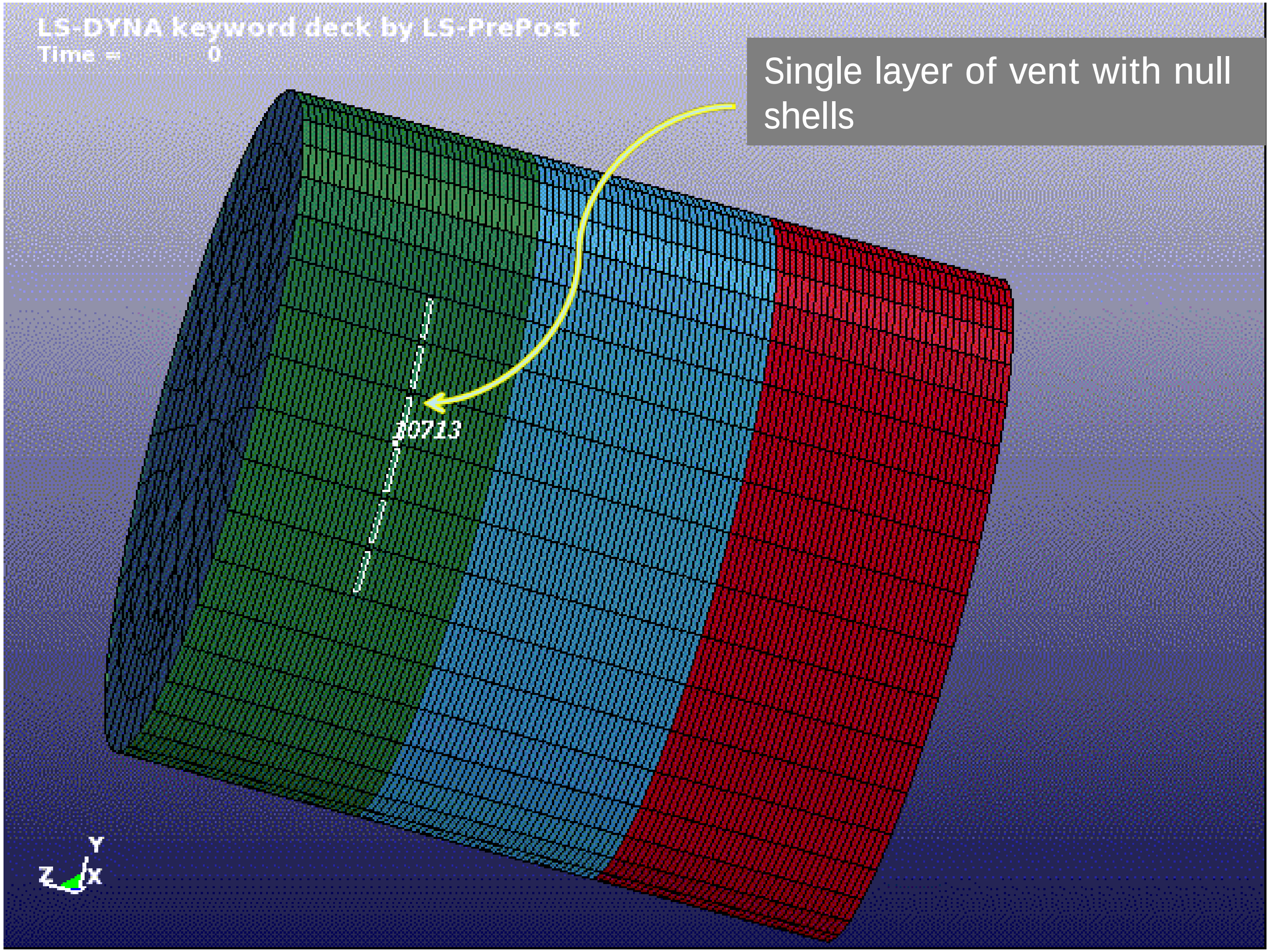
LSTC Livermore Software Technology Corp.

Performance issue using null shells to cover vent holes

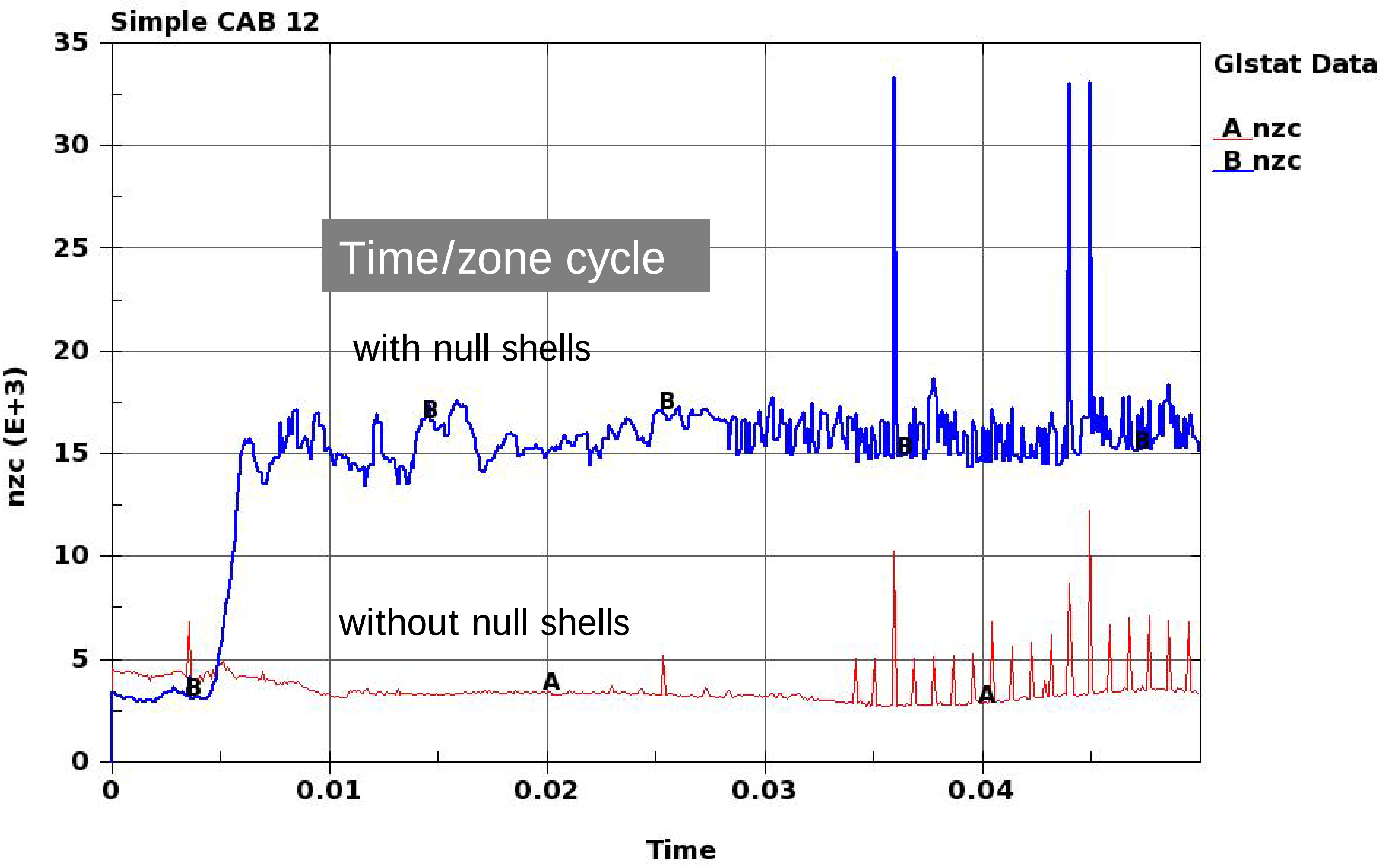
- Problem
  - Single layer to ensure the flatness around vents
  - Those elements will stretch a lot from their original geometry
  - Bucket sort region size will increase by L^3 for correct searching

- Solution
  - A multi-step bucketsort algorithm is implemented in the latest R5.1.1 and development code

Performance issue with null shells

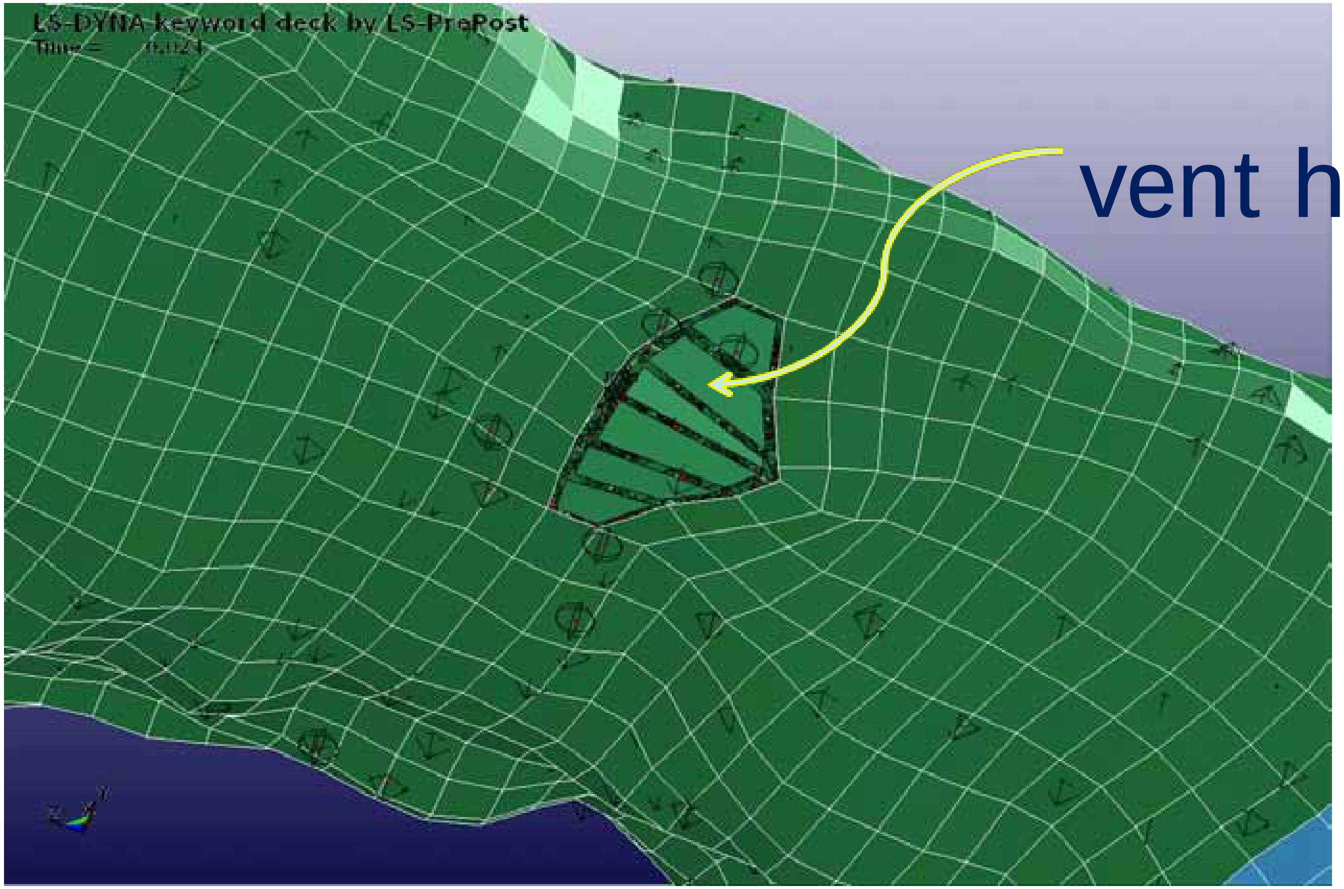


Performance issue with null shells

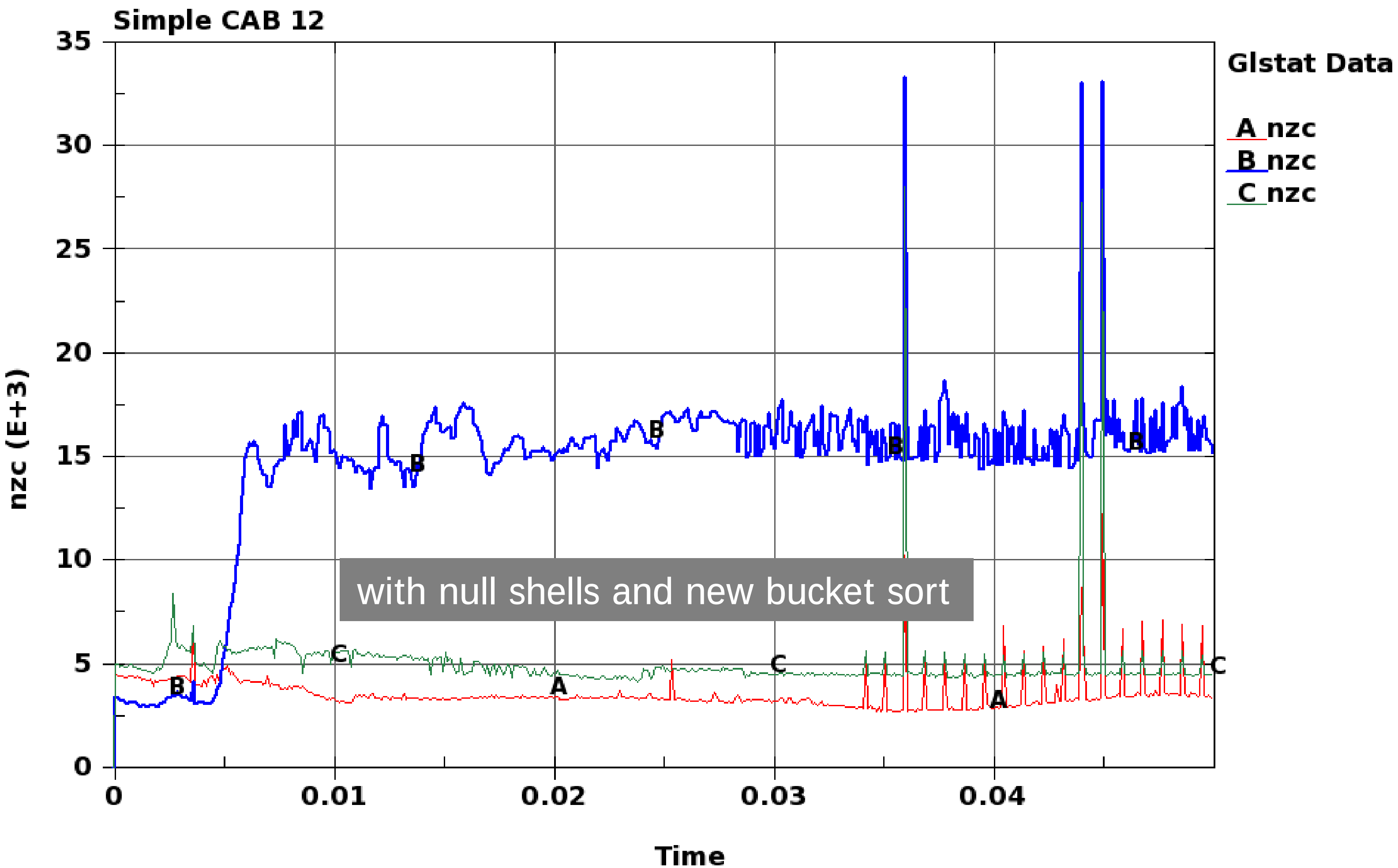


LSTC Livermore Software Technology Corp.

Performance issue with null shells

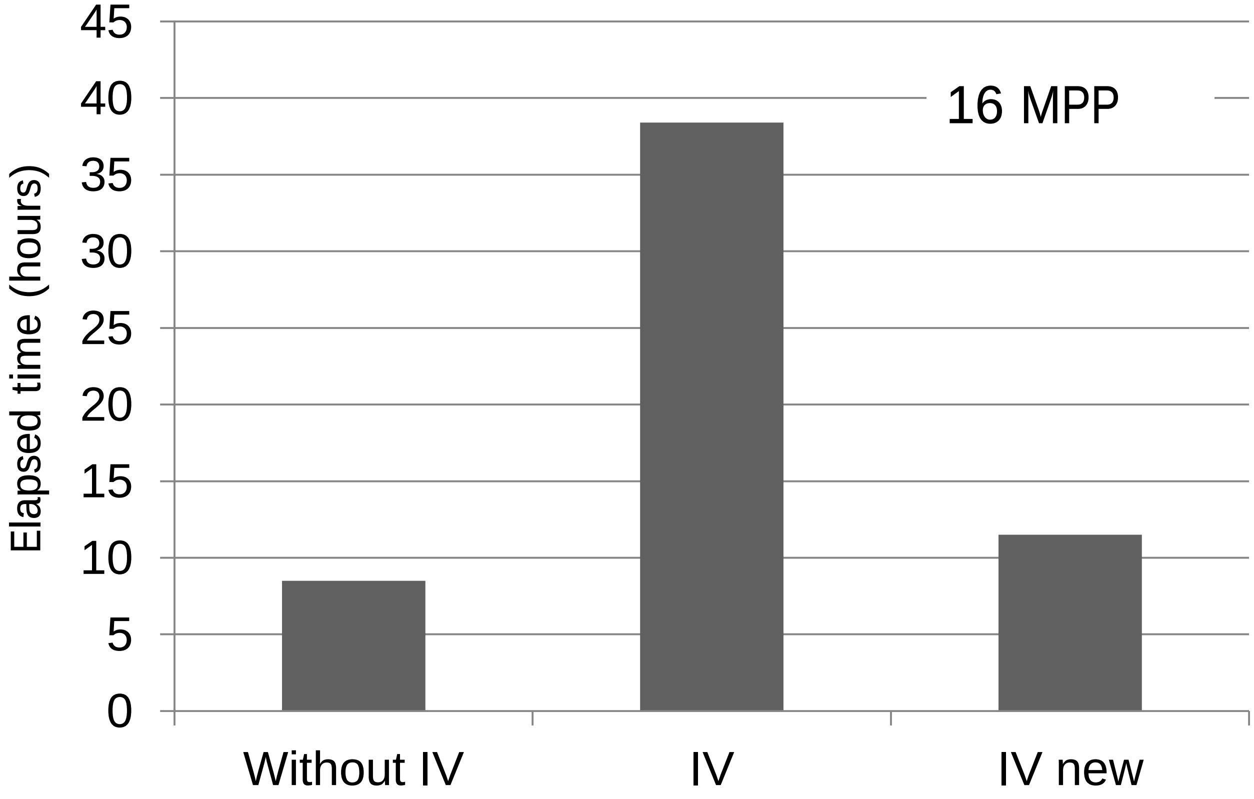


Performance issue with null shells



LSTC Livermore Software Technology Corp.

Performance issue with null shells



Implemented a new bucket sort algorithm to improve the performance – Please download the latest exe from beta site

Conclusions: Summary

- LSTC is working to be the leader in cost effective large scale numerical simulations
  - LSTC is providing dummy, barrier, and head form models to reduce customer costs.
  - LS-PrePost, LS-Opt, and LS-TaSC are continuously improving and gaining more usage within the LS-DYNA user community
  - LSTC is actively working on seamless multistage simulations in automotive crashworthiness, manufacturing, and aerospace
- The scalable implicit solver is quickly gaining market acceptance for linear/nonlinear implicit calculations and simulations
  - Robustness, speed, accuracy, and scalability have rapidly improved
  - New developments:
    - Combined implicit and explicit running together
    - Linear analysis combined with h-adaptivity

Conclusions: future

- LSTC is not content with what has been achieved
- New features and algorithms will be continuously implemented to handle new challenges and applications
  - Electromagnetics,
  - Acoustics,
  - Compressible and incompressible fluids
  - Isogeometric elements will be available soon
  - Discrete element methodology for modeling granular materials
  - Simulation based airbag folding and THUMS dummy positioning underway
- Multiscale capabilities are under development
  - Implementation underway (New approach which is more user friendly)
- Hybrid MPI/OPENMP developments are showing significant advantages at high number of processors for both explicit and implicit solutions