SAND2008-7131C

Contact Algorithms for Extreme Loadings on Underground Structures with SIERRA mechanics

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

Current Divine Strake Model Definition

Preload (Adagio)

- Currently not modeled

Blast Loading (CTH)

- One way coupling.
- Eulerian shock physics code CTH code run first. CTH predicts pressure and velocity history on cavity wall from explosive charge.

Structural Response (Presto)

- Presto, Sierra mechanics solid dynamics module (explicit transient dynamics)
- Sandia Geomodel for rock material model, with material parameters fit from experimental data on core samples
- Tetrahedra elements used to simplify meshing. Nodal-based tetrahedrons for stress wave response
- Non-reflecting boundaries at model edges.
- ✓ Momentum preserving surface-surface contact treatment, “Dash”, for joint modeling
- Dynamically inserted cohesive zones for rock fracture

Revisiting Contact Algorithms in SIERRA solid mechanics for Extreme Loadings on Underground Structures

Characteristics of interface modeling

- Large pressures transmitted across rock joints
- Stick-Slip response of rock joints is an important response
- Potentially many rock joints with intersections

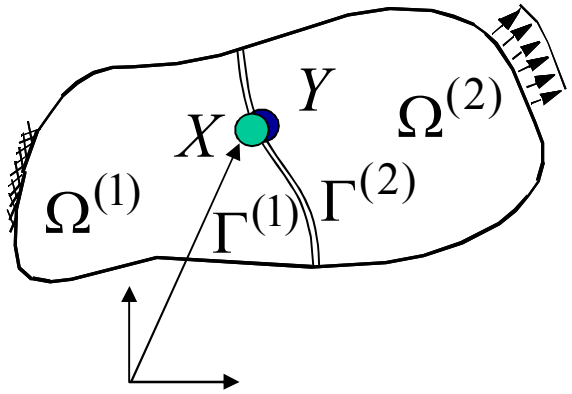
Improvements needed in Node-Face algorithms

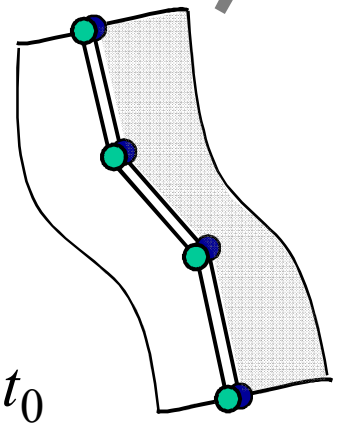
- Deteriorating accuracy under extreme interface pressures
- Numerical tolerances (e.g.extending face size) is often problematic
- Improve robustness for intersecting contact surfaces
- Capability to accommodate Nodal-based tet w/ remeshing
- Capability to accommodate dynamically inserted cohesive zones
- Performance
- Parallel consistency

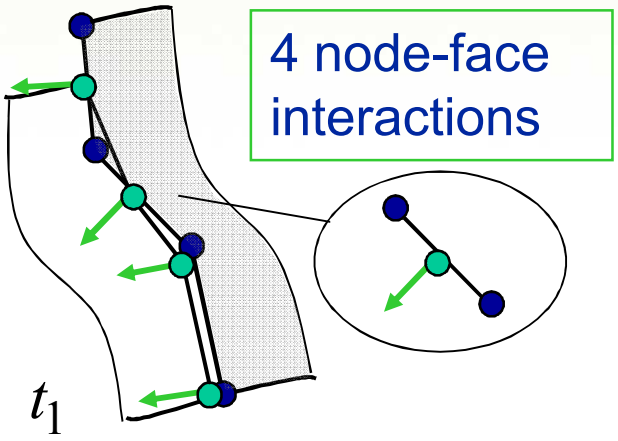
Approach → DASH, a face-face contact algorithm

Contact search algorithm: 2 strategies

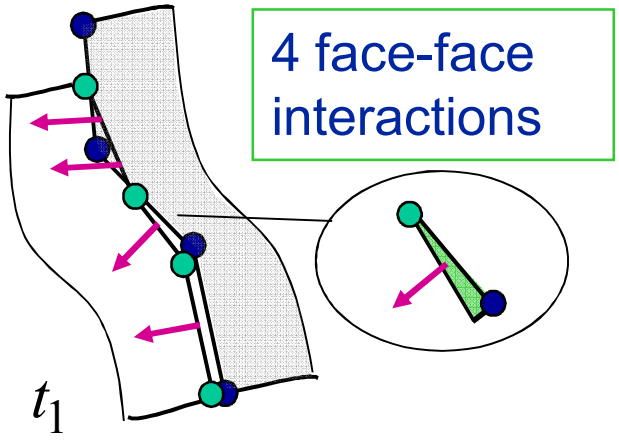
A closest point projection defines “node-face interactions”, from which the constraints $\mathbf{G}^{nf}\mathbf{v}^{n+1/2} = 0$ are defined (a contact gap)







A surface projection defines “face-face interactions”, from which the constraints $\mathbf{G}^{ff}\mathbf{v}^{n+1/2} = 0$ are defined (a volume overlap)



Contact constraint enforcement: Central difference time integrator with contact

Central time difference, applied to transient dynamics leads to an explicit update of the configuration

$$
\begin{aligned}
&\rightarrow \quad \mathbf{a}^{n} = \mathbf{M}^{-1}\left(\mathbf{F}_{n}^{ext} - \mathbf{F}_{n}^{int} - \mathbf{F}_{n}^{c}\right) \\
&\quad \mathbf{v}^{n+1/2} = \mathbf{v}^{n-1/2} + \Delta\bar{t}\,\mathbf{a}^{n} \\
&\quad \mathbf{d}^{n+1} = \mathbf{d}^{n} + \Delta t^{n+1/2}\mathbf{v}^{n+1/2} \\
&\quad \mathbf{x}^{n+1} = \mathbf{X} + \mathbf{d}^{n+1} \\
&\quad next\ \mathrm{n}
\end{aligned}
$$

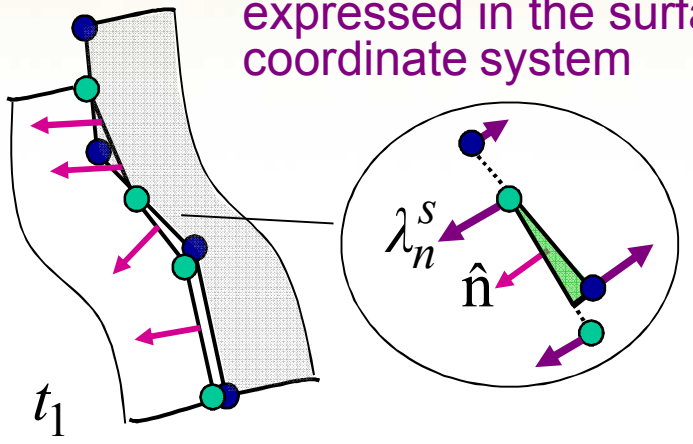
However, the contact force at n , $\mathbf{F}_{n}^{c}$, must be calculated to satisfy the constraint $\mathbf{G}\mathbf{v}^{n+1/2} = 0$

Central time difference with contact

The contact force is the "scatter" of the Lagrange multipliers: $\mathbf{F}_{\mathrm{n}}^{c} = \mathbf{G}^{T}\boldsymbol{\lambda}_{n}$

e.g.: $F_{\mathrm{n}}^{c}\Big|_{s} = G\Big|_{s}^{T}\lambda_{n}^{s}$

Lagrange multiplier expressed in the surface coordinate system



The constraint $\mathbf{G}\mathbf{v}^{\mathrm{n}+1/2} = 0$ can be re-expressed as:

$$\mathbf{G}\mathbf{v}^{\mathrm{n}+1/2} = \mathbf{G}\left(\mathbf{v}^{\mathrm{n}-1/2} + \Delta\bar{t}\,\mathbf{a}^{\mathrm{n}}\right)$$

$$= \mathbf{G}\left(\mathbf{v}^{\mathrm{n}-1/2} + \Delta\bar{t}\,\mathbf{M}^{-1}\left(\mathbf{F}_{\mathrm{n}}^{ext} - \mathbf{F}_{\mathrm{n}}^{int} - \mathbf{F}_{\mathrm{n}}^{c}\right)\right) = 0$$

which leads to a set of non-diagonal coupled equations:

$$\Delta\bar{t}\left[\mathbf{G}\,\mathbf{M}^{-1}\mathbf{G}^{T}\right]\boldsymbol{\lambda}_{n} = \mathbf{G}\left[\mathbf{v}^{\mathrm{n}-1/2} + \Delta\bar{t}\,\mathbf{M}^{-1}\left(\mathbf{F}_{\mathrm{n}}^{ext} - \mathbf{F}_{\mathrm{n}}^{int}\right)\right]$$

Iterative solution for constraint enforcement

compute predictor configuration, assuming $\mathbf{F}_{\mathrm{n}}^{c} \approx \mathbf{F}_{\mathrm{n-1}}^{c}$

$$\tilde{\mathbf{v}}^{\mathrm{n+1/2}} = \mathbf{v}^{\mathrm{n-1/2}} + \Delta\bar{t}\mathbf{M}^{-1}\left(\mathbf{F}_{\mathrm{n}}^{ext} - \mathbf{F}_{\mathrm{n}}^{int} - \mathbf{F}_{\mathrm{n-1}}^{c}\right)$$

$$\tilde{\mathbf{d}}^{\mathrm{n+1}} = \mathbf{d}^{\mathrm{n}} + \Delta t^{\mathrm{n+1/2}}\tilde{\mathbf{v}}^{\mathrm{n+1/2}}$$

compute G by contact search

iterate subscript j, beginning with $\mathrm{j} = 0, \quad \boldsymbol{\lambda}_0^n = 0 \quad \mathbf{v}_0^{\mathrm{n+1/2}} = 0$

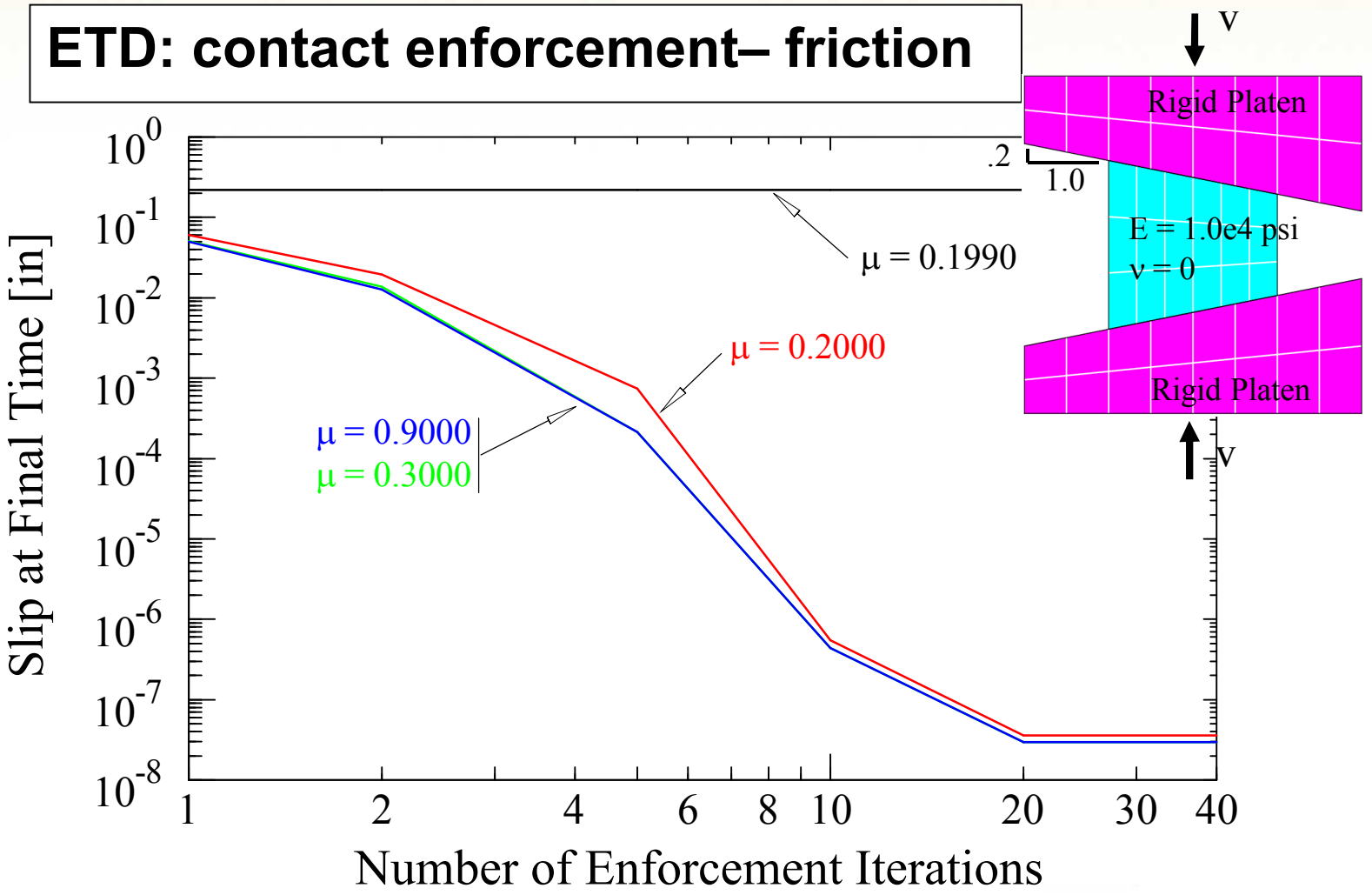
$$\boldsymbol{\lambda}_{j+1}^{n} = \left(\mathbf{H}_{\beta^{auto}}^{-1}\mathbf{G}\,\mathbf{v}_j^{\mathrm{n+1/2}}\right)\Big/\Delta\bar{t} + \boldsymbol{\lambda}_j^n$$

$$\mathbf{v}_{j+1}^{n+1/2} = \mathbf{v}_j^{n+1/2} - \Delta\bar{t}\mathbf{M}^{-1}\mathbf{G}_N{}^{T}\left(\boldsymbol{\lambda}_{j+1}^{n} - \boldsymbol{\lambda}_j^{n}\right)$$

$$j \leftarrow j+1, \text{next } j$$

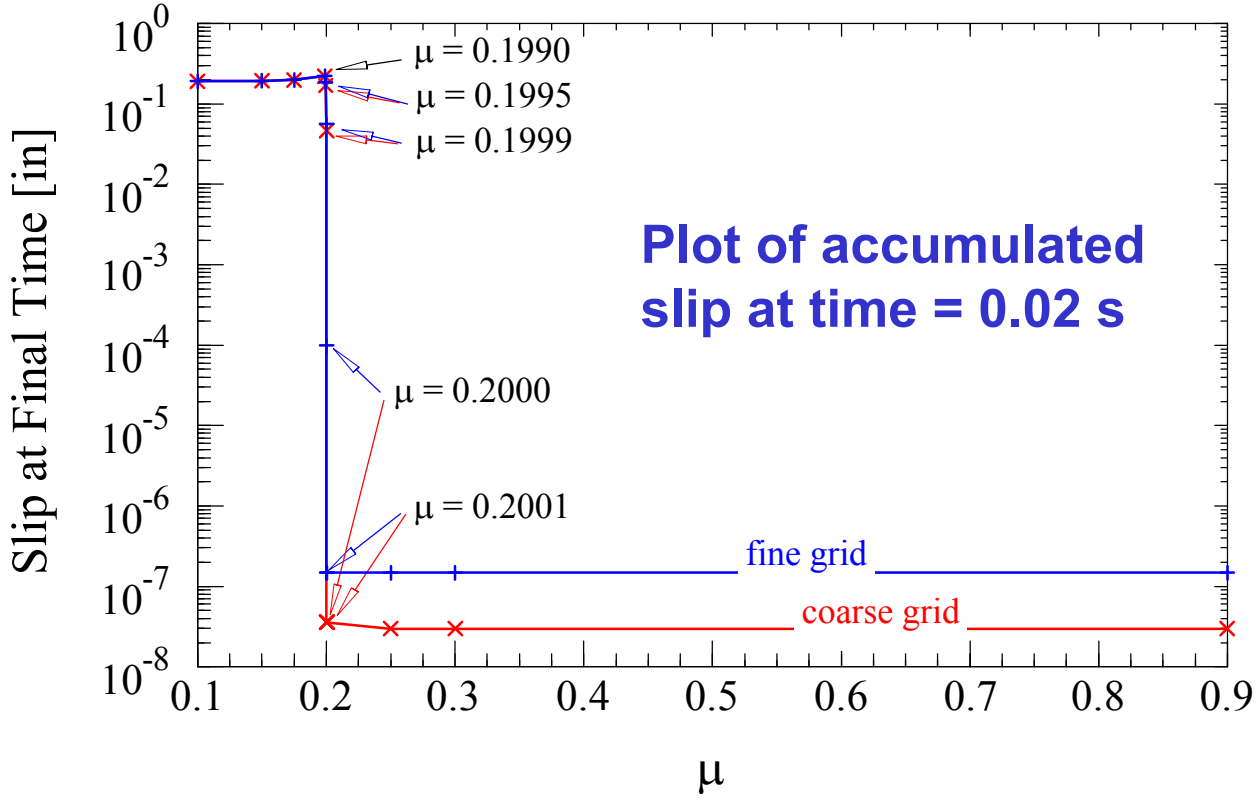
update contact force, $\mathbf{F}_{\mathrm{n}}^{c} = \mathbf{G}^{T}\boldsymbol{\lambda}_j^n$

Enforcement accuracy improves with iterations

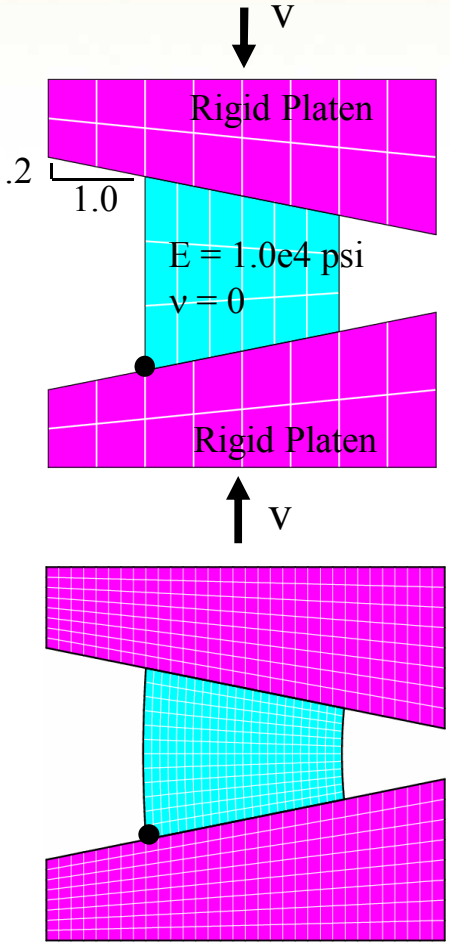


Verification of Incipient frictional sliding: 20 enforcement iterations

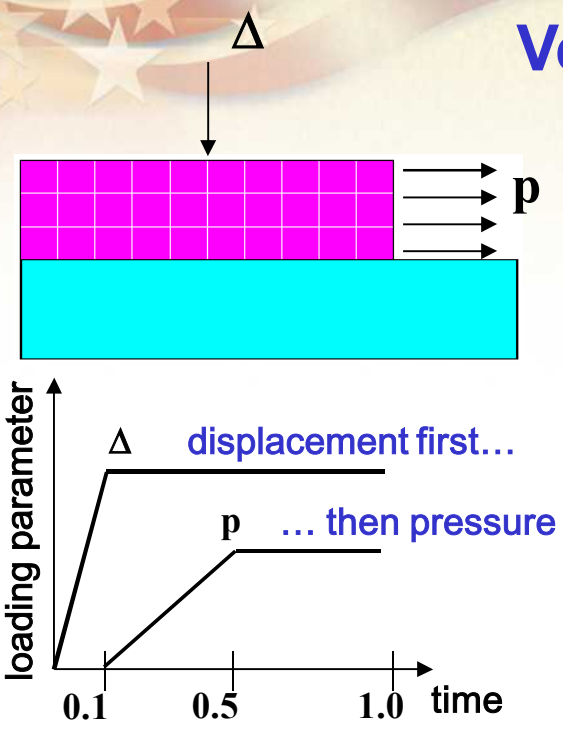
ED: contact enforcement– friction

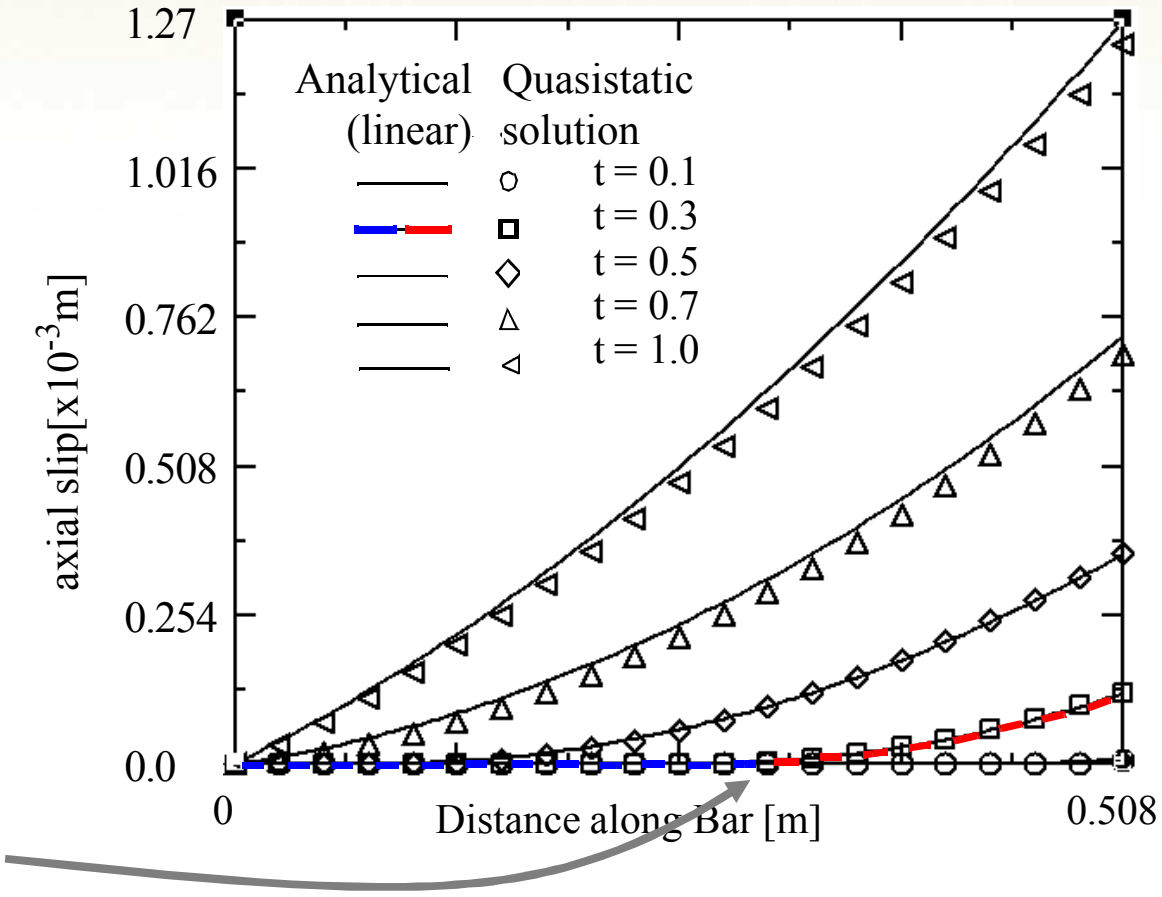


Plot of accumulated slip at time = 0.02 s



Verification of Moving Slip front



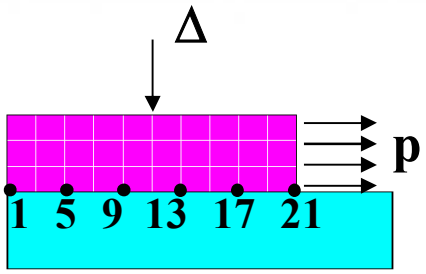


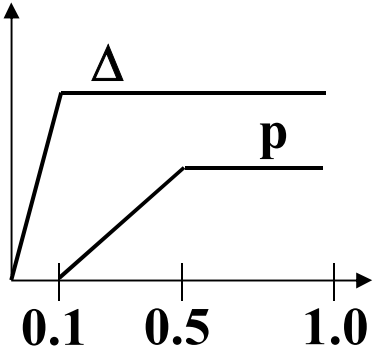
At time t=0.3 the stick/slip boundary is located at approximately 0.3175m along the length of the bar

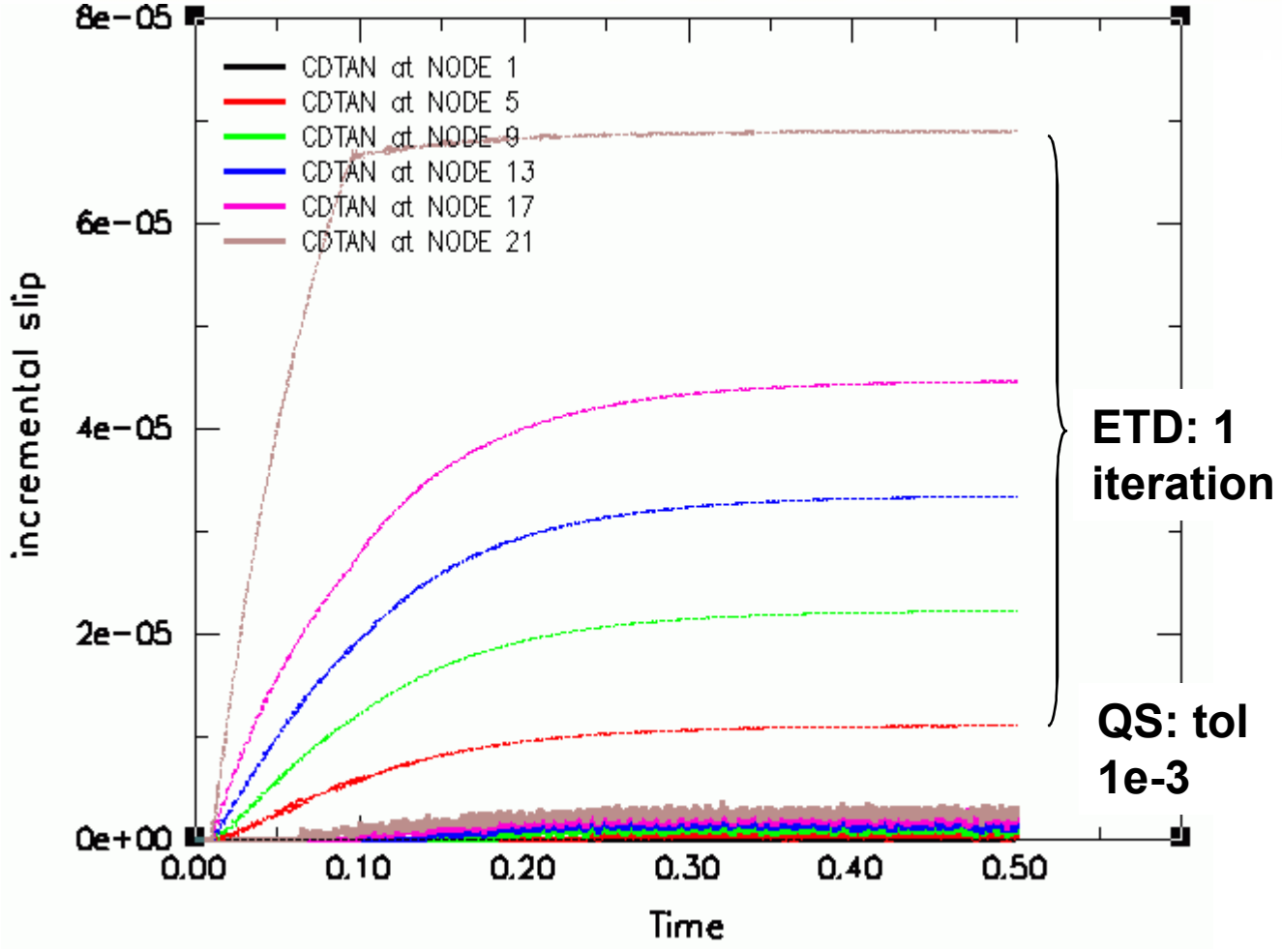
Comparison of a verified Quasistatic and an Explicit Transient Dynamic solution (at slow loading rates)…
is often our only way to verify Explicit contact enforcement

Verification of Moving Slip front

QS/ETD - beam slip test problem

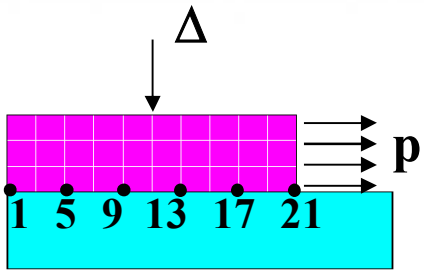


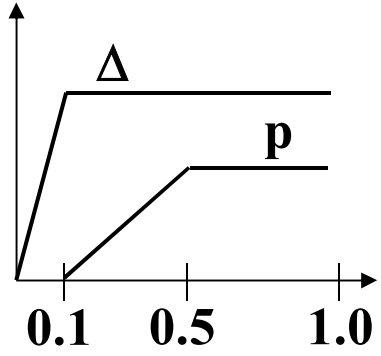


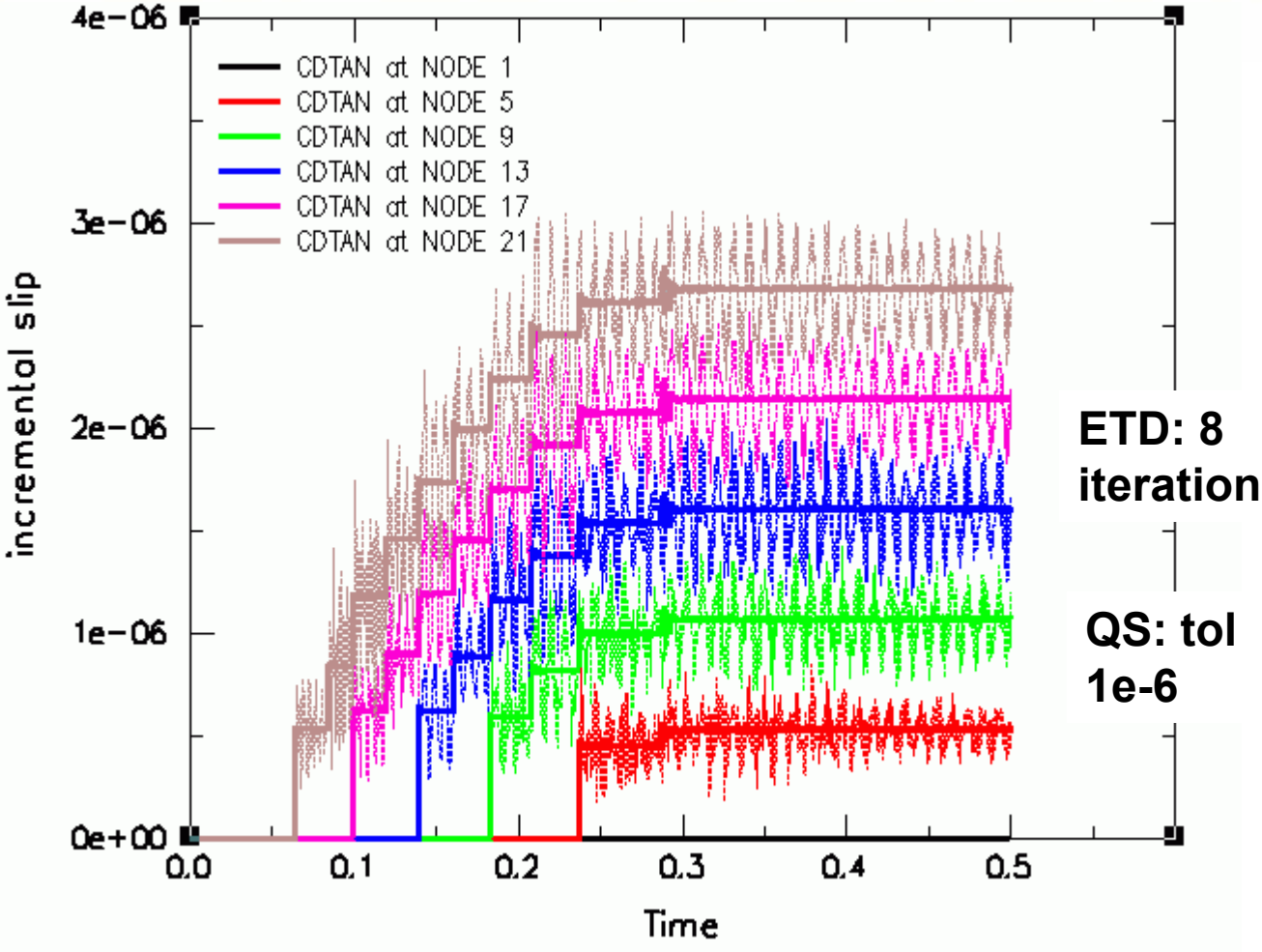


Verification of Moving Slip front

QS/ETD - beam slip test problem





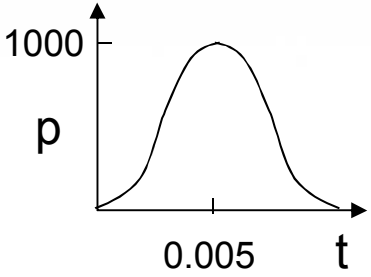


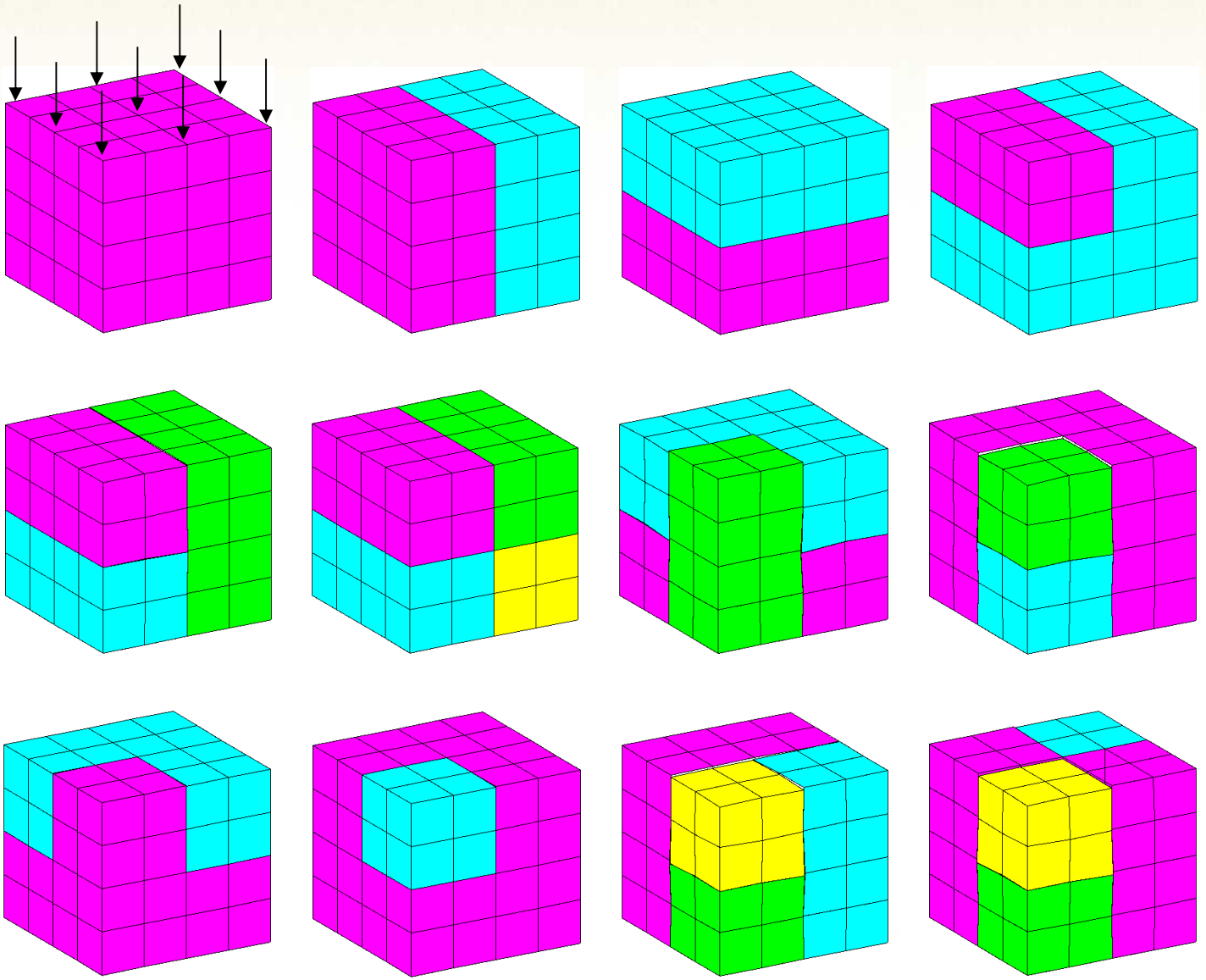
ETD: 8 iterations

QS: tol 1e-6

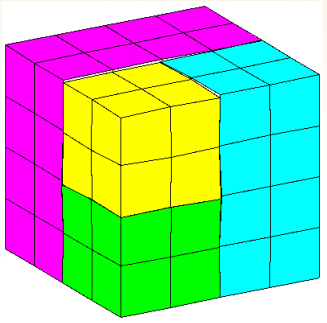
Verification of Intersecting surfaces : contact puzzle patch test

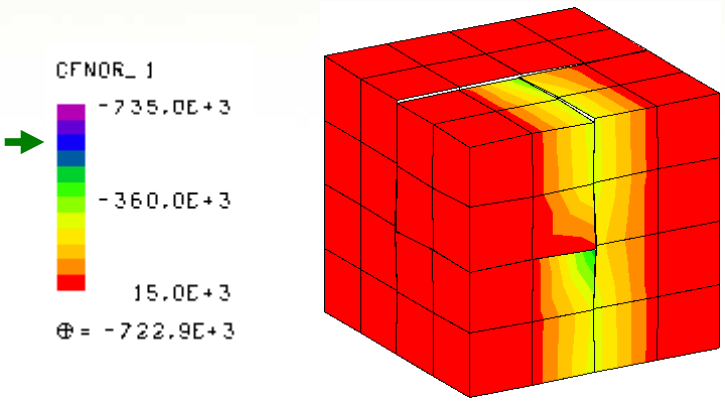
Pressure load
(sine pulse)



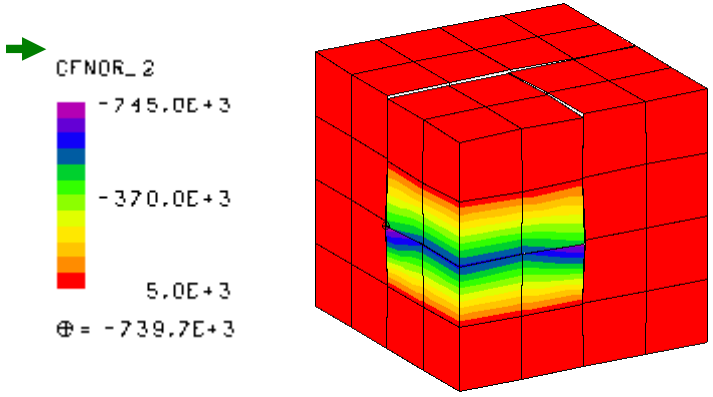


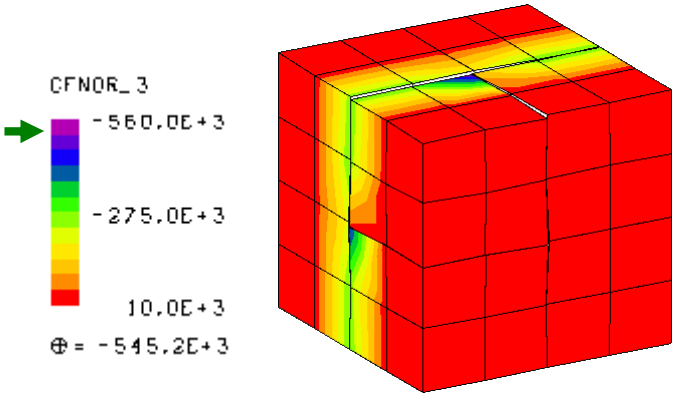
Verification of Intersecting surfaces : contact puzzle patch test



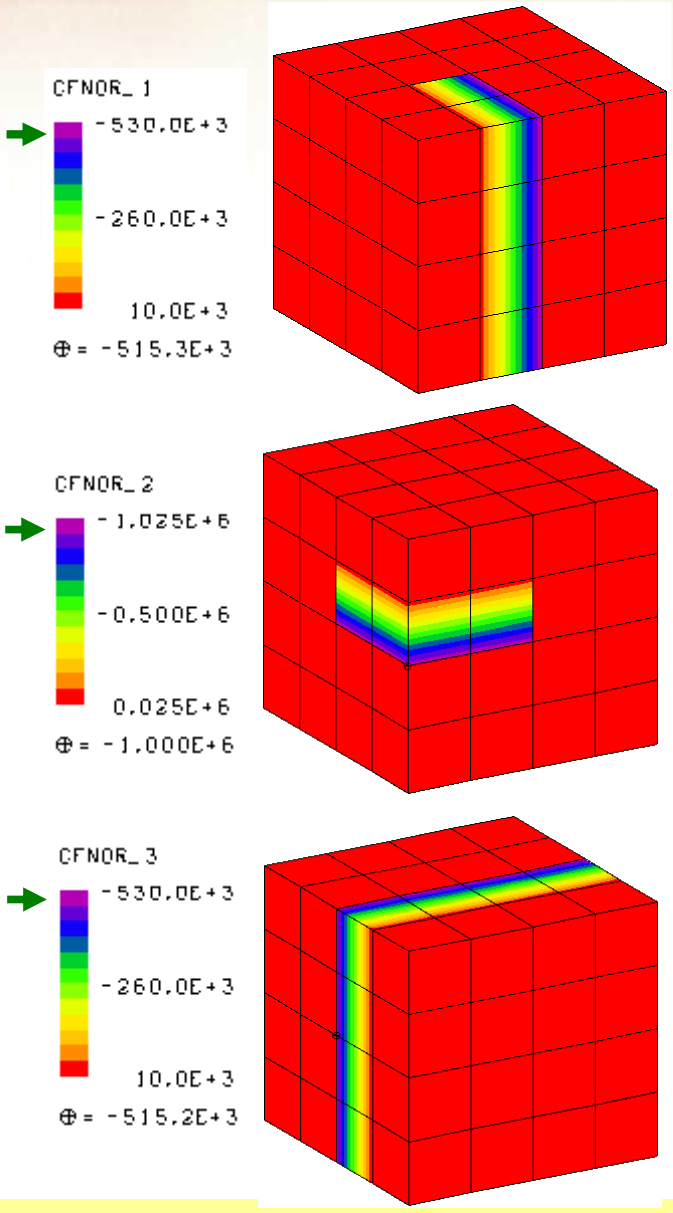


expected solution is not obtained (due to inability of Node-Face algorithm to reflect symmetric contact)

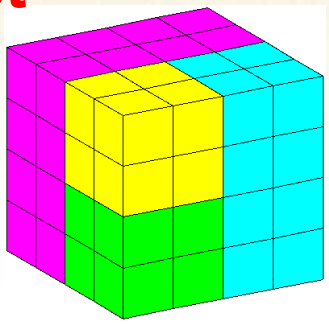


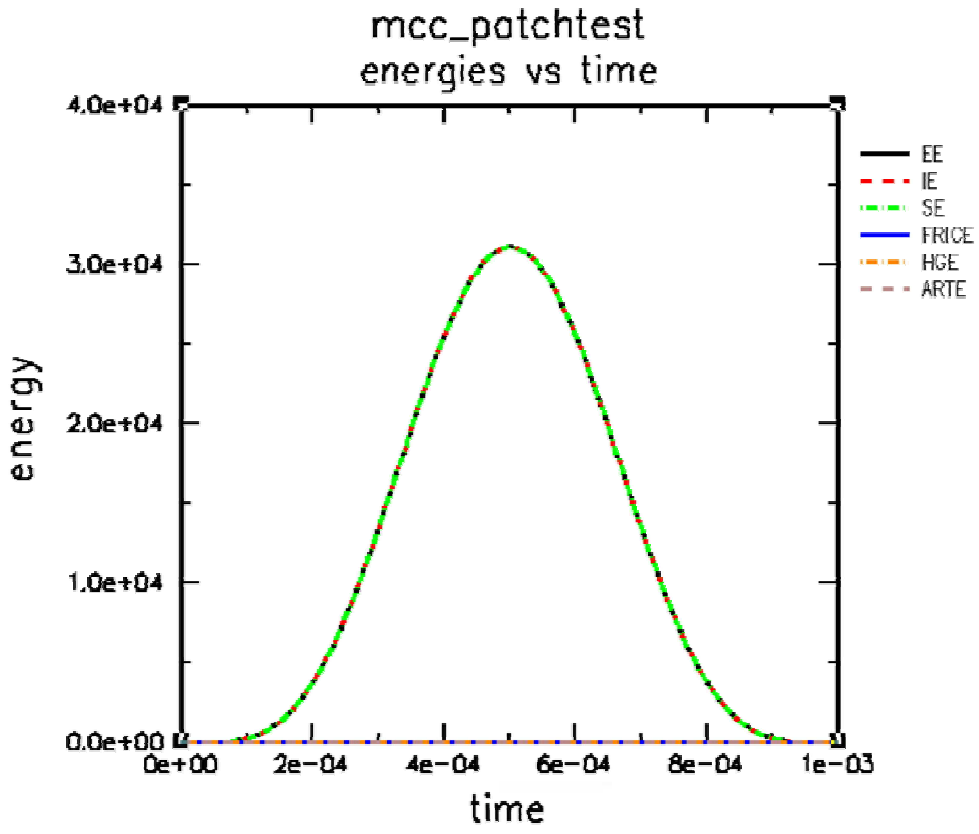


Verification of Intersecting surfaces : contact puzzle patch test



expected solution





Benchmark testing of Node-Face & Face-Face Contact Algorithm

Accuracy

- momentum preserving normal impact/contact
- accuracy of frictional contact enforcement
- capability for extreme interface pressures
- parallel repeatability

Robustness

- numerical tolerances (extending face size)
- capability to accommodate Nodal-based tet w/ remeshing & dynamically inserted cohesive zones

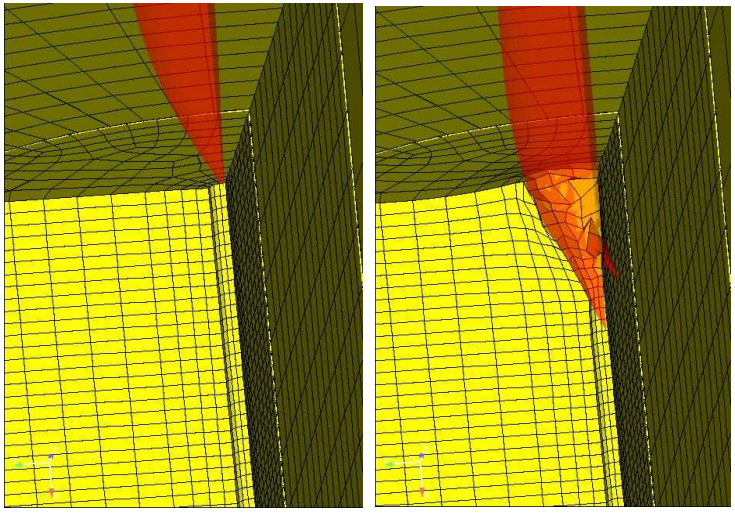
Performance

- Raw serial performance
- Parallel scalability

Presto performance test suite (PTS) is a collection of problems typical of the range of problems solved by an Explicit Transient Dynamics code

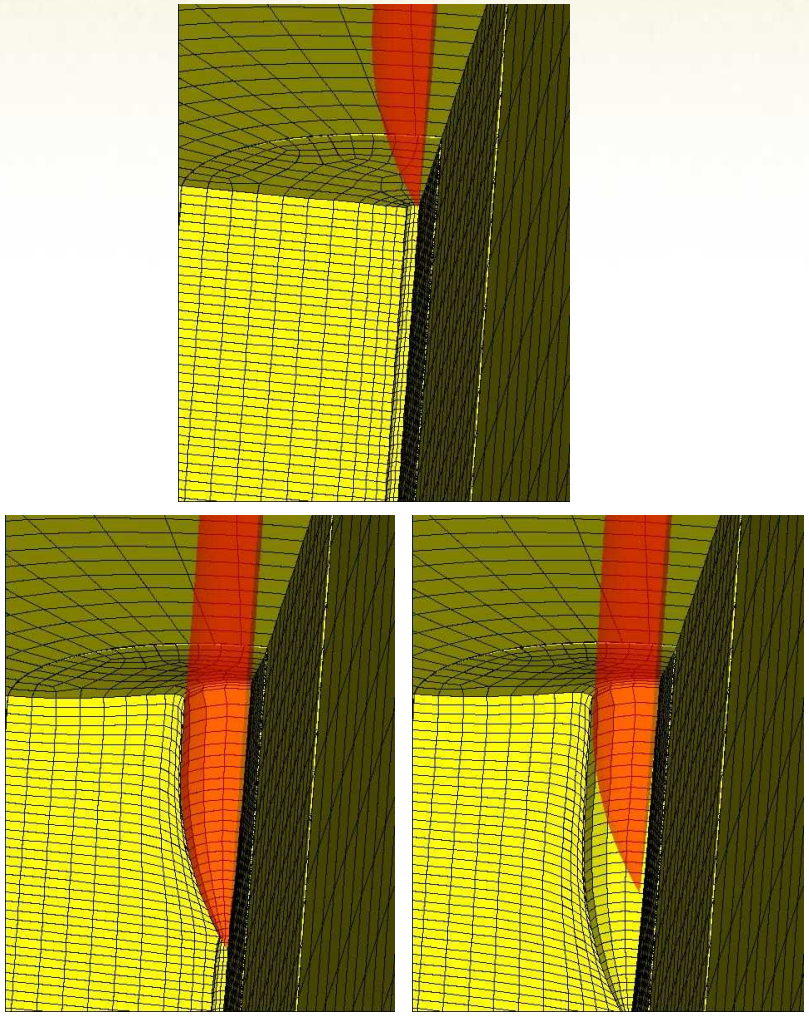
Robustness test: Large impact pressure

Example **A010_Pilot_hole**



ACME: Node-Face algorithm

Impact pressures are severe, node face constraints do not smoothly load penetrator

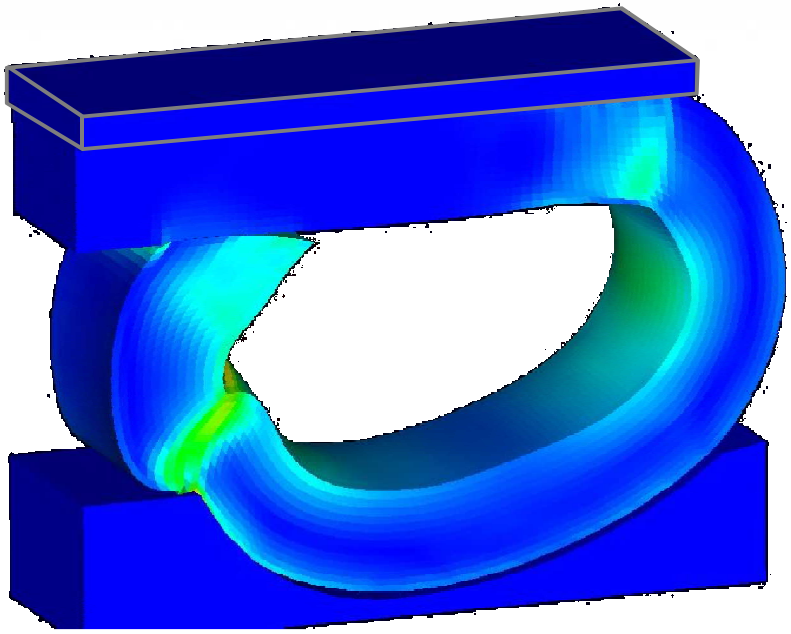


DASH: Face-Face algorithm

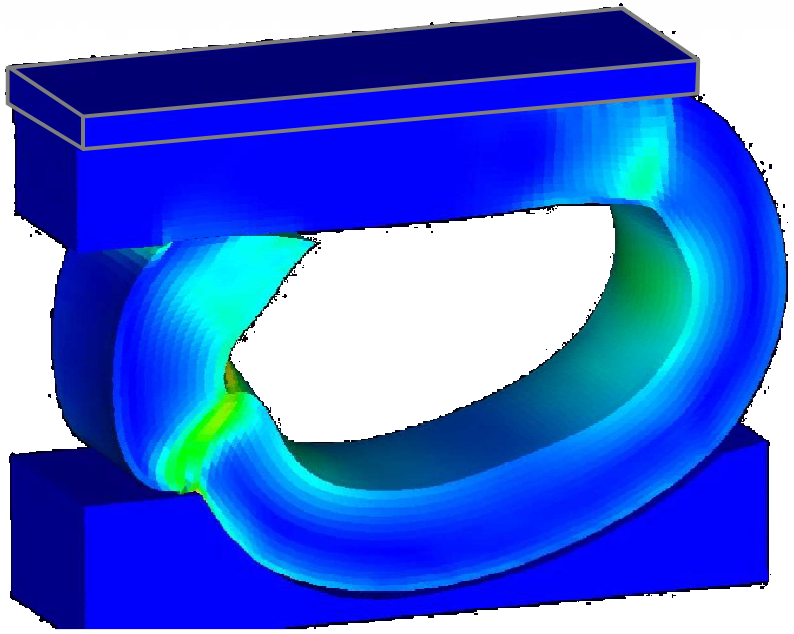
Robust result during full-depth penetration and rebound

Accuracy test: Large frictional sliding

Example: **P013_staple**



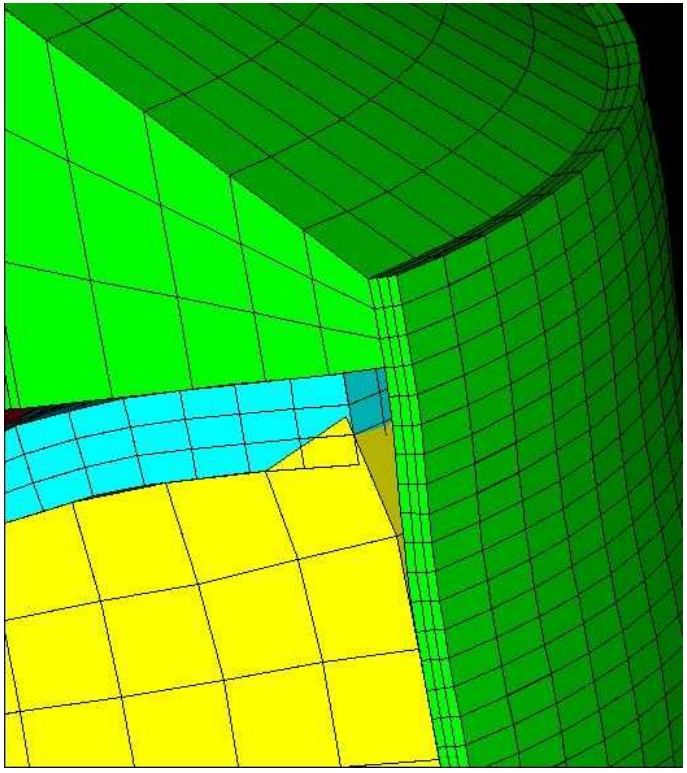
ACME: Node-Face algorithm



DASH: Face-Face algorithm

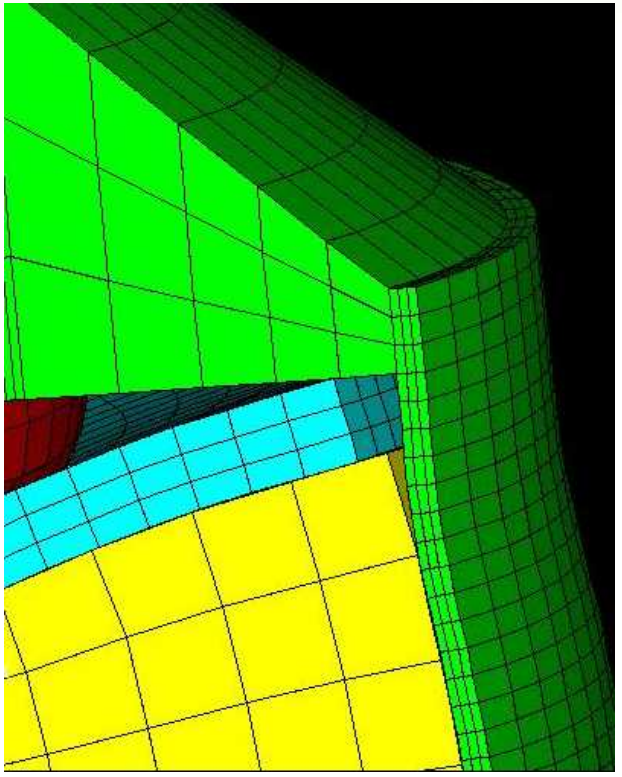
Accuracy test: Numerical tolerances

Example: **P007_two_layer_cake**



ACME: Node-Face algorithm

Edge tolerance is exceeded, thus constraints are lost around plate perimeter

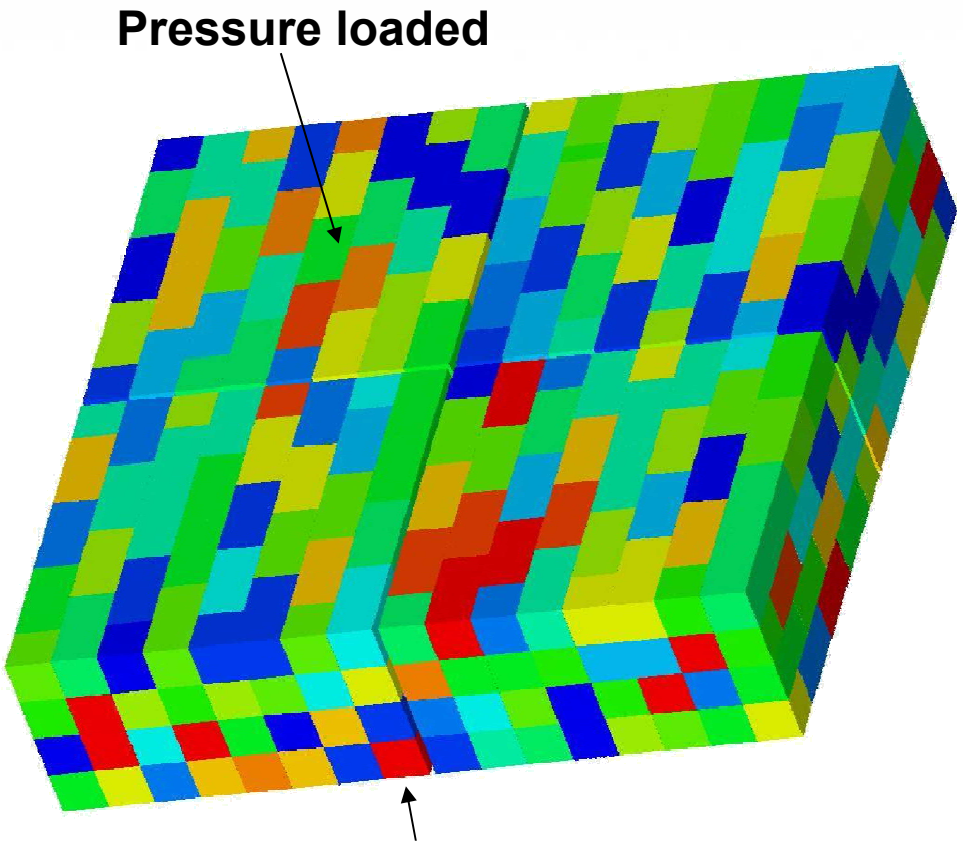


DASH: Face-Face algorithm

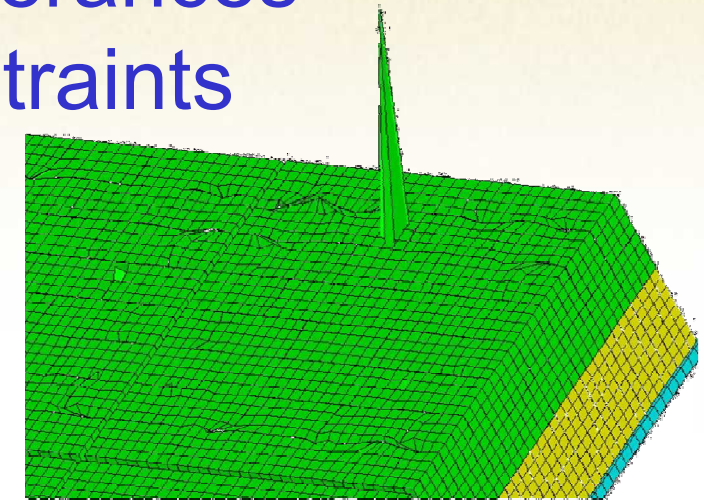
No need for edge tolerance, volume overlap naturally maintains constraints around plate perimeter

Robustness test: tolerances w/ multiple constraints

Example: **P012-Walls**

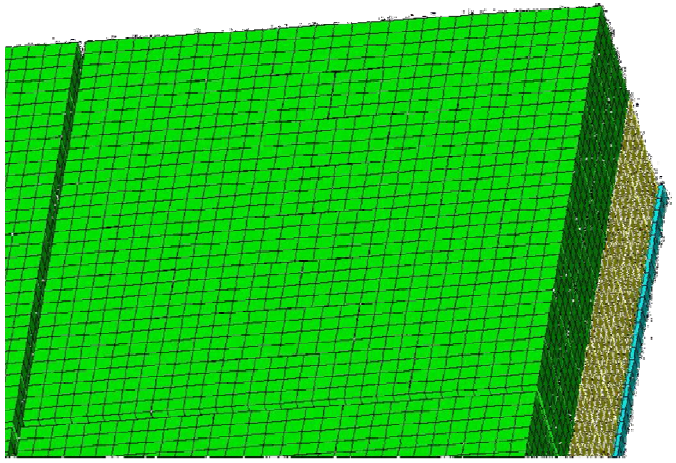


ACME : Node-Face algorithm



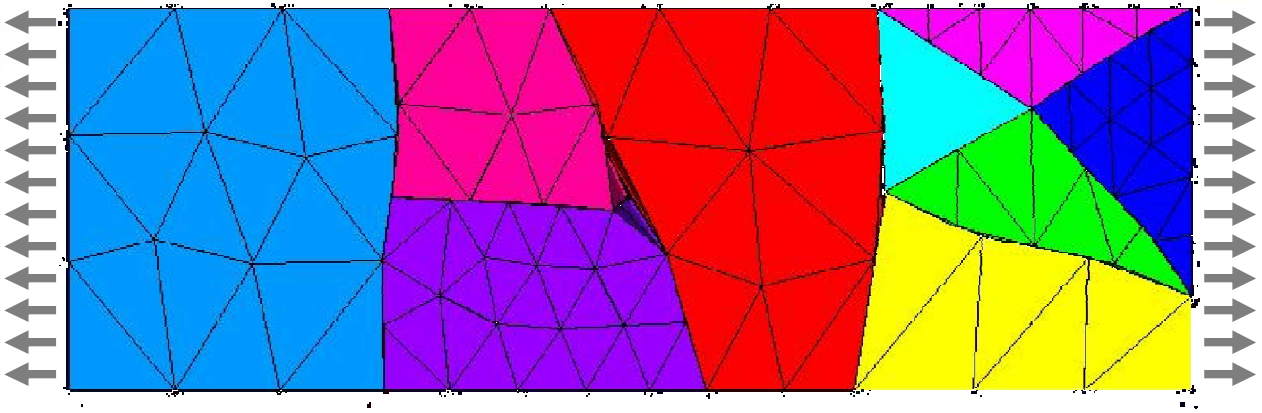
Some Node-Face constraints missed due to edge tolerance

***DASH* : Face-Face algorithm**



All Face-Face constraints detected & enforced

Accuracy & Robustness test: preserving linear consistency for tied contact

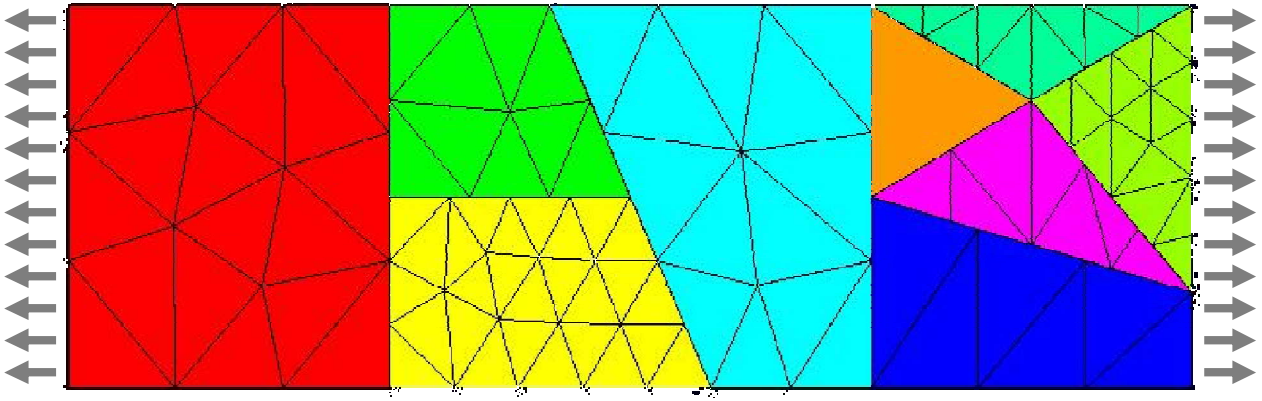


ACME:

Node-face constraints

Stress Error = 81.2%

4 / 12 multiple interaction puzzle tests fails



Dash:

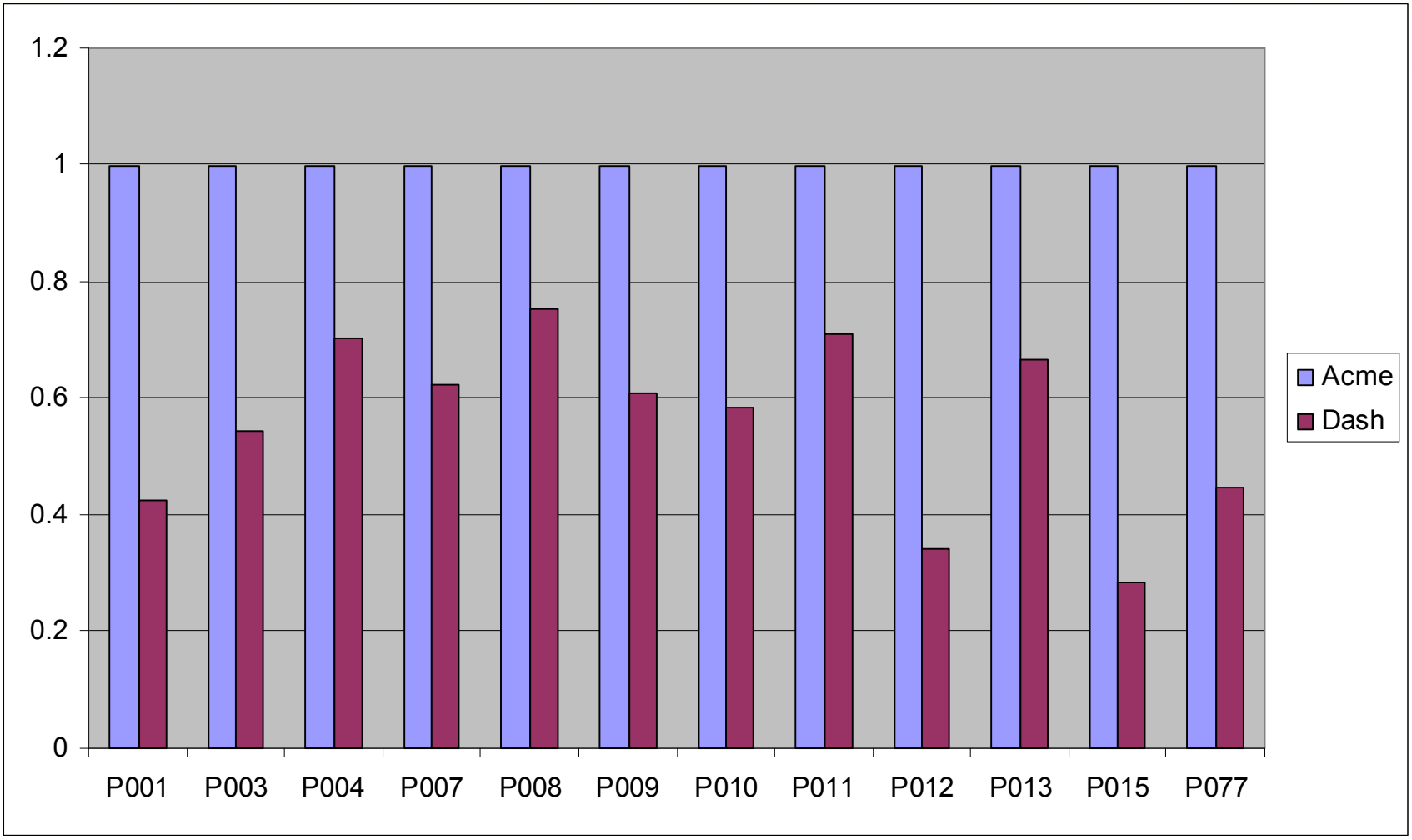
Face-face constraints

Stress Error = 1.5%

All 12 multiple interaction puzzle tests pass

Performance testing: ACME vs. DASH

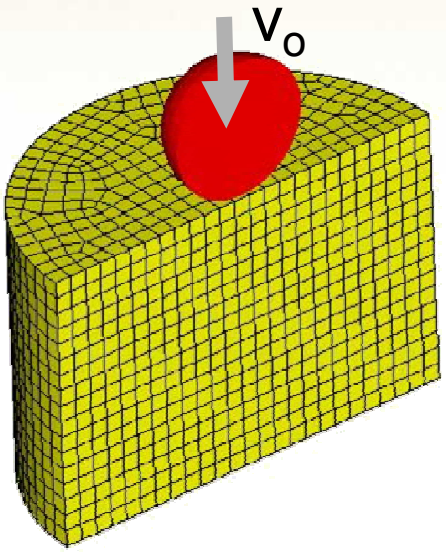
Performance test suite: Total run time

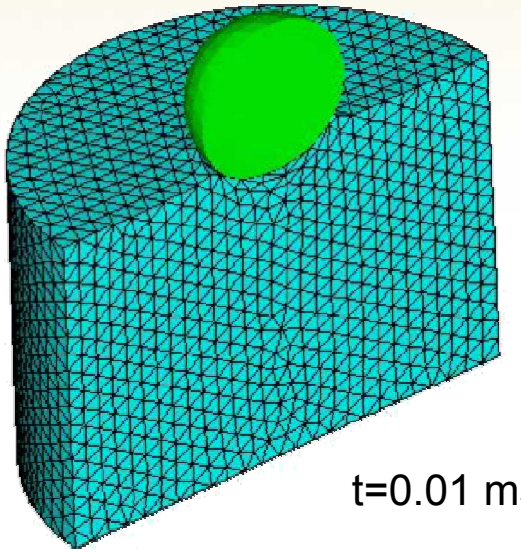


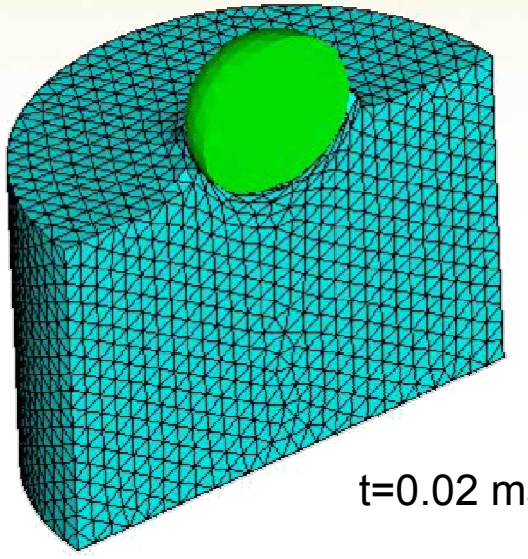
Parallel consistency test: ACME vs. *DASH*

P003 – Can Crush: 1, 2, 4, 16 Procs: Reported: Standard Deviation of quantity divided by average value of quantity.		
quantity	ACME	*DASH*
Final Internal Energy	8.28e-02%	1.46e-10 %
Final displacement at specified node	1.8e-01%	5.45e-09 %
Final velocity at specified node	1.16%	1.70e-08%
Max acceleration (raw) at specified node	77.5%	1.07e-06%

Enhanced capability: NBTet w/ remeshing

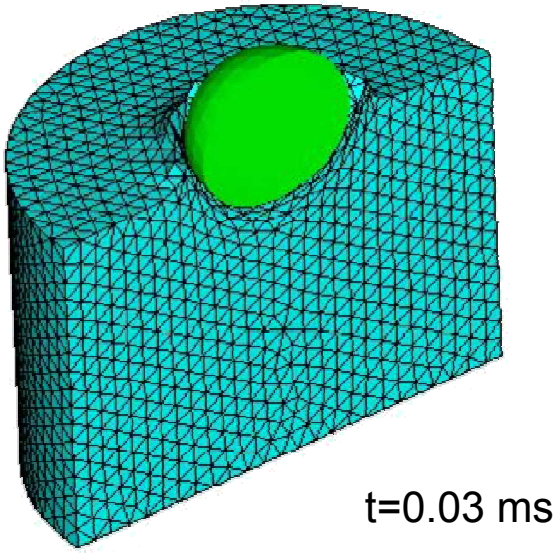


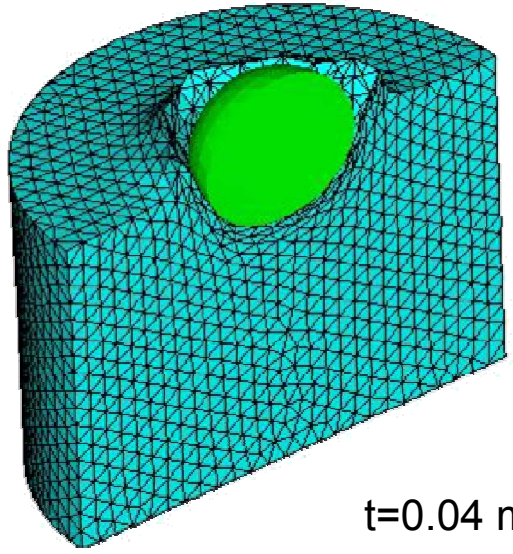




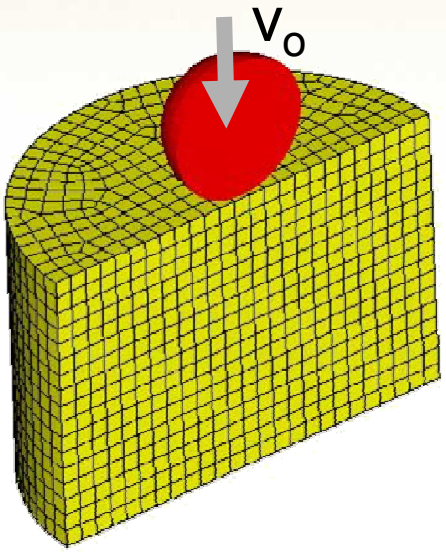
NBTet w/ distortion induced remeshing

No element death… instead automatic remeshing is invoked based on element distortion, DASH contact is used



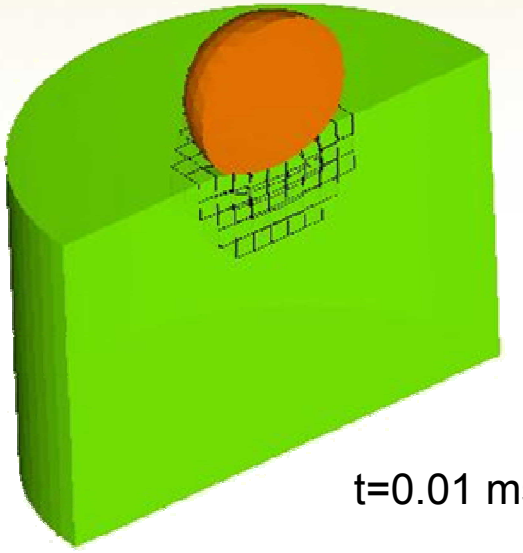


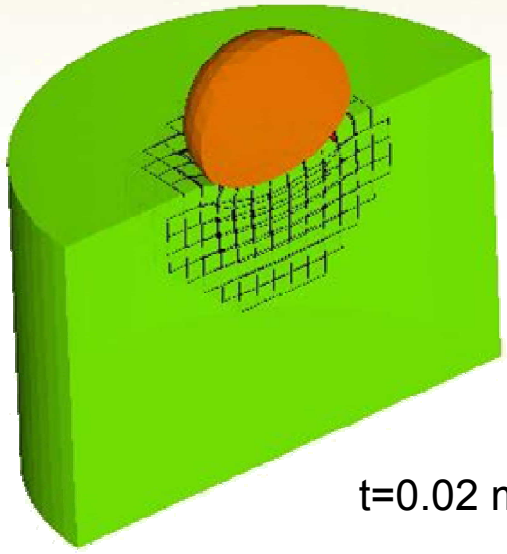
Enhanced capability: Dynamic insertion of Cohesive zones

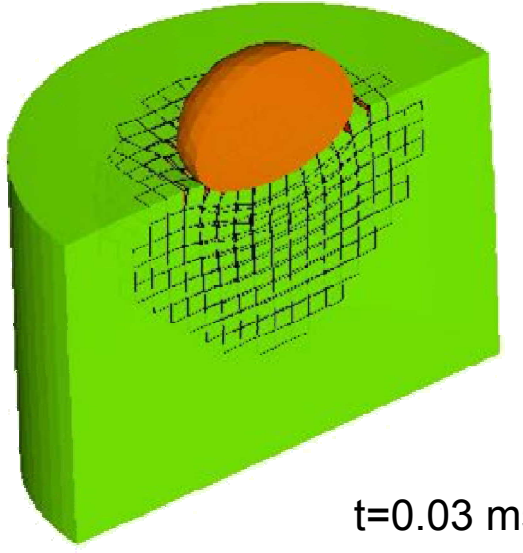


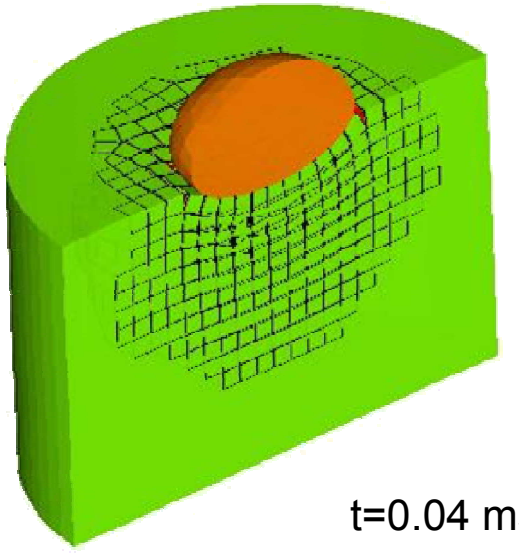
Cohesive Zone Insertion @ 10% eqps

Dynamic insertion around elements as they reach 10% equivalent plastic strain

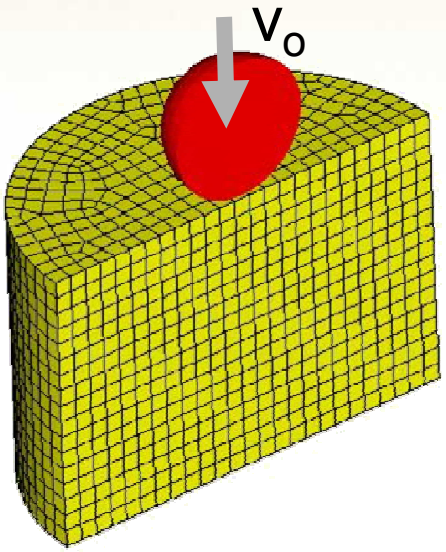


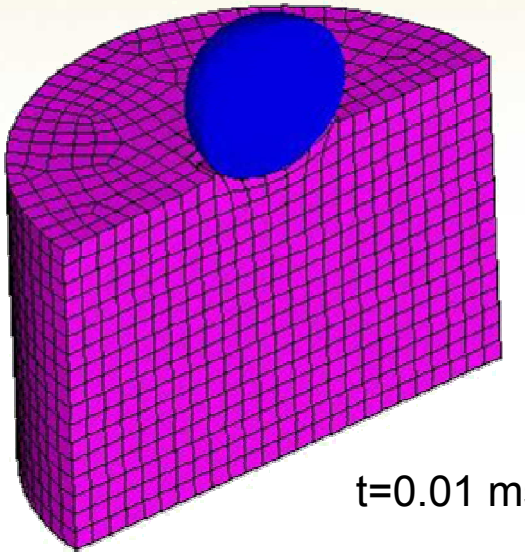




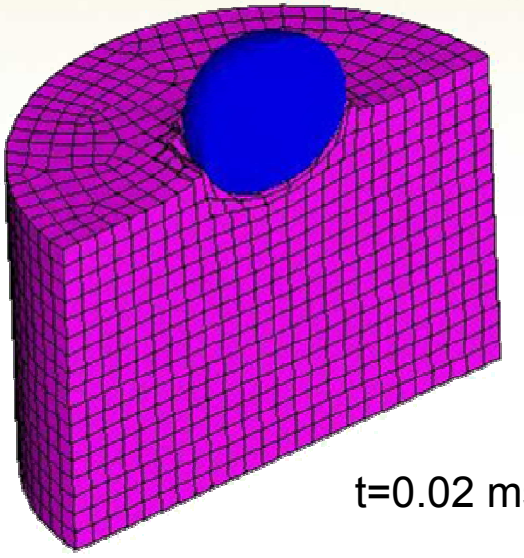


Enhanced capability: Dynamic element disconnection





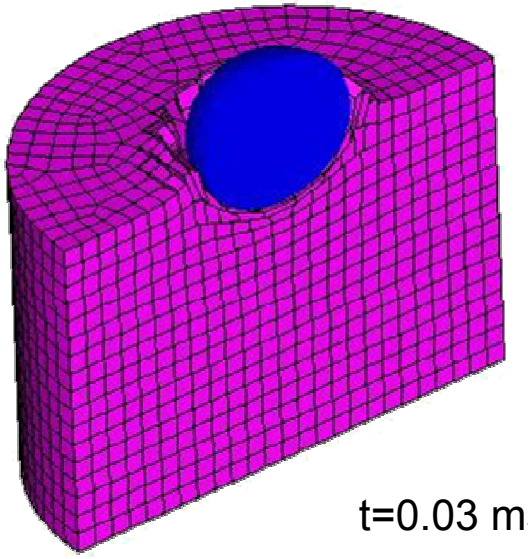
t=0.01 ms



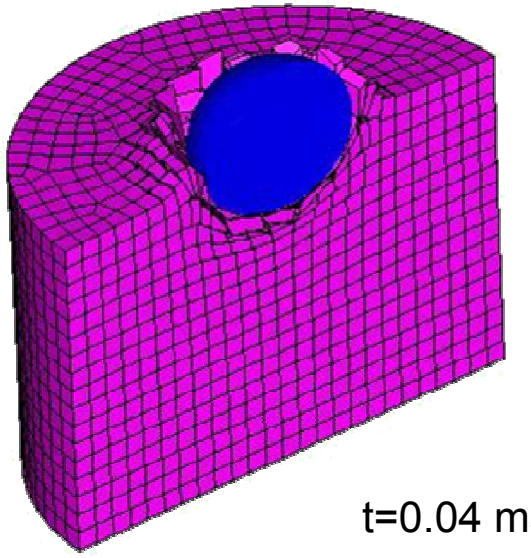
t=0.02 ms

Element disconnection @ 10% eqps

Element is disconnected from its neighbors when equivalent plastic strain reaches 10%, DASH contact is invoked between resulting elements



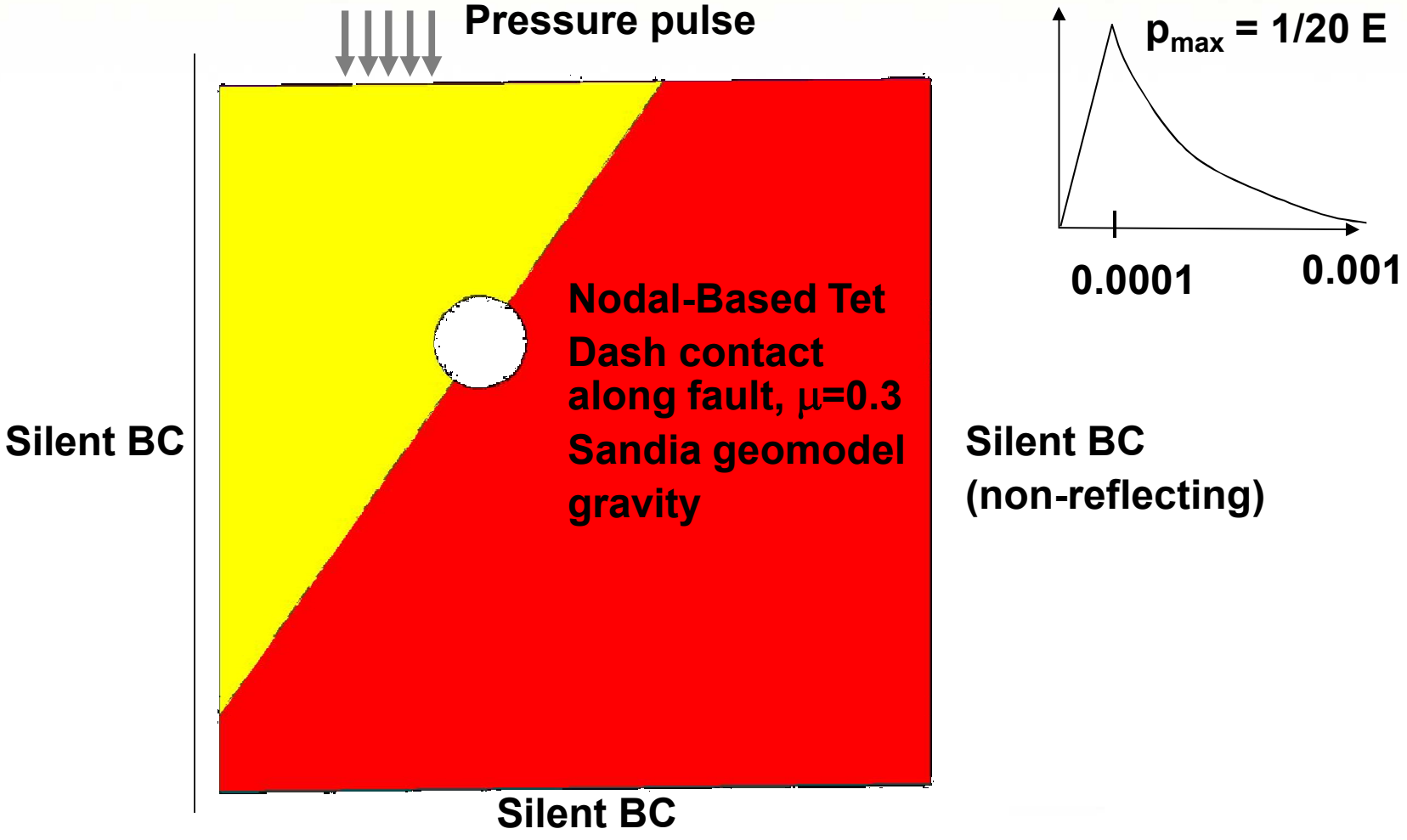
t=0.03 ms



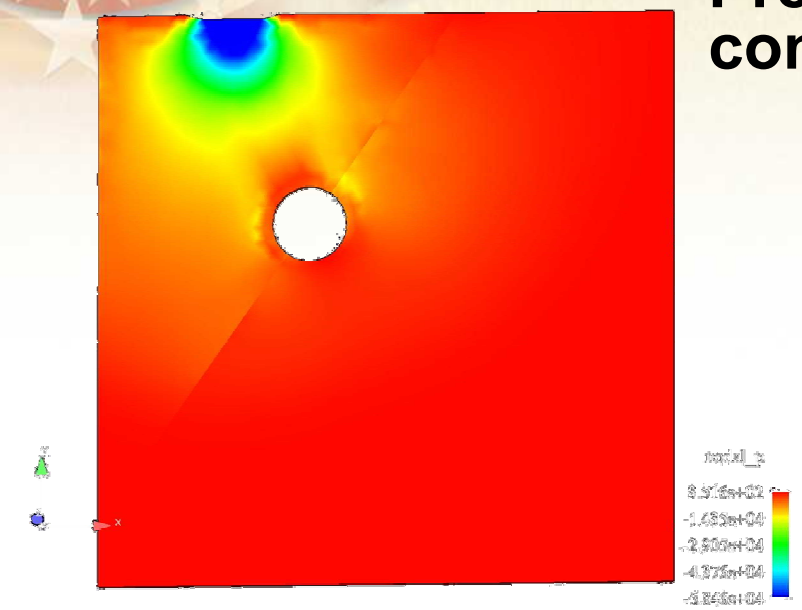
t=0.04 ms

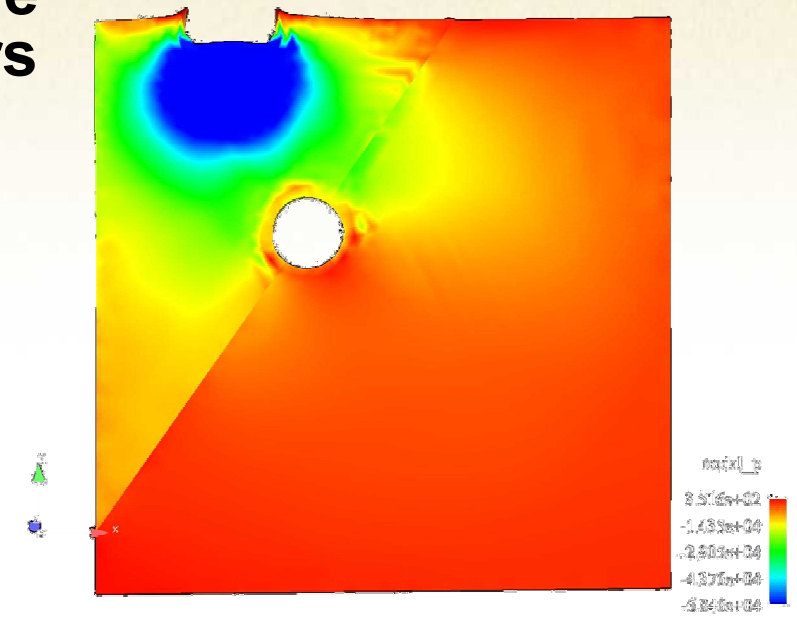
Evaluation of Nodal-Based Tet & DASH

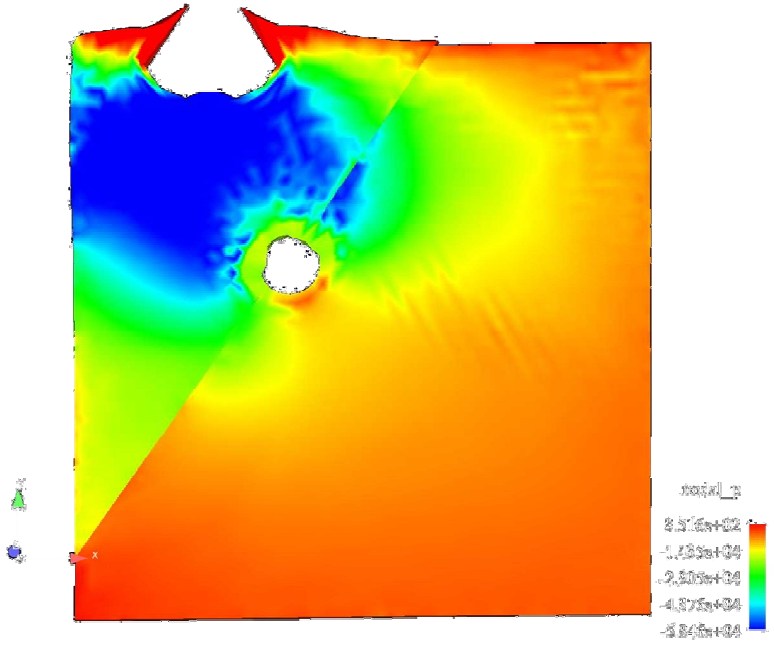
"2D slice" problem:



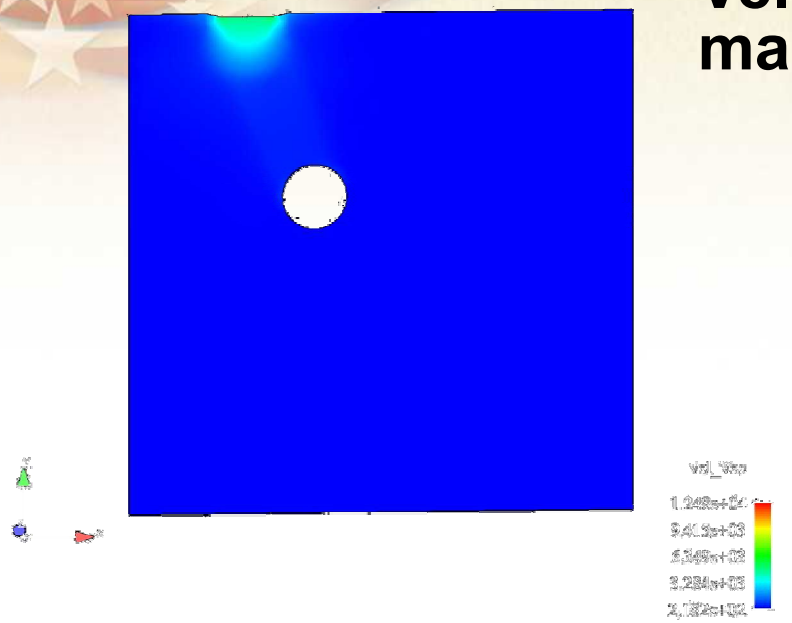
Pressure contours

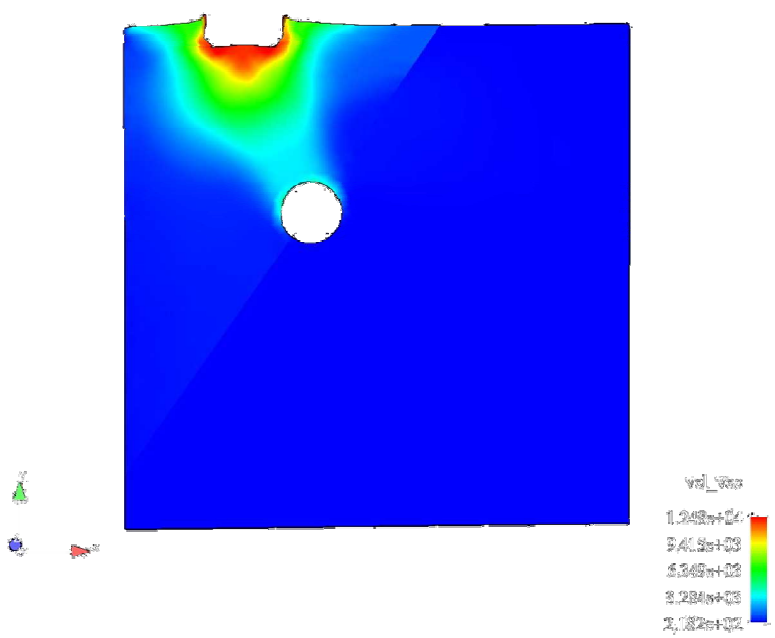


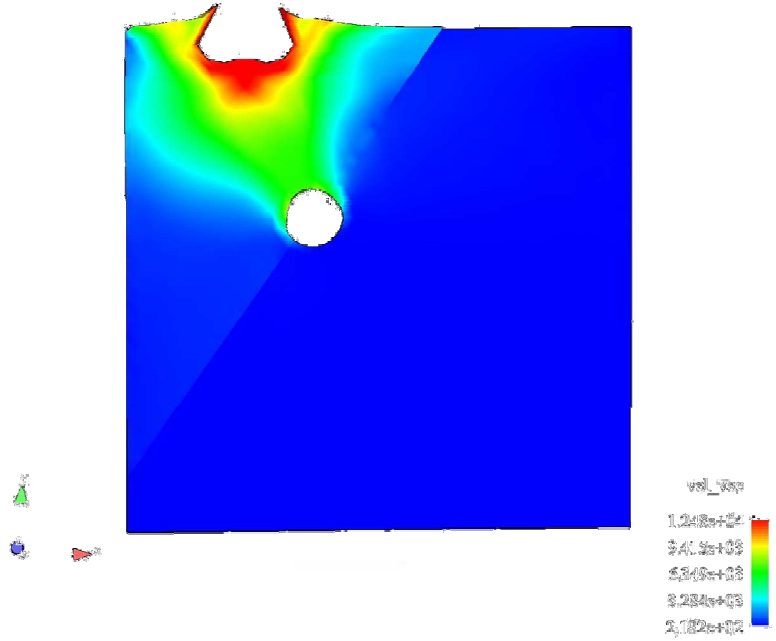




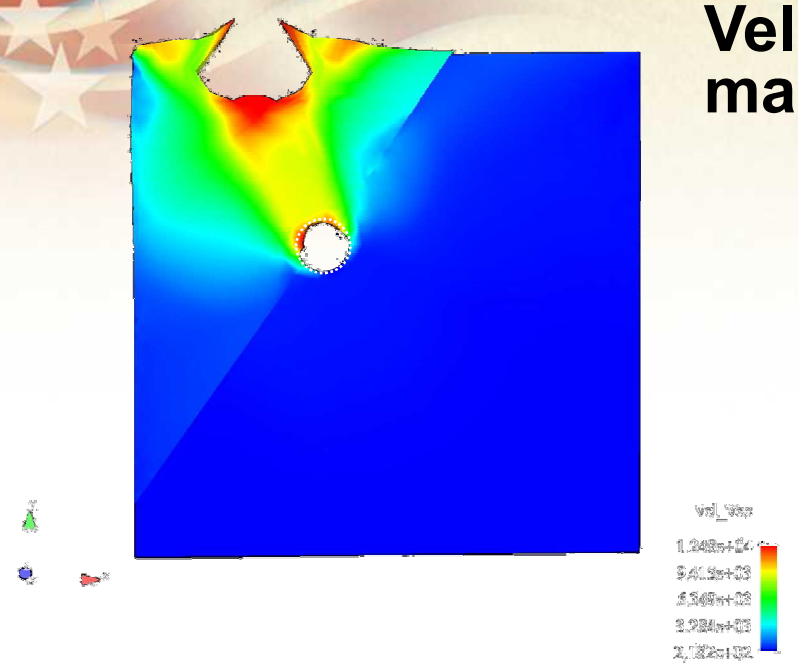
Velocity magnitude

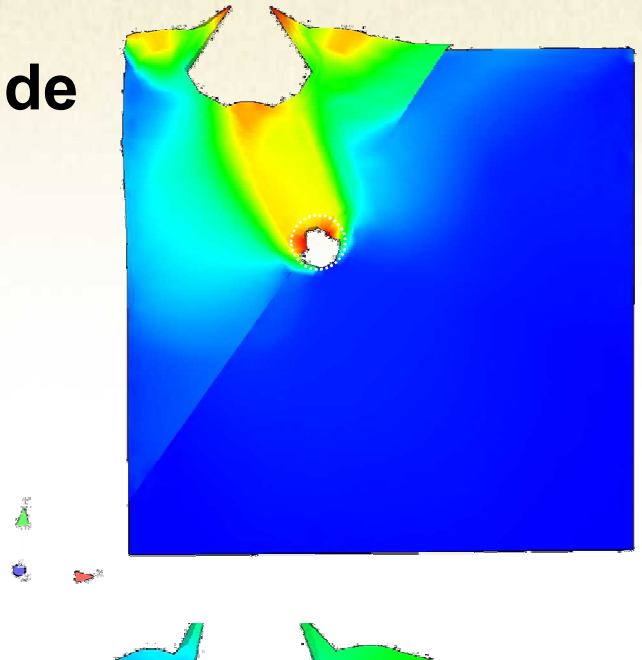


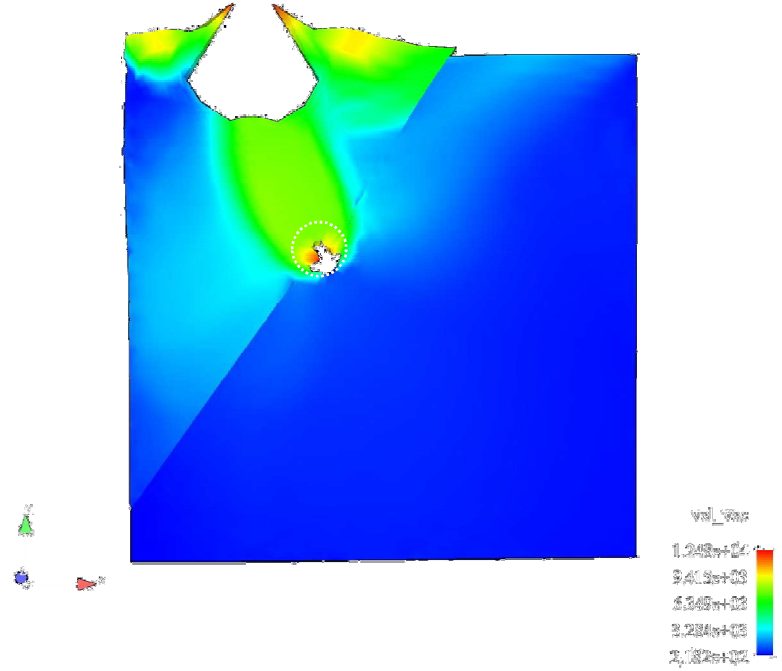


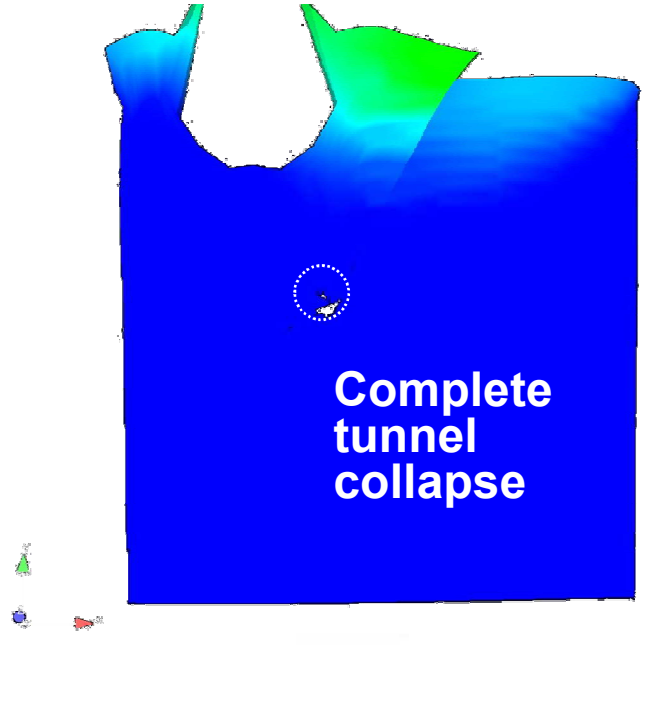


Velocity magnitude



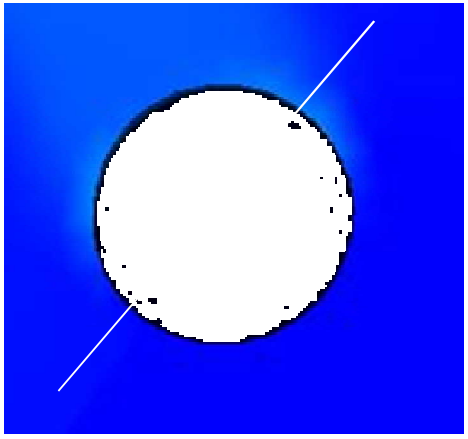


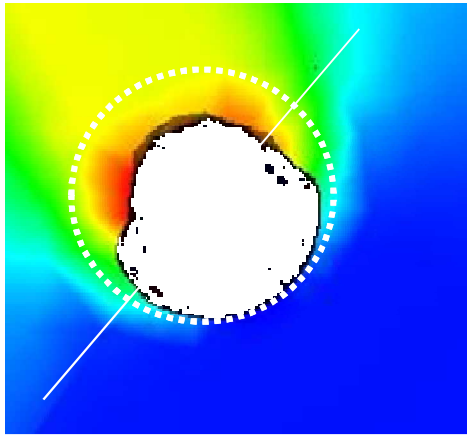


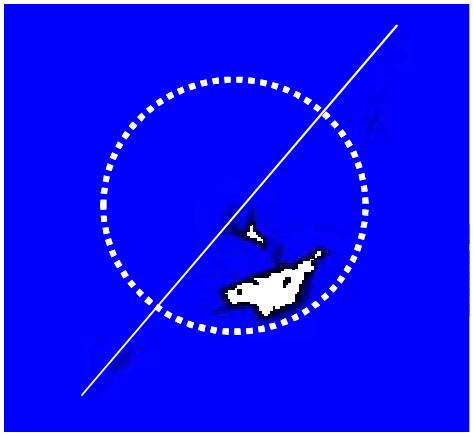


Complete tunnel collapse

Velocity magnitude producing (nearly) complete tunnel collapse







Summary of Face-Face Contact Algorithm for Extreme Loadings on Underground Structures

Accuracy

- Maintains momentum preserving normal impact/contact
- Maintains accuracy of frictional contact enforcement
- Improved capability for extreme interface pressures
- Improved parallel repeatability

Robustness

- Eliminates use of numerical tolerances (extending face size)
- Expands capability to accommodate Nodal-based tet w/ remeshing & dynamically inserted cohesive zones

Performance

- Raw serial performance as good as if not better than node-face algorithm
- Demonstrated parallel scalability