Remap of material damage and failure in unstructured ALE calculations

MultiMat 2013

Sam Schofield
ALE3D Research & Development

Lawrence Livermore National Laboratory

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Abstract

Shock hydrodynamics calculations often involve complex materials including damage and failure models. The models are naturally formulated in a Lagrangian frame and have parameters calibrated to experiments using “pure” Lagrangian calculations. However, complex multi-material flows with large deformation require mesh relaxation and remap. The diffusive nature of remap distributes damage when the preservation of local features in essential to realistic modeling. Material states relative to failure thresholds can change during remap leading to instantaneous failure or healing. Three particular aspects of failures models create challenges for typical conservative, monotonic remap methods: porosity/void nucleation and growth [1], damage variables [2], and discrete failure criteria based on stress or porosity thresholds [3].

In this work, the remap of damage and failure is examined in a multi-material ALE code. The preservation of local features including both void/porosity based and damage variable based failure are addressed through Lagrangian material particles and feature reconstruction methods. These are presented in the context of both swept region and local intersection based remap. In addition, the interaction of failure criteria with the pre- and post-remapped state is discussed.

References

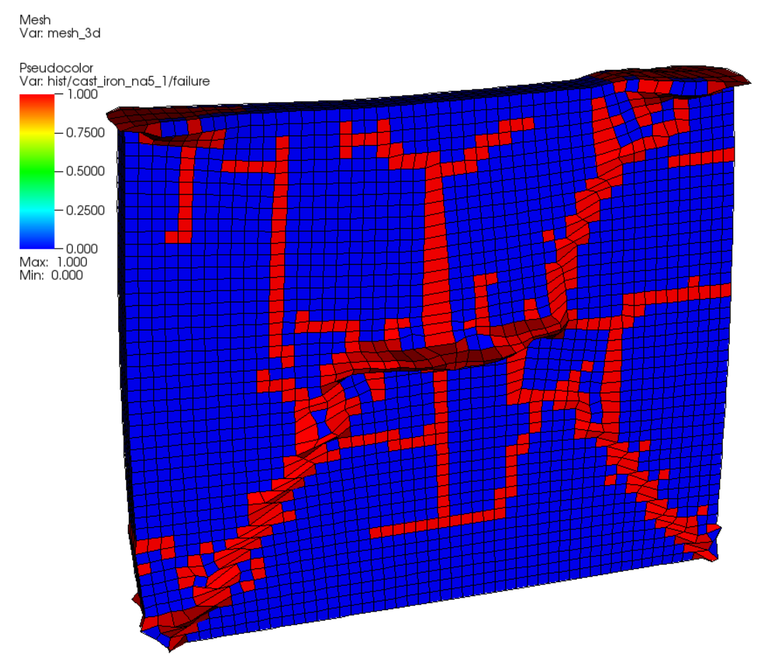
1. J. H. Johnson and F. L. Addessio, “Tensile plasticity and ductile failure”, J. Appl. Physics, 64(12), pp. 6699-6712
2. G. R. Johnson and W. H. Cook “Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures”, Engineering Fracture Mechanics, 21(1), pp. 31–48, 1985.
3. R. Becker, “Ring fragmentation predictions using the Gurson model with material stability conditions as failure criteria”, Intl. J. of Solids and Structures, 39, pp. 3555–3580, 2002.

Acknowledgments

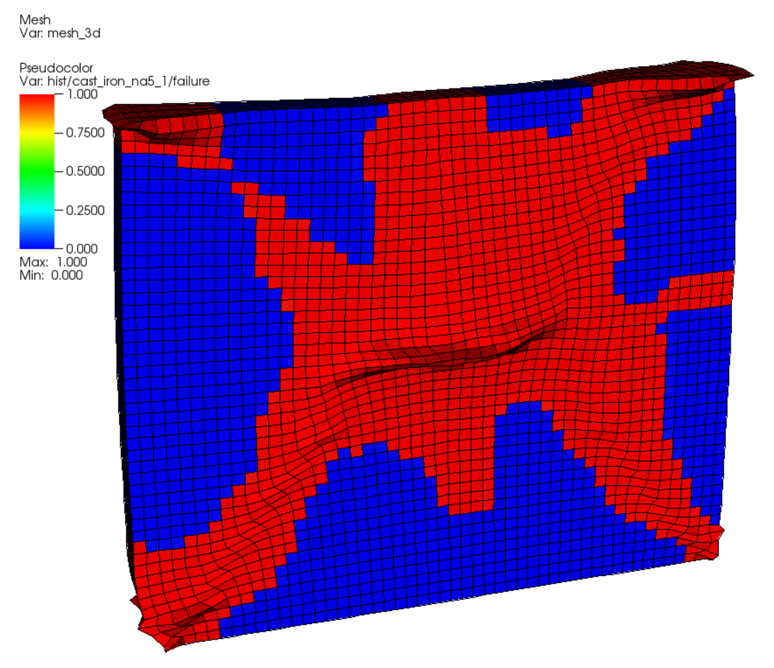
- Paul Amala, Armand Attia, Nathan Barton, Rich Becker, Ben Liu, Al Nichols, James Stolken
- ALE3D Team

Fracture and failure models are often poorly suited for ALE

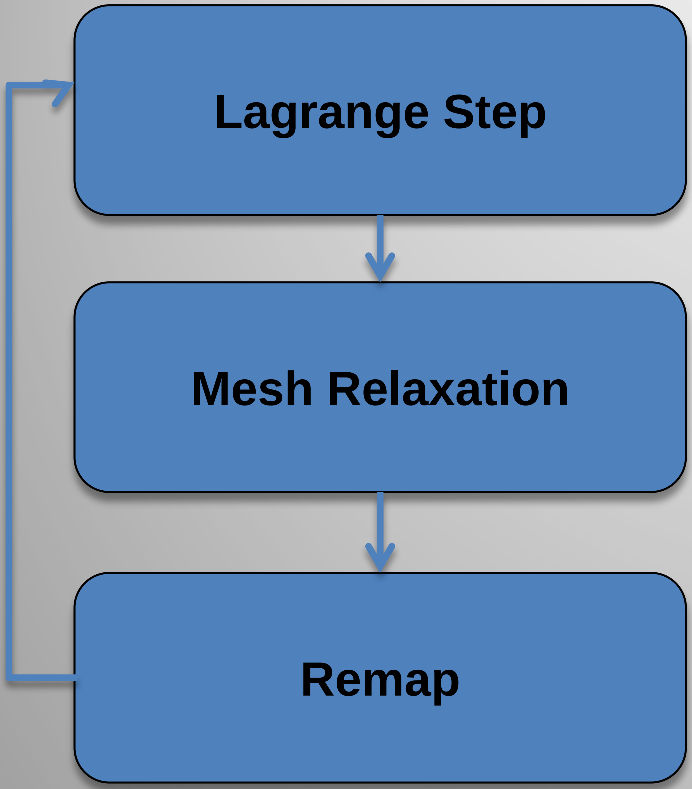
Lagrangian fractured plate



With mesh perturbation and remap



Fracture and failure models are common in Lagrangian hydrocodes but often poorly suited for ALE.



Fracture and failure models are usually developed and calibrated with Lagrangian calculations

Large deformation problems require mesh relaxation and remap but the models are often poorly suited to standard remap methods.

Post remap “fixup” routines are available for each material but cannot fix all the problems.

Outline

- Damage and Failure Models
  - Johnson-Cook
  - Gurson
- Damage, Failure and ALE
  - Method I: Tracking/reconstruction
  - Method II: Sub-region method
- Void insertion and seeding
- Conclusions and Future Directions

I. Damage and Failure Models

Johnson-Cook failure is widely implemented and used.

A *damage* variable is evolved in time – accumulated at each timestep

$$D = \sum_n \frac{\Delta\epsilon^n}{{\epsilon_f}^n}$$

$\Delta\epsilon^n$ is the plastic strain increment and ${\epsilon_f}^n$ is the strain to failure.

$${\epsilon_f}^n = [D_1 + D_2 \exp\,(D_3\sigma^*)\,]\,[1\ + D_4 \ln \dot{\epsilon}^*]\,[1\ + D_5 T^*]$$

- Material is failed when damage exceeds 1 – the deviatoric stress is set to negligible or zero value.

- *After failure damage is no longer well defined and left at the value obtained at failure.*

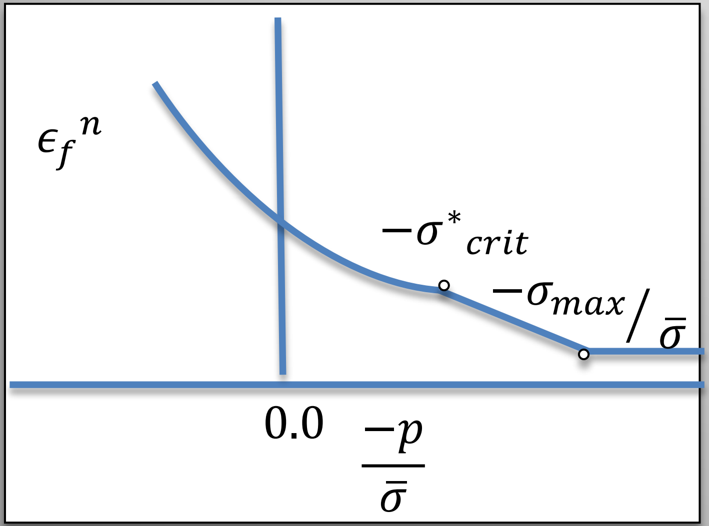
G. R. Johnson and W. H. Cook. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures, and pressures. *Engineering Fracture Mechanics*, **21**:31–48, 1985.

Johnson-Cook strain to failure model has stress triaxiality, strain rate, and temperature dependence

- Strain to failure has dependence on stress triaxiality, strain rate and temperature through material dependent parameters, D_1, D_2, D_3, D_4, D_5

$$\epsilon_f{}^n = [D_1 + D_2 \exp\,(D_3\sigma^*)\,]\,[1\ + D_4 \ln \dot{\epsilon}^*]\,[1\ + D_5 T^*] \qquad \dot{\epsilon}^* = \frac{\dot{\epsilon}}{\dot{\epsilon}_0}$$

where $\sigma^* = -\frac{\bar{\sigma}}{p}$ and $\bar{\sigma} = \sqrt{\frac{3}{2}\sigma_{ij}{}'\sigma_{ij}{}'}$ Is the von Mises effective stress



- In tension, above critical triaxiality, failure strain decreases linearly to a prescribed minimum.

Gurson derived models are representative of void/porosity growth models

The Gurson flow surface explicitly accounts for void volume fraction, *f*,

$$F = -\overline{\sigma^2} - Y^2[1 + \left(1 + q_1^2 f^{*2}\right) + 2q_1 \cosh\left(\frac{3}{2} q_2 \frac{p}{Y}\right)]$$

The void fraction evolves due to plastic volume change and accounts for rapid loss of strength at large void fractions

$$\dot{f} = (1 - f) d_v^p \qquad f^* = \begin{cases} f & f \le f_c \\ f_c + (f - f_c)\dfrac{f_u - f_c}{f_f - f_c} & f > f_c, f_u = 1/q_1 \end{cases}$$

Gurson, A. L. Continuum theory of ductile rupture by void nucleation and growth: part I yield criteria and flow rules for porous ductile media. *J. of Eng. Materials and Tech*., **99**:2-5, 1977

The failure criteria is often much more complex than a simple damage threshold

$\left(\frac{f}{f_l}\right)^2 + D^2 \geq 1$ Addessio & Johnson (TEPLA-f)

$\det[R_{ij}] \leq 0$ Becker (Bifurcation condition)

Becker, R. Ring fragmentation predictions using the Gurson model with material stability conditions as failure criteria. *Intl. J. of Solids and Structures*, **39**:3555-3580, 2007.

Johnson, J. N. and Addessio, F. L. Tensile plasticity and ductile fracture. *J. Appl. Phys*. **64**:6699-6712, 1988.

Void insertion is available with several models

- When criteria is satisfied, void material is inserted into a zone to maintain relative volume within bounds.

- Void material is inserted when material is failed AND relative volume exceeds threshold

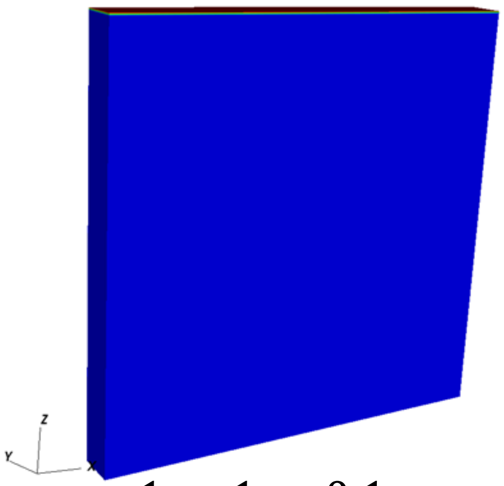
- Void is treated as typical void material with usual multi-material treatment.

II. Damage, Failure, and ALE

Fracture/failure models are typically mesh and resolution dependent.

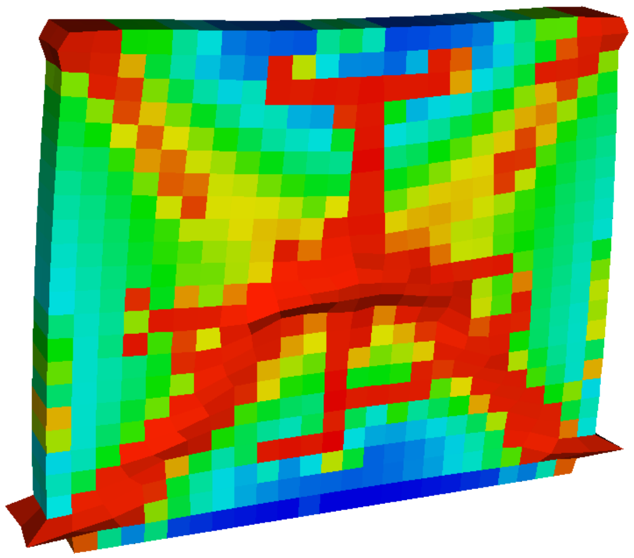
- The top of a vertical cast iron plate plane has an imposed velocity of $-2.4\times 10^{-3}\,(0.01,0,1)$ partially supported on bottom.
- Mie-Grüneisen EOS
- Specific cast iron model used for yield surface with Johnson-Cook failure model

Johnson-Cook parameters			
D_1	0.0	σ^*_{crit}	-0.8
D_2	0.0320	σ_{max}	-0.01
D_3	3.59	ϵ_{min}	8.18e-4
D_4, D_5	0		



$1 \times 1 \times 0.1$

Fracture/failure models are typically mesh and resolution dependent.



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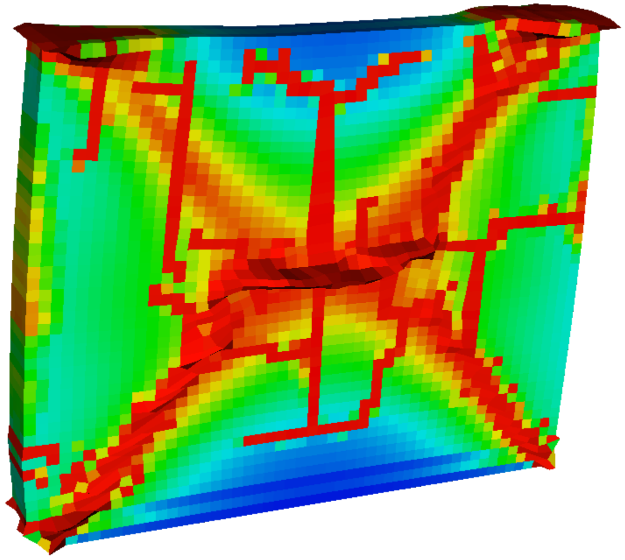
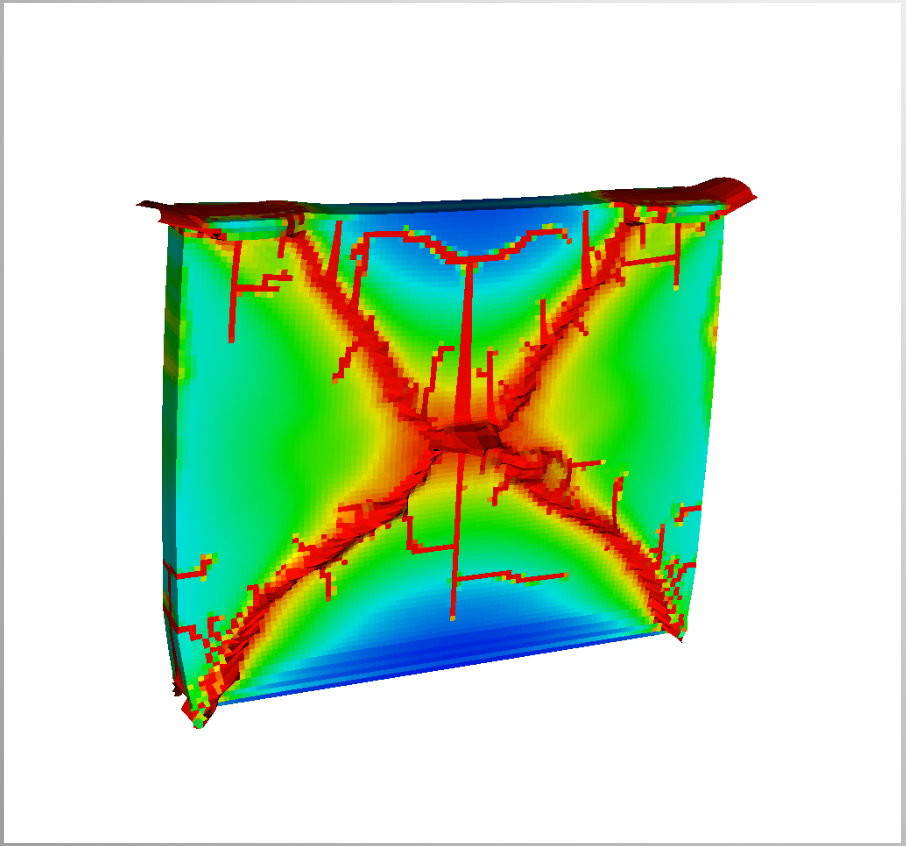
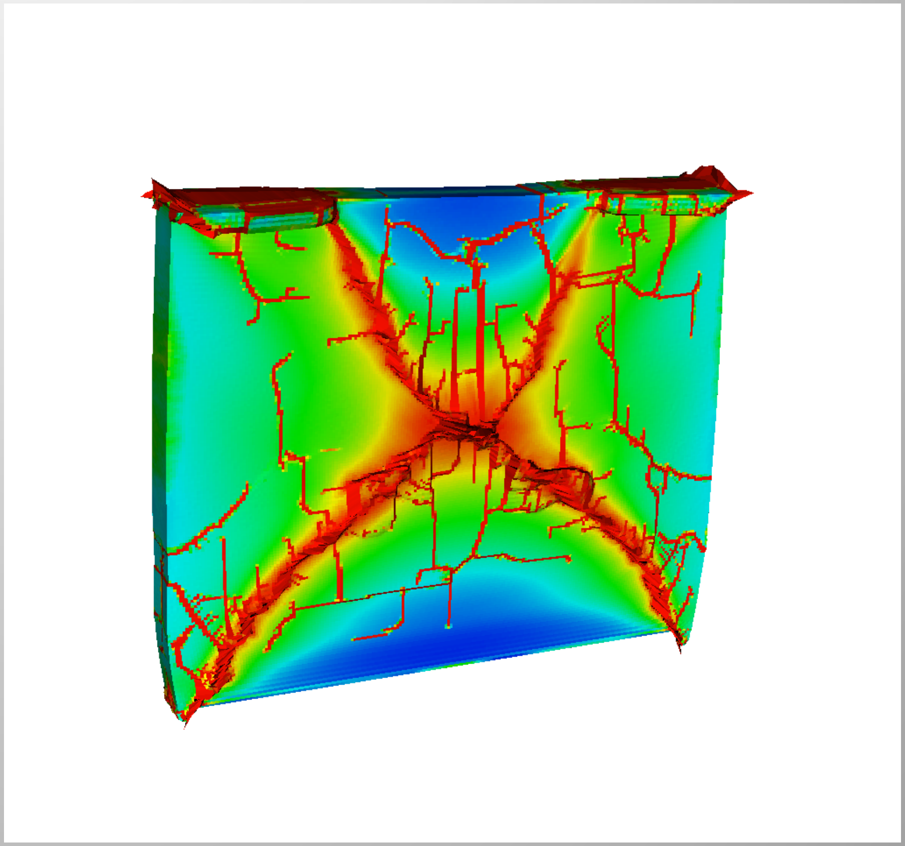


48 x 48 x 4

Fracture/failure models are typically mesh and resolution dependent.



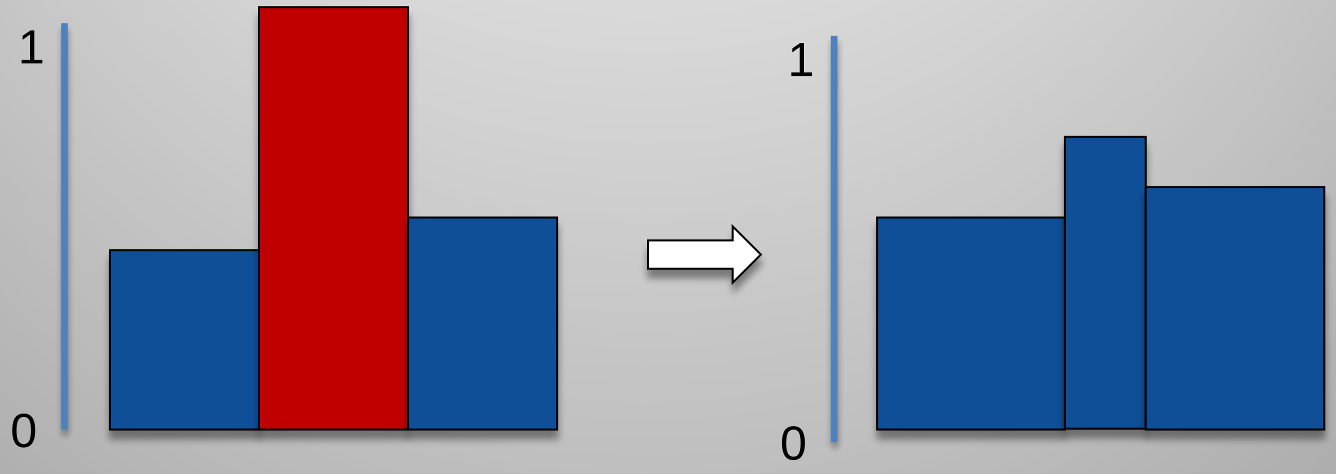
96 x 96 x 8



192 x 192 x 16

Damage is remapped as a volume weighted intensive variable and may heal or expand failure features

- Conserves the volume integral of damage, but localization is much more important.
- After remap, failure is recomputed from remapped damage *and other state variables* which can expand or eliminate failure regions

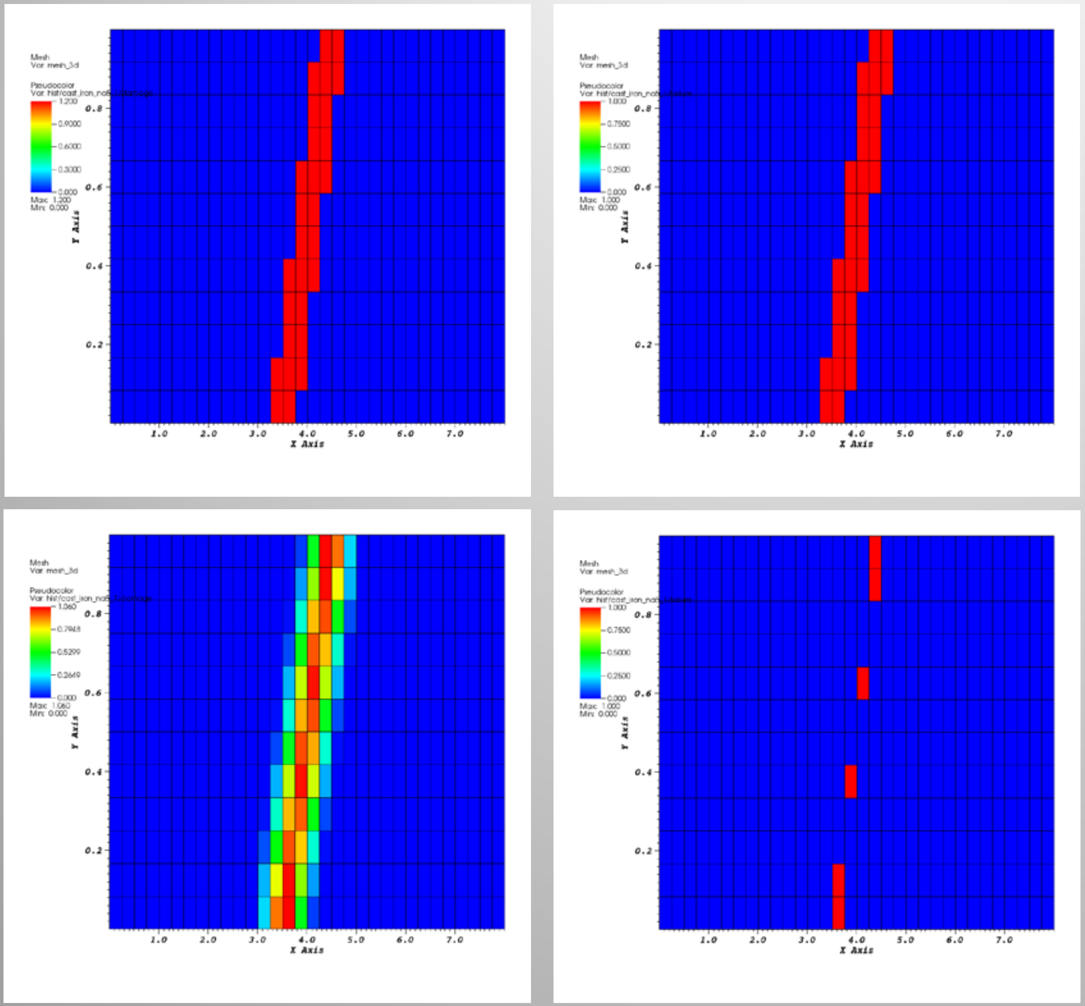


Damage is "diffused" during mesh relaxation and remap

Diffusion of damage during remap can significantly change the material

Damage

Failure



Initial condition

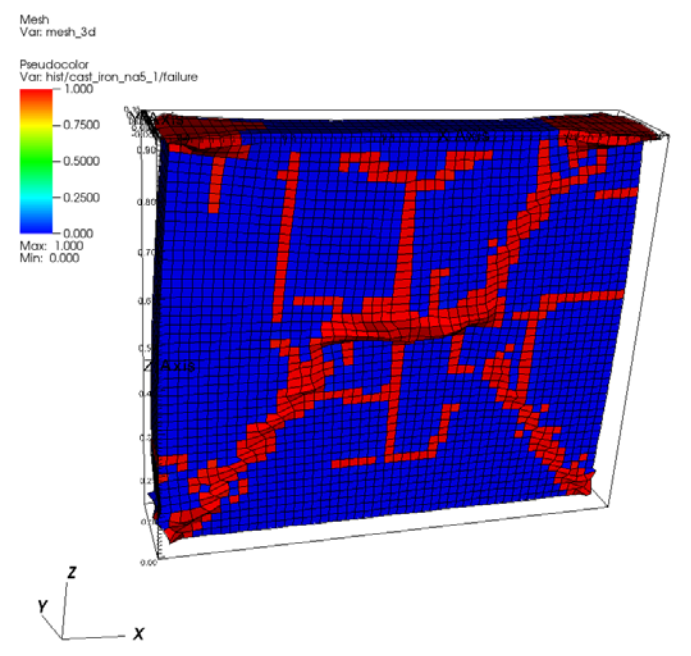
After 100 cycles of mesh perturbation and remap

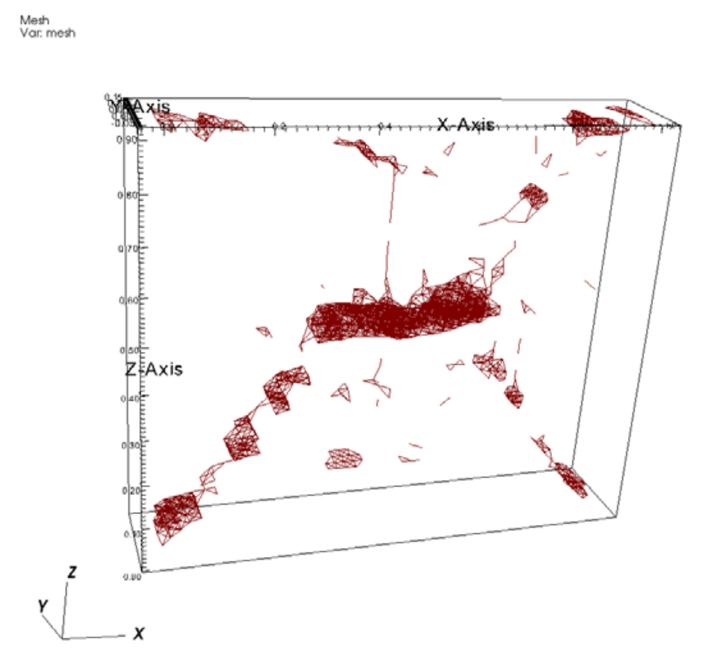
Method I: Marker/reconstruction methods

- Dynamic method: at failure construct a fracture plane in the zone with a normal in direction of principal tensile stress.
- Use fracture planes to preserve fracture during remap.
- The details get messy:
  - deviatoric stress is zero after failure so the normal must be evolved Lagrangian but invariant to rigid body rotation
  - If failure is set, how is the material state modified to be consistent with failure (void fraction, damage, etc).
  - Fracture intersections need to be consistent with swept-region fluxes or overlay intersections

A simplified failure marker method was implemented and evaluated

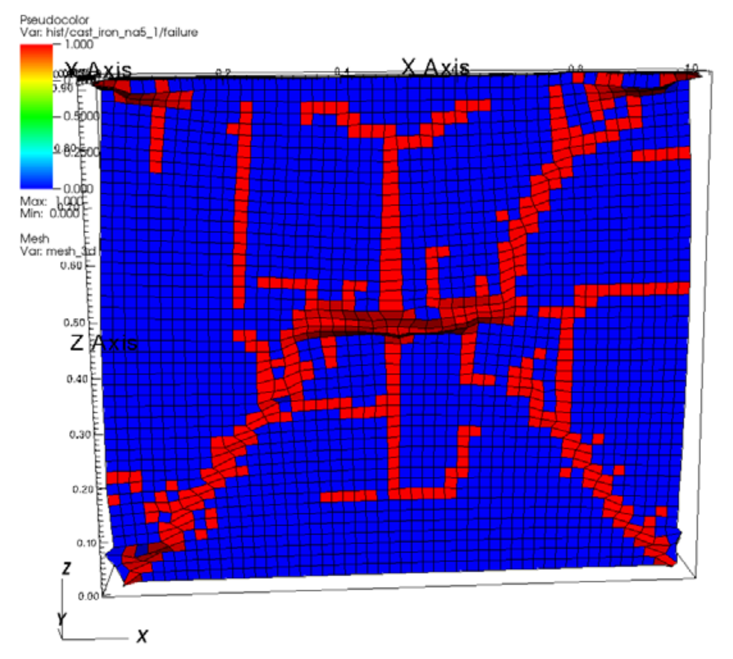
- Failed zones were connected with line segments to represent failure.
- Line segments are intersected with the relaxed mesh.
- Any intersection above length threshold forces the zone to failure



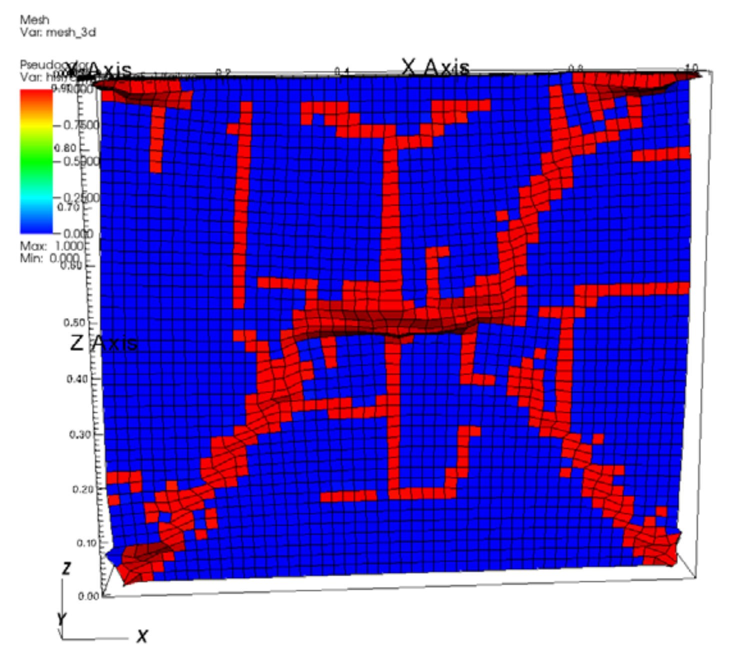


Damage has to be “corrected” by the remapped failure state

- Difficult to extend to more complex failure criteria
- Method tends to grow the failure one zone per cycle.



Before remap

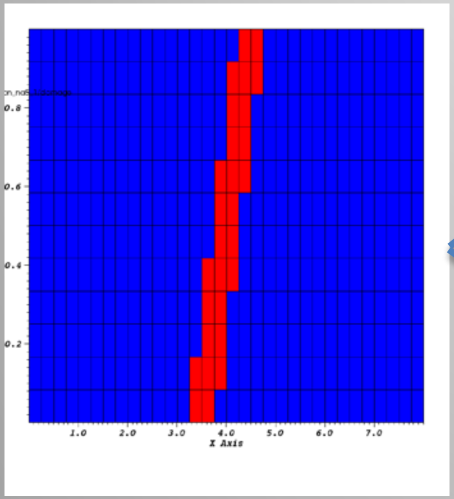


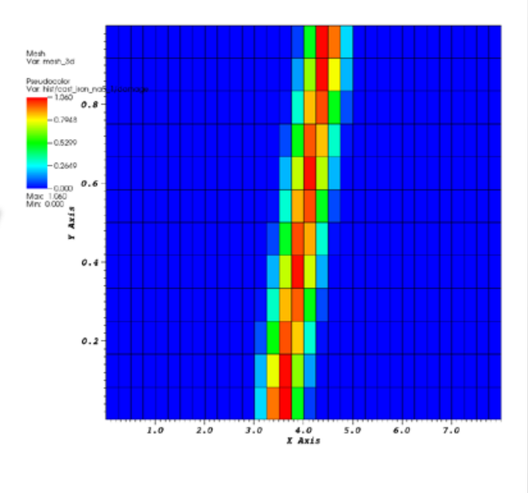
After remap

Method II: A multi-material treatment - sub-region method

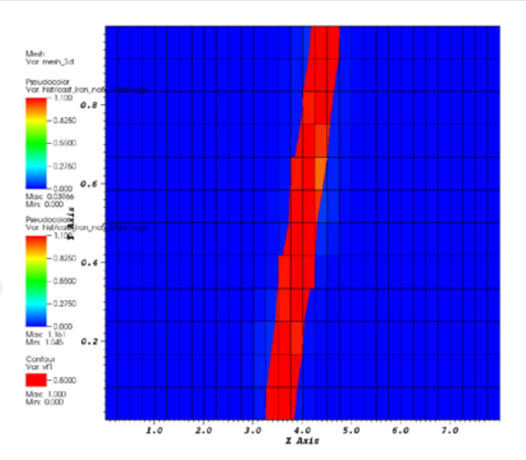
- When a zone fails, it becomes a different material element distinct from the unfailed material. This creates “mixed” zones.

Initial J-C Damage





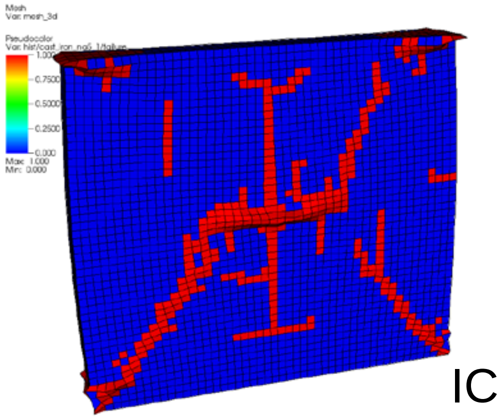
Old, continuous method has diffused the damage and eliminated the cohesive failure zone.



The sub-region method preserves the volume of the failed region but creates mixed zones.

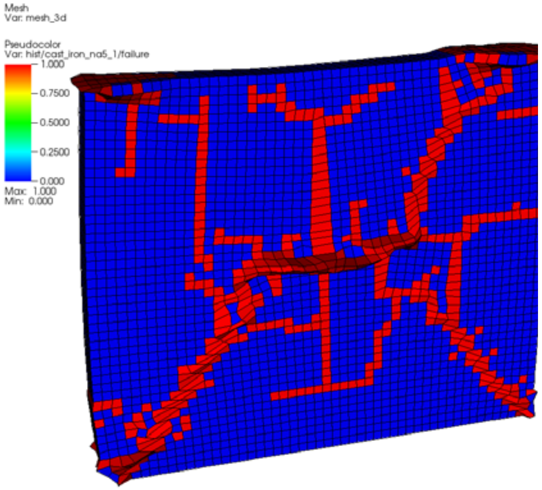
After 100 cycles of mesh perturbation and relaxation

With the sub-region method, dynamic calculations are closer to Lagrangian results

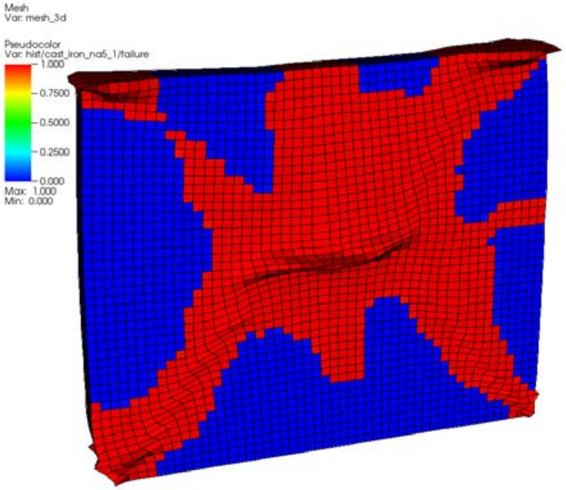


IC

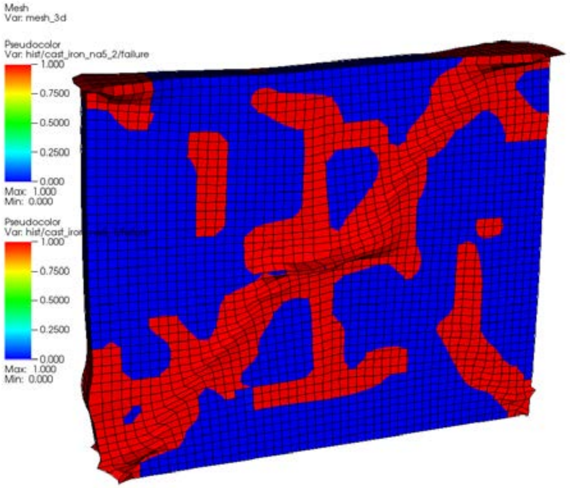
Running the cast iron plate problem with the mesh perturbations starting at 32 us,



Lagrangian



Default method



Sub-region method

Mixed zone mechanics are important

- In mixed zones, the strain increment has to be assigned to each material

- Equi-partition

$$\delta\varepsilon_i = F_i \delta\varepsilon$$

Failed zones can experience high strain rates – this can transfer to the unfailed material.

- Reuss average

$$\delta\varepsilon_i = \frac{\frac{1}{\mu_i}}{\sum_k \frac{F_k}{\mu_k}} \delta\varepsilon$$

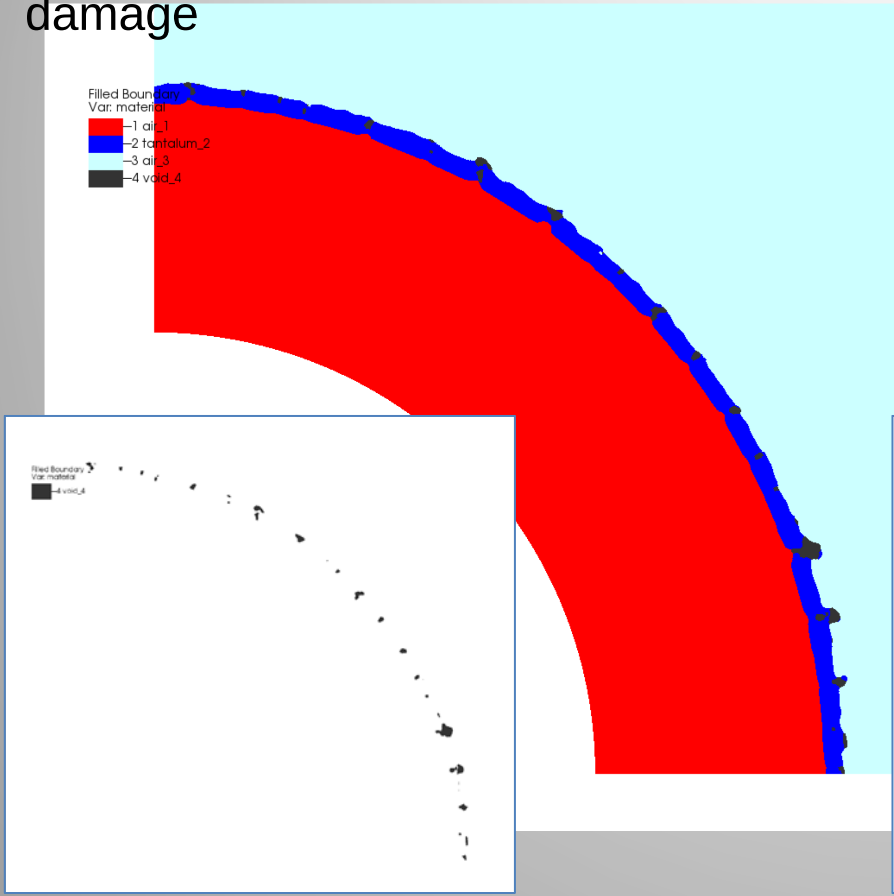
A shear modulus has to be chosen for failed material.

- No accounting for directionality – a motivation for tracking fractures

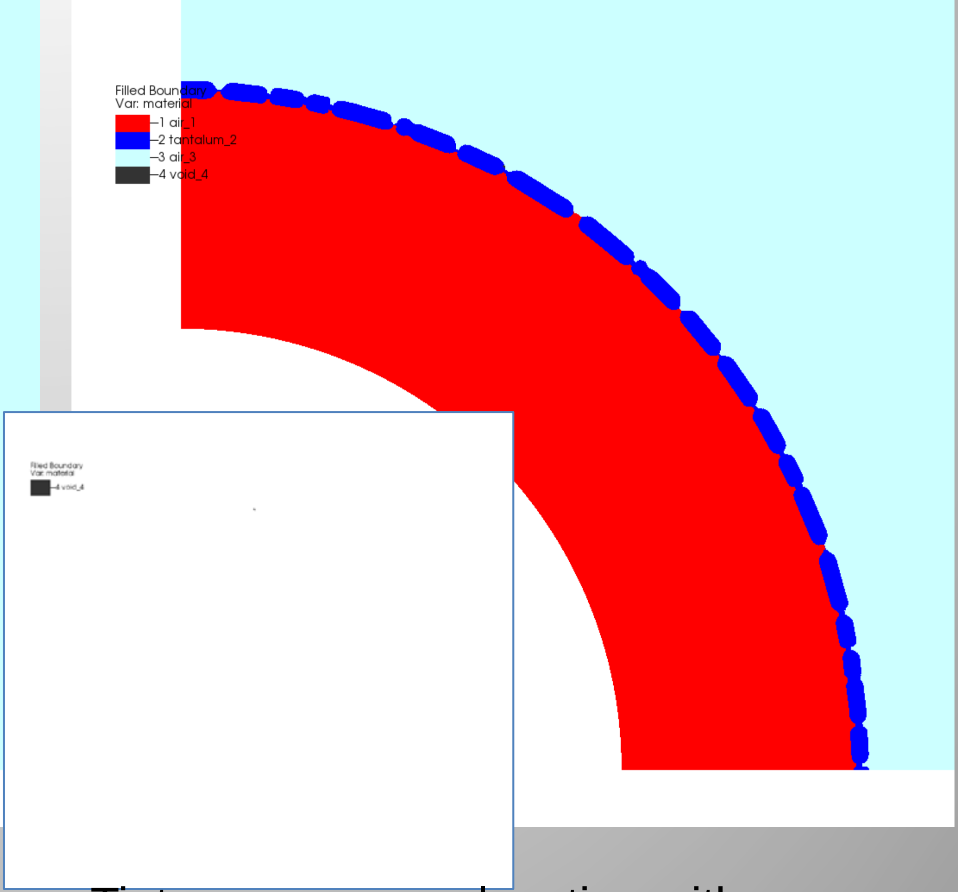
III. Void insertion and Seeding

Void/void seeding behavior depends on pressure relaxation and material advection

High pressure gamma-law gas bursting a cylinder using a Gurson model with JC damage



No pressure relaxation



Tipton pressure relaxation with Canfield & Harrison void treatment

Tipton pressure relaxation with Canfield & Harrison void treatment improves results

- Without pressure relaxation void could never compress out.
- Model is based on volume fraction updates to relax pressure toward a compliance weighted average pressure.
- Existing method used a prescribed pressure and bulk modulus for void. Canfield & Harrison model excludes void from the calculation and was more stable.

$$p = \frac{\sum_k \frac{F_k p_k}{\widetilde{B_k}}}{\sum_k \frac{F_k}{\widetilde{B_k}}}$$

$$\widetilde{B_k} = \rho_k {C_k}^2 + \rho_k C_k \frac{l}{\Delta t}$$

Shashkov, M. Closure models for multimaterial cells in arbitrary Lagrangian-Eulerian hydrocodes. *Intl. J. for Num. Methods in Fluids*. **56**:1497-1504, 2007

Canfield, T. R. and Harrison, A. K. Treatment of void in a compliance based closure model for mixed cell hydrodynamics. Tech. Report. LANL LA-UR-09-05813, 2009.

Proportioning volume change is problematic.

- The energy update is done with pdV work.
- dV from Lagrangian motion must be proportioned to the materials
- Volume fraction weighted average respects constraints automatically and works with pressure relaxation
- However, it often leads to unphysical material response. Pressure relaxation has to “clean up the mess”
- New model is being implemented that uses compliance with an FCT inspired explicit limiter calculation.

$$dV_i^h = \frac{\left(\frac{F_i}{B_i}\right)}{\sum_k \left(\frac{F_k}{B_k}\right)} dV + \Delta F_i (V + dV)$$

$$dV_i^f = F_i dV + \Delta F_i (V + dV)$$

$$dV_i = dV_i^f + \phi(dV_i^h - dV_i^f)$$

Conclusions and Future Directions

- Marker or reconstruction based methods are probably not viable as a general remap solution but may be useful in mixed zone mechanics.

- A multi-material treatment, switching materials on failure better preserves local failure features in ALE calculations

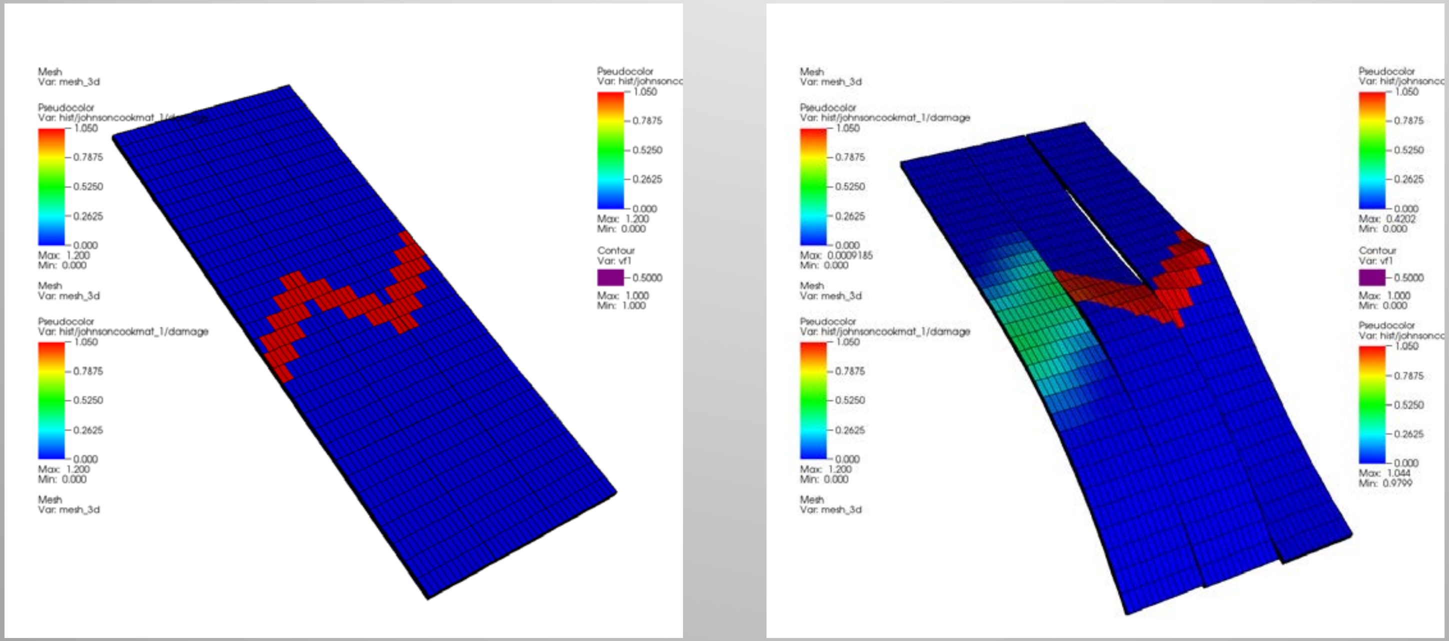
- Improvements to mixed zone mechanics and material advection are needed and in progress.

- **How material model aware should remap be?**

- **How ALE aware should material models be?**

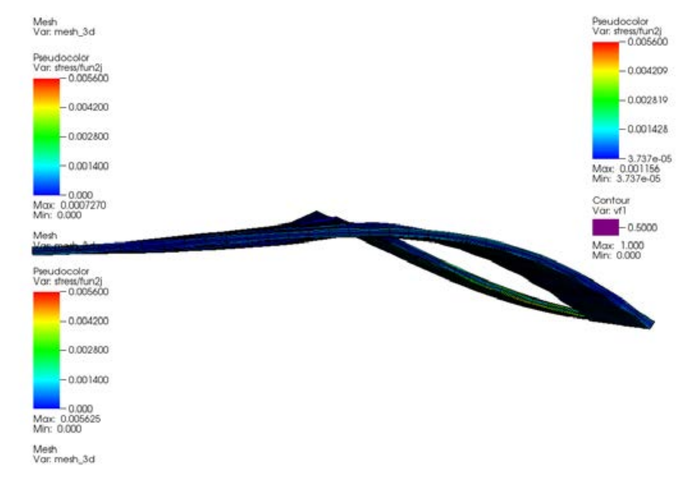
The sub-region method can preserve local features

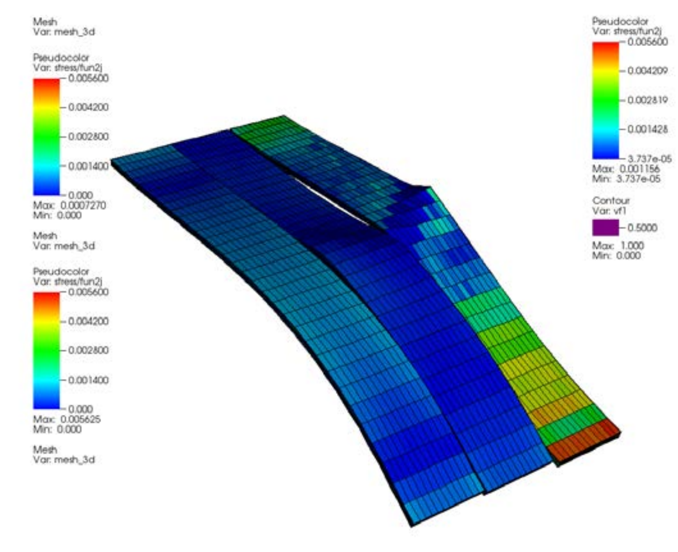
- Initial failed zones are imprinted on mesh.
- End of the thin plate is fixed, the opposite end is given a prescribed velocity.
- Deformation is constrained to be purely elastic.
- For ALE calculations, the mesh is perturbed each cycle



Left or right ALE old method, ALE sub-region method, Lagrangian

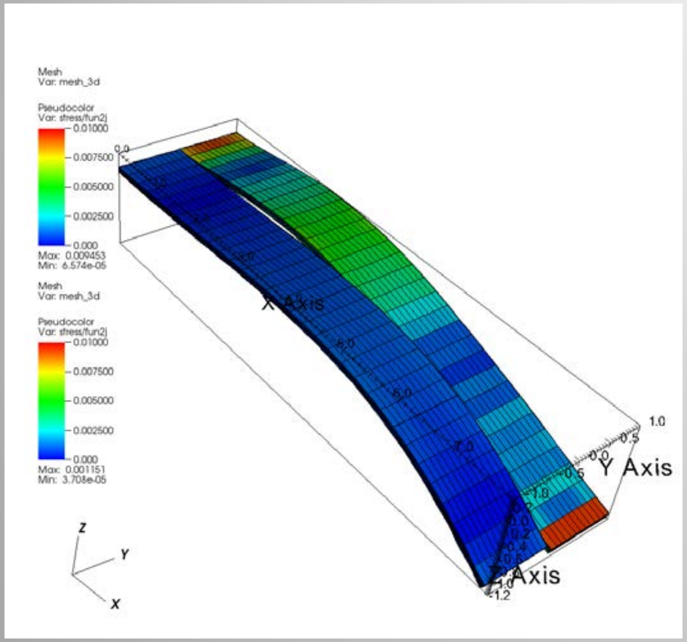
With the sub-region method, dynamic calculations are closer to Lagrangian results

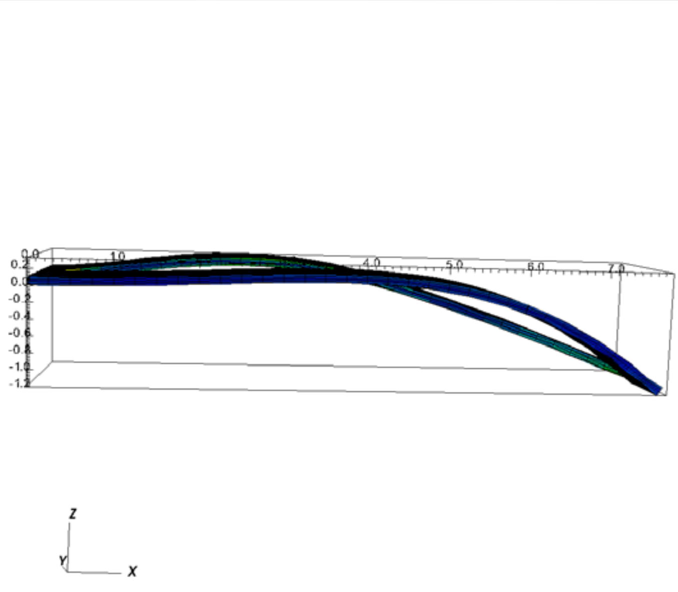




The deformation of the plate with the subregion method is between the Lagrangian and the old ALE method. However, the stress is more closely related to the other ALE calculation,

Perturbing the mesh and remapping significantly changes the calculation even without failure





A similar behavior is observed without the failed zones – the mesh perturbations and remap significantly change the stress distribution,

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