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Markers Methods

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Project Goals

- Joint effort between SNL and LANL
- Full Lagrangian capability in CTH
- Fully coupled fluid-structure interactions
  - Numerical method integrated into CTH
    - Common input between CTH and Lagrange method
  - Coupled to Adaptive Mesh Refinement (AMR)
    - Dynamic load balancing between CTH and Lagrange method
- Improve strength and failure mechanics
  - Lagrangian fracture mechanics
  - Reduce advection errors in damage and failure
- Fast, Robust and Easy to use

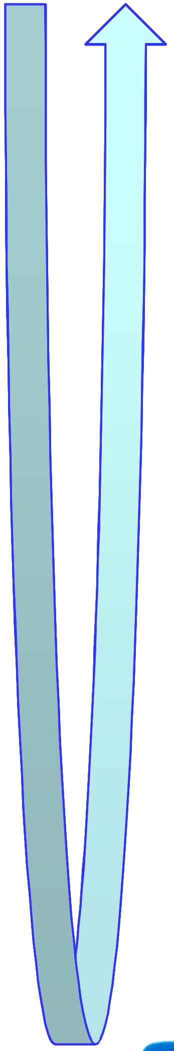
Capabilities

- 1D, 2D and 3D
- Interface into existing material insertion capability in CTH
  - Diatom insertion of marker fields
- Strength
  - Track material behavior through grid to marker differences (Material tracking)
  - Compute stress and accelerations on markers and update to grid (MPM)
- Boundary Conditions
  - Symmetric, outflow, inflow and outflow
- Failure
  - Material switch from shear supporting to hydrodynamic
  - Void insertion based on marker failure
  - No failure
- Massively parallel marker capability with/without AMR
  - Ghost markers
  - Combining and splitting
- All existing CTH material models have been integrated
  - All EOS models
  - Full stress tensor or deviatoric tensor options (except GEFFS and PSDAM)
  - All failure models

Capabilities – cont.

- Composite model integration with markers
  - Initializing marker with material direction using existing layering techniques
  - Separate strain rates for markers in layers
  - With multifield can track layer interaction for delamination and other failure processes
- Plate, shell and beam theories added to CTH
  - Implemented existing plate theory from Los Alamos National Laboratory
  - Working with Los Alamos National Laboratory to add new thin structure theory
- Discard
- New mass footprint of marker fields
  - Second order accurate and sharp object interfaces
- Convective Particle Domain Insertion (CPDI)
  - University of Utah, Rebecca Brannon
  - Currently only in serial
- New material models
  - Full-stress tensor with MPM
    - SWRIG glass model
  - Integration of deformation tensor
  - Hyperelastic Models
    - Mooney-Rivlin
    - Transverse-Isotopic Mooney Rivlin
  - Stochastic models
    - Research on stochastic energetic ignition models

Marker Order of Operations



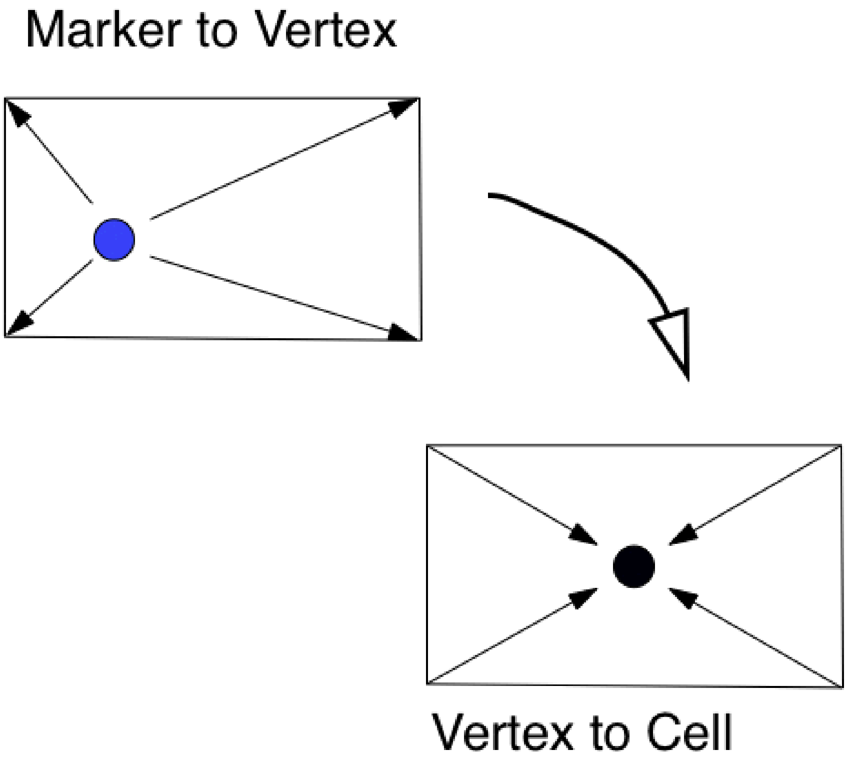
- Lagrangian
  - Compute stress on Markers
  - Determine failure, but do not moved to failure yet
  - Artificial viscosity
  - Compute velocity change of stress, store change
  - Pressure acceleration
  - Lagrangian energy and volume changes
  - Update marker fields, grid to Marker
    - Energy, density, velocity and position
    - Move failed Markers to failed Marker fields
  - Update grid velocities from Markers
- Eulerian
  - Remap
  - Update Marker mass and velocity to grid
  - EOS, compute new P,T based on ρ,E
  - CTH fracture
  - Update Marker P,T,E,ρ,*

Marker to Cell

- Shape functions
  - Linear
  - CPDI

- Mass weighted values to cell center or face

$$\delta_c = \frac{\sum_v \sum_m (\delta_m M_m) S_{mv}}{\sum_v \sum_m M_m S_{mv}}$$



Marker to Vertex

Vertex to Cell

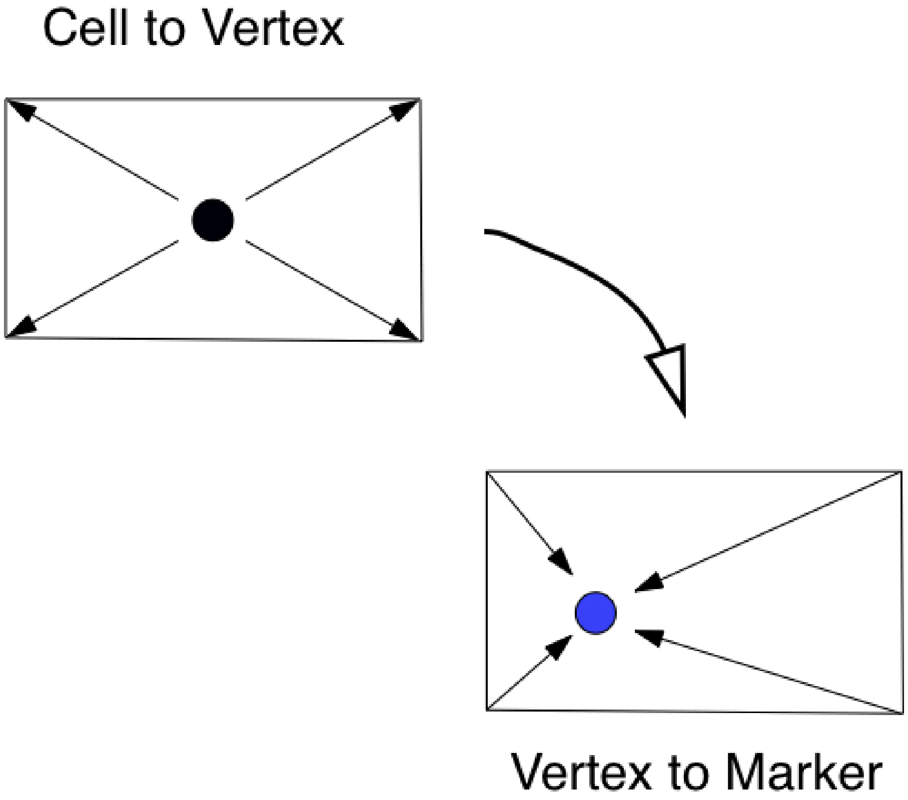
Cell to Marker

- Volume or area weighted to vertex

$$\delta_v = \frac{\frac{\sum \delta_c}{V_c}}{\sum \frac{1}{V_c}}$$

- Vertex to marker shape functions
  - Linear
  - CPDI

$$\delta_m = \sum \delta_v S_{vm}$$



MMP4
Multiple Material Pressures/Temperatures

- MMP4 option created – Must be used with markers
- Mixture pressure:

$$P_c = \frac{\frac{\theta_s P_s}{\rho_s C_s^2}}{\sum_s \frac{\theta_s}{\rho_s C_s^2}}$$

- Mixture sound speed:

$$C_c = \sqrt{(1-\theta_v)\frac{V}{\sum_s M_s \sum_s \rho_s C_s^2}}$$

- Mixture weights:

$$f_s^\theta = \frac{\frac{\theta_s^2}{M_s C_s^2}}{\sum_s \frac{\theta_s^2}{M_s C_s^2} + \frac{\theta_v}{MAX(P, P_{vtol})}}$$

- Changes:

$$\Delta v_s = f_s^\theta \frac{\Delta V}{M_s}$$

$$\Delta e_s = -P\Delta v_s$$

Using Markers

- Mark and endmark designate marker input section

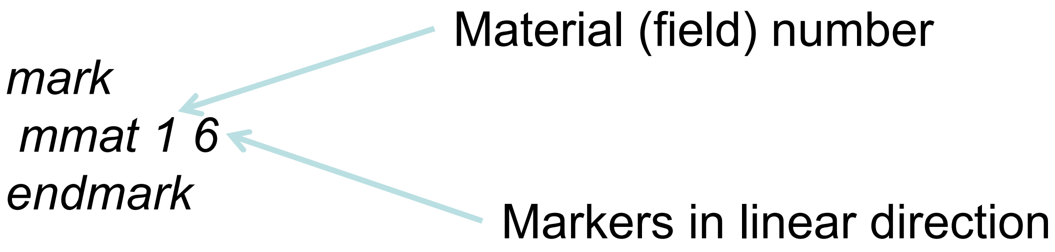
Marker start

```
mark
 mmat 1 6
 mmat 2 4
 stren 3
endmark
```

Marker end

MMAT

- MMAT = Marker MATerial



```
mark
 mmat 1 6
endmark
```

Material (field) number

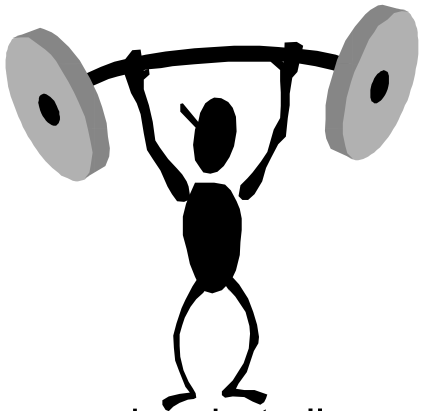
Markers in linear direction

- This will put markers is the grid for material 1. 6 markers in a linear direction, 1D 6 markers in x, 2D 36 markers in cell and 3D 216 markers in cell. (Assuming material completely fills cell)

Marker Output Sample

```
***********************************
   MARKER OUTPUT
   Marker material number =     1
   Memory for marker material per processor =        2048
   Total markers for material  =        2048
   Marker material number =     2
   Memory for marker material per processor =       36992
   Total markers for material  =       36992
   Marker material number =     3
   Memory for marker material per processor =        2048
   Total markers for material  =           0
   Marker material number =     4
   Memory for marker material per processor =       36992
   Total markers for material  =           0
   Total markers in problem  =       39040
   Markers are using MPM, option =     3
   Lagrange Failure ON
   Marker failure on =     3
   Using Marker fracture
   Marker material number =     1 has failure material number =     3
   Marker material number =     2 has failure material number =     4
   Marker material number =     3 has failure material number =     0
   Marker material number =     4 has failure material number =     0
   Stress power is total = rev + irr
   Acceleration option --> sts + P+Q
   Mark Material MPM Options for Material =     1
   Mark Material MPRES Option =     0
   Acceleration option --> devsts = sts + Peos
   Mark Material MKPRES Option =     1
   Full stress tensor option for deviatoric stress models --> sts = devsts + sqrt(rho*cs**2)*volstrn
   Mark Material MEOS Option =     0
   Mark Material MFINT Option =     0
   Acceleration option --> sts + P+Q
   Mark Material MPM Options for Material =     2
   Mark Material MPRES Option =     0
   Acceleration option --> devsts = sts + Peos
   Mark Material MKPRES Option =     1
   Full stress tensor option for deviatoric stress models --> sts = devsts + sqrt(rho*cs**2)*volstrn
   Mark Material MEOS Option =     0
   Mark Material MFINT Option =     0
   Acceleration option --> sts + P+Q
   Mark Material is hydrodynamic =     3
   Acceleration option --> sts + P+Q
   Mark Material is hydrodynamic =     4
   MARKER module real memory   4540568 locations
   MARKER module int memory    548666 locations
   MARKERS MEMORY STORAGE IS =       36.73 megabytes
***********************************
```

STREN



- STREN 1
  - Material Tracking
  - What does this mean: Material “state” will be transported Lagrangian, but all variables are mapped to/from the grid were the state of the material is evaluated.
  - Standard CTH accelerations

$$\rho\frac{d\bar{u}}{dt} = -\overline{\nabla}(P\bar{I} + \bar{Q}) + \overline{\nabla}\cdot\bar{\bar{\sigma}}' + \rho\bar{b}$$

- STREN 3
  - Material Point Method
  - What does this mean: Material “state” will be transported Lagrangian, EOS is evaluated on the grid and the strength and failure are evaluated on the marker.
  - Standard CTH acceleration with MPM acceleration from the marker field.

$$\rho\frac{d\bar{u}}{dt} = -\overline{\nabla}(P\bar{I} + \bar{Q}) + \overline{\nabla}\cdot\left(\bar{\bar{\sigma}} + P\bar{I} + \bar{Q}\right) + \rho\bar{b}$$

Material Point Method cont.

$$\rho \frac{d\bar{\mathrm{u}}}{dt} = -\overline{\overline{\nabla(}}P\bar{\bar{I}} + \bar{\bar{Q}}) + \bar{\bar{\nabla}} \cdot \left(\bar{\bar{\sigma}} + P\bar{\bar{I}} + \bar{\bar{Q}}\right) + \rho\bar{b}$$

$$\int -\bar{\bar{\nabla}}\left(P\bar{\bar{I}} + \bar{\bar{Q}}\right)dV + \Delta t \int \left[\bar{\bar{\nabla}} \cdot \left(\bar{\bar{\sigma_s}} + P\bar{\bar{I}} + \bar{\bar{Q}}\right)\right]S_s dV + \Delta t \int \rho_s \bar{b}\, dV$$

Pressure acceleration

$$\Delta\bar{\mathrm{u}}_{s_{pressure}} = -\frac{\Delta t}{m_s}\bar{\bar{\nabla}}\left(P\bar{\bar{I}} + \bar{\bar{Q}}\right)$$

Body force acceleration

$$\Delta\bar{\mathrm{u}}_{s_{body}} = \Delta t\bar{b}$$

Stress acceleration

$$\Delta\bar{\mathrm{u}}_{s_{stress}} = \frac{\Delta t}{\rho}\int \bar{\bar{\nabla}} \cdot S_s\left(\bar{\bar{\sigma_s}} + P\bar{\bar{I}} + \bar{\bar{Q}}\right)dV - \frac{\Delta t}{\rho}\int \left(\bar{\bar{\sigma_s}} + P\bar{\bar{I}} + \bar{\bar{Q}}\right) \cdot \bar{\bar{\nabla}}S_s dV$$

$$\frac{\Delta t}{\rho}\int \hat{\mathrm{n}} \cdot \left\{S_s\left(\bar{\bar{\sigma_s}} + P\bar{\bar{I}} + \bar{\bar{Q}}\right)\right\}dS = 0$$

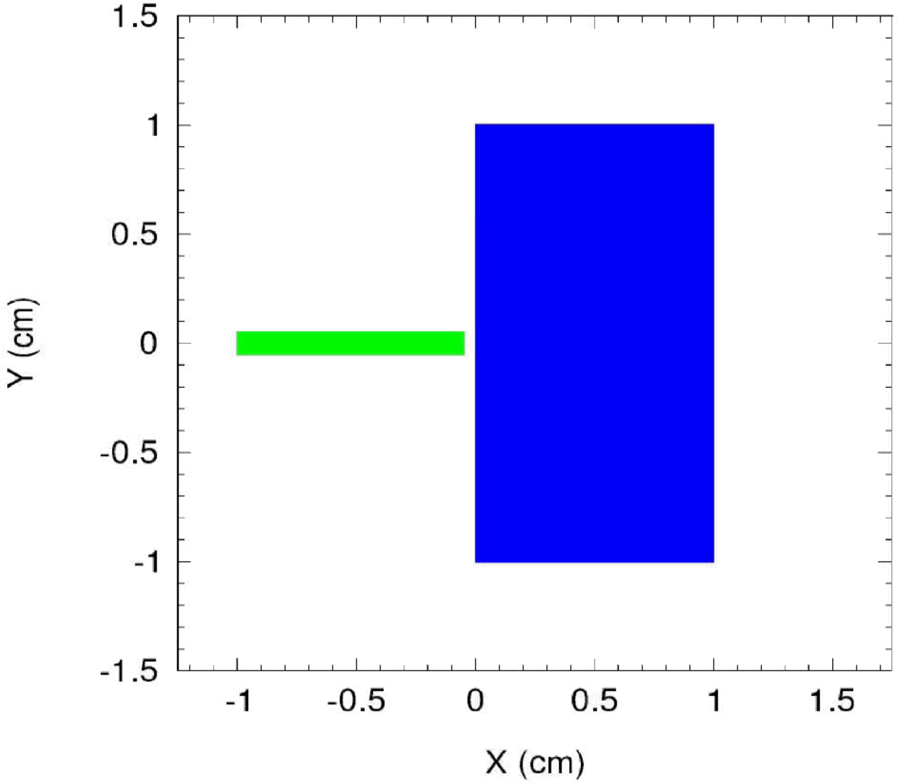
$$\Delta\bar{\mathrm{u}}_{vs_{stress}} = \frac{\Delta t}{M_{vs}}\sum\nolimits_m M_{ms}v_{ms}\left(\overline{\overline{\sigma_{ms}}} + P_{ms}\bar{\bar{I}}\right) \cdot \bar{\bar{\nabla}}S_{mvs}dV$$

Failure with Markers

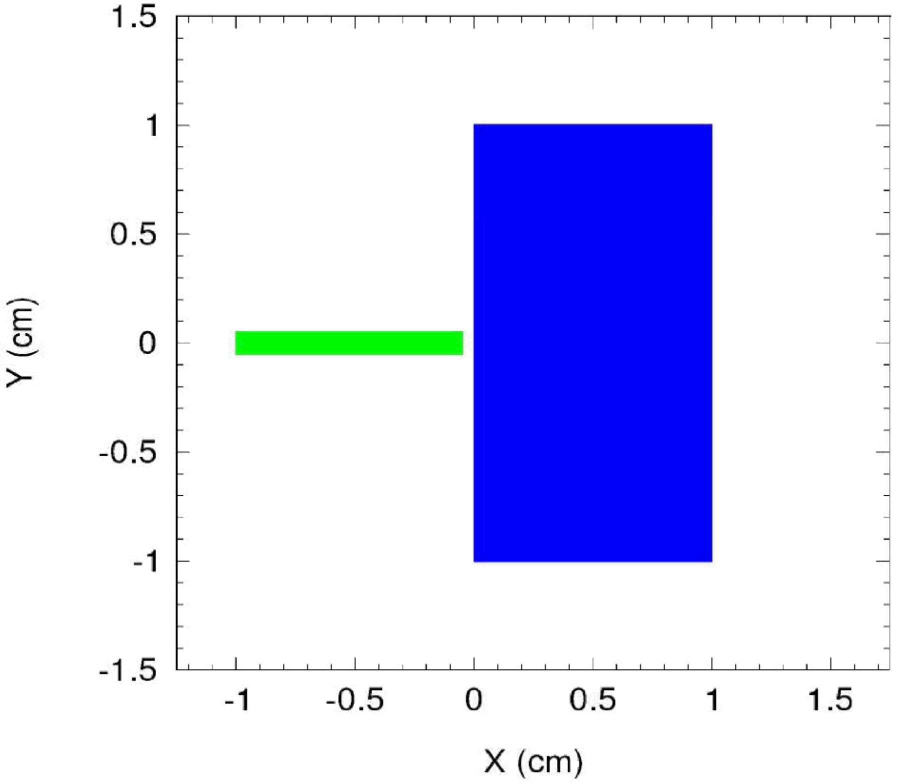
- Failure by material model
  - CTH uses void insertion
- Material switching
  - (Default) Strength bearing material switches to hydrodynamic material
    - Failed material uses CTH void insertion
  - Deviatoric stress = 0, fail=2
  - Fail 3, default, material switching using damage for certain models
  - Fail 1, uses the original CTH logic for markers to determine failure
    - Stress of pressure comparison
- Uses damage to indicate failure
  - Johnson-Cook Fracture
  - Grady Kipp
  - BFK concrete
  - Transverse Isotropic
  - MCM
  - MCMPLAS
- Failure in tension and compression

Failure differences

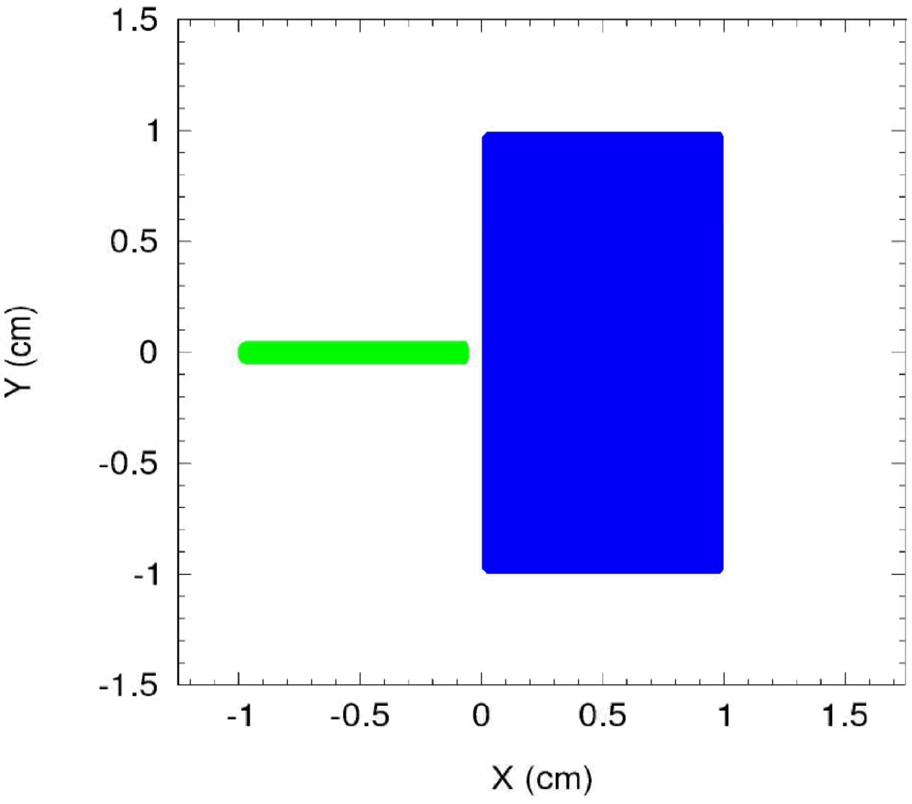
JFRAC using spherical stress, (fail 1)

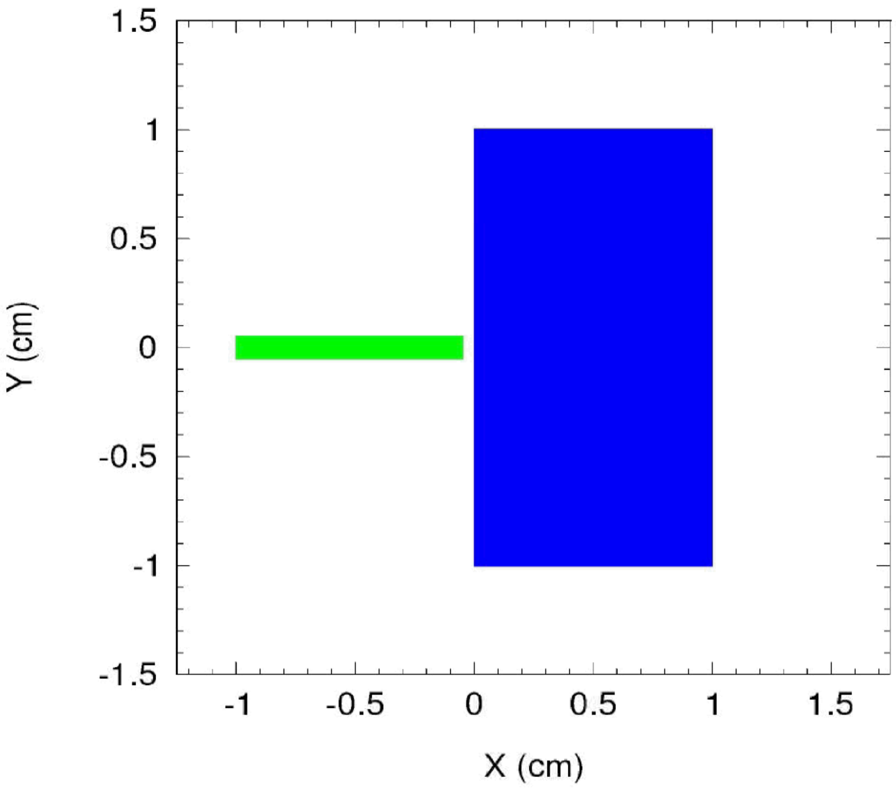


JFRAC using damage (fail 3)



Failure differences cont.


CTH stress option in pfrac


JFRAC using damage (fail 3)

MFTEN

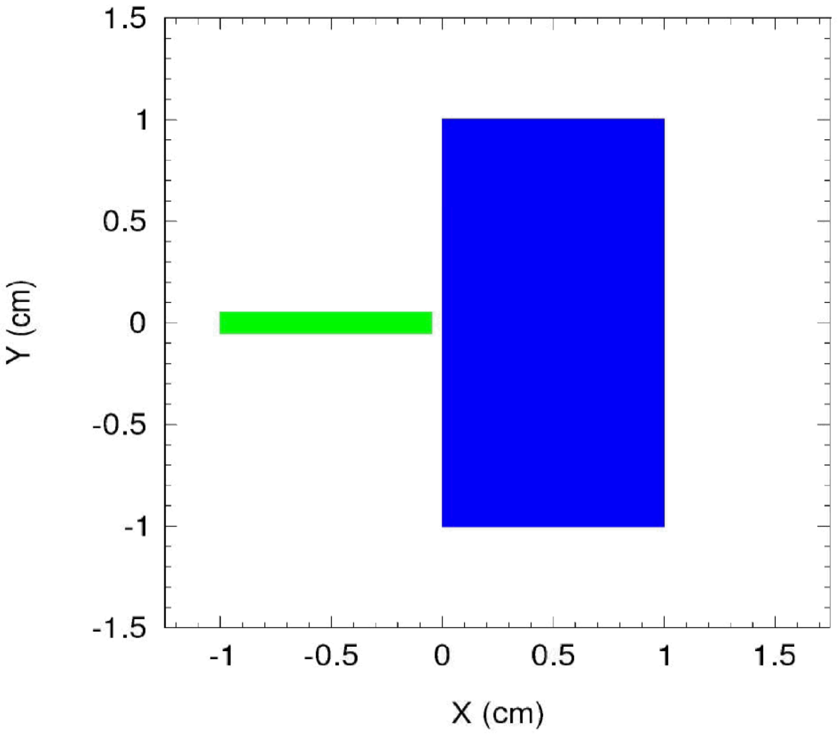
- MFTEN 0 – tension and compression (default), 1 - tension only
  - Failure control in tension and compression
  - What does this mean: Default, markers fail in tension and compression. CTH without Markers, void is inserted in tension only. Therefore, this control mimics CTH with only tensile failure when MFTEN is on (MFTEN 1)
  - Set by material

```
mark
 mmat 1 6
 mften 1
 mmat 2 4
 stren 3
endmark
```

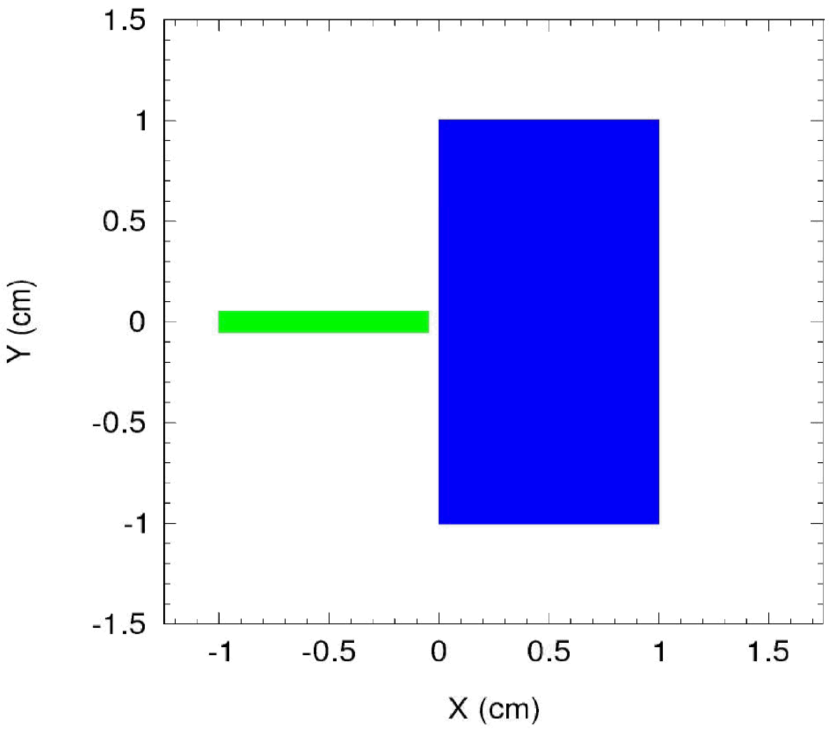
Tensile failure only for material 1

MFTEN cont.

MFTEN 0 (Default)



MFTEN 1



MTENEOS

- MTENEOS 0 – off (default), 1 - on
  - Equation of state limited to compression only

  - What does this mean: Default, Equation of state (EOS) used in tension and compression. Limits the EOS to be used only in compression. In tension, trace of stress tensor computed from marker material.
  - Set by material
  - Recommend using with a failure model, ie. jfrac

Compression $P = f(\rho, E, *)$

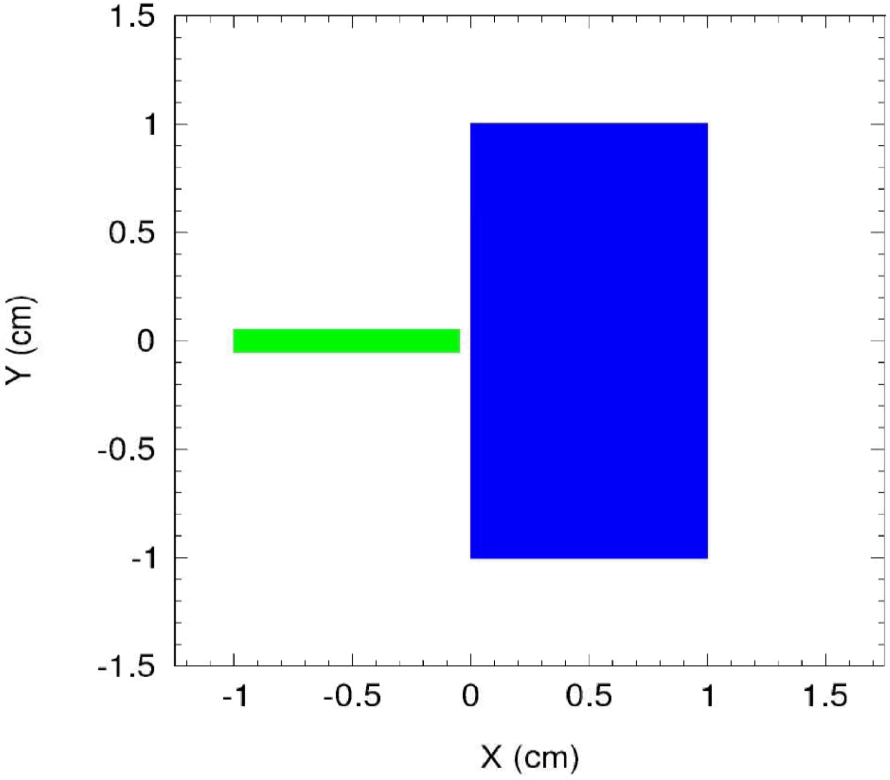
Tension $P = -\frac{1}{3} trc(\bar{\bar{\sigma}})$ Pressure is positive in compression

```
mark
 mmat 1 6
 mteneos 1
 mmat 2 4
 stren 3
endmark
```

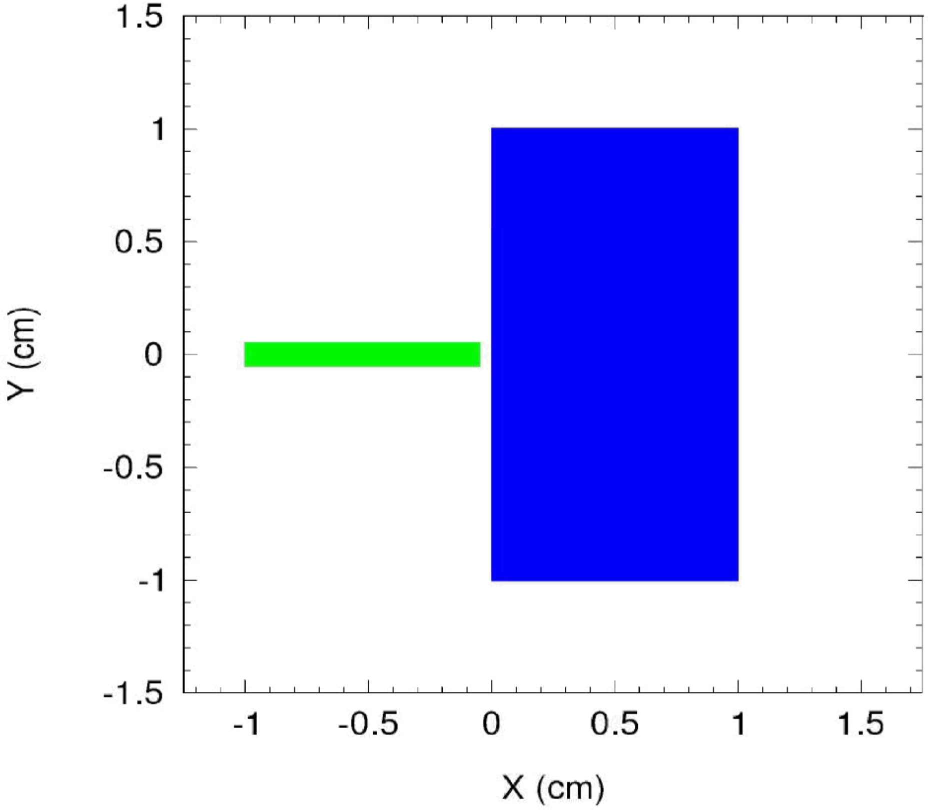
Compression EOS only

MTENEOS cont.

MTENEOS 0 (Default)



MTENEOS 1



SENRG

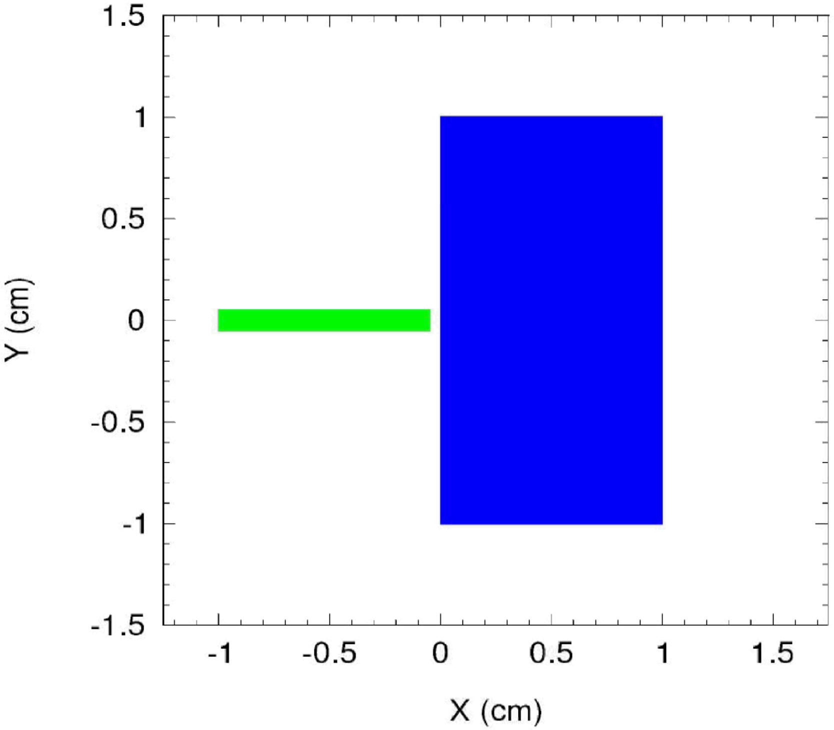
- SENRG 0 – off (default), 1 – on
  - Stress power energy control
  - What does this mean: Default, off, compute total energy, reversible + irreversible energy go into internal energy. On, only irreversible energy go into internal energy changes

```
mark
 mmat 1 6
 mmat 2 4
 stren 3
 snerg 1
endmark
```

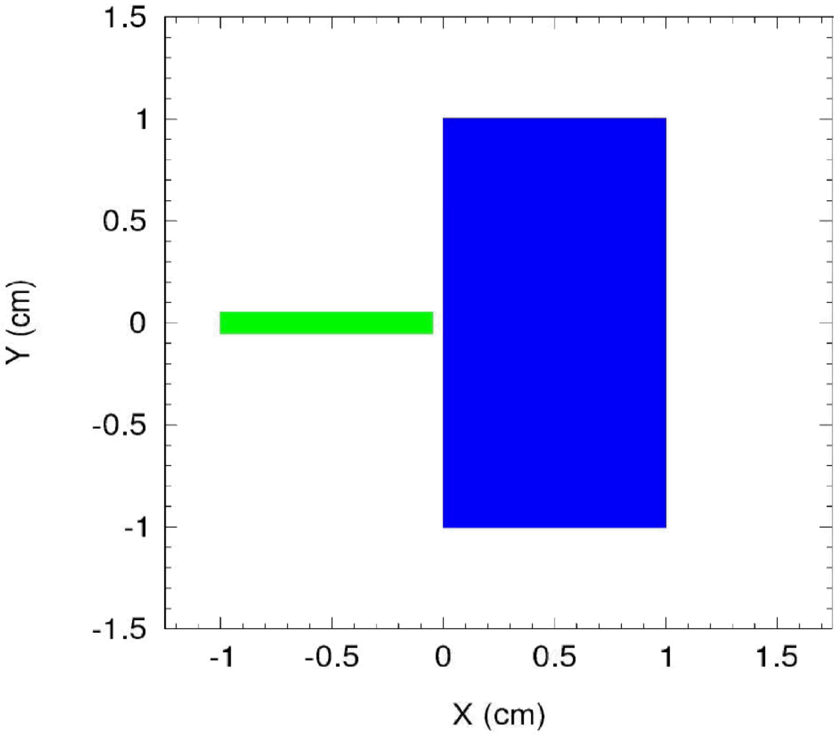
Senrg on

SENRG cont.

SENRG 0 (Default)



SENRG 1



MEMFAC

- MEMFAC 8 (default)
  - Memory factor for parallel processing
  - What does this mean: Takes the computed memory and multiplies by the factor. For moving markers from processor to processor

```
mark
 mmat 1 6
 mteneos 1
 mmat 2 4
 stren 3
memfac 2
endmark
```

Memory factor from 8x to 2x

Markers with AMR

- Do not want to refine on Marker fields
  - Why, typically already resolved.
  - Marker numbers grow in refinement
    - 1D 2x on refinement per cell
    - 2D 4x on refinement per cell
    - 3D 8x on refinement per cell
- Typically set marker field by using MAXL
  - Initialize marker fields and memory at the start of the problem
- Use MEMFAC to help control memory

SpypIt with Markers

- All commands work for 1D, 2D and 3D

- DrawMarkers(“size”,”shape”);
  - Size will scale the marker size
  - Shape, 0 for squares, 1 for spheres + additional options in the future
  - Example DrawMarkers(4,0);

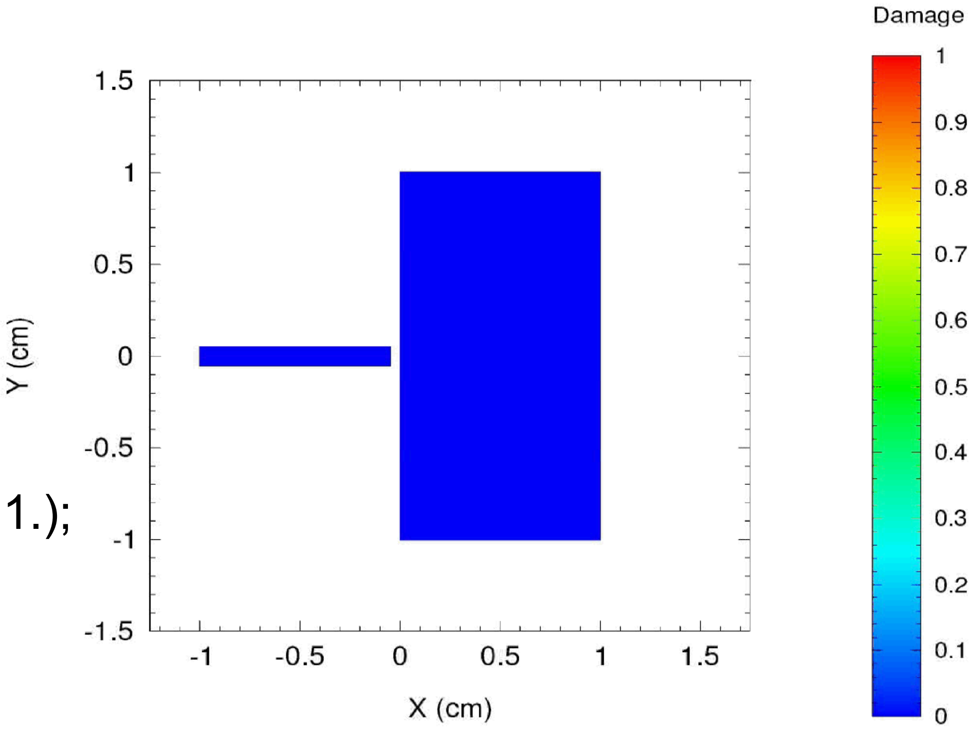
- PaintMarkers(“material #”,”variable”,”size”,”shape”);
  - Material number is the material in the analysis
  - Variable is the plot variable – See Marker Manual for list of available variables
  - Size will scale the marker size
  - Shape 0 for squares, 1 for spheres + additional options in the future

  - Example PaintMarkers(2,”P”,4,0);
    - Plots the Marker pressure for material 2
  - Example PaintMarkers(1,”DAM1”,4,0);
    - Plots the state variable, DAM1, for material model 1
  - Example PaintMarkers(0,”P”,4,0);
    - Plots the Marker pressure on all materials, 0 means all materials.

SpypIt Example

```
Image("mrks_dam",WHITE,BLACK);
    Window(0.,0.,0.85,1.);
    HotMap;
    ColorMapRange(0.,1);
    PaintMarkers(1,"DMG1",2,0);
    PaintMarkers(2,"DMG2",2,0);

DrawColorMap("Damage",0.85,0.1,1.,1.);
   EndImage;
```



Tracers with Markers

- Spyhis operation is the same
- Tracer “attaches” itself to a Marker to output data
  - Chooses the Marker closest to the Tracer location at initialization
- Example:

```
Tracer
 add 0.1 0.1 0.1 mrk
endtracer
```

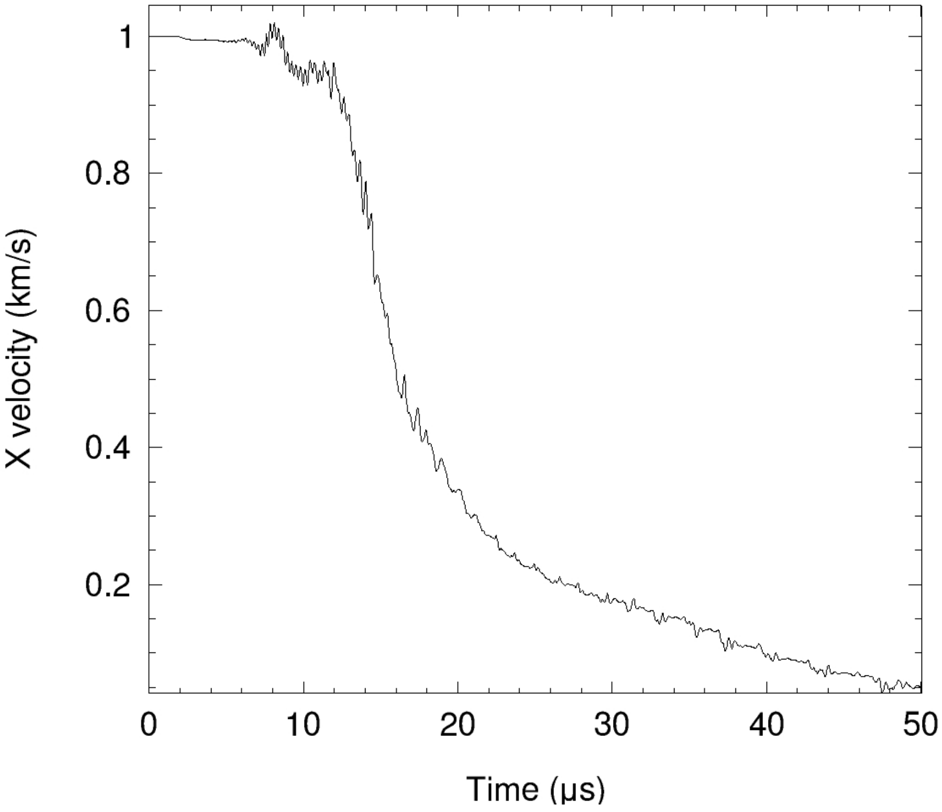
Set tracer to attach to marker

- Output variables the same as SpypIt with Markers in previous slide.

Spyhis Example

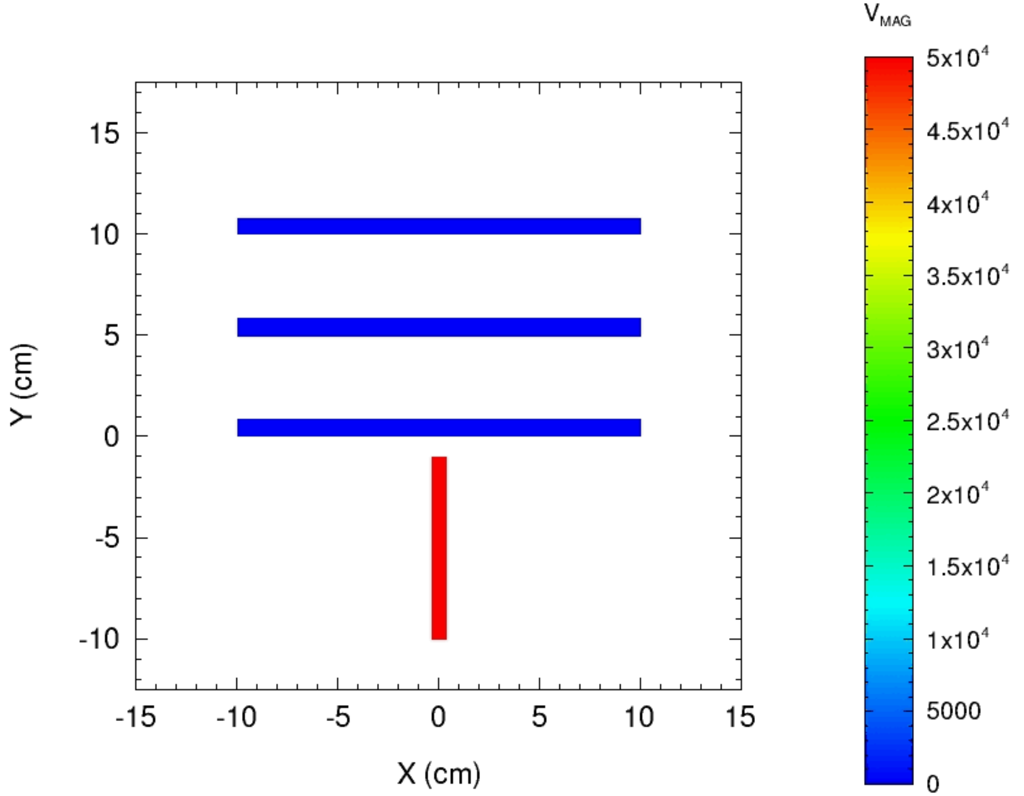
```
tracer
  add -.9 0 MRK
endtracer
```

```
define spyhis_main()
{
  HisLoad(1,"hscth");
  HisImageName("pene");
  TPlot("VX.1",1,AUTOSCALE);
}
```

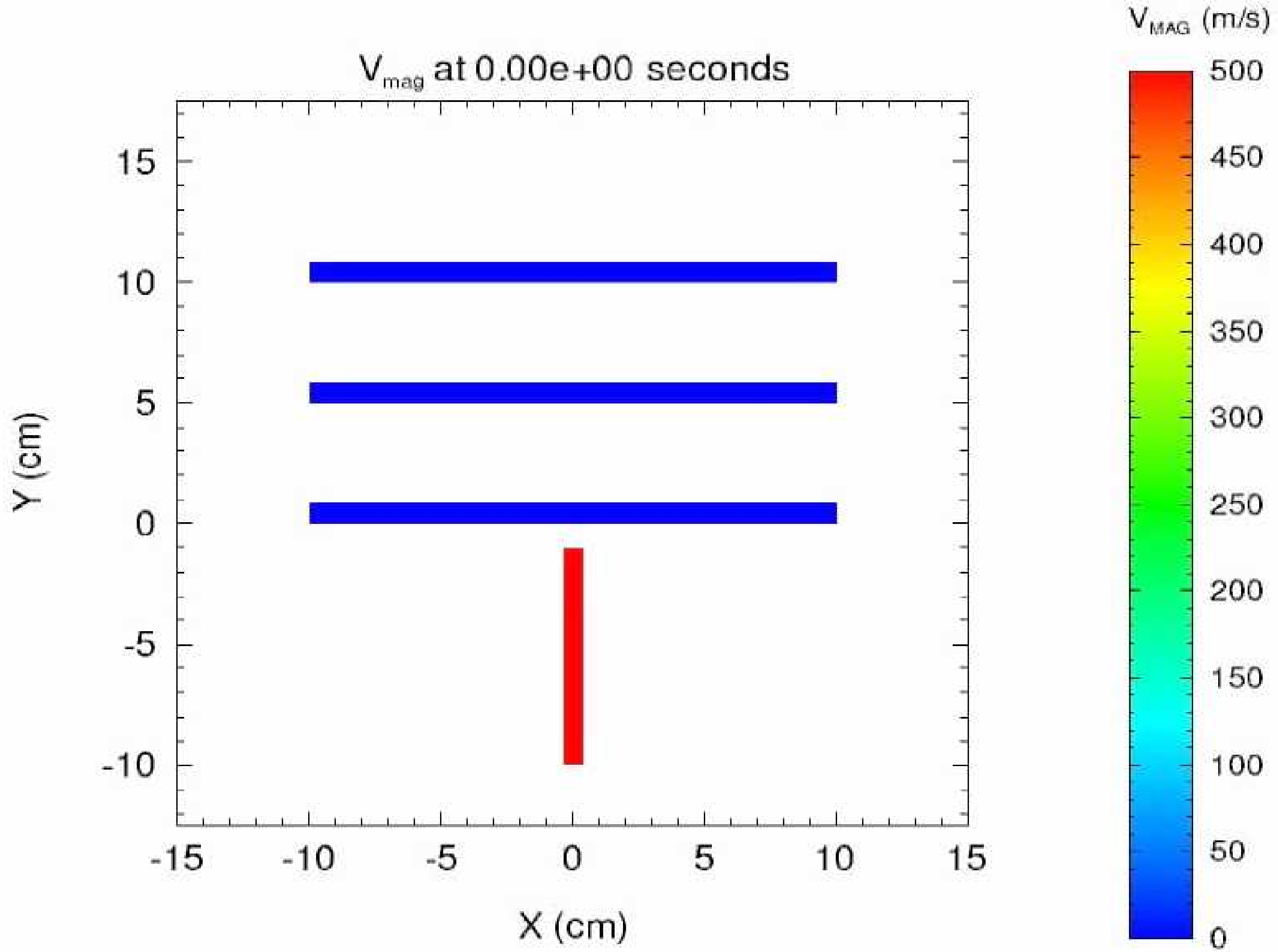


Triple Plate

- Two-dimensional cylindrical
- Rod impacting flat plates
- Velocity is 500 m/s



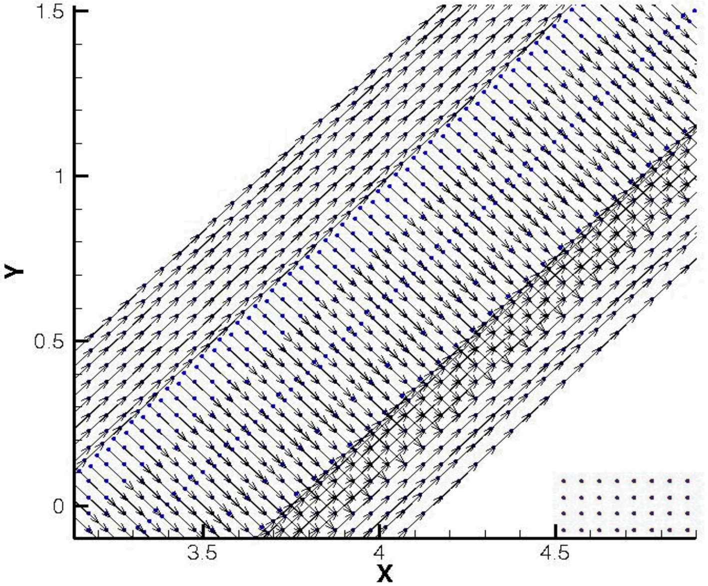
Triple Plate

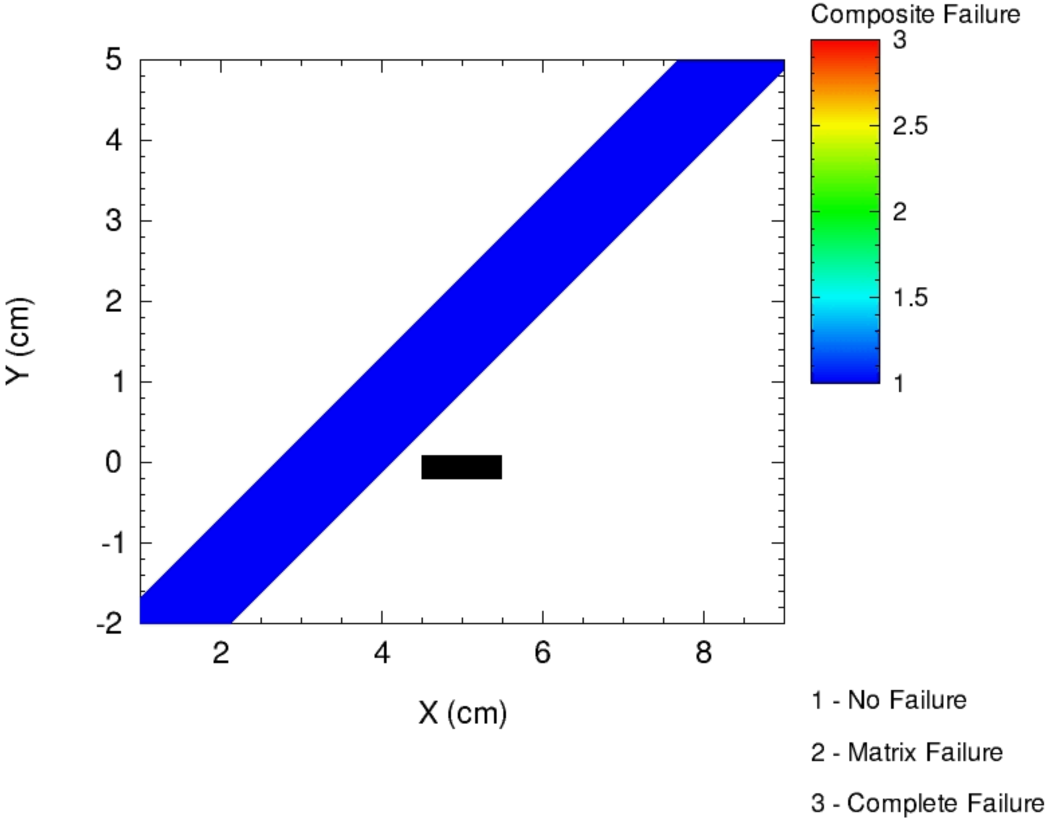


Oblique Composite Plate

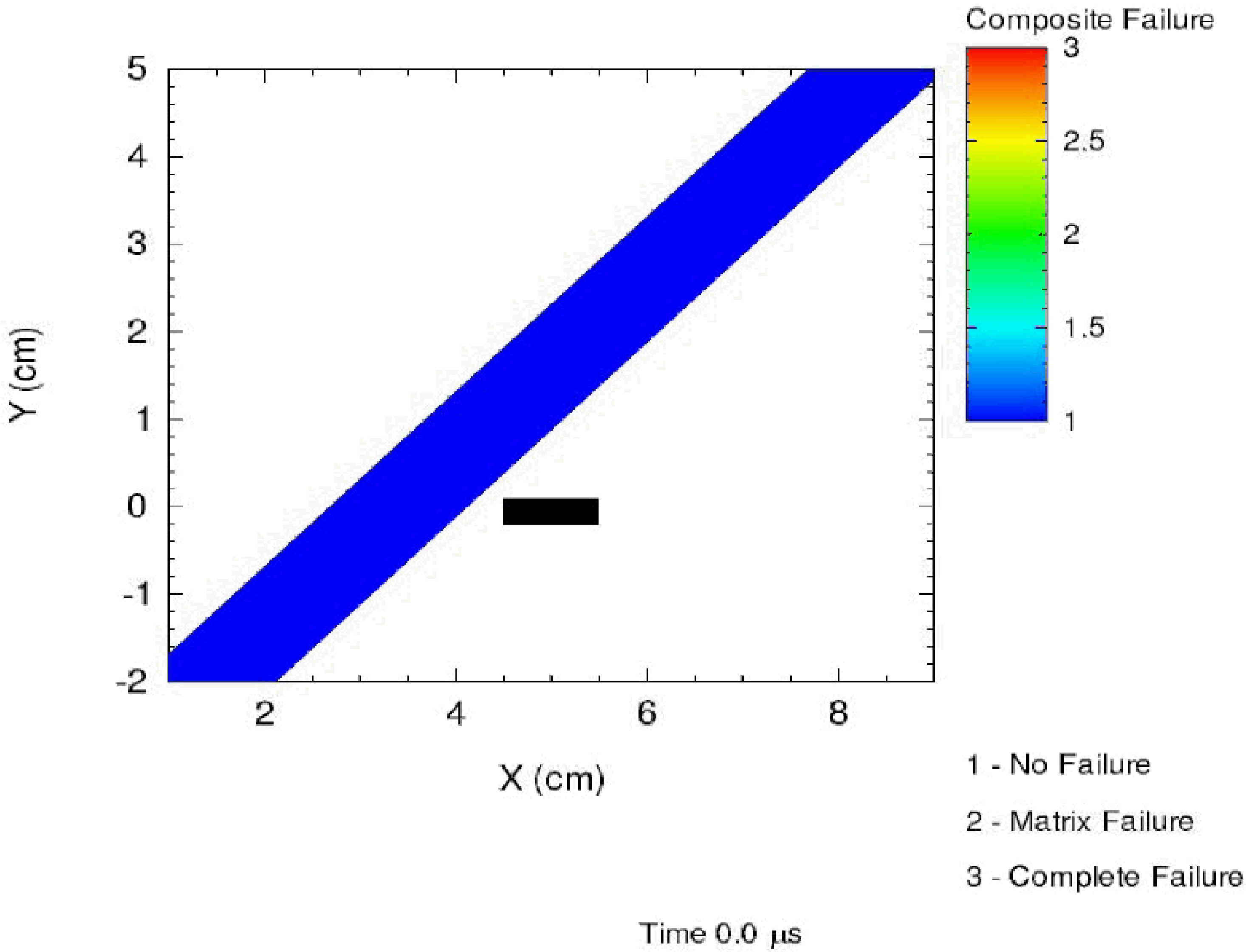
- Two dimensional rectangular
- Thin metal projectile
- Velocity of 100 m/s
- Composite
  - [0°,90°,90°,0°]

Material Vector Plot





Oblique Composite Plate



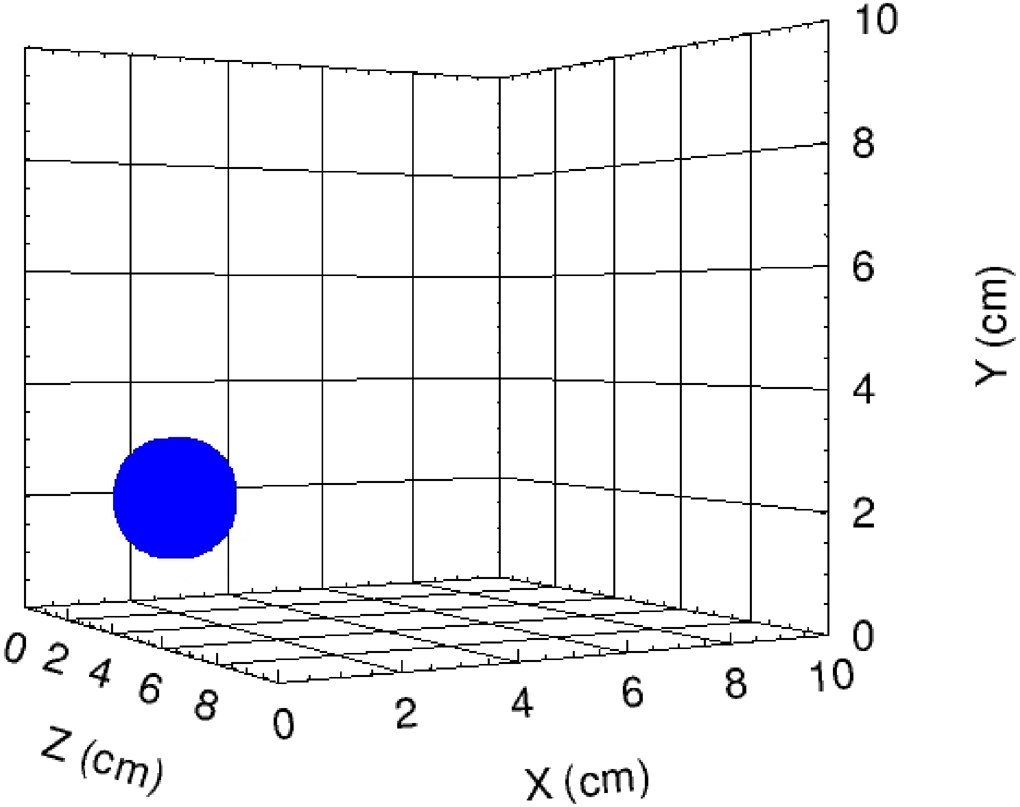
1 - No Failure

2 - Matrix Failure

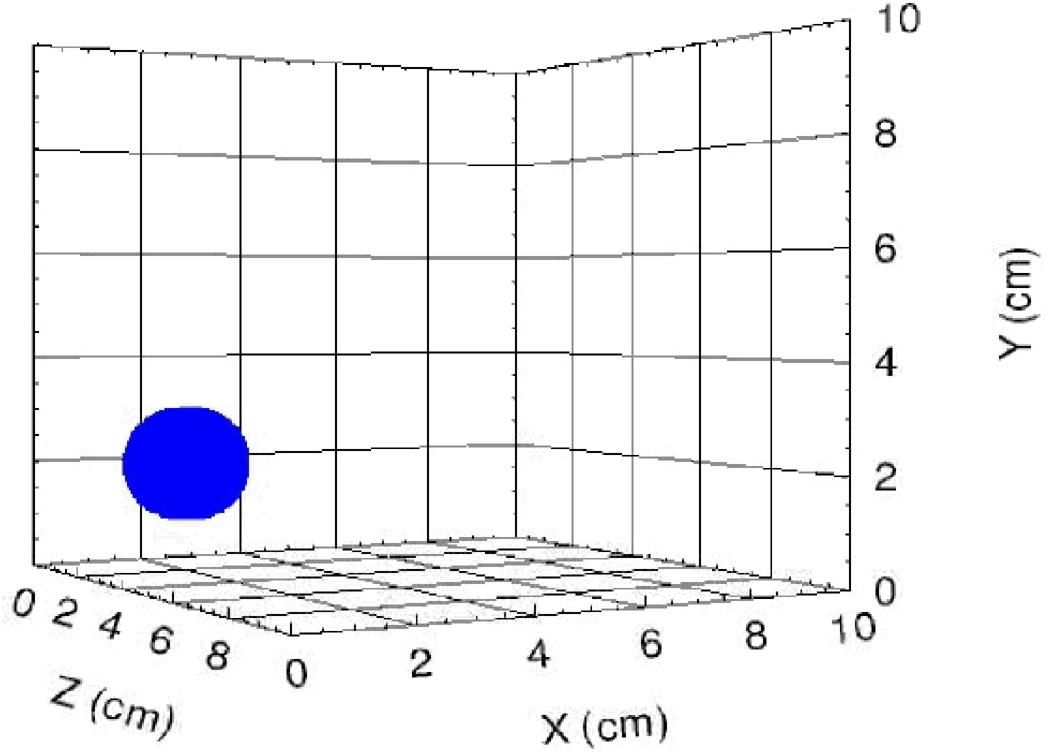
3 - Complete Failure

Elastic Ball

- Three dimensional rectangular
- Elastic ball
- Velocity 500 m/s



Elastic Ball



Time 0.0 µs

Marker Troubles

- Marker separated by one cell or more
  - More markers is better, expansion problems
  - CPDI fixes problem, expands the marker domain to retain connectivity
- Marker insertion is perfectly graded
  - No “randomization”, so fracture patterns are perfectly symmetric for a sphere
  - Tessellation methods available, need to be implemented
- Markers are not as forgiving as CTH
  - Really need accurate material model input data

Marker Development Areas

- Thin structure theory for blast/penetration of thin structures
- Implicit Continuous Eulerian (ICE++)
  - AMR (+) with shear waves (+)
- Tessellation of Marker solid objects
- Parallelization of CPDI
- Fracture and failure of Marker field
  - Marker splitting, etc.
- Visualization options
- Multifield

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