Structured ALE Solver

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Me

- Hao Chen, hao@lstc.com, 925-245-4552
- 1997-2002, Northwestern University, Ph.D., Computational Mechanics
- Jan 2003, joined LSTC, ALE and FSI
- Mar 2015, the new Structured ALE solver

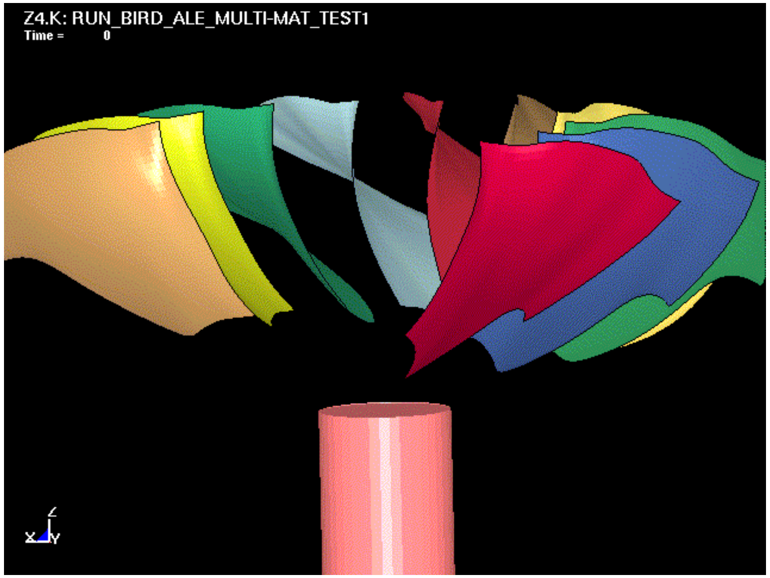
Structured ALE solver

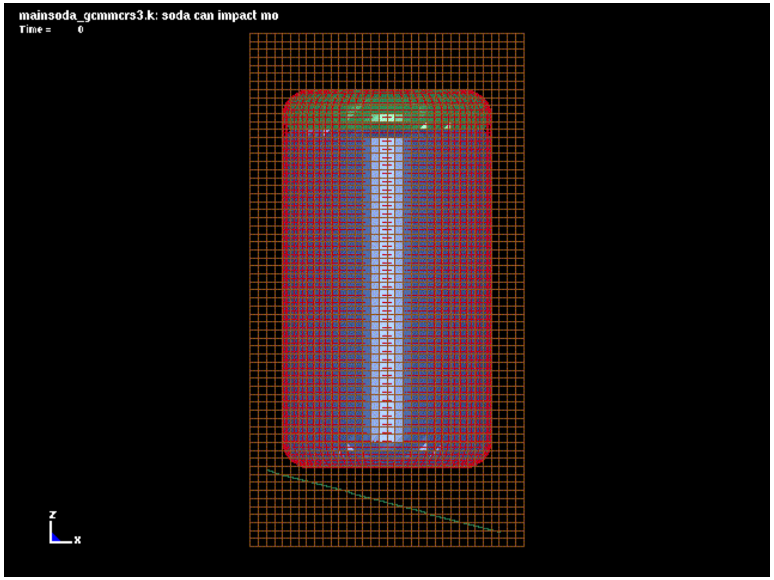
- http://ftp.lstc.com/anonymous/outgoing/hao/sale
- Jan 2015, an automated mesh generator
- Mar 2015, started implementation
- Nov 2015, debuted in LS-DYNA China Conf.
- June 2016, Detroit LS-DYNA Conference, Training Class

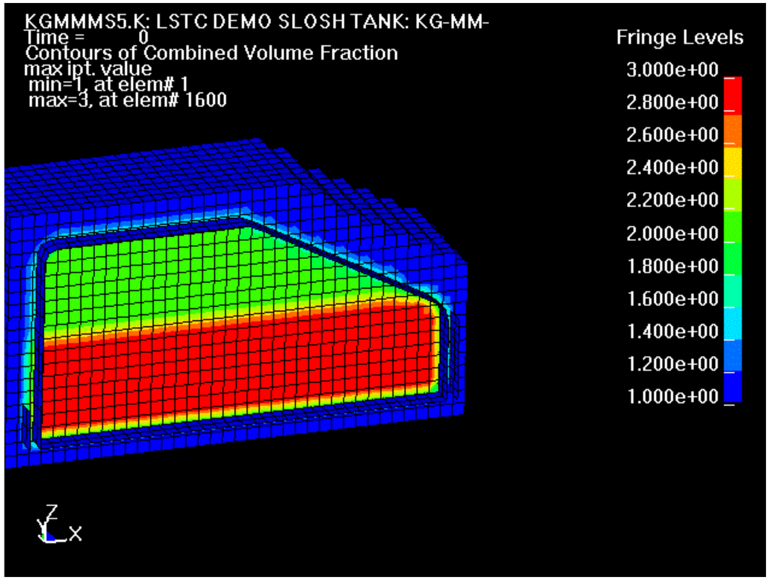
ALE – Arbitrary Lagrangian Eulerian

- ALE = Eulerian Method + Mesh Motion
- Solving Momentum Equation
  - Lagrange timestep
  - Advection timestep (remapping)
- Multi-material Formulation
  - Element volume fraction
  - 1 strain rate, multiple stresses per element
  - Interface reconstruction
- FSI – Fluid structure Interaction
  - Structure mesh/ ALE mesh: separate and overlapping

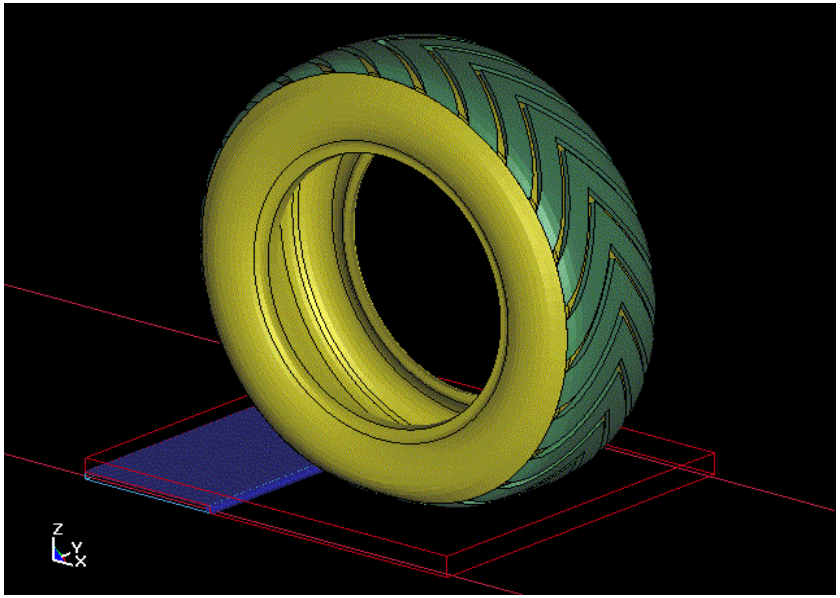
ALE Applications

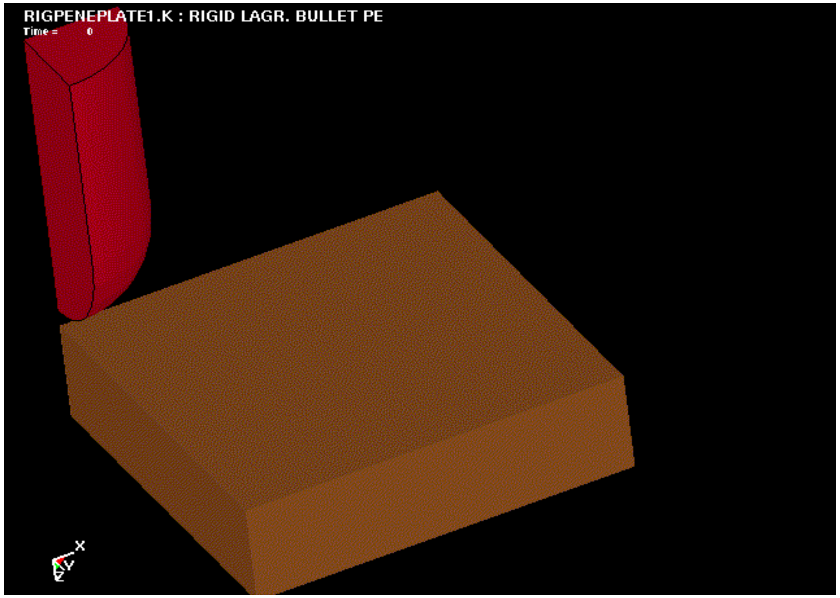


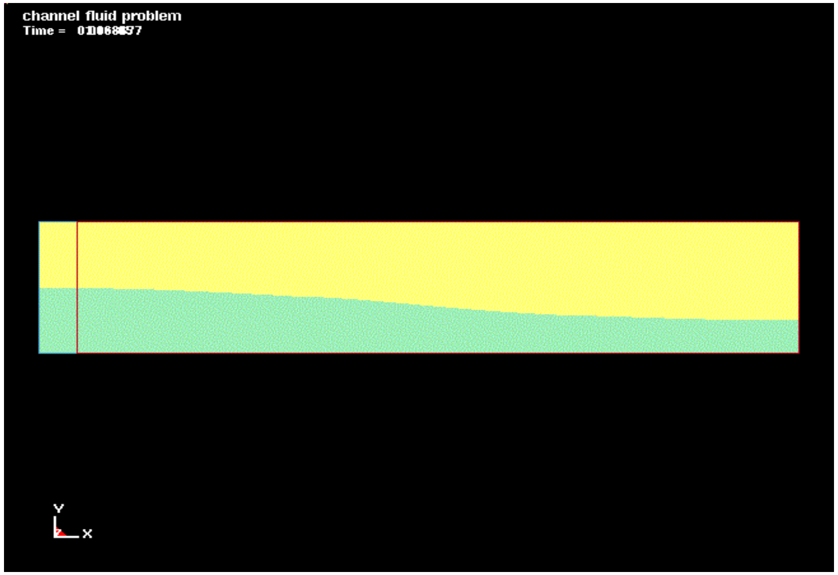


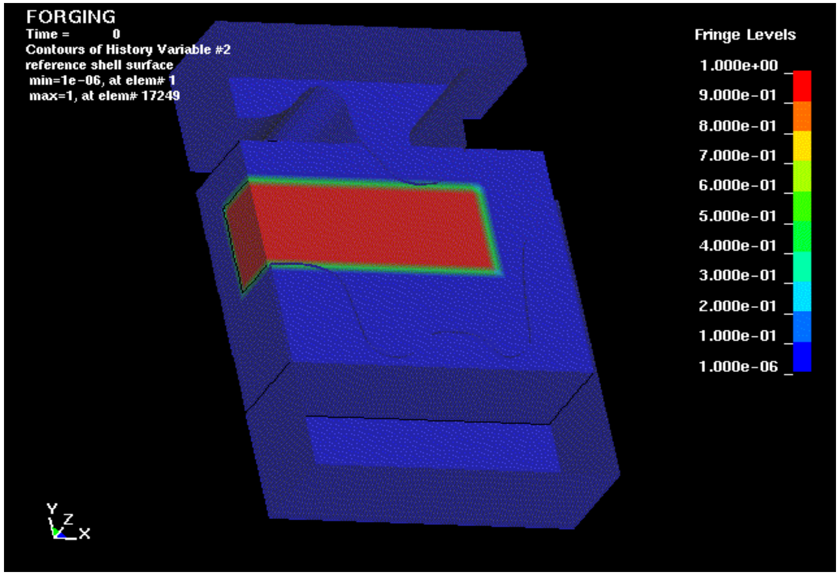


ALE Applications







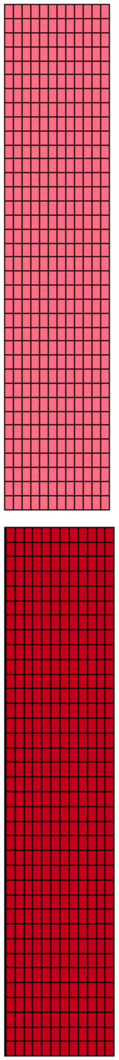


S-ALE – Structured ALE Solver

- Same theory
  - Advection (remapping)
  - Interface reconstruction
  - FSI – coupling to Lagrange structure
- Different Implementation
  - New automated mesh generation
  - A much more compact solver
  - Time saving in searching and sorting
  - Stable and user-friendly

Motivation

- S-ALE (Structured ALE) solver and ALE solver
  - Same algorithm (advection, interface reconstruction)
  - Separate coding
- Engineering applications evolved.
  - Solid → fluids
  - Single material → multiple materials
  - Conforming mesh → structured mesh
- Computing Technology evolved.
  - SMP → MPP → MPP+SMP (MPP Hybrid)
- A better user experience
  - Stable code behavior
  - Conceptually clear setup
  - Compact database

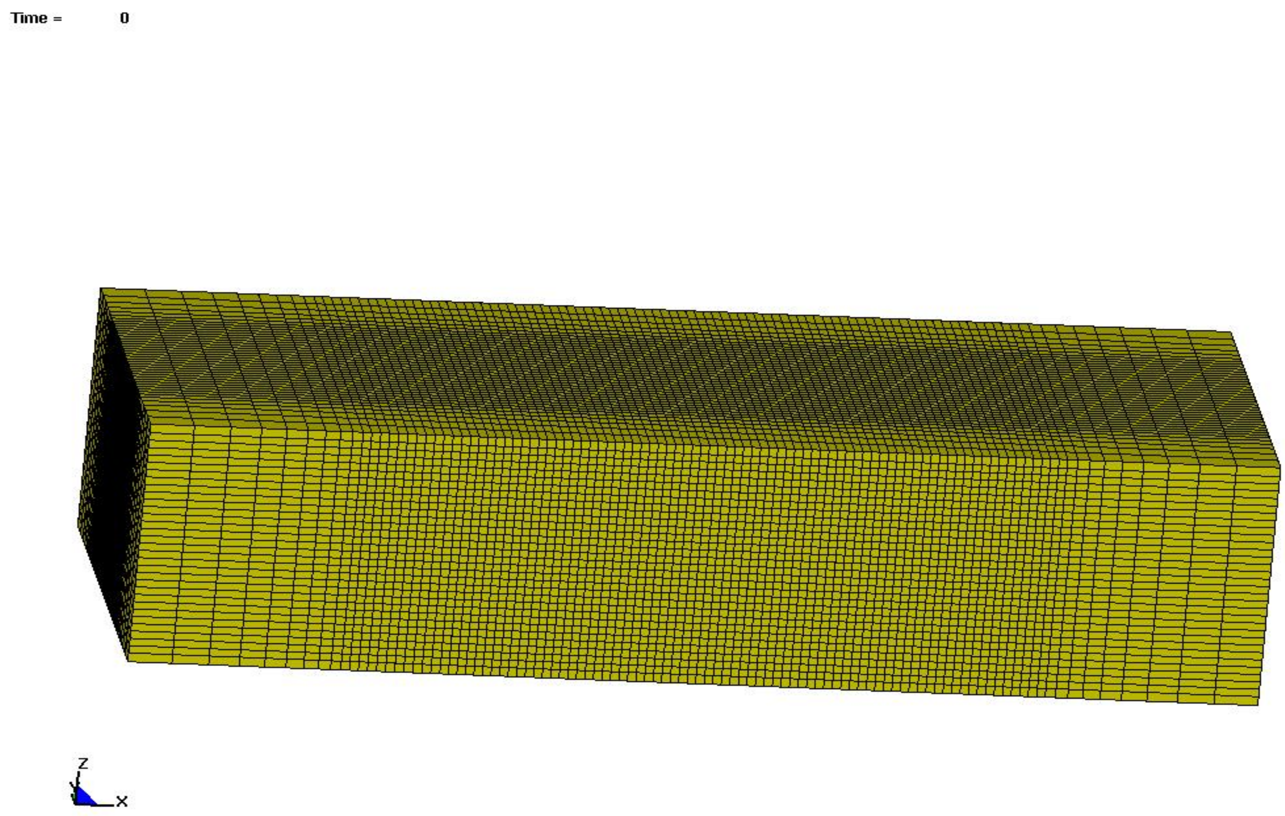


Overview

- Structured ALE mesh automatically generated
  - Smaller input deck; Easier modifications to the mesh; Less I/O time.
- Shorter calculation time
  - Sorting, searching faster and more efficient; Also more accurate.
- Less memory
  - A rewritten leaner, cleaner code using less memory to accommodate larger problems.
- SMP, MPP, MPP-Hybrid supported
  - Redesigned algorithm enabled SMP parallelization hence MPP Hybrid.
  - Enhancement on MPP efficiency

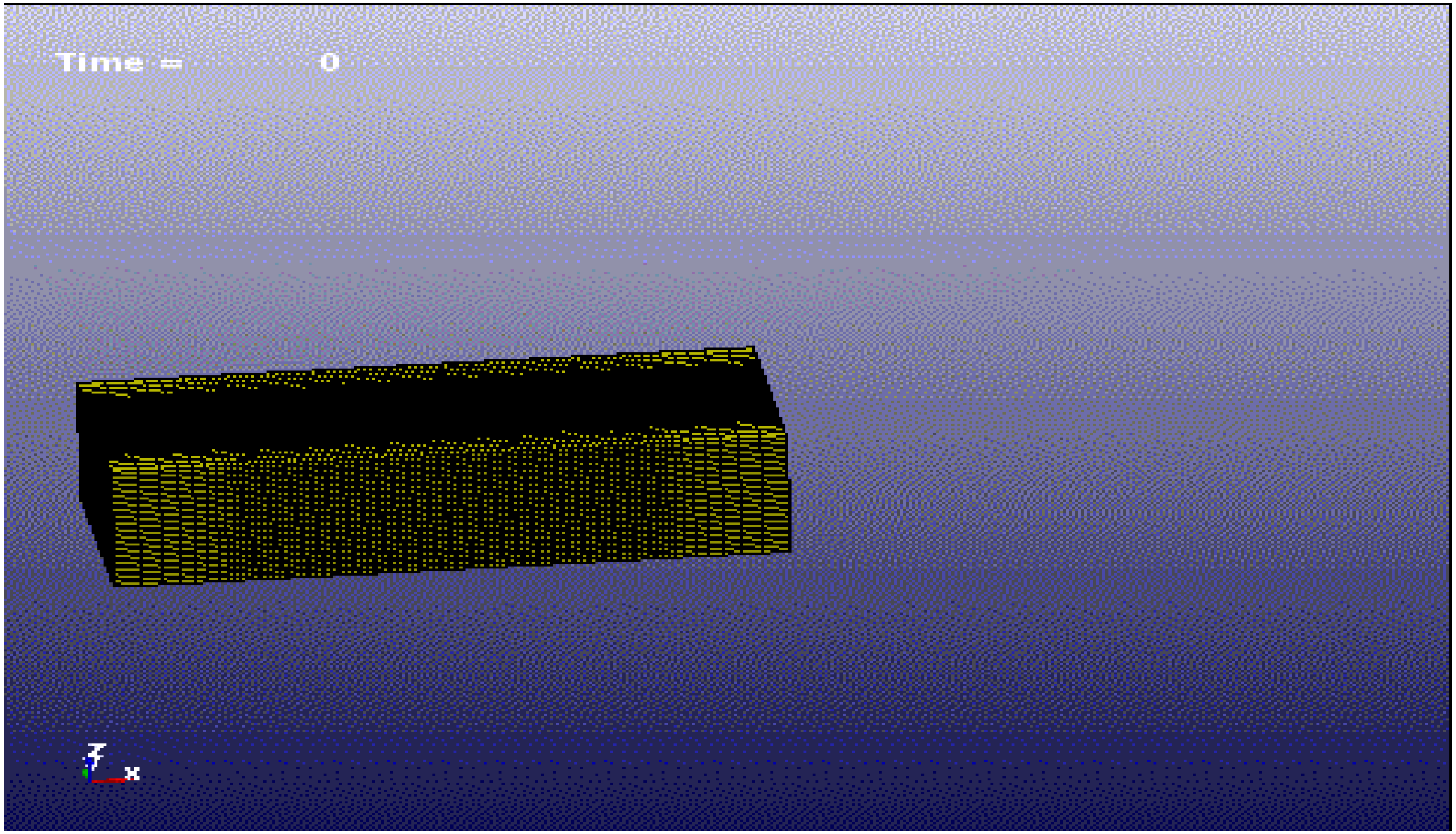
Automated Mesh Generation

- User specifies mesh spacing information along three directions
- One node for mesh origin and another three for local coordinate system



Mesh Motion

- Motion of the origin node defines translational mesh motion
- Motion of the three nodes defining the local coordinate system defines mesh rotation.



Keywords

- *ALE_STRUCTURED_MESH

*ALE_STRUCTURED_MESH					
MSHID	PID	NBID	EBID		
CPIDX	CPIDY	CPIDZ	NID0	LCSID	

- *ALE_STRUCTURED_MESH_CONTROL_POINTS

*ALE_STRUCTURED_MESH_CONTROL_POINTS					
CPID			SFO		OFF0
NID1		X1			
NID2		X2			

S-ALE: Faster Runs

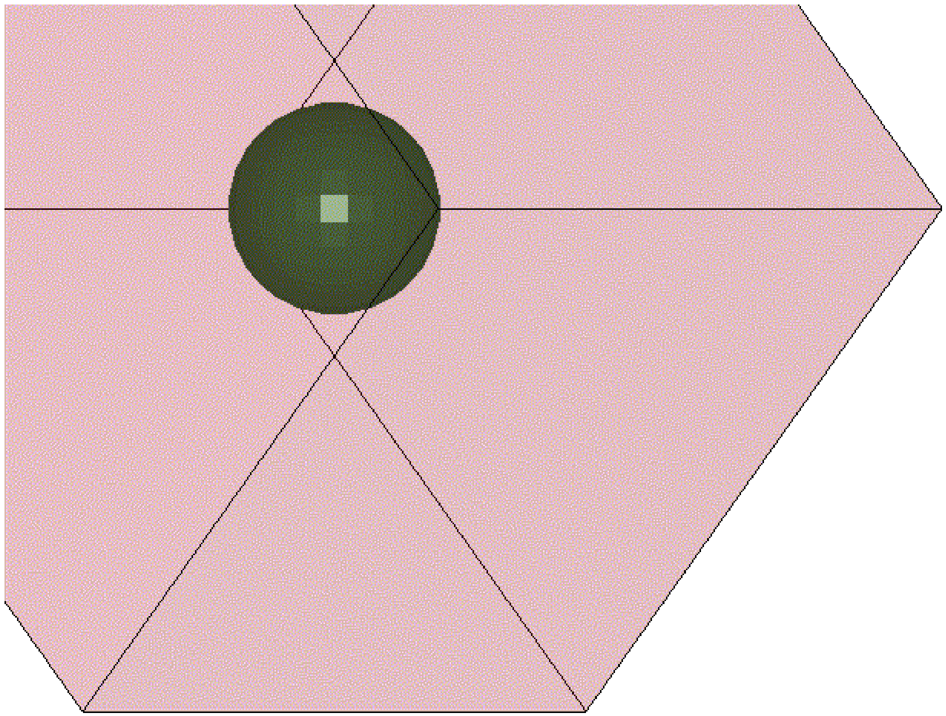
- Much faster FSI (Fluid structure interaction) searching for structured ALE mesh
- A faster advection scheme with SMP implemented.

Time saving in a Bridgestone tire rolling in mud model

	ALE	S-ALE	Reduction
Total Time	30941s	18566s	40%
FSI	15449s	5828s	62%
S-ALE	7595s	5377s	29%

134400 S-ALE solid elements; Simulation time 2000ms.
Single precision MPP dev.103813 48 cpus

SMP & MPP Hybrid: Model Description



Airbag inflated by ideal gas and then kept still; 9261 ALE solids elements with 294 shells.

Donor Cell (1st order)

SMP Result: Single precision -1, -2, -4, -8 cpu;
clock time spent in S-ALE solver listed in the table (Haswell1)

NCPU	-1	-2	-4	-8
Time (s)	298	168	103	70
Speedup		1.77	2.87	4.25

MPP Hybrid Result: Single precision 24x-1, 12x-2, 8x-3, 6x-4
clock time spent in S-ALE solver listed in the table (Barstow); 1x-1 case 530s

NCPU	24x-1	12x-2	8x-3	6x-4
Time (s)	55	57	60	60
Speedup	9.72	9.32	8.80	8.80

Both SMP and MPP Hybrid provide consistent answers with multiple threads (NCPU=-N);

Van Leer (2^{nd} order)

SMP Result: Single precision -1, -2, -4, -8 cpu;
clock time spent in S-ALE solver listed in the table (Haswell1)

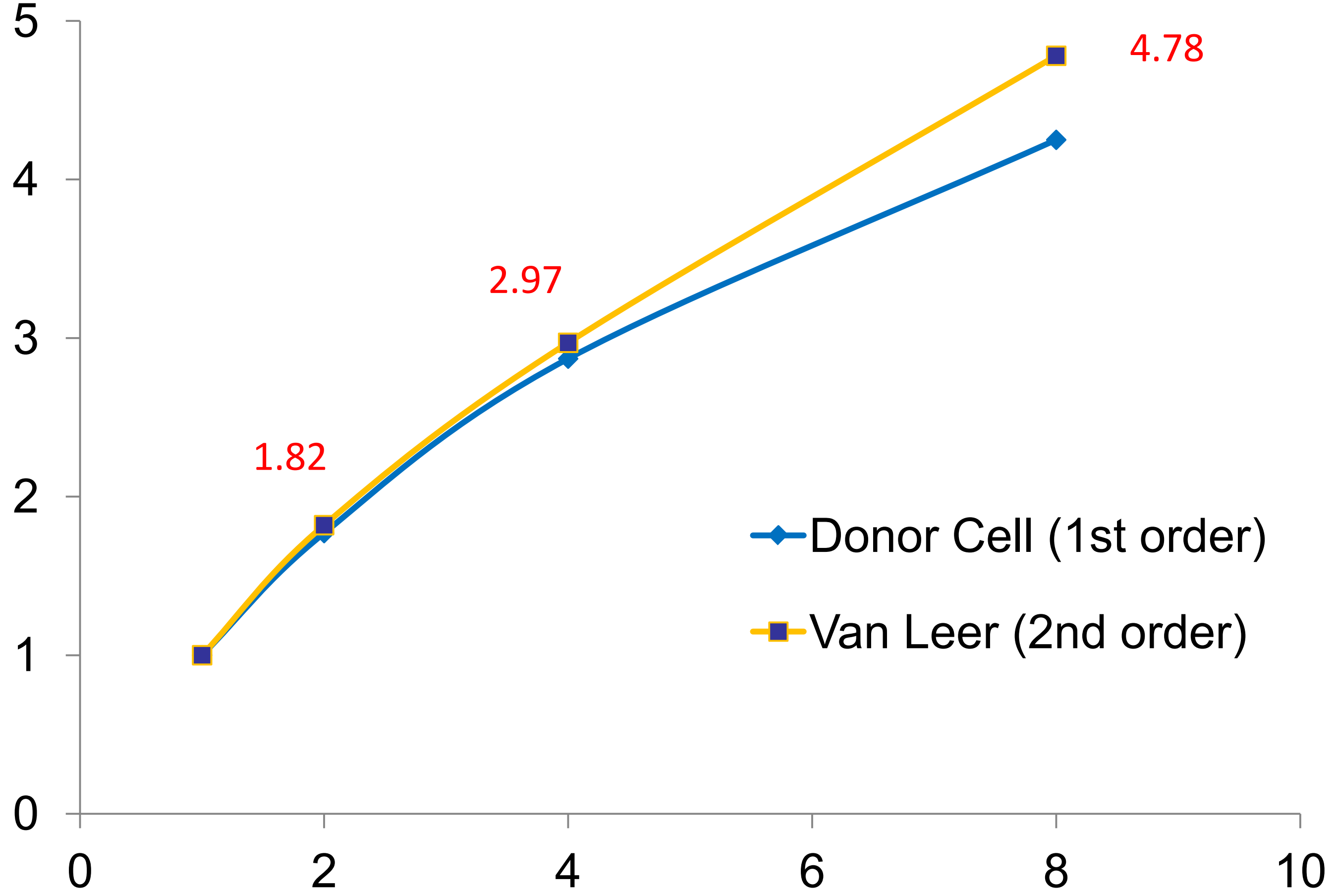
NCPU	-1	-2	-4	-8
Time (s)	531	292	179	111
Speedup		1.82	2.97	4.78

MPP Hybrid Result: Single precision 24x-1, 12x-2, 8x-3, 6x-4
clock time spent in S-ALE solver listed in the table (Barstow); 1x-1 case 1000s

NCPU	24x-1	12x-2	8x-3	6x-4
Time (s)	90	94	99	98
Speedup	11.05	10.68	10.13	10.16

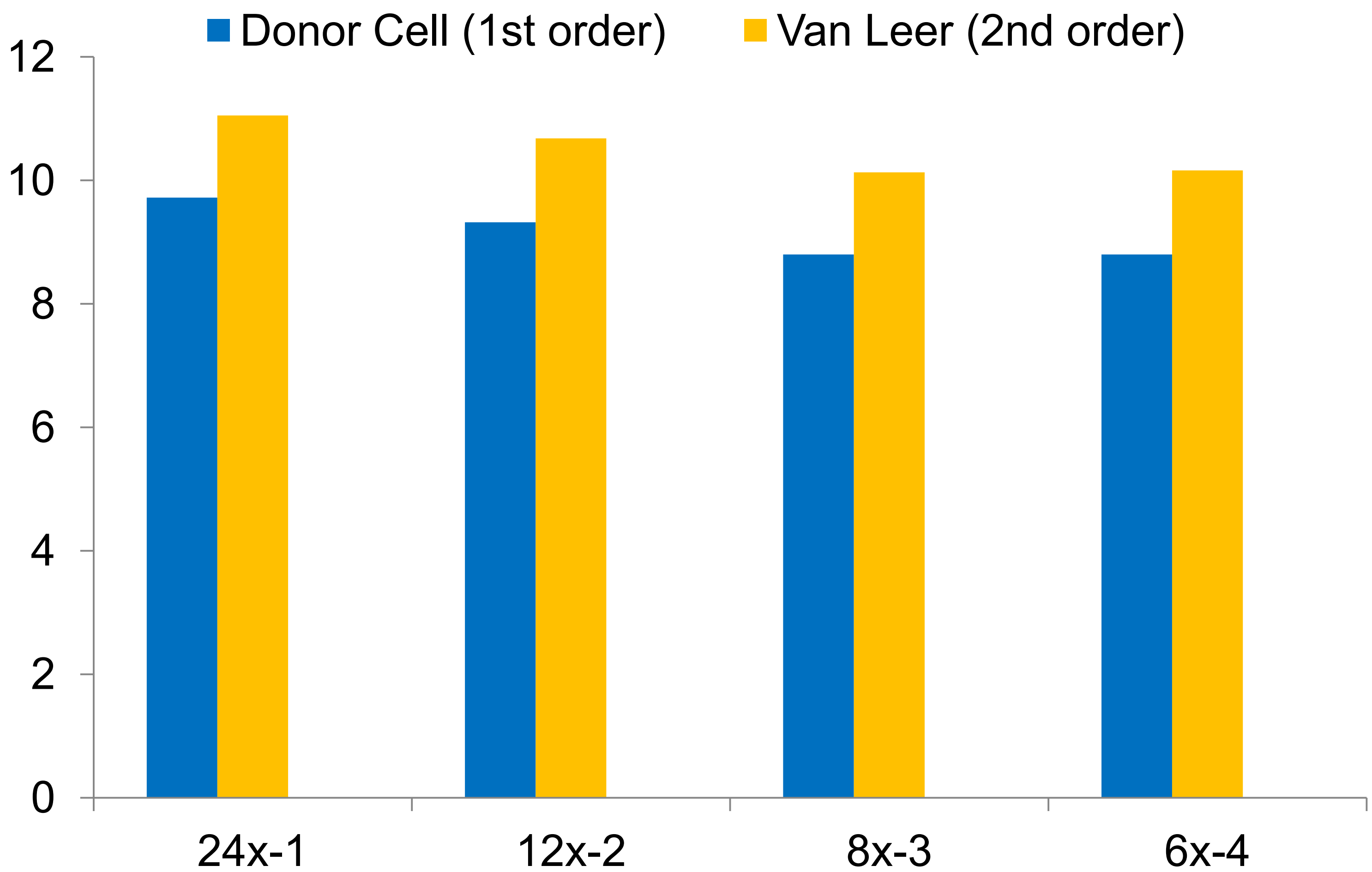
Both SMP and MPP Hybrid provide consistent answers with multiple threads (NCPU=-N);

SMP Scalability



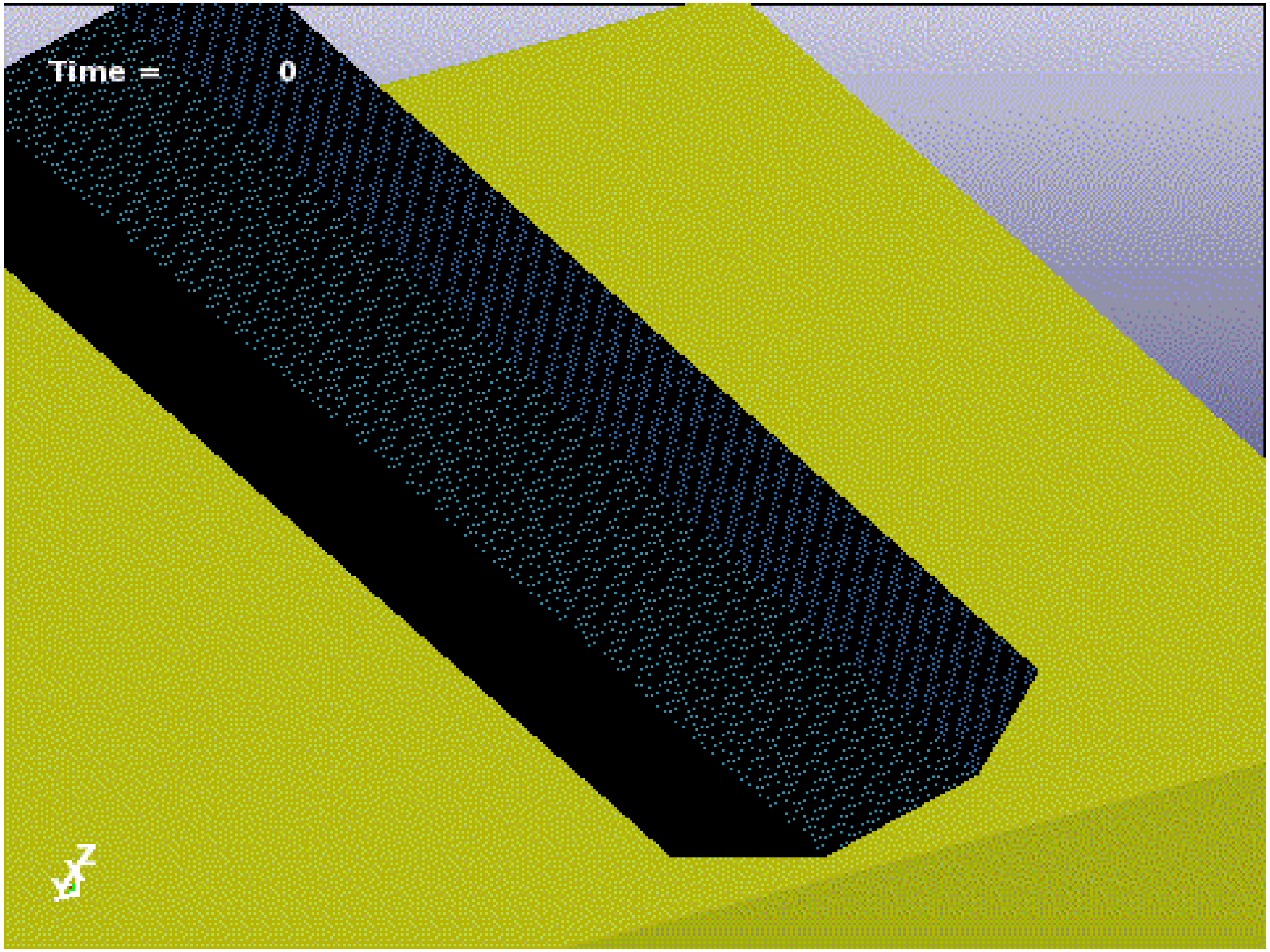
Speedup versus number of cores

MPP Hybrid Performance



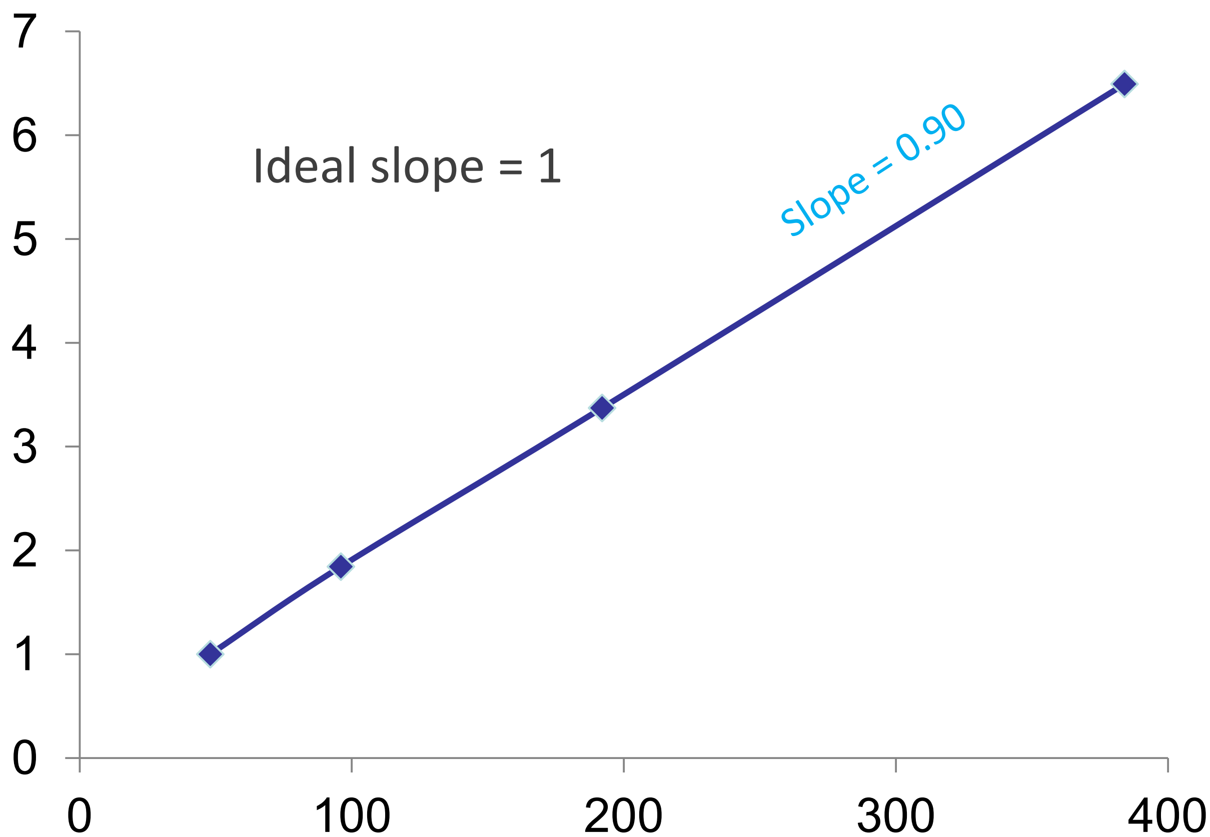
Speedup versus number of MPP x SMP cores

MPP Performance: Model Description



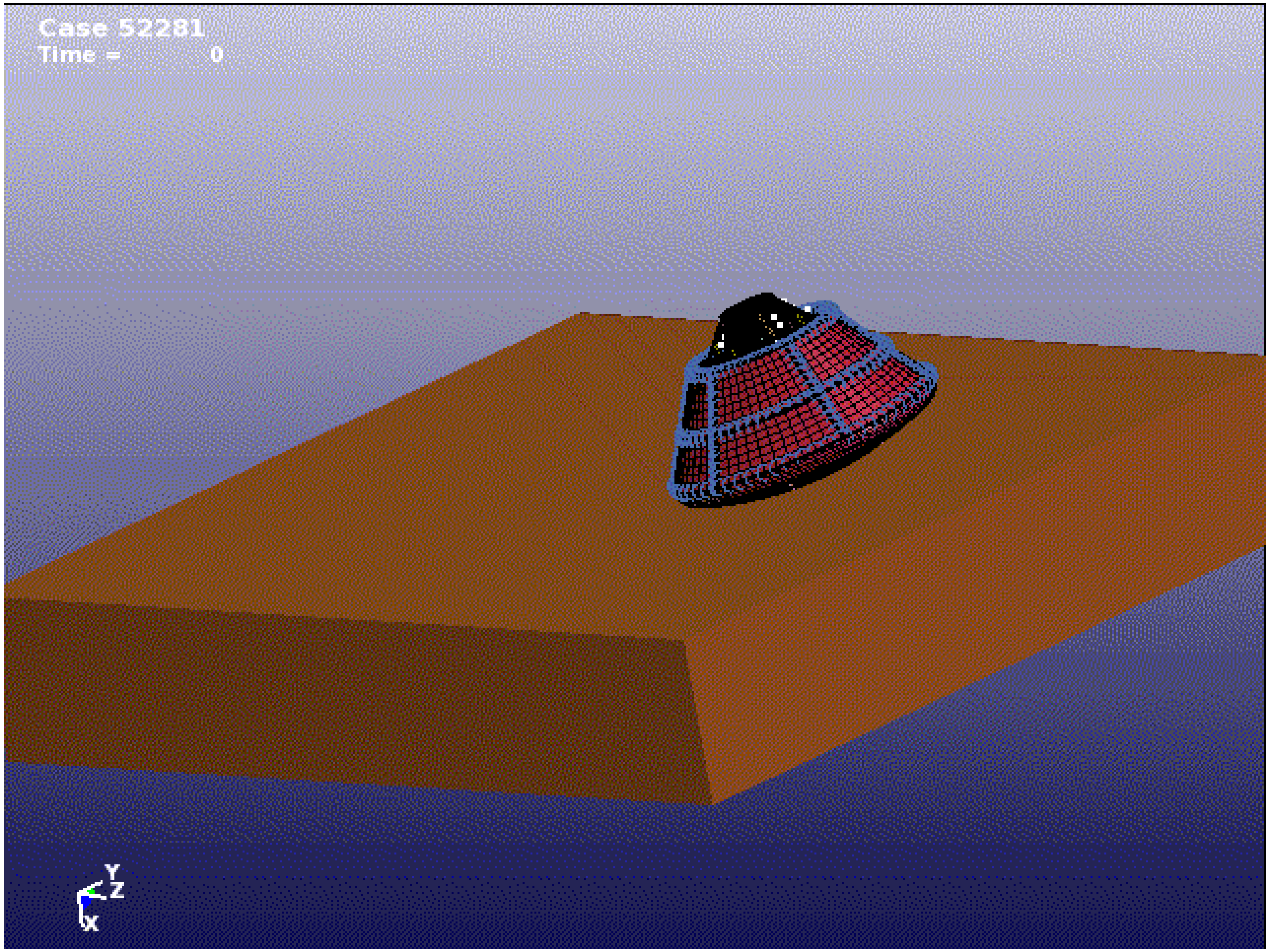
Mine buried under soil; Generic Hull Structure; 5.5 million ALE elements; Simulation time 80ms.

MPP Scalability



Speedup versus number of cores

AWG/Orion Problem



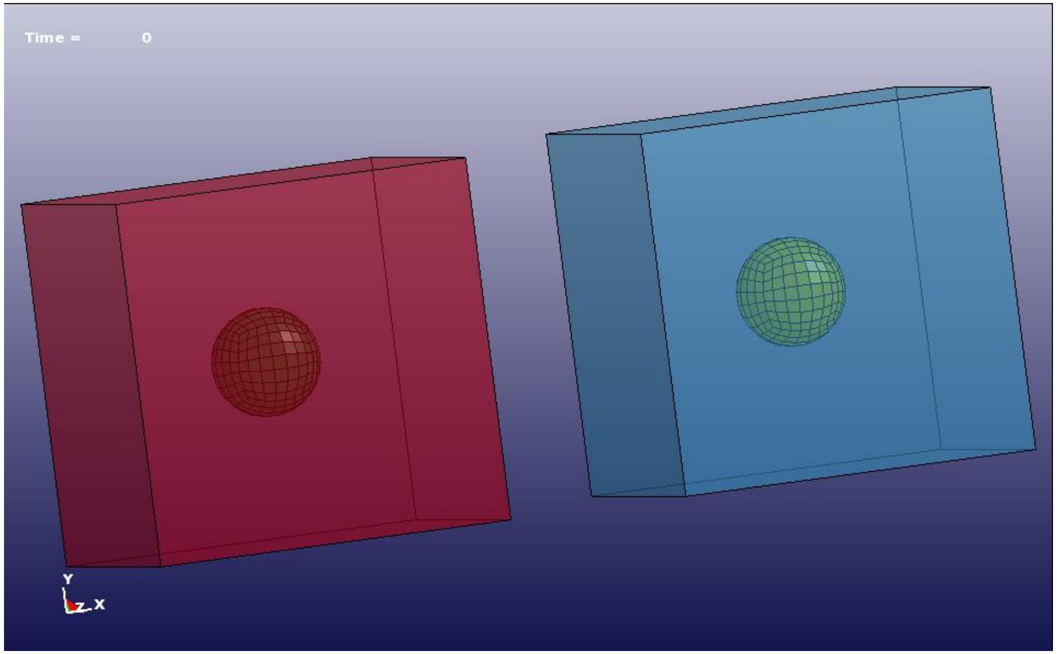
AWG/Orion Problem: Speedup & Memory

	ALE	S-ALE
Total time	25,276 s	14,204 s (1.81)
Advection	11,140 s	5,350 s (2.08)
FSI	5,746 s	3,983 s (1.44)
Maximum memory	34M	23M (1.47)

MPP dev.100943 single precision 12 cpu run on a 2.2G Xeon E5-4640 cluster

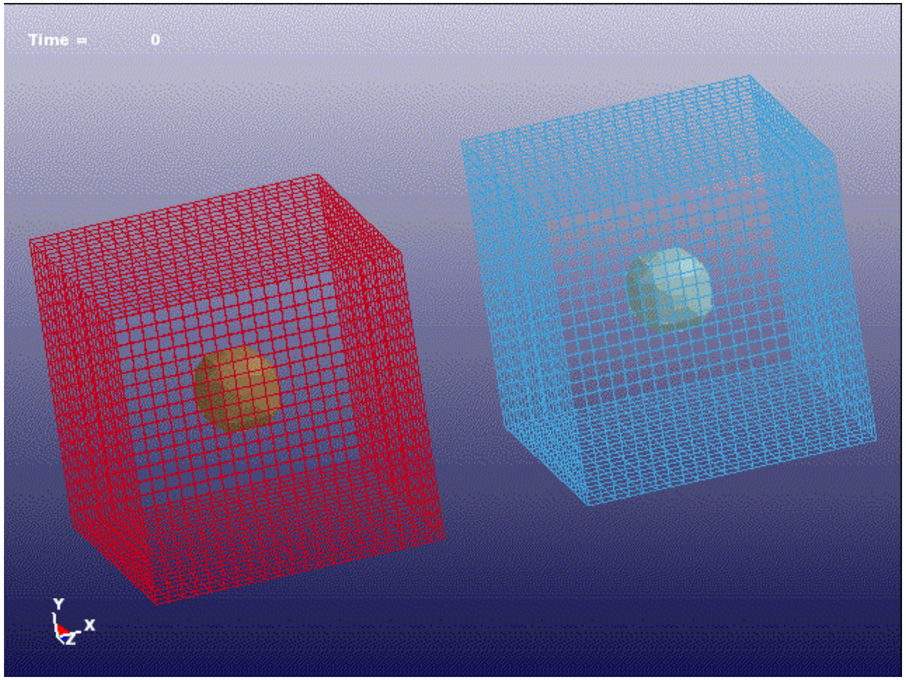
Multiple Mesh Domains

- Multiple meshes can be generated.
- Each mesh domain is solved independently; unaware of others' existence.
- Different meshes can occupy SAME spatial domain.

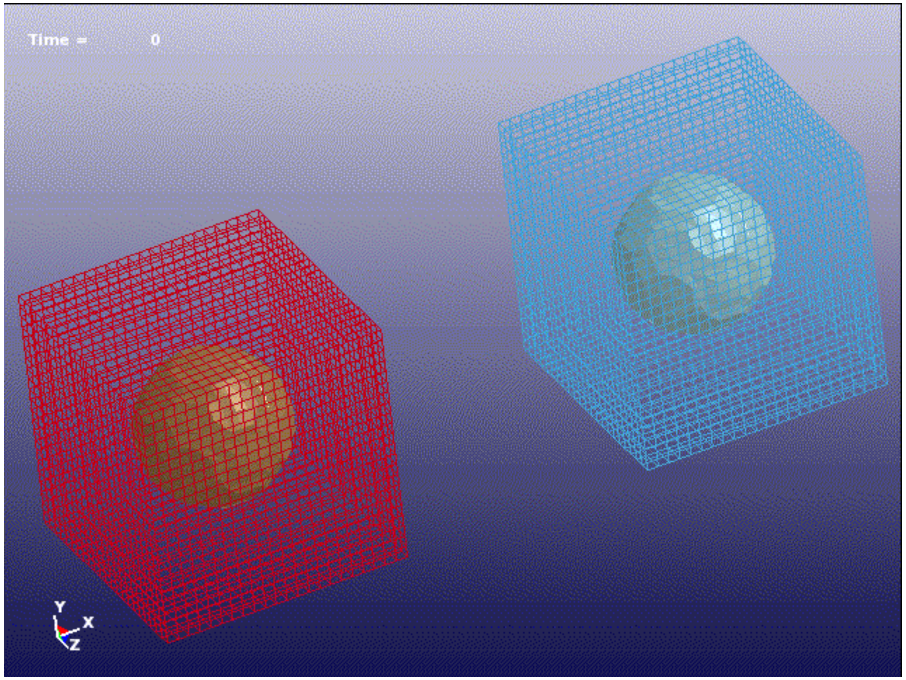


Multiple Mesh Domains

Two pressurized airbags, each inside an independent S-ALE mesh.



Contact between bags DISABLED



Contact between bags ENABLED

Supporting Large Problems

- S-ALE uses much less memory in MPP decomposition phase. For the underwater explosion case, 36 million elements run uses less than 2G words. The largest problem tested so far is with 140 million elements.

Refinement	Number of Elements	Clock Time	Number of Cycles
8x8x8	2,359,296	199s	745
16x16x16	18,874,168	2891s	1514
20x20x20	36,864,000	6693s	1904

- Comparison for the 8x8x8 refinement case between ALE and S-ALE

Solver	MAX Memory (words)	Clock Time (s)
ALE	414M	312
S-ALE	129M	199

48 CPU MPP
Single Precision

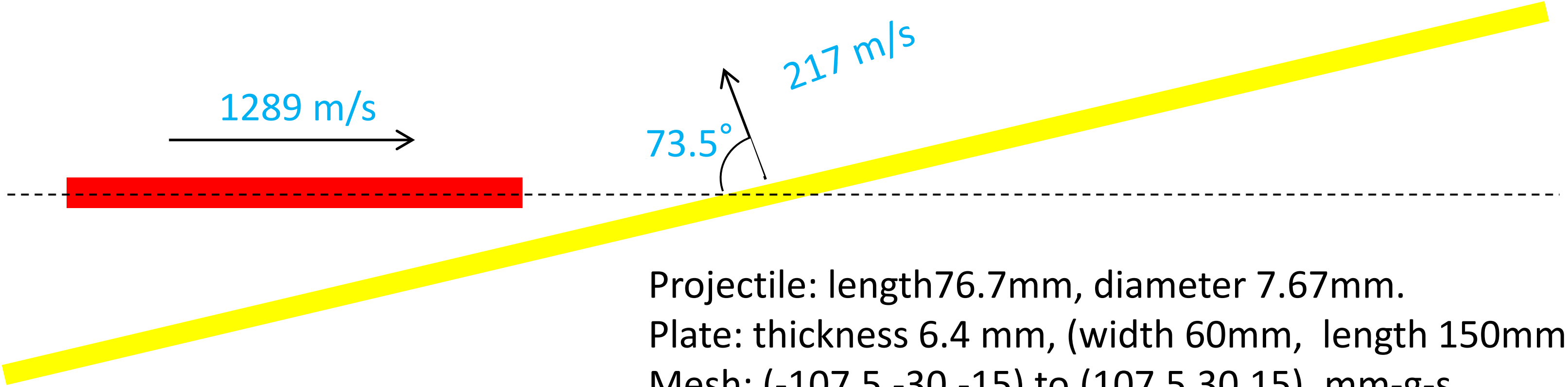
Future Work

- Leaner database for faster post-processing
  - Reduction in geometric data; compact volume fraction storage
  - Users' choice of history variables to database
- Interactively mesh generation
  - GUI interface for easier model construction
- Optimization
  - Cleanup to reduce memory waste and achieve further speedup
- Enhance parallelization efficiency
  - Explore MPP decomposition methods; Reduce serial coding for better SMP, MPP/Hybrid efficiency
- Explore different advection methods

S-ALE Applications

Application: Penetration – Model Description

- A long rod projectile impacting an oblique steel plate (Fugelso & Taylor 1978).
- Model dimensions from ARL-TR-2173 (Schraml & Kimsey 2000)
- Material MAT_JOHNSON_COOK+EOS_LINEAR_POLYNOMIAL, "Numerical Simulation of High-Velocity oblique Impacts of Yawed Long Rod Projectile Against Thin-Plate" (Yo-Han Yoo 2002)

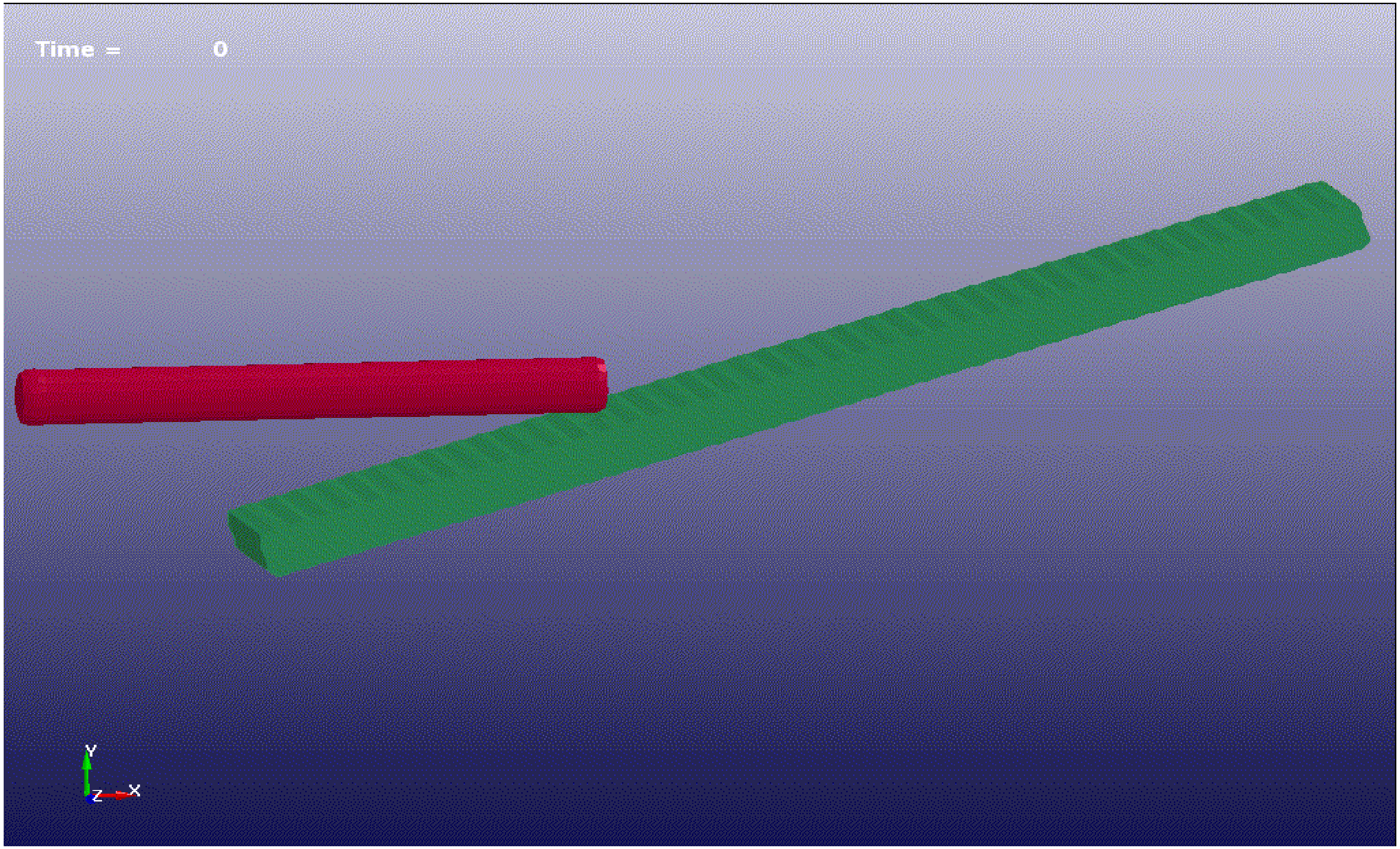


Projectile: length76.7mm, diameter 7.67mm.
Plate: thickness 6.4 mm, (width 60mm, length 150mm)
Mesh: (-107.5,-30,-15) to (107.5,30,15), mm-g-s

	RO	G	E	PR	A	B	N	C	M	TM	TR	C1
ROD	18.6e-3	63.7e3	165.6e3	0.3	1.079e3	1.12e3	0.25	0.007	1.00	1473	283	138.0e3
PLATE	7.87e-3	76.7e3	200.1e3	0.3	0.792e3	0.51e3	0.26	0.014	1.03	1809	283	166.7e3

Application: Penetration – Simulation

- 1mmx1mmx1mm regular HEX mesh with 387,000 elements (215x60x30)
- Simulation time of 0.04s took 7 minutes on a single thread SMP.



Application: Penetration – Model Setup

- S-ALE: A straight-forward 3-step setup
  1. Mesh generation – to generate a single mesh part.
  2. Define ALE multi-materials – to define materials reside in the S-ALE mesh.
  3. Fill in the multi-materials – to fill in the S-ALE mesh with the multi-materials at the initial stage.
- Two kinds of *PART definition in S-ALE
  - Mesh PART: refers to S-ALE mesh – a collection of elements and nodes; no material info; only one mesh PART.
  - Material PART: refers to multi-materials flow inside the S-ALE mesh; no mesh info; multiple cards each defines one multi-material (*MAT+*EOS+*HOURGLASS).

Application: Penetration – Model Setup 1

*ALE_STRUCTURED_MESH					
MSHID	PID	NBID	EBID		
1	11	100001	100001		
CPIDX	CPIDY	CPIDZ	NID0	LCSID	
1001	1002	1003			

MSHID: Mesh ID (for future use)

PID: Part ID assigned to the mesh
NO NEED to define *PART card

NBID: Starting Node ID

EBID: Starting Element ID

NID0: Origin Node ID

LCSID: Local Coordinate System ID

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1001			
	1	-107.5	
	216	107.5	

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1002			
	1	-30.0	
	61	30.0	

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1003			
	1	-15.0	
	31	15.0	

Application: Penetration – Model Setup 2

*ALE_MULTI-MATERIAL_GROUP	
PID	PTYPE
1	1
3	1
2	1

⟺

*PART				
PID	SECID	MID	EOSID	HGID
1	1	1	1	1
3	1	2	2	1
2	1	3		1

1 to 1 correspondence

PID	MATERIAL	AMMG
1	ROD	1
3	VACUUM	2
2	PLATE	3

- *PART definitions to define multi-materials reside in S-ALE mesh; one to one correspondence.
- These PART IDs only appear in *ALE_MULTI-MATERIAL_GROUP; NOT to be used anywhere else.
- Material PARTs have neither elements nor nodes; serves as a wrapper to include *MAT+*EOS+HOURGLASS

Application: Penetration – Model Setup 3

*INITIAL_VOLUME_FRACTION_GEOMETRY							
SID	IDTYP	BAMMG					
11	1	2					
TYPE	FILLOPT	FAMMG	VELX	VELY			
1	1	3	-61.631	208.06			
PID	IDTYP						
101	1						
TYPE	FILLOPT	FAMMG	VELX				
4	0	1	1289				
X0	Y0	Z0	X1	Y1	Z1	R1	R2
-103.0	0.0	0.0	-26.33	0.0	0.0	3.835	3.835

1. First set all elements in PART 11 to vacuum (AMMG2)
2. Next switch vacuum (AMMG2) inside LAG part 101 to plate (AMMG3)
3. Finally switch vacuum (AMMG2) inside a cylinder to rod (AMMG1)

Application: Penetration – Model Setup MISC

*CONTROL_ALE							
DCT	NADV	METHOD	AFAC	BFAC	CFAC	DFAC	EFAC
	1	1					
START	END	AAFAC	VFACT	PRIT	EBC	PREF	NSIDEBC

*CONTROL_TERMINATION	
ENDTIME	ENDCYCL
0.04	

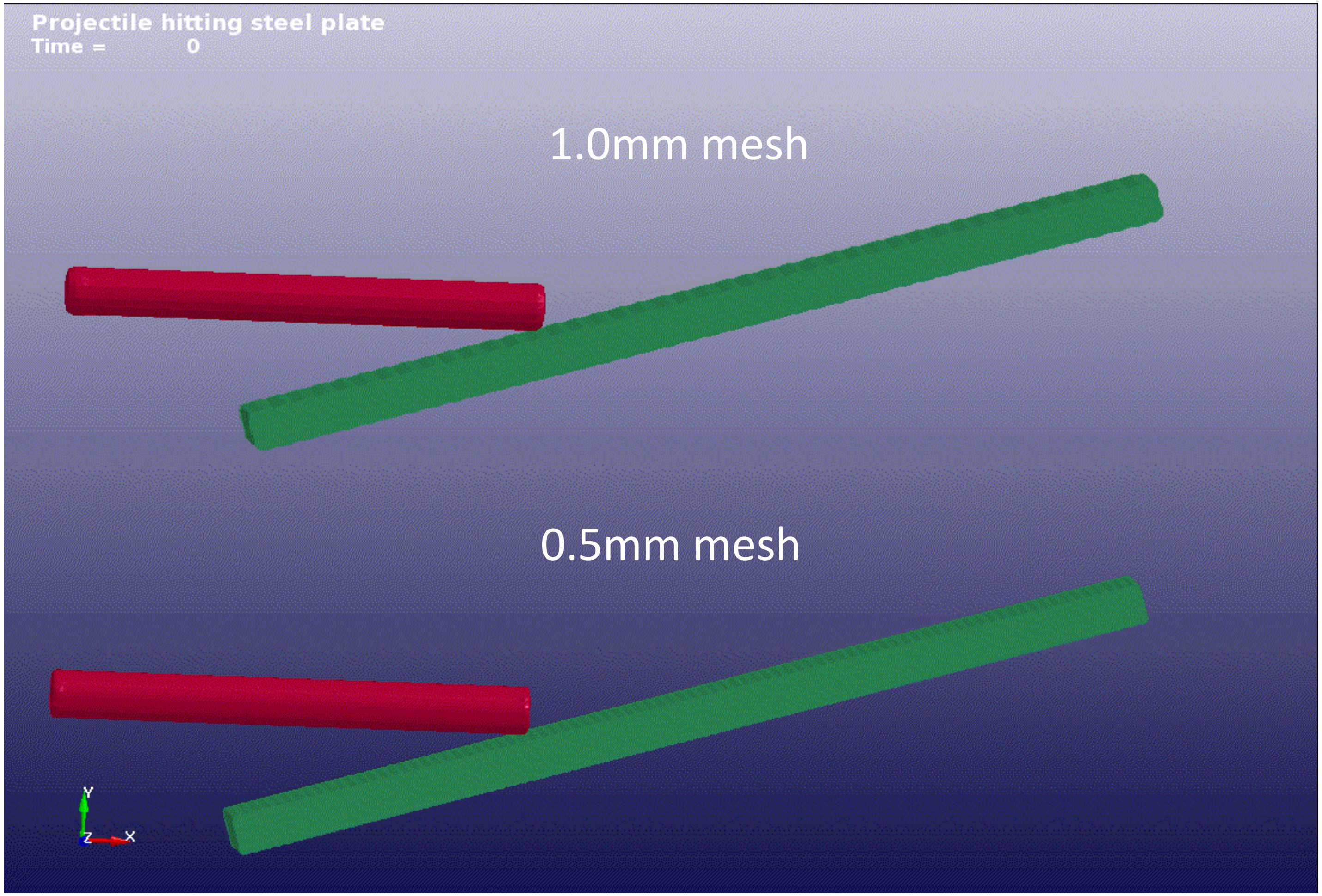
*CONTROL_TIMESTEP	
DTINIT	TSSFAC
	0.600

*DATABASE_BINDARY_D3PLOT	
DT	LCDT
0.001	

Optional card: refine the mesh for better accuracy

*ALE_STRUCTURED_MESH_REFINE			
MSHID	NX	NY	NZ
1	2	2	2

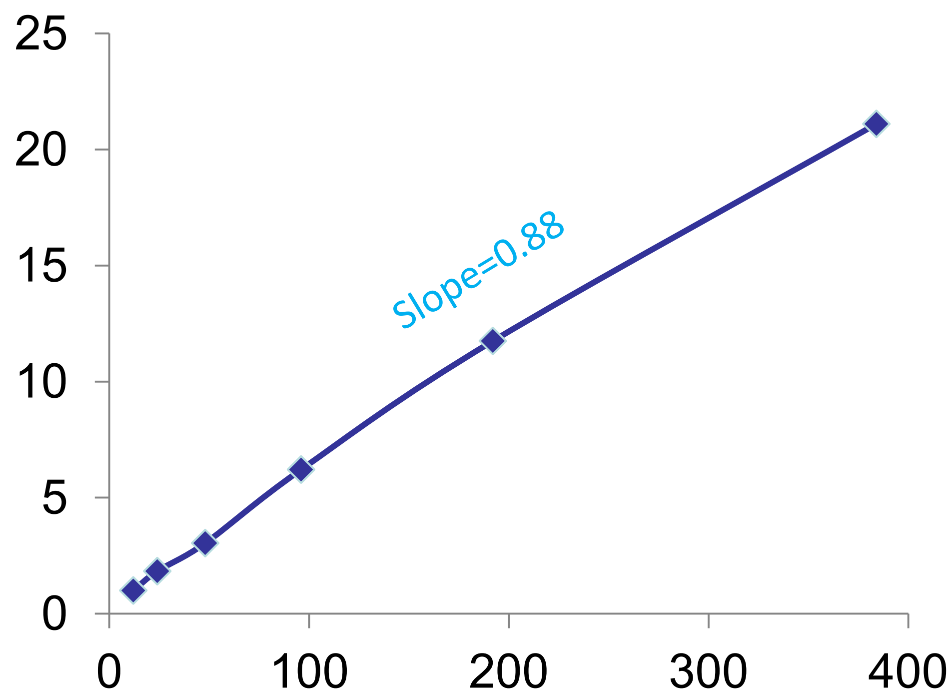
Application: Penetration – Refinement



Model size: 387,000 vs. 3,096,000
Running time: 14m vs. 3h16m.

Application: Penetration – MPP Performance

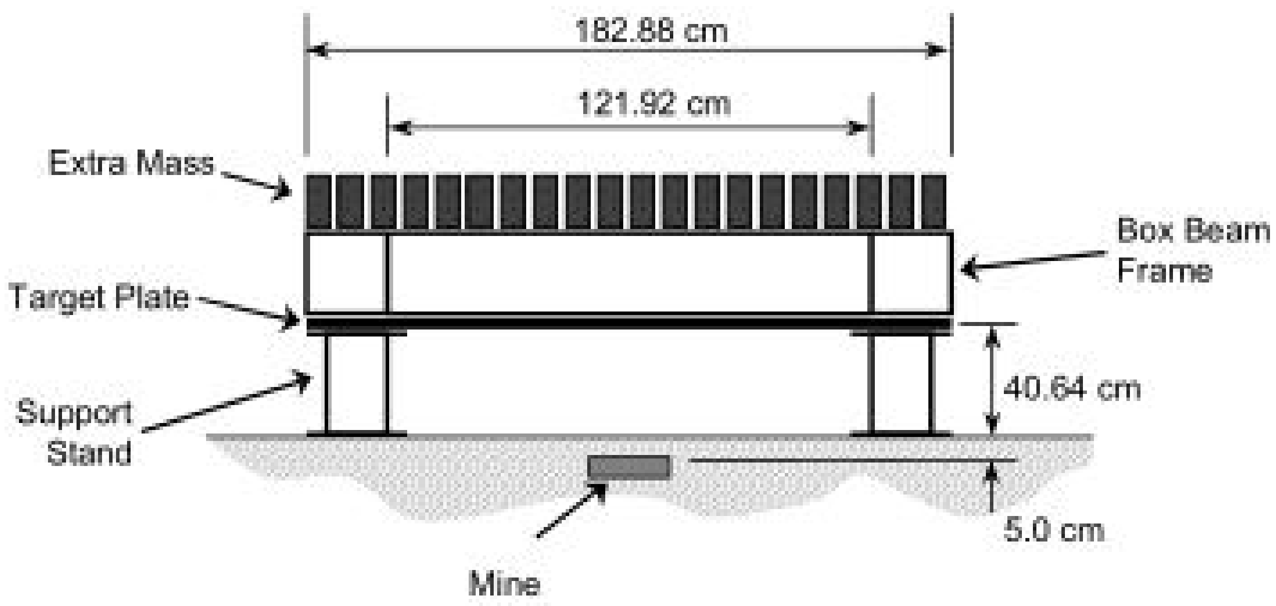
NCPU	12	24	48	96	192	384
Total Time	2068	1128	680	333	176	98
S-ALE	1327	733	451	220	118	62



Note: 3 million elements, total time excluded MPP decomposition time

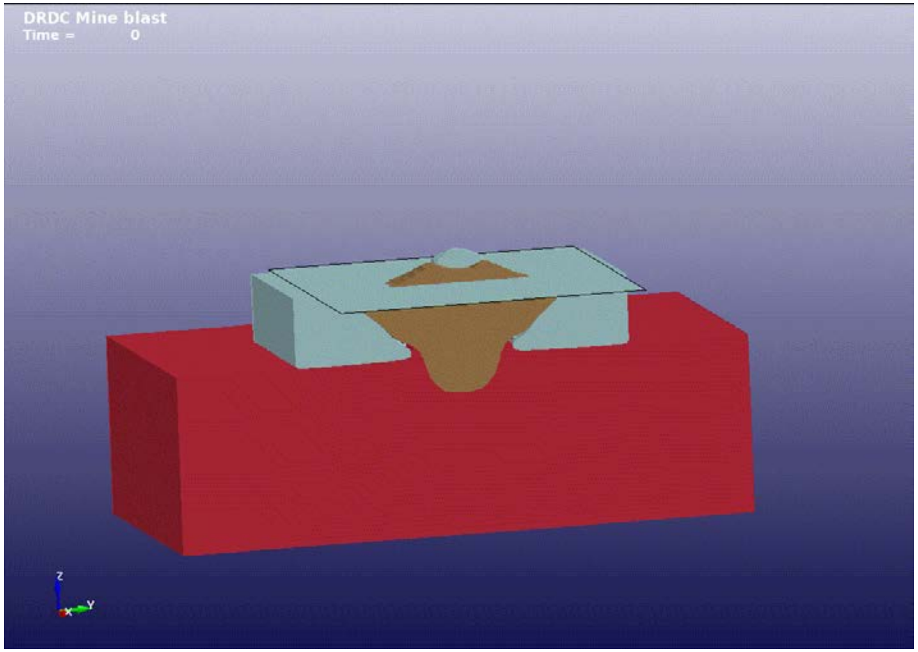
Application: Explosion – Model Description

- Blast mine on plate; Model dimensions and material properties from "Validation of a Loading Model for Simulating Blast Mine Effects on Armoured Vehicles", Williams et al, 7th International LS-DYNA Users Conference; DRDC (Defence R&D Canada)



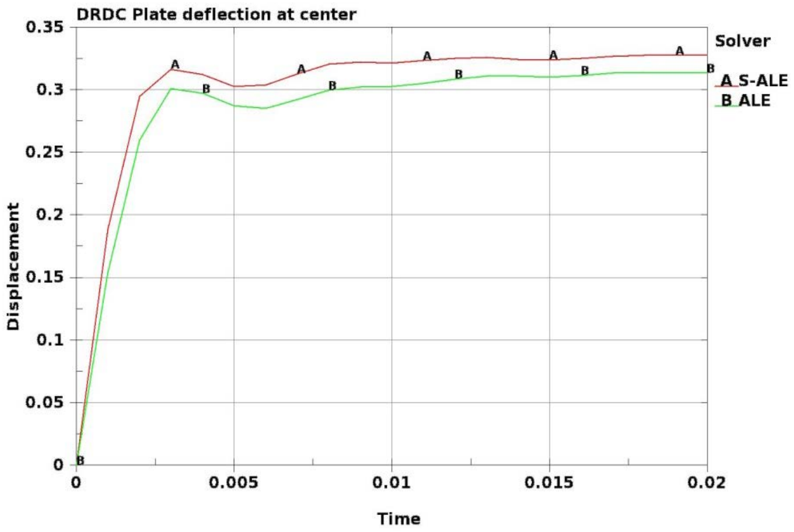
- S-ALE mesh spans from (-1.714, -1.714, -1.0) to (1.714, 1.714, 1.321) modeled by 1,339,200 (120x120x93) elements.

Application: Explosion – Simulation



20ms simulation time
1.3 million S-ALE elements
MPP 48 cpus

S-ALE: 1 hrs 47 mins
ALE: 4 hrs 28 mins



Application: Explosion – Model Setup 1

*ALE_STRUCTURED_MESH					
MSHID	PID	NBID	EBID		
1	999	5000001	5000001		
CPIDX	CPIDY	CPIDZ	NID0	LCSID	
1001	1001	1003			

MSHID: Mesh ID (for future use)

PID: Part ID assigned to the mesh
NO NEED to define *PART card

NBID: Starting Node ID

EBID: Starting Element ID

NID0: Origin Node ID

LCSID: Local Coordinate System ID

*ALE_STRUCTURED_MESH_CONTROL_POINTS	
1001	
1	-1.714290
121	1.714290

*ALE_STRUCTURED_MESH_CONTROL_POINTS	
1003	
1	-1.000000
32	-0.131200
37	0.000000
94	1.321190

Application: Explosion – Model Setup 2

*ALE_MULTI-MATERIAL_GROUP	
PID	PTYPE
3000	1
1000	1
2000	1
2001	1

1 to 1

*PART				
PID	SECID	MID	EOSID	HGID
3000	3000	3001	3001	3000
1000	1000	1001	1000	1000
2000	2000	2000	2000	2000
2001	2000	2000	2000	2000

PID	MATERIAL	AMMG
3000	HE	1
1000	SOIL	2
2000	AIR Below	3
2001	AIR Above	4

- *SECTION should always be 11. Same SECID OK.
- *HOURGLASS form and coefficient should always be 1 and 1.0e-6. Same HGID OK.
- PIDs not used elsewhere. Only to be put into *ALE_MULTI-MATERIAL_GROUP card.

Application: Explosion – Model Setup 3

*INITIAL_VOLUME_FRACTION_GEOMETRY							
SID	IDTYP	BAMMG					
999	1	4					
TYPE	FILLOPT	FAMMG				“5 = BOX”	
5	0	3					
X0	Y0	Z0	X1	Y1	Z1		
-1.0	-1.0	0.0	1.0	1.0	0.39404		
TYPE	FILLOPT	FAMMG				“3 = PLANE”	
3	0	2					
X0	Y0	Z0	NX	NY	NZ		
0.0	0.0	0.0	0.0	0.0	-1.0		
TYPE	FILLOPT	FAMMG				“4 = CYLINDER”	
4	0	1					
X0	Y0	Z0	NX	NY	NZ	R1	R2
0.0	0.0	-0.1312	0.0	0.0	-0.05080	0.12	0.12

1. All to “AIR Above”; 2. Inside box to “AIR below”;
3. Below plane to “SOIL”; 4. Inside Cylinder to “HE”

Application: Explosion – Model Setup FSI

Couple plate to air below

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
5000	999	1	1	2	4	2	-33
START	END	PFAC	FRIC	FRCMIN	NORM	NORMT	DAMP
		-54		0.3			
CQ	HMIN	HMAX	ILEAK	PLEAK			
			2	0.1			

Couple plate to HE and soil

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
5000	999	1	1	2	4	2	-12
START	END	PFAC	FRIC	FRCMIN	NORM	NORMT	DAMP
		-55		0.3			
CQ	HMIN	HMAX	ILEAK	PLEAK			
			2	0.1			

Application: Explosion – Model Setup MISC

*CONTROL_ALE							
DCT	NADV	METHOD	AFAC	BFAC	CFAC	DFAC	EFAC
	1	1					
START	END	AAFAC	VFACT	PRIT	EBC	PREF	NSIDEBC
						101325.0	

Define NODESET SEGSET using *SET_”?”_GENERAL

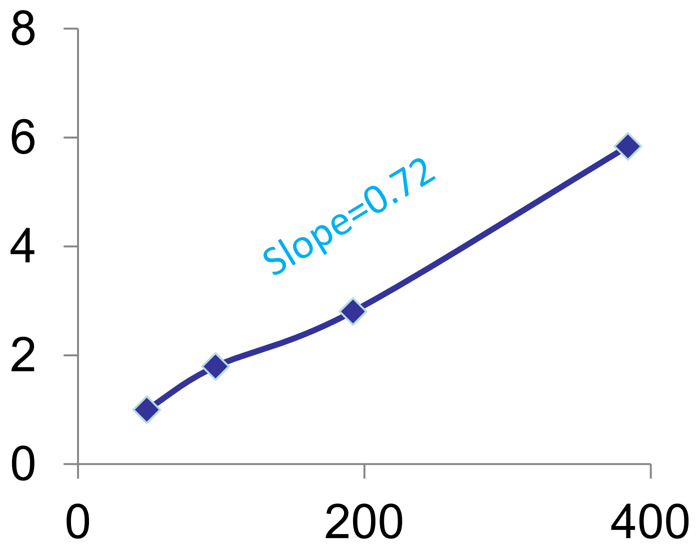
*SET_SEGMENT_GENERAL							
SID							
1							
OPTION	MSHID	-X	X	-Y	Y	-Z	Z
SALEFAC	1	1	1				

*BOUNDARY_NON_REFLECTING		
SSID	AD	AS
1	0.0	0.0
2	0.0	0.0
3	0.0	0.0

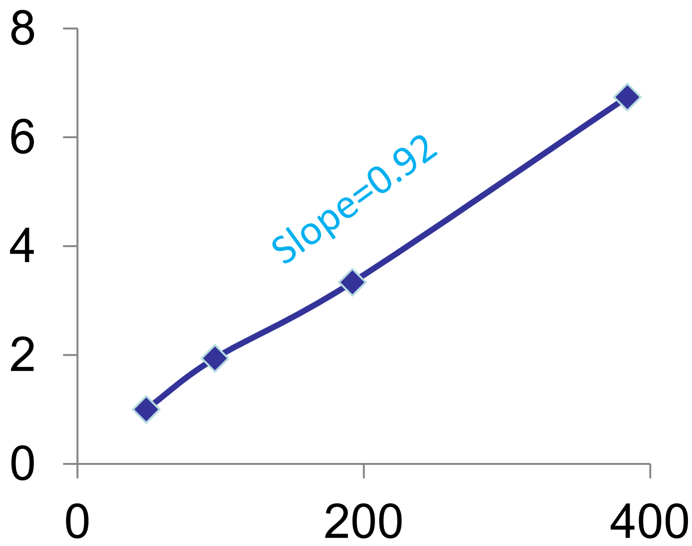
Another newly added option in SET_?_GENERAL SALECPT: It is to define a box with (xmin,ymin,zmin) to (xmax,ymax,zmax) in Control point nodal index. Nodes/Segments/Solids inside the box are included.

Application: Explosion – MPP Performance

NCPU	48	96	192	384
Total Time	6422	3580	2290	1440
S-ALE	4110	2120	1232	610
FSI	242	202	233	303



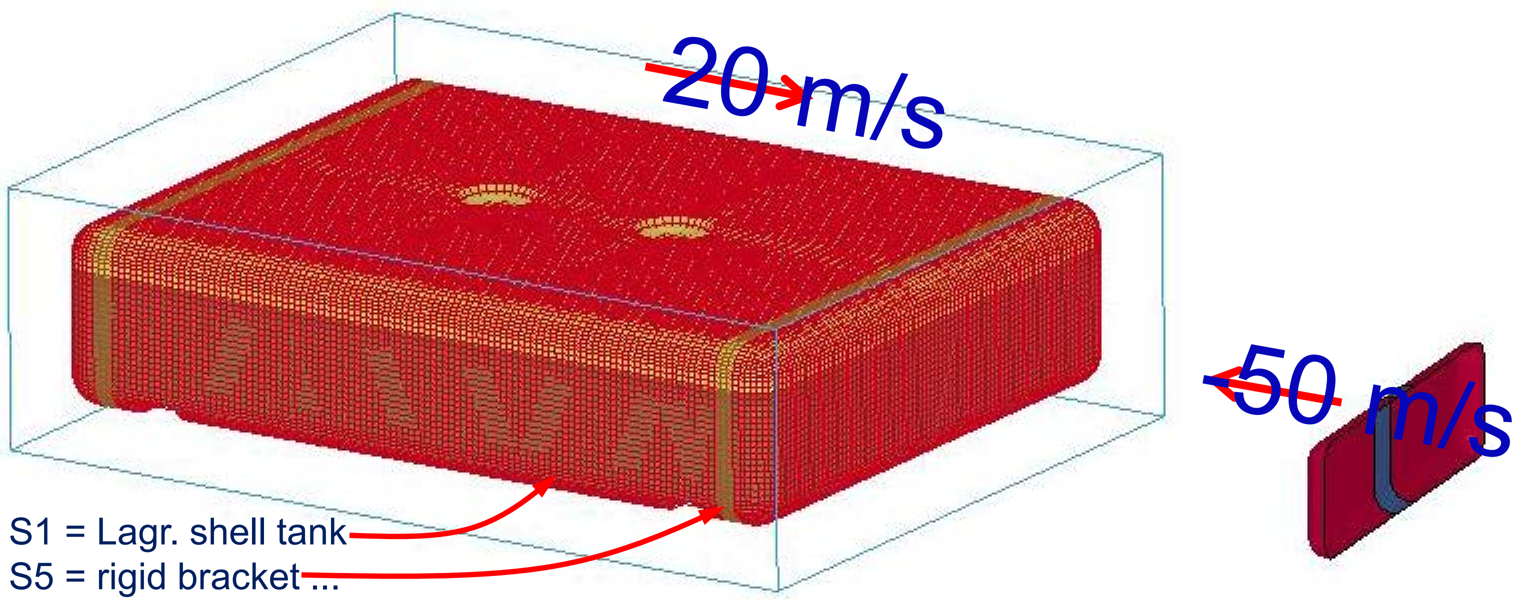
MPP Scalability on Total Time



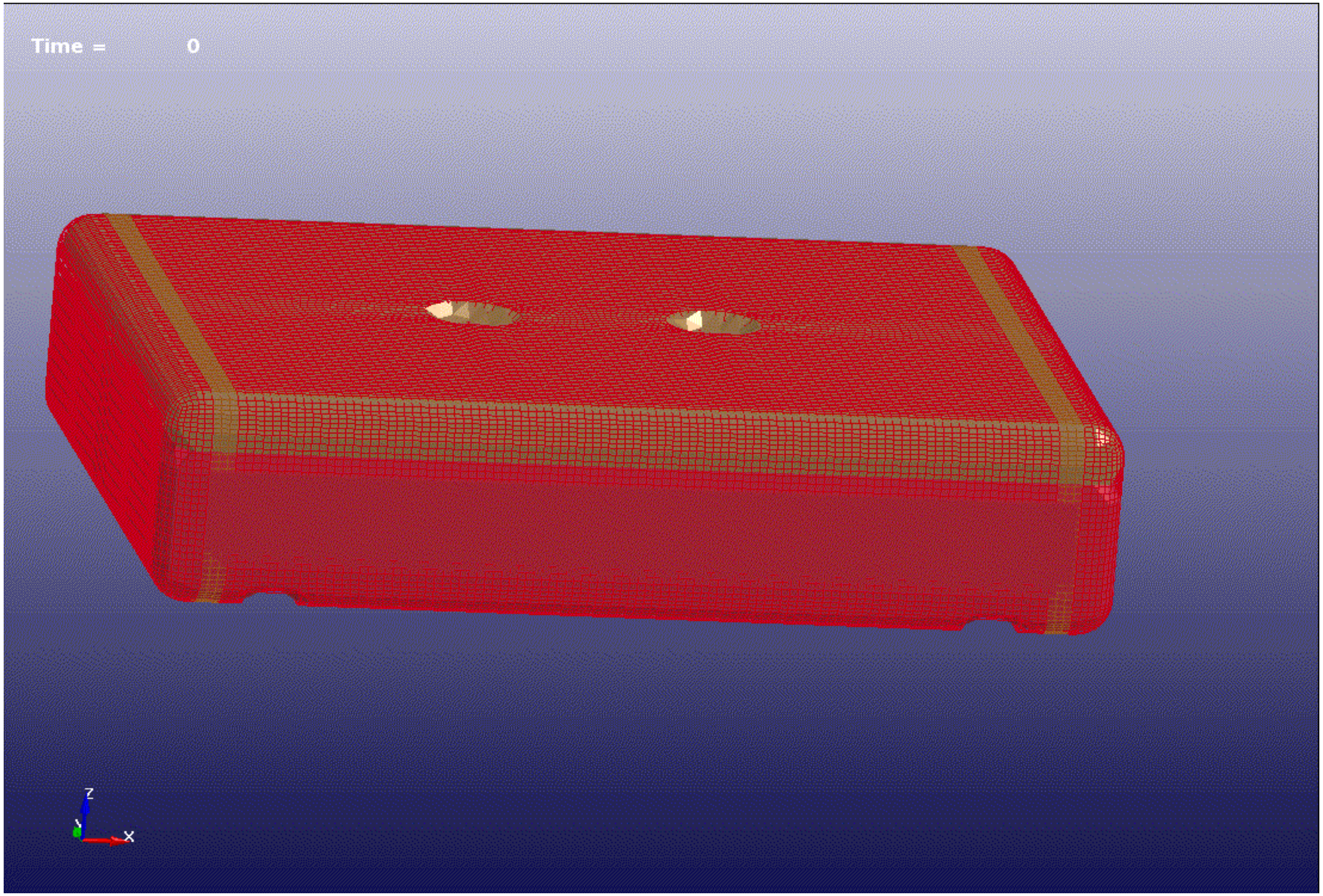
MPP Scalability on S-ALE

Application: Tank Sloshing – Model Description

- Fluids and tank system starts at rest (equilibrates for 1 ms). Tank then accelerates to 20 m/s, then decelerates to 0m/s to create sloshing.
- An impactor moving at -50 m/s strikes the tank.
- Unit system: kg-mm-ms-K; Total run time = 40 ms.



Application: Tank Sloshing – Simulation



S-ALE: 1h41m; ALE: 2h30m (32% speedup)

MPP dev.105342 single precision 12 CPU

Application: Tank Sloshing – Model Setup 1

*ALE_STRUCTURED_MESH					
MSHID	PID	NBID	EBID		
1	202	2000001	2000001		
CPIDX	CPIDY	CPIDZ	NID0	LCSID	
1001	1002	1003	34081	234	

MSHID: Mesh ID (for future use)

PID: Part ID assigned to the mesh
NO NEED to define *PART card

NBID: Starting Node ID

EBID: Starting Element ID

NID0: Origin Node ID

LCSID: Local Coordinate System ID

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1001			363.31729
1		-500.	
75		525.	

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1002			-107.0625
1		-375.	
57		375.	

*ALE_STRUCTURED_MESH_CONTROL_POINTS			
1003			
1		-90.	
23		260.	

Application: Tank Sloshing – Model Setup 1

*ALE_STRUCTURED_MESH					
MSHID	PID	NBID	EBID		
1	202	2000001	2000001		
CPIDX	CPIDY	CPIDZ	NID0	LCSID	
1001	1002	1003	34081	234	

*DEFINE_COORDINATE_NODES				
234	34081	33961	25032	1

Node 34081, 33961, 25032 are three nodes on the Lagrange rigid body part

*NODE			
34081	-3.6331729e+2	-1.070625e+2	0.0000000
33961	-3.432692e+2	-1.070625e+2	0.0000000
25032	-3.6331729e+2	2.0965269e+2	0.0000000

Application: Tank Sloshing – Model Setup 2

*ALE_MULTI-MATERIAL_GROUP	
PID	PTYPE
2	1
3	1
4	1

1 to 1 ⟺

*PART				
PID	SECID	MID	EOSID	HGID
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4

PID	MATERIAL	AMMG
2	AIR outside	1
3	Vapor inside	2
4	Fuel inside	3

- *SECTION should always be 11. Same SECID OK.
- *HOURGLASS form and coefficient should always be 1 and 1.0e-6. Same HGID OK.
- PIDs not used elsewhere. Only to be put into *ALE_MULTI-MATERIAL_GROUP card.

Application: Tank Sloshing – Model Setup 3

*INITIAL_VOLUME_FRACTION_GEOMETRY							
SID	IDTYP	BAMMG					
202	1	3					
TYPE	FILLOPT	FAMMG				“3 = PLANE”	
3	0	2					
X0	Y0	Z0	X1	Y1	Z1		
-6.5	-300.0	132.0	0.0	0.0	0.0		
TYPE	FILLOPT	FAMMG				“1 = PART/PSET”	
1	1	1					
SETID	SETTYP	NORMD					
15	0						

1. All to “Fuel”; 2. Above the plane to “Vapor”;
3. Outside the part 1+5 to “Air”

Application: Explosion – Model Setup FSI

Couple tank to air outside

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
15	202	0	1	2	4	2	-11
START	END	PFAC	FRIC	FRCMIN	NORM	NORMT	DAMP
		-3			1		
CQ	HMIN	HMAX	ILEAK	PLEAK			
			2	0.1			

Couple tank to vapor inside

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
15	202	0	1	2	4	2	-22
START	END	PFAC	FRIC	FRCMIN	NORM	NORMT	DAMP
		-3					
CQ	HMIN	HMAX	ILEAK	PLEAK			
			2	0.1			

Application: Explosion – Model Setup FSI

Couple tank to Fuel inside

*CONSTRAINED_LAGRANGE_IN_SOLID							
SLAVE	MASTER	SSTYP	MSTYP	NQUAD	CTYPE	DIREC	MCOUP
15	202	0	1	2	4	2	-33
START	END	PFAC	FRIC	FRCMIN	NORM	NORMT	DAMP
		-4					
CQ	HMIN	HMAX	ILEAK	PLEAK			
			2	0.1			

Different combinations of coupling cards can be defined.

1. 1 card only
    - tank to inside vapor + fuel
2. 2 cards
    - tank to inside vapor + fuel
    - tank to outside air
3. 3 cards
    - tank to inside vapor
    - tank to inside fuel
    - tank to outside air

Application: Explosion – Model Setup MISC

*CONTROL_ALE							
DCT	NADV	METHOD	AFAC	BFAC	CFAC	DFAC	EFAC
	1	1					
START	END	AAFAC	VFACT	PRIT	EBC	PREF	NSIDEBC
						1.01325e-4	

Include hydrostatic pressure in the calculation

*INITIAL_HYDROSTATIC_ALE				
SID	STYPE	VECID	GRAV	PBASE
202	1	1	9.81e-3	1.01325e-4
NID	MMGBelow			
294095	1			
900001	2			
900002	3			

*LOAD_BODY_Z	
LCID	SF
6	0.00981

Thank You