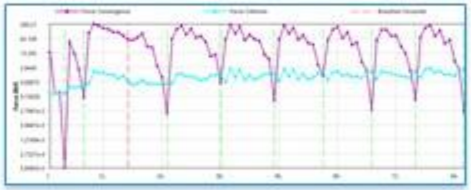
Epsilon

# Twin Cities
# ANSYS® User Meeting

November 2019

# Stabilization Damping for Nonlinear Convergence

| | |
|---|---|
| Stabilization | Constant |
| --Method | Energy |
| --Energy Dissipation Ratio | 1.e-004 |
| --Activation For First Substep | No |
| --Stabilization Force Limit | 0.2 |



*... within Epsilon*

# Agenda

1. Epsilon FEA Introduction
2. Stabilization Overview
3. Stabilization Procedure
4. Stabilization Case Studies
5. Q&A

# Intro to Epsilon

- Epsilon FEA provides engineering analysis (10 yrs!)
- Making Simulation Accurate
  - In-depth knowledge of the tools
    - ANSYS® Suite of Multi-Physics software
  - Experience with industry successes/failures
    - Aerospace, Rotating Machinery, Electronics, Manufacturing, Packaging, etc.
  - We validate with calibration runs and hand-calcs
    - Experienced Assessing Discretization Error


- Making Simulation Affordable
  - Low hourly rates and/or fixed-price estimates
  - We use specialized experienced engineers
  - Detailed statements of work, scope and budget tracking
  - Automation (APDL, ACT, Journaling)

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# Epsilon's Customers

- Our customers need load-leveling with:
  - Analyst is a team-member, not a black-box
    - Interface with same Epsilon analyst to leverage past experiences
  - Open and frequent communication
  - Any new FEA methods/lessons learned are well communicated

    Critical!
  - Schedule/budget fidelity with frequent status updates
    - Achieved by using the right person, tools, and technical approach
- Our customers benefit from external expertise
  - We infuse up-to-date FEA methods/tools
    - Leverage other industries' FEA innovations
  - We share our knowledge, files, and lessons learned!
  - We help with tool selection, infrastructure advice

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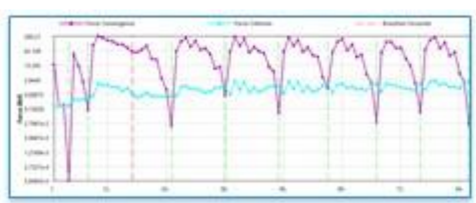
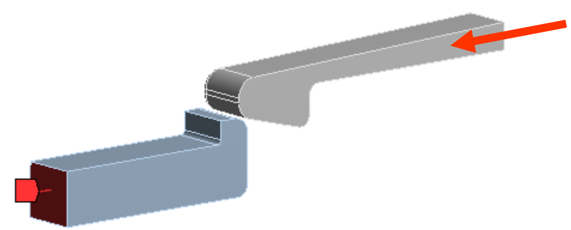
# Stabilization Damping

- Aids solver in converging rigid body motions
  - Force imbalance occurs resulting in high/infinite deflection
  - Still in static domain (time integration is off!)
  - Caused by pivoting, buckling, contact changes, etc.
- Stabilization is useful for analyses with stable beginning and end states but periods of instability
- STABILIZE command in APDL
  - Exposed in Workbench

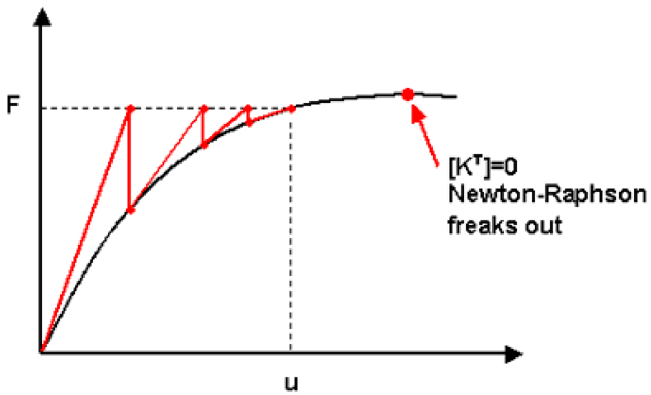
| | |
|---|---|
| Stabilization | Constant |
| --Method | Energy |
| --Energy Dissipation Ratio | 1.e-004 |
| --Activation For First Substep | No |
| --Stabilization Force Limit | 0.2 |



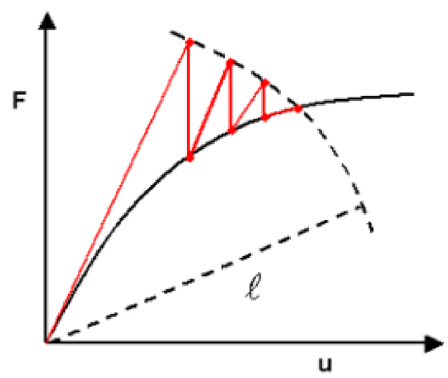


# Stabilization Vs.
# Arc Length Method

- Stabilization is an alternative to Arc Length Method, allows for simulating instability with Newton-Raphson Method
  - See previous user meeting documentation “Nonlinear Convergence” from November 2010 on our website
  - See PADT’s The Focus issue 14 from 2002
  - See Unstable Structures ANSYS documentation page




**Newton Raphson Method**




**Arc-Length Method**

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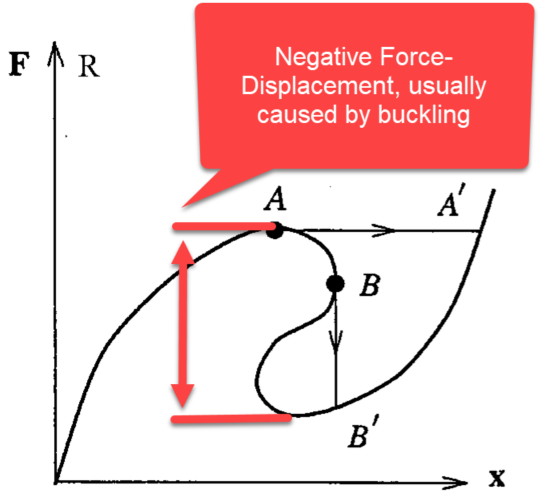
# Stabilization Damping Features

1. Adds numerical viscous damping to affected nodes
   – Internal to the solver
2. Damps “pseudo-velocity” of motion without requiring time step reduction to characterize highly nonlinear activity
3. Allows force-based loads to be used in analyses that would require displacement-based
4. Can be applied globally (all nodes) or to individual contact regions
   – Aids in detecting abrupt changes in contact
   – Can also be applied locally by reverting non-stabilized regions to legacy elements
5. Can be turned on/off between load steps or with restarts
6. Reduces number of iterations by allowing larger time steps
7. Does not preclude the use of any other solver controls/contacts
   – Arc Length Method does not support nonlinear contact

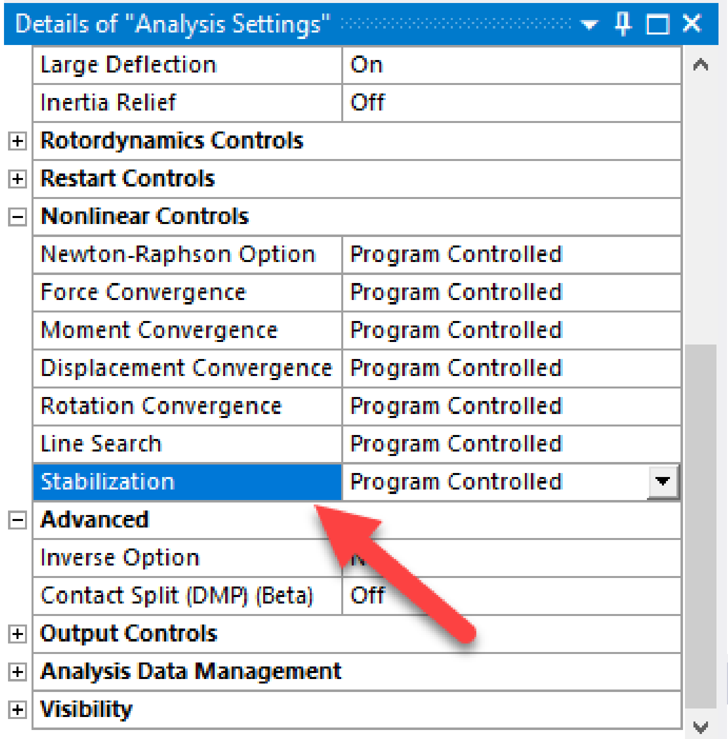
# Stabilization Damping Limitations

1. Cannot simulate negative slope region of load-displacement response curve
   – Snap-through regions, etc.
   – Requires global stability in end-state for results to be viable
2. Possible to overdamp analyses with overly large time stepping or damping ratios
   – Can force convergence to a wildly inaccurate result
3. Damping dissipates energy from the model
   – Reduces accuracy, especially for nonlinear materials
4. Helps with high-strain element distortion errors, but not ones caused by other (linear) contacts in the model



# Global Stabilization Damping Procedure

- Enable global stabilization in the Analysis Settings
- Reduce or Constant application
  - Reduce will start at prescribed stabilization value and reduce linearly to zero by the end of solution
  - Constant applies stabilization through entire solution



# Global Stabilization Damping Procedure

- Choose Energy or Damping Method
  - Energy method sets amount of energy allowed to be dissipated by damping
  - Ratio must be tuned based on load magnitude and time step duration
  - Damping factor is calculated from energy dissipation ratio and average element size
  - Alternatively, manually set damping factor

We will vary these inputs in the case studies

| | |
|---|---|
| Stabilization | Reduce |
| --Method | Energy |
| --Energy Dissipation Ratio | Energy<br>Damping |

| | |
|---|---|
| Stabilization | Reduce |
| --Method | Energy |
| --Energy Dissipation Ratio | 1.e-004 |
| --Activation For First Substep | No |
| --Stabilization Force Limit | 0.2 |

| | |
|---|---|
| Stabilization | Reduce |
| --Method | Damping |
| --Damping Factor | 0. |
| --Activation For First Substep | No |
| --Stabilization Force Limit | 0.2 |

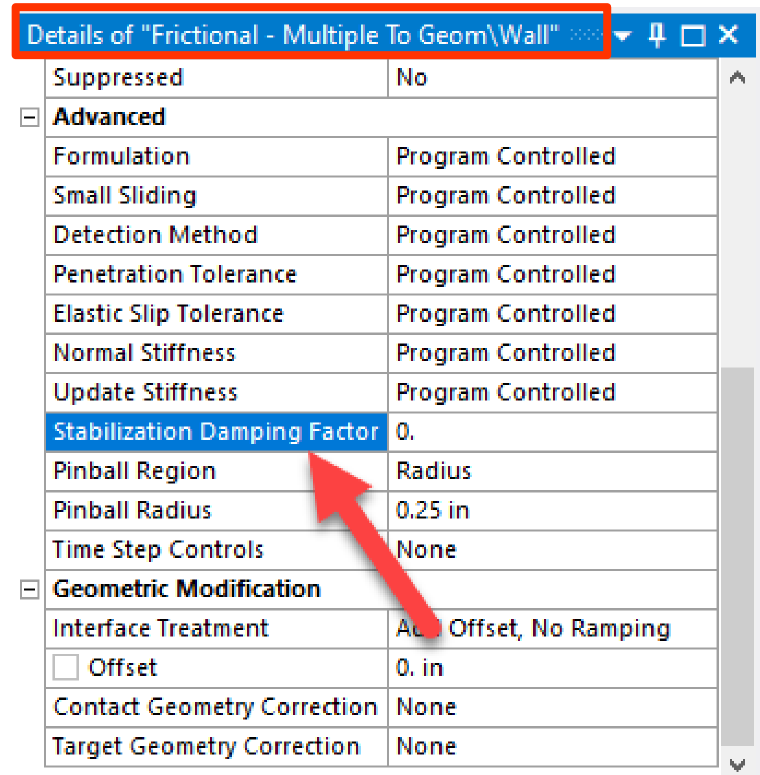
# Global Stabilization Damping Procedure

- Set Damping Factor/Dissipation Ratio
  - Default energy dissipation ratio of 1E-4 generally useful
  - Damping factor has no default value due to being model-specific, caution when using
- First substep activation
  - Only required for models beginning in an unstable state, avoid if possible
    - Can cause severe overdamping if not properly tuned
- Set Force Limit
  - Checks ratio of stabilization forces to internal forces
  - Does not have any affect on convergence/bisecting or solving, simply gives warnings when exceeded

| Nonlinear Controls | |
|---|---|
| Newton-Raphson Option | Program Controlled |
| Force Convergence | Program Controlled |
| Moment Convergence | Program Controlled |
| Displacement Converge... | Program Controlled |
| Rotation Convergence | Program Controlled |
| Line Search | Program Controlled |
| Stabilization | Reduce |
| --Method | Damping |
| --Damping Factor | 0.1 |
| --Activation For First Su... | Yes |
| --Stabilization Force Limit | 0.2 |

# Contact Stabilization Damping Procedure

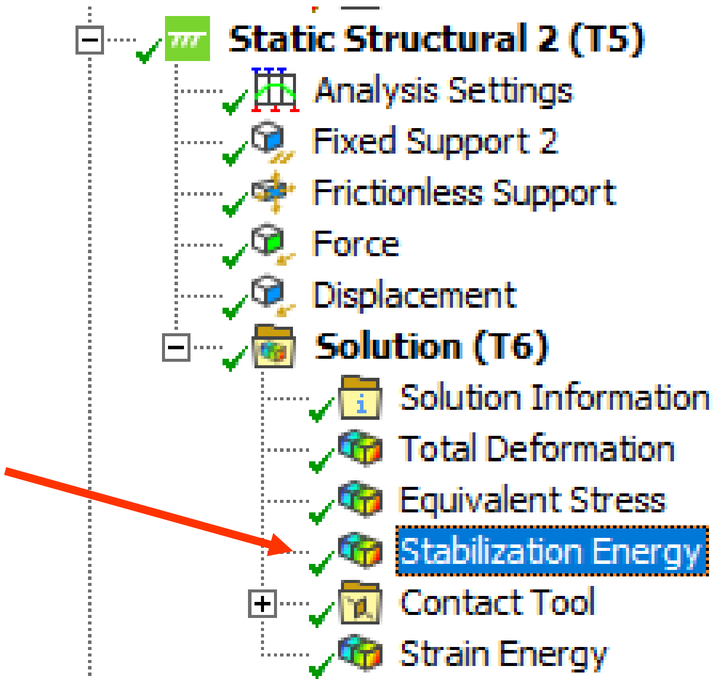
- Stabilization can be applied at nonlinear contacts only
- Useful for analyses with abrupt contact changes but general global stability
- Set damping factor within individual contacts
- No energy option, must calculate your own damping factor




We will compare contact damping to global damping in the case studies

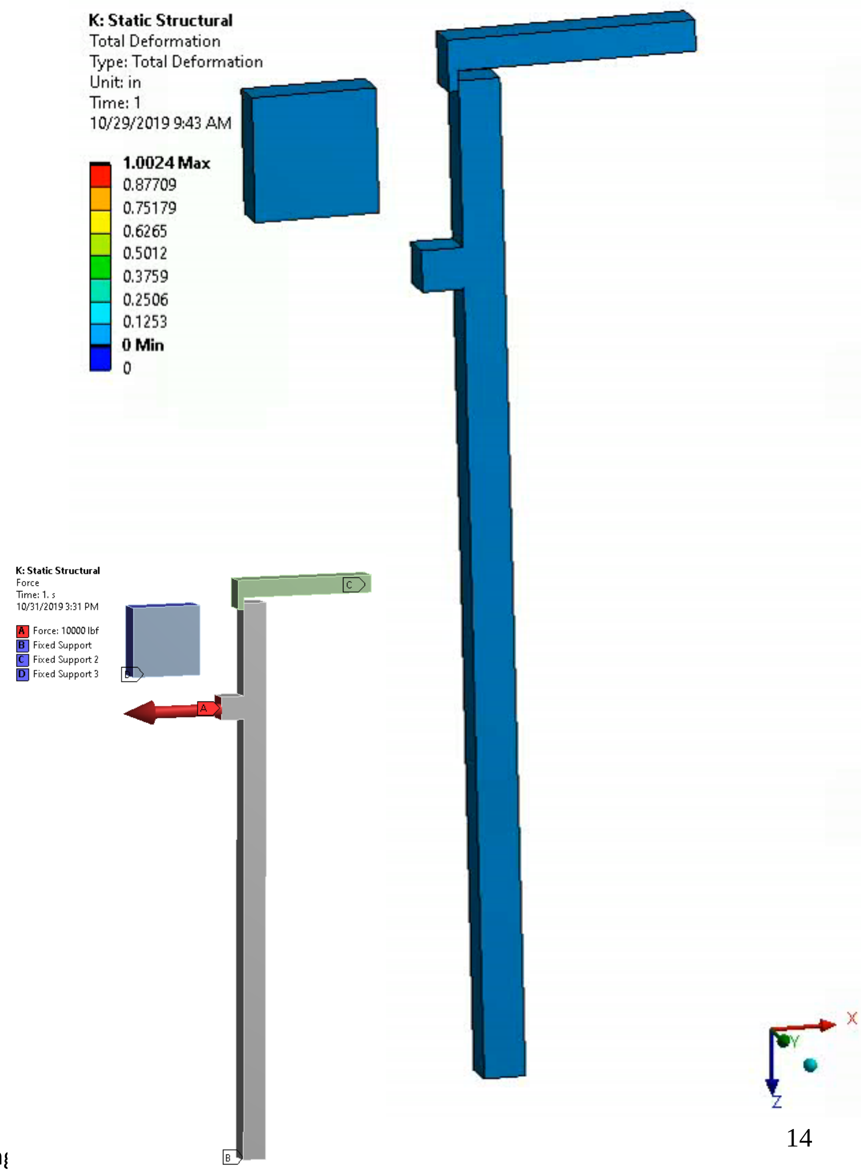
# Stabilization Damping Results

- Stabilization Energy Result can plot Energy dissipation per element
- Allows checking for excessive damped energy as well as identifying damped areas
- Not compatible with contact-only damping



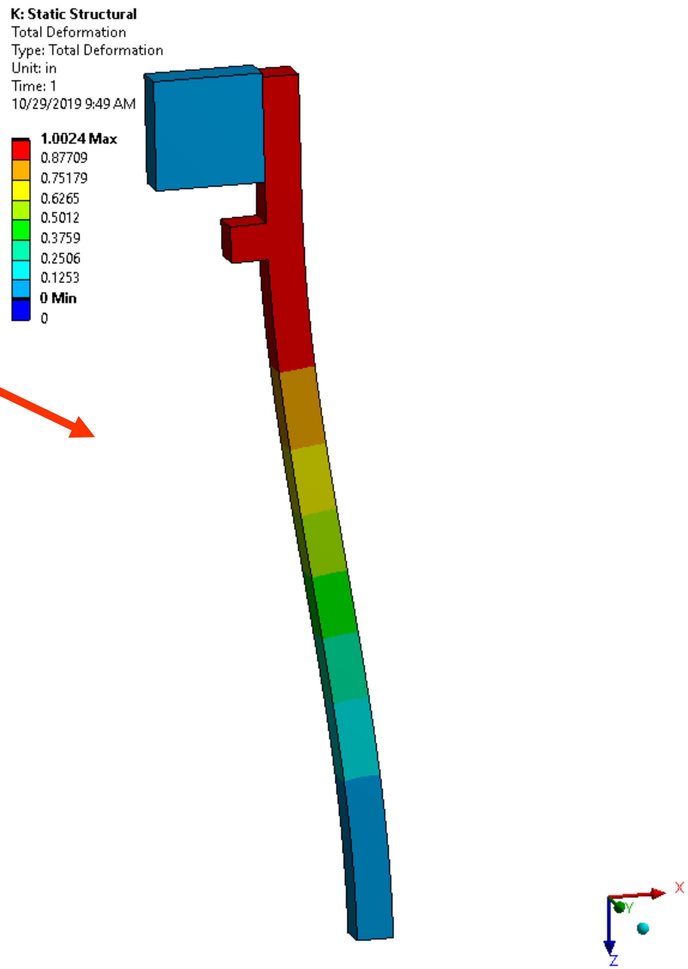
# Case Study 1: Snap-Through Skipping Analysis

- Analysis begins in stable state, then as force overcomes frictional contact at latch, experiences a short period of instability before coming to a new stable state resting on fixed block
- No actual buckling "snap through" is occurring, but similar style force-displacement curve
- Representative of most model instabilities, such as due to buckling, material failure, abrupt contact changes, etc.
- Stabilization can be turned off for first substep
- Stabilization will help skip over the region where the main member becomes unloaded and pseudo-velocity becomes very high, as a result of a very high force controlled loading

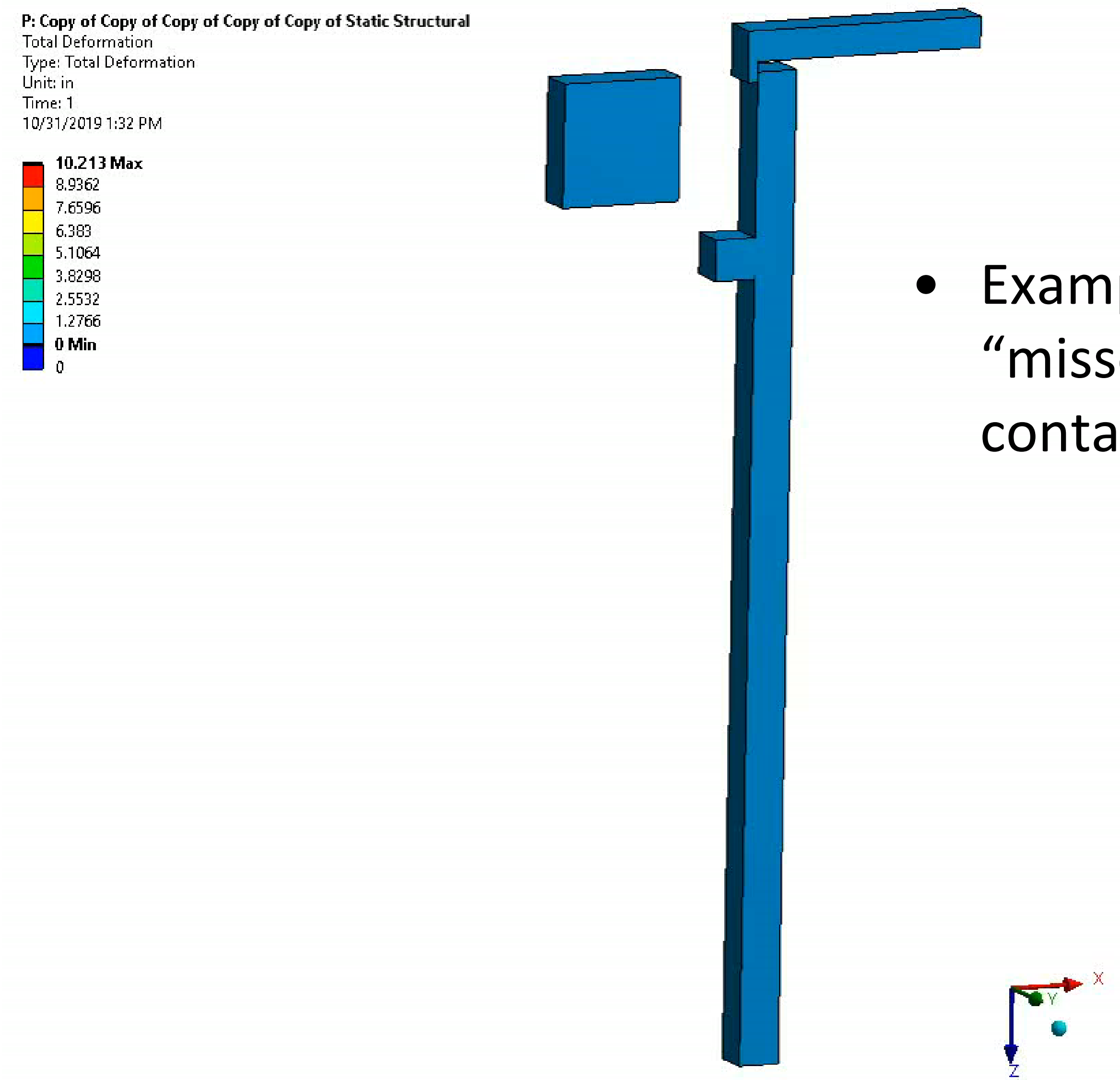


# Case Study 1: Snap-Through Skipping Analysis

- For baseline comparison, re-solved
  - Since the end-state is known, we can solve for this directly by skipping the first phase
- This will allow us to determine the effect of damping energy loss on results to a known control result
- Instabilities are localized to contact areas, so contact-only damping can also be used

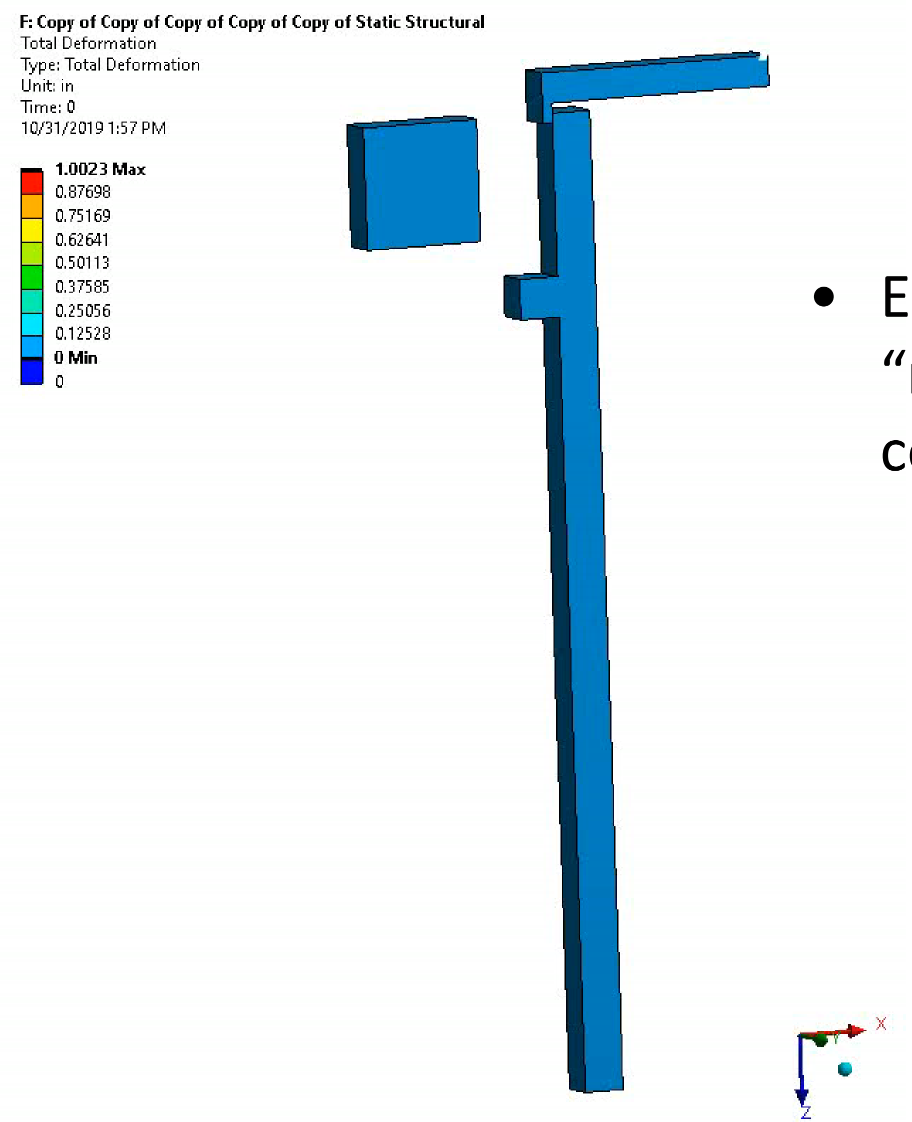


# Case Study 1: Damping Effects on Accuracy




- Example of a “missed” second contact detection

# Case Study 1: Damping Effects on Accuracy




- Example of a “missed” initial contact detection

# Case Study 1: Damping Effects on Accuracy

| 10 substeps | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Value | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Damping | 0.05 | 2.49E+06 | 10.4 | 4.23E-03 | 84 | 496.65 | 2.46E+06 | 10.161 | 9.76E-03 | 90 | 488.85 |
| Damping | 0.1 | 2.46E+06 | 10.233 | 8.27E-03 | 94 | 489.28 | FAILED | FAILED | FAILED | 255 | FAILED |
| Damping | 0.2 | 2.45E+06 | 10.069 | 1.72E-02 | 87 | 484.86 | 4.21E+05 | 1.0024 | 5.64E-04 | 68 | 0.69 |
| Damping | 0.25 | 4.21E+05 | 1.0024 | 3.15E-04 | 64 | 0.69 | 4.21E+05 | 1.0024 | 7.05E-04 | 72 | 0.69 |
| Damping | 0.5 | 4.21E+05 | 1.0024 | 6.30E-04 | 68 | 0.69 | 4.22E+05 | 1.0024 | 1.84E-03 | 106 | 0.81 |
| Damping | 0.8 | FAILED | FAILED | FAILED | 96 | FAILED | 2.42E+06 | 10.213 | 1.85E+00 | 241 | 479.86 |
| | | | | | | | | | | | |
| Energy | 1.00E-04 | 2.45E+06 | 10.068 | 5.42E-03 | 74 | 484.96 | 2.51E+06 | 10.47 | 1.22E-02 | 87 | 499.43 |
| Energy | 5.00E-04 | 4.21E+05 | 1.0024 | 4.14E-04 | 64 | 0.69 | FAILED | FAILED | FAILED | 186 | FAILED |
| Energy | 1.00E-03 | 4.22E+05 | 1.0024 | 6.18E-04 | 148 | 0.91 | 4.22E+05 | 1.0024 | 2.88E-03 | 95 | 0.82 |
| Energy | 1.00E-02 | 2.42E+06 | 10.225 | 2.11E+00 | 281 | 479.96 | 4.21E+05 | 1.0024 | 1.54E-02 | 93 | 0.78 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 4.18E+05 | 1.0024 | 63 |

- Solving with 10 initial substeps
- Damping that is either too low or too high results in unconverged solves or missed contact detection
- Damping values do not correlate with number of iterations

# Case Study 1: Damping Effects on Accuracy

| 4 substeps | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Value | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Damping | 0.05 | FAILED | FAILED | FAILED | 217 | FAILED | FAILED | FAILED | FAILED | 169 | FAILED |
| Damping | 0.1 | FAILED | FAILED | FAILED | 164 | FAILED | FAILED | FAILED | FAILED | 203 | FAILED |
| Damping | 0.2 | FAILED | FAILED | FAILED | 172 | FAILED | 4.21E+05 | 1.0024 | 1.32E-03 | 111 | 0.81 |
| Damping | 0.25 | FAILED | FAILED | FAILED | 170 | FAILED | FAILED | FAILED | FAILED | 181 | FAILED |
| Damping | 0.5 | FAILED | FAILED | FAILED | 170 | FAILED | FAILED | FAILED | FAILED | 159 | FAILED |
| Damping | 0.8 | 4.22E+05 | 1.0024 | 1.48E-03 | 114 | 0.82 | 2.45E+06 | 10.15 | 6.49E-01 | 160 | 484.88 |
| | | | | | | | | | | | |
| Energy | 1.00E-04 | FAILED | FAILED | FAILED | 218 | FAILED | FAILED | FAILED | FAILED | 195 | FAILED |
| Energy | 5.00E-04 | 2.45E+06 | 10.118 | 4.87E-01 | 198 | 486.87 | 4.22E+05 | 1.0024 | 6.63E-03 | 78 | 0.83 |
| Energy | 1.00E-03 | 4.22E+05 | 1.0024 | 1.03E-02 | 171 | 0.91 | 2.42E+06 | 10.214 | 2.15E+00 | 255 | 478.98 |
| Energy | 1.00E-02 | 4.21E+05 | 1.0024 | 1.67E-02 | 39 | 0.72 | 2.38E+06 | 10.052 | 1.9046 | 124 | 468.55 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 4.18E+05 | 1.0024 | 63 |

- Solve with 4 initial substeps rather than 10
- Damping that is either too low or too high results in unconverged solves or missed contact detection
- Very few damping values lead to convergence

# Case Study 1: Damping Effects on Accuracy

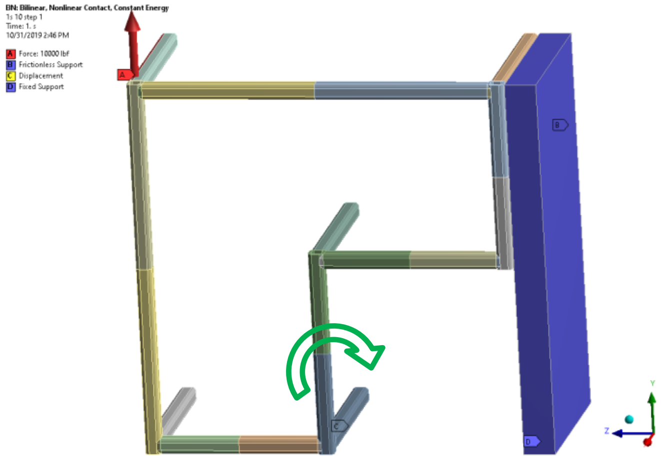
| Method | Value | Stress (psi) | Deformation (in) | # of iterations | % difference in stress from nominal |
|---|---|---|---|---|---|
| Contact Damping, 10 substeps | 0.05 | 4.21E+05 | 1.0023 | 47 | 0.78 |
| Contact Damping, 10 substeps | 0.1 | 4.20E+05 | 1.0023 | 178 | 0.42 |
| Contact Damping, 10 substeps | 0.2 | 4.21E+05 | 1.0024 | 97 | 0.63 |
| Contact Damping, 10 substeps | 0.5 | FAILED | FAILED | 183 | FAILED |
| | | | | | |
| Contact Damping, 1 substep | 0.05 | 4.28E+05 | 1.0023 | 14 | 2.33 |
| Contact Damping, 1 substep | 0.1 | FAILED | FAILED | 32 | FAILED |
| Contact Damping, 1 substep | 0.2 | 4.31E+05 | 1.0023 | 17 | 3.00 |
| Contact Damping, 1 substep | 0.5 | 4.25E+05 | 1.0023 | 14 | 1.73 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 4.18E+05 | 1.0024 | 63 |

- Contact damping of 0.1 provides most accurate stress value at expense of number of iterations
- Single Substep has low iterations, but higher error
- Using program controlled time stepping, initial contact is ignored but secondary contact detected

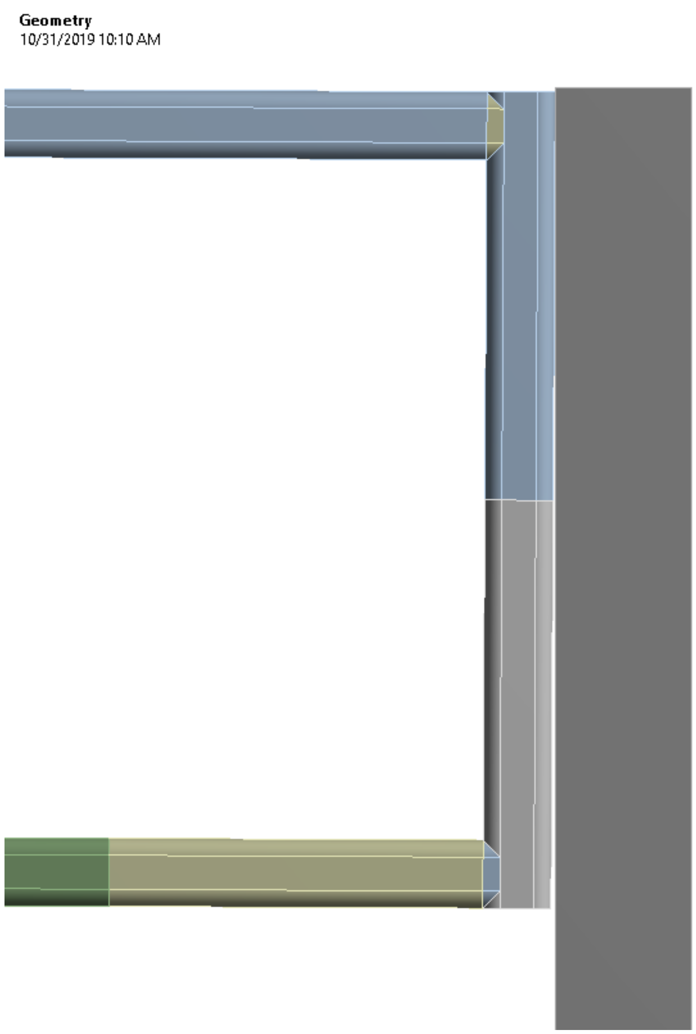
# Case Study 2: No Initial Contact

- Analysis of a tubular frame, held with a simple pin support at bottom corner to allow rotations (as well as planar symmetry)
- Vertical force at upper rear corner to push frame into nearby wall with frictional contact
- Frame is not in initial contact with wall, and force magnitude is significant enough to raise the pseudo-velocity beyond manageable substep sizes
- Since frame begins from an unstable position, stabilization must be turned on for first substep
  - Alternatively, contact stabilization can be used to slow the initial contact




# Case Study 2: No Initial Contact

- For baseline comparison, solved without stabilization by rotating frame into initial contact
- Check for effects of time step length as well as plasticity



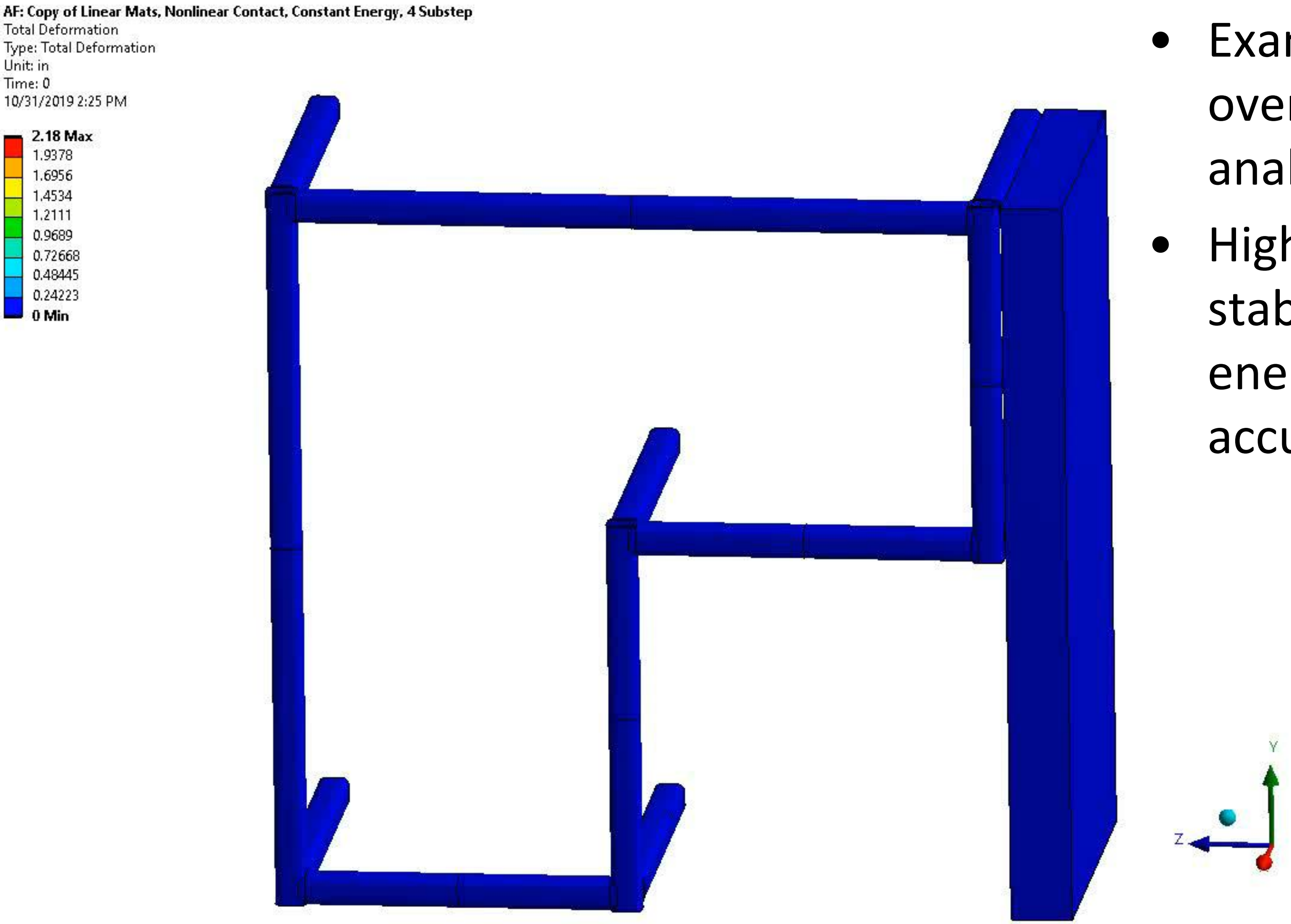
# Case Study 2: Time Stepping Effects on Accuracy

| Linear Materials | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Time Stepping | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Global Damping = 0.1 | 1s, 10 step | 1.09E+06 | 3.4117 | 1.09E-03 | 145 | 6.05 | 1.09E+06 | 3.4152 | 1.87E-03 | 130 | 5.98 |
| Global Damping = 0.1 | 1s, 4 step | 1.09E+06 | 3.4121 | 1.01E-03 | 161 | 6.05 | 1.09E+06 | 3.4146 | 1.78E-03 | 157 | 5.99 |
| Global Damping = 0.1 | 1s, 1 step | 9.33E+05 | 13 | 1.19E-01 | 65 | -8.90 | 9.35E+05 | 13.061 | 0.116 | 64 | -8.76 |
| Global Damping = 0.1 | 4s, 10 step | 1.09E+06 | 3.4155 | 3.12E-04 | 182 | 6.04 | 1.09E+06 | 3.4146 | 5.07E-04 | 180 | 6.03 |
| Global Damping = 0.1 | 4s, 1 step | FAILED | FAILED | FAILED | 30 | FAILED | FAILED | FAILED | FAILED | 30 | FAILED |
| | | | | | | | | | | | |
| Global Energy Ratio = 1E-4 | 1s, 10 step | 1.09E+06 | 3.4149 | 1.22E-02 | 103 | 6.04 | 1.09E+06 | 3.4149 | 1.05E-02 | 104 | 6.04 |
| Global Energy Ratio = 1E-4 | 1s, 4 step | 1.09E+06 | 3.4157 | 8.46E-02 | 118 | 6.04 | 1.09E+06 | 3.4139 | 6.49E-02 | 129 | 6.04 |
| Global Energy Ratio = 1E-4 | 1s, 1 step | 1.09E+06 | 3.4161 | 3.60E-01 | 146 | 6.03 | 6.48E+05 | 2.18 | 0.72431 | 12 | -36.75 |
| Global Energy Ratio = 1E-4 | 4s, 10 step | 1.09E+06 | 3.4149 | 1.22E-02 | 103 | 6.04 | 1.09E+06 | 3.4149 | 1.05E-02 | 104 | 6.04 |
| Global Energy Ratio = 1E-4 | 4s, 1 step | 1.09E+06 | 3.4161 | 3.60E-01 | 146 | 6.03 | 6.48E+05 | 2.18 | 7.24E-01 | 12 | -36.75 |
| | | | | | | | | | | | |
| Contact Damping = 0.1 | 1s, 10 step | N/A | N/A | N/A | N/A | N/A | 1.03E+06 | 3.442 | N/A | 102 | 0.91 |
| Contact Damping = 0.1 | 1s, 4 step | N/A | N/A | N/A | N/A | N/A | 1.03E+06 | 3.4328 | N/A | 80 | 0.87 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 1.02E+06 | 3.413959 | 112 |

- With program controlled time stepping (one substep), contact is often missed, or damped too highly
- Note that Energy Dissipation Ratio method is unaffected by time step lengths, but Damping Factor is
- Significantly less accurate than previous case study, likely due to extended sliding contact
- Contact Damping significantly more accurate stresses than global damping, but less accurate deformation
  - Due to maximum stress being far from contact area

# Case Study 2: Time Stepping Effects on Accuracy




- Example of an overdamped analysis
- High stabilization energy and low accuracy

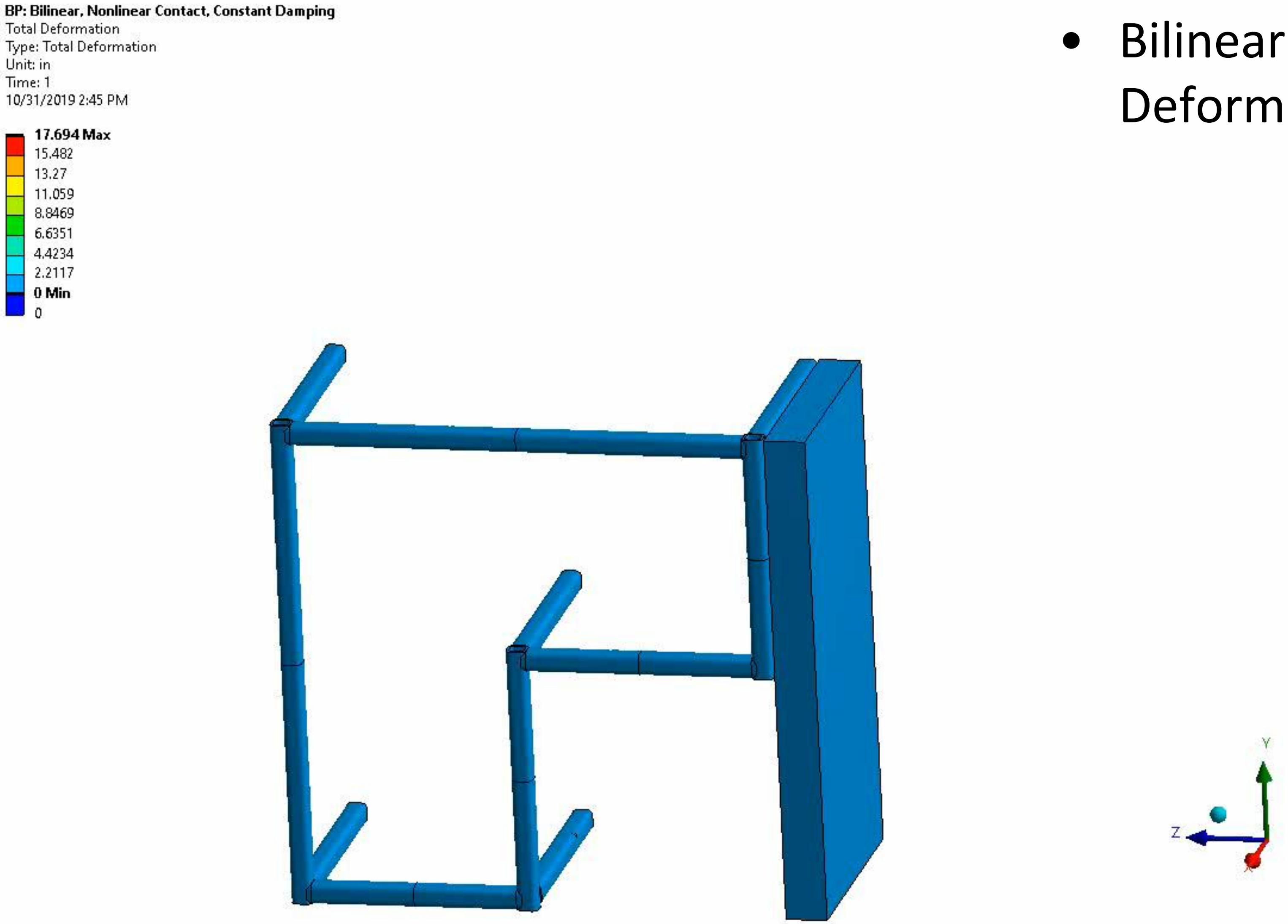
# Case Study 2: Time Stepping Effects on Accuracy

| Linear Materials | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Time Stepping | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Global Damping = 0.1 | 1s, 10 step | 1.51E+05 | 17.694 | 9.14E-02 | 640 | 6.34 | 1.51E+05 | 17.694 | 1.13E-01 | 668 | 6.36 |
| Global Damping = 0.1 | 1s, 4 step | 1.51E+05 | 17.692 | 9.15E-02 | 740 | 6.29 | 1.51E+05 | 17.692 | 1.13E-01 | 757 | 6.35 |
| Global Damping = 0.1 | 1s, 1 step | 1.51E+05 | 17.692 | 9.18E-02 | 756 | 6.28 | 1.51E+05 | 17.693 | 0.11354 | 698 | 6.33 |
| Global Damping = 0.1 | 4s, 10 step | 1.51E+05 | 17.692 | 2.37E-02 | 674 | 6.26 | 1.51E+05 | 17.692 | 2.93E-02 | 695 | 6.27 |
| Global Damping = 0.1 | 4s, 1 step | 1.51E+05 | 17.692 | 2.37E-02 | 699 | 6.26 | 1.51E+05 | 17.692 | 2.93E-02 | 713 | 6.25 |
| | | | | | | | | | | | |
| Global Energy Ratio = 1E-4 | 1s, 10 step | 1.51E+05 | 17.695 | 8.51E-02 | 684 | 6.31 | 1.51E+05 | 17.694 | 1.10E-01 | 799 | 6.29 |
| Global Energy Ratio = 1E-4 | 1s, 4 step | FAILED | FAILED | FAILED | 53 | FAILED | FAILED | FAILED | FAILED | 71 | FAILED |
| Global Energy Ratio = 1E-4 | 1s, 1 step | FAILED | FAILED | FAILED | 60 | FAILED | FAILED | FAILED | FAILED | 69 | FAILED |
| Global Energy Ratio = 1E-4 | 4s, 10 step | 1.51E+05 | 17.695 | 8.51E-02 | 684 | 6.31 | 1.51E+05 | 17.694 | 1.10E-01 | 799 | 6.29 |
| Global Energy Ratio = 1E-4 | 4s, 1 step | FAILED | FAILED | FAILED | 60 | FAILED | FAILED | FAILED | FAILED | 69 | FAILED |
| | | | | | | | | | | | |
| Contact Damping = 0.1 | 1s, 10 step | N/A | N/A | N/A | N/A | N/A | 1.47E+05 | 17.686 | N/A | 693 | 3.79 |
| Contact Damping = 0.1 | 1s, 4 step | N/A | N/A | N/A | N/A | N/A | 1.47E+05 | 17.686 | N/A | 556 | 3.79 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 1.42E+05 | 17.69236 | 585 |

- Bilinear material properties required a higher Energy Dissipation Ratio (1E-3) for convergence
- Similar accuracy to linear case, contact damping less effective at increasing accuracy

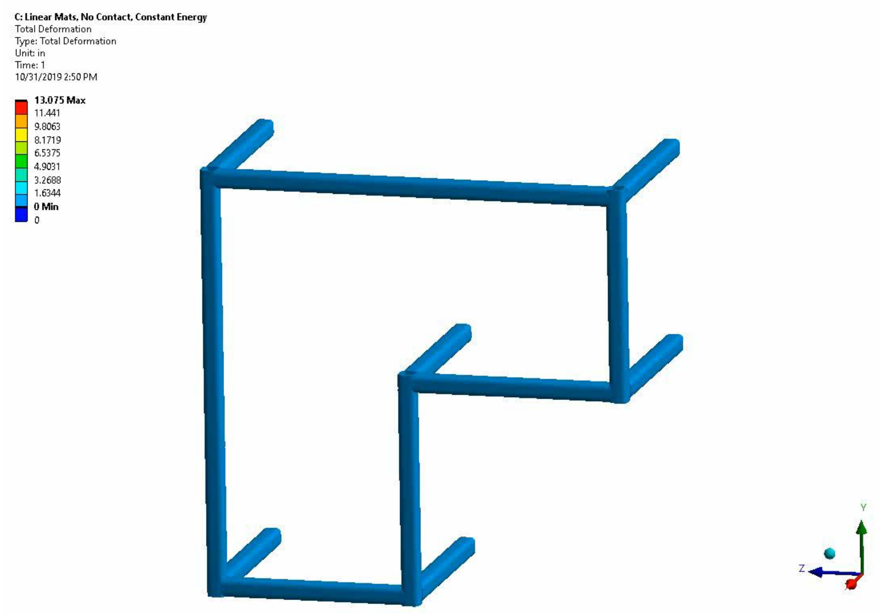
# Case Study 2: Time Stepping Effects on Accuracy




- Bilinear Deformation

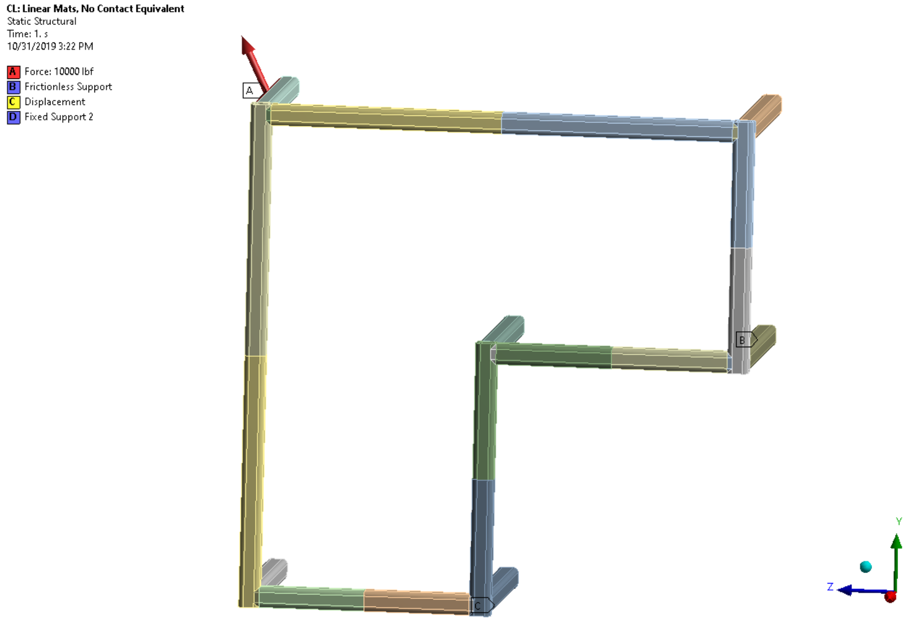
# Case Study 3: Inherently Unstable Models

- Same tubular frame as Case Study 2, with wall removed
- Model has a large pivot/rigid body response to applied load – no nonlinear contacts
- Unstable equilibrium point does exist



# Case Study 3: Inherently Unstable Models

- Can be solved without stabilization by applying load in equivalent vector to deformed shape
- Still requires use of weak springs for inherent instability (very low reaction force)



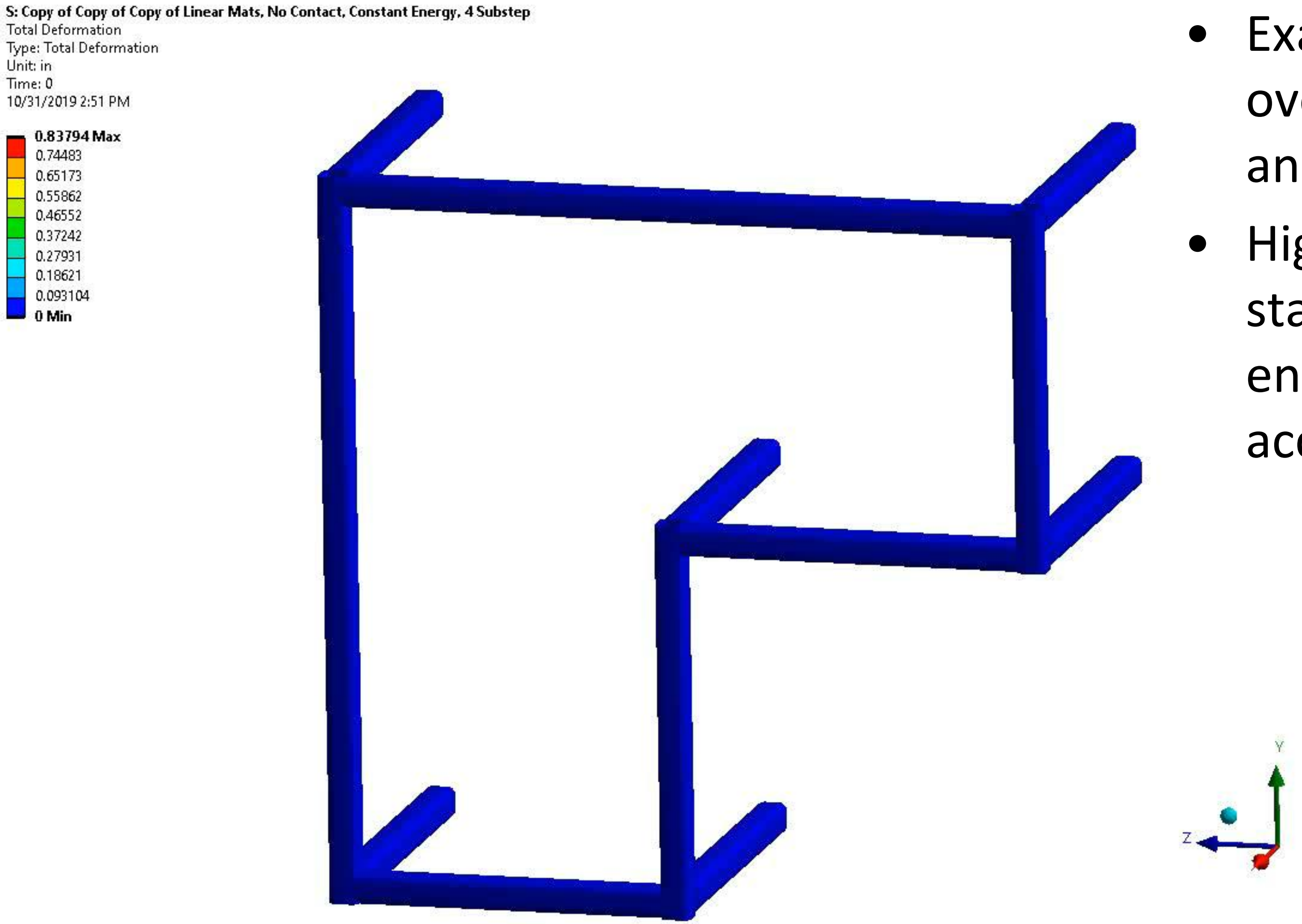
# Case Study 3: Time Stepping Effects on Accuracy

| Linear Materials | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Time Stepping | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Global Damping = 0.1 | 1s, 10 step | 9.31E+05 | 13.053 | 2.05E-01 | 100 | 0.01 | 9.31E+05 | 13.053 | 2.09E-01 | 91 | -0.06 |
| Global Damping = 0.1 | 1s, 4 step | 9.31E+05 | 13.037 | 1.95E-01 | 78 | -0.02 | 9.29E+05 | 13.05 | 2.03E-01 | 79 | -0.18 |
| Global Damping = 0.1 | 1s, 1 step | FAILED | FAILED | FAILED | 10 | FAILED | FAILED | FAILED | FAILED | 10 | FAILED |
| Global Damping = 0.1 | 4s, 10 step | 9.30E+05 | 13.049 | 1.04E-01 | 95 | -0.13 | 9.30E+05 | 13.049 | 1.06E-01 | 94 | -0.14 |
| Global Damping = 0.1 | 4s, 1 step | FAILED | FAILED | FAILED | 18 | FAILED | FAILED | FAILED | FAILED | 11 | FAILED |
| | | | | | | | | | | | |
| Global Energy Ratio = 1E-4 | 1s, 10 step | 9.32E+05 | 13.05 | 4.02E-01 | 62 | 0.12 | 9.29E+05 | 13.075 | 4.86E-01 | 57 | -0.21 |
| Global Energy Ratio = 1E-4 | 1s, 4 step | 9.31E+05 | 13.043 | 6.51E-01 | 62 | -0.01 | 9.30E+05 | 13.015 | 8.82E-01 | 52 | -0.17 |
| Global Energy Ratio = 1E-4 | 1s, 1 step | FAILED | FAILED | FAILED | 81 | FAILED | 5.04E+05 | 0.83794 | 0.36625 | 4 | -45.82 |
| Global Energy Ratio = 1E-4 | 4s, 10 step | 9.32E+05 | 13.05 | 4.02E-01 | 62 | 0.12 | 9.29E+05 | 13.075 | 4.86E-01 | 57 | -0.21 |
| Global Energy Ratio = 1E-4 | 4s, 1 step | FAILED | FAILED | FAILED | 81 | FAILED | 5.04E+05 | 0.83794 | 0.36625 | 4 | -45.82 |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 9.31E+05 | 13.05192775 | 50 |

- Significant variations in accuracy depending on time stepping with little correlation
- Reduce method significantly more accurate than Constant in all cases
- Overdamped case exists using program controlled time stepping

# Case Study 3: Time Stepping Effects on Accuracy




- Example of an overdamped analysis
- High stabilization energy and low accuracy

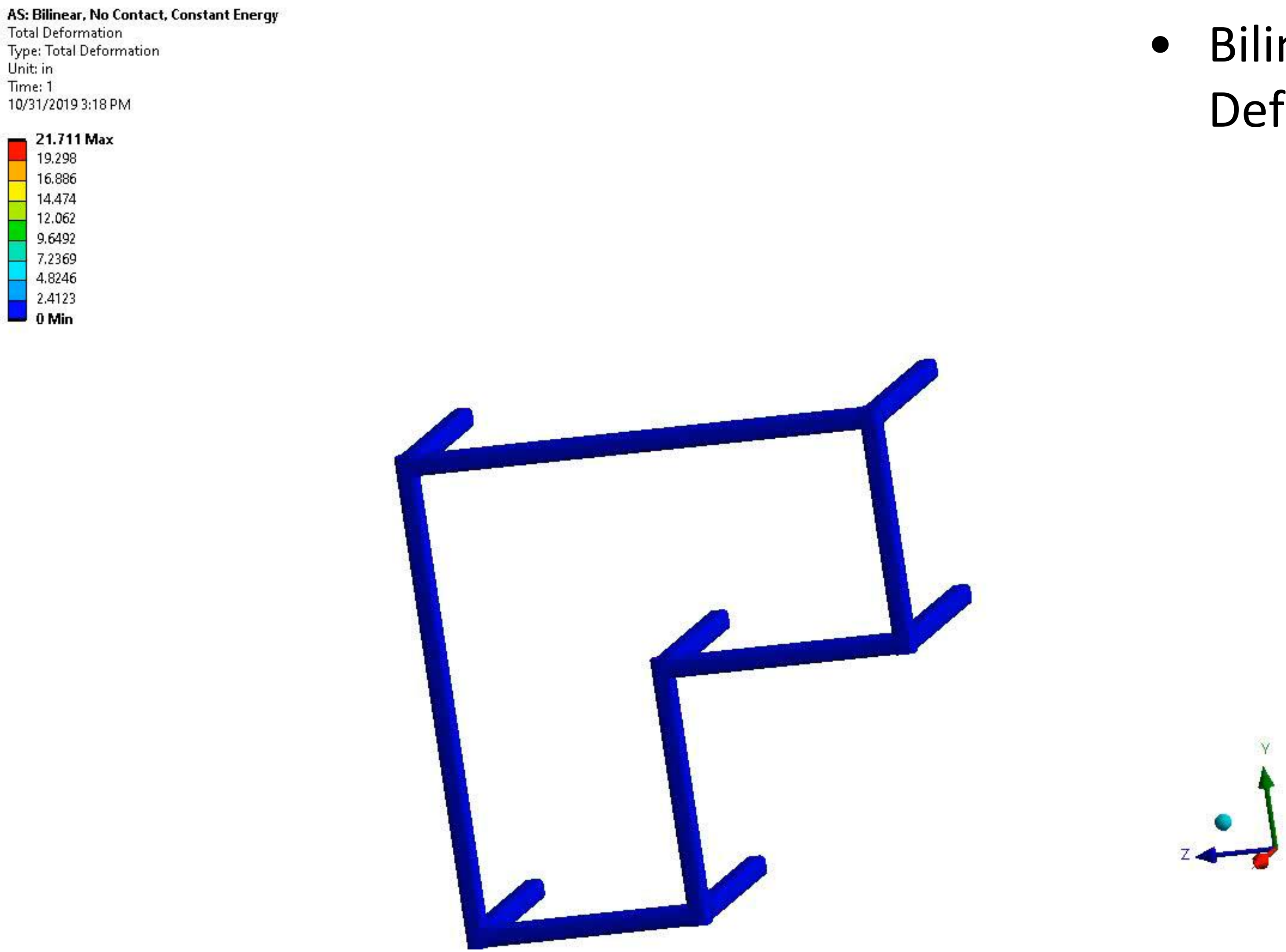
# Case Study 3: Time Stepping Effects on Accuracy

| Linear Materials | | Reduce | | | | | Constant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Time Stepping | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal | Stress (psi) | Deformation (in) | Stabilization Energy (BTU) | # of iterations | % difference in stress from nominal |
| Global Damping = 0.1 | 1s, 10 step | 1.45E+05 | 21.688 | 2.76E-01 | 398 | 0.08 | 1.45E+05 | 21.69 | 3.00E-01 | 397 | 0.10 |
| Global Damping = 0.1 | 1s, 4 step | 1.45E+05 | 21.688 | 2.77E-01 | 399 | 0.08 | 1.45E+05 | 21.69 | 3.01E-01 | 399 | 0.12 |
| Global Damping = 0.1 | 1s, 1 step | 1.45E+05 | 21.689 | 2.73E-01 | 393 | 0.11 | 1.45E+05 | 21.69 | 0.2967 | 384 | 0.11 |
| Global Damping = 0.1 | 4s, 10 step | 1.45E+05 | 21.687 | 1.22E-01 | 375 | 0.01 | 1.45E+05 | 21.687 | 1.29E-01 | 387 | 0.04 |
| Global Damping = 0.1 | 4s, 1 step | 1.45E+05 | 21.687 | 1.23E-01 | 387 | 0.01 | 1.45E+05 | 21.687 | 1.30E-01 | 385 | 0.03 |
| | | | | | | | | | | | |
| Global Energy Ratio = 1E-4 | 1s, 10 step | 1.45E+05 | 21.697 | 4.33E-01 | 417 | 0.04 | 1.45E+05 | 21.711 | 4.80E-01 | 420 | 0.03 |
| Global Energy Ratio = 1E-4 | 1s, 4 step | FAILED | FAILED | FAILED | 20 | FAILED | FAILED | FAILED | FAILED | 26 | FAILED |
| Global Energy Ratio = 1E-4 | 1s, 1 step | FAILED | FAILED | FAILED | 25 | FAILED | FAILED | FAILED | FAILED | 27 | FAILED |
| Global Energy Ratio = 1E-4 | 4s, 10 step | 1.45E+05 | 21.697 | 4.33E-01 | 417 | 0.04 | 1.45E+05 | 21.711 | 4.80E-01 | 420 | 0.03 |
| Global Energy Ratio = 1E-4 | 4s, 1 step | FAILED | FAILED | FAILED | 25 | FAILED | FAILED | FAILED | FAILED | 27 | FAILED |

| Nominal Values | | |
|---|---|---|
| Stress (psi) | Deformation (in) | # of iterations |
| 1.45E+05 | 21.65429474 | 310 |

- Bilinear materials converged more often due to necessary bisecting

# Case Study 2: Time Stepping Effects on Accuracy




- Bilinear Deformation

Epsilon

# Conclusions

1. Viable solution to momentarily unstable models
2. Ideal to use local contact damping when possible as opposed to global damping
3. Stabilization Energy dissipated does not necessarily correlate to lost accuracy
4. Reduce method generally more accurate than Constant and less likely to produce overdamped/unconverged analyses
5. Energy dissipation can result in either over or under conservative stress predictions
6. As with all analyses, sanity checks very important

# Input / Questions

Epsilon

*... within Epsilon*