Tipps und Tricks mit dem Explicit Solver SIMULIA

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General equations for mechanical system

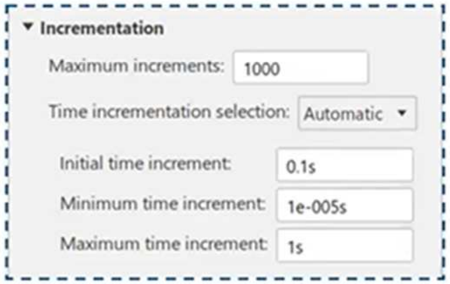
- Dynamic equilibrium
  - The dynamic equilibrium equations are written for convenience with the inertial forces isolated from the other forces:

$$P - I = M\ddot{u}$$

- P = the external applied force vector
- I = the internal force vector
- $M\ddot{u}$ = inertial forces (mass × acceleration)

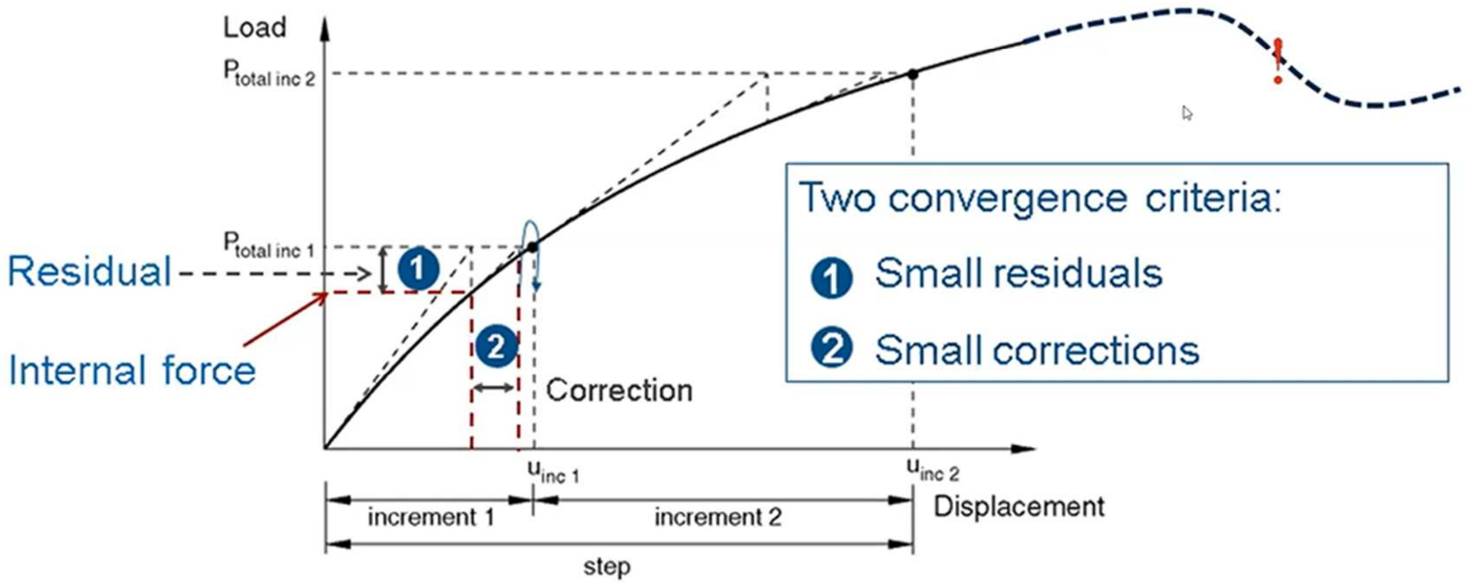
Implicit: Method for Nonlinear Static Simulation

- Nonlinear problems are generally solved in an incremental fashion.
  - For a static problem a fraction of the total load is applied to the structure and the equilibrium solution corresponding to the current load level is obtained.
  - The load level is then increased (i.e., incremented) and the process is repeated until the full load level is applied.



  - The implicit solution scheme uses an incremental-iterative solution technique based on the Newton-Raphson method.
  - The method is unconditionally stable (any size increment can be used).
    - Accuracy in dynamic simulation is affected by the increment size, however.
  - Each increment usually requires several iterations to achieve convergence, and each step usually consists of several increments.

Implicit: Method for Nonlinear Static Simulation



Explicit Dynamics

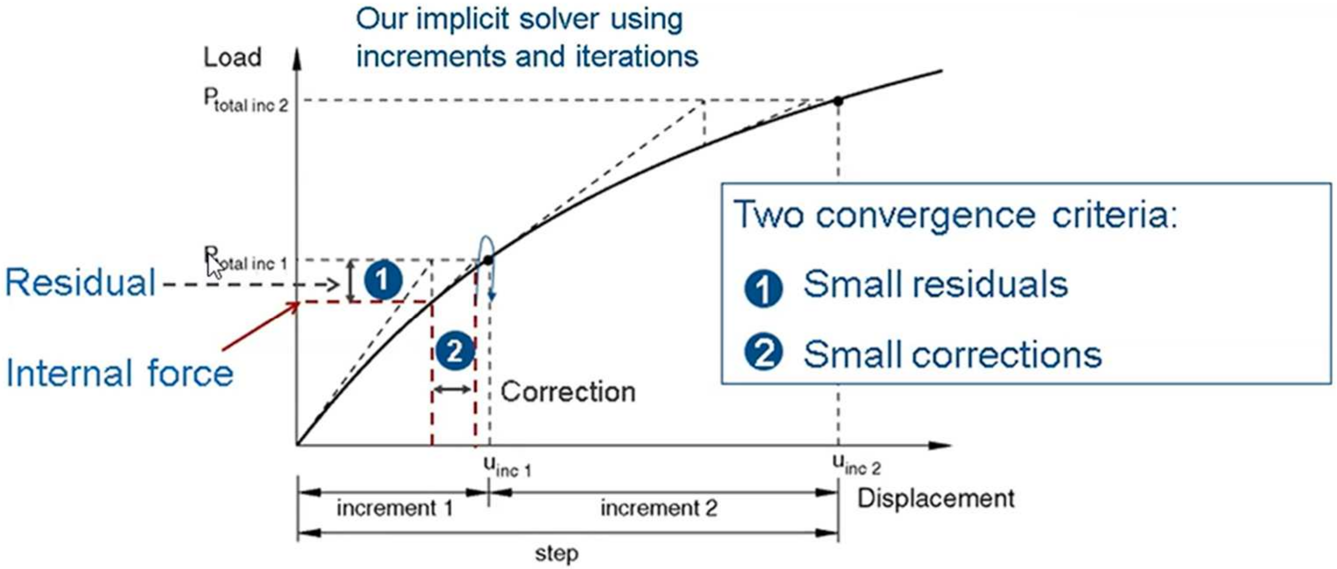
- Explicit dynamics is a mathematical technique for integrating the equations of motion through time.

  - The explicit dynamic integration method is also known as the forward Euler or central difference algorithm.
    - Values are updated from information already known:
      1. Calculate velocity at the half-step from the current acceleration
      2. Calculate the displacement an increment forward in time from the half-step velocity
      3. Use the displacement to calculate the strain, stress and internal forces in the element
      4. Use the internal forces and applied loads to calculate the new acceleration
      5. Repeat…

- Stress wave propagation

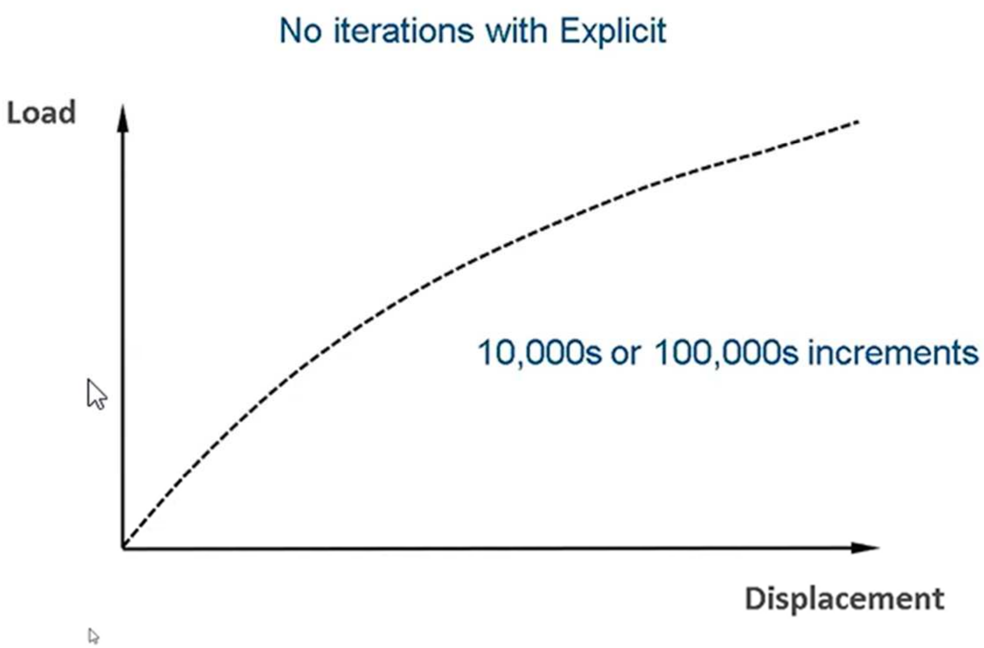
  - This stress wave propagation example illustrates how the explicit dynamics solution procedure works without iterating or solving sets of linear equations.

Explicit Dynamics vs Implicit

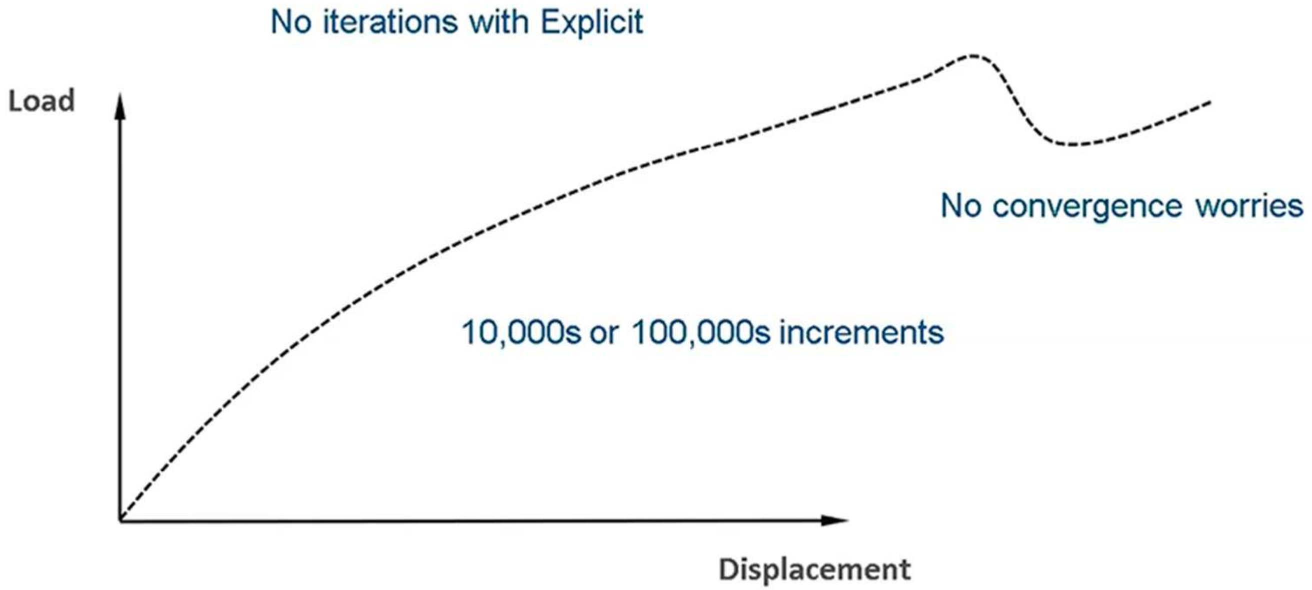


- ❑ No inherent limitation on increment size
- ❑ Increment size determined from accuracy and convergence
- ❑ Number of increments required is generally orders of magnitude smaller than Explicit
- ❑ The computational cost per increment in implicit is much greater than Explicit

Explicit Dynamics vs Implicit



Explicit Dynamics vs Implicit



- ❑ Explicit requires a really small increment size
- ❑ Simulations take on the order of 10^4 or 10^6 increments
- ❑ The computational cost of these increments is relatively small

Explicit Dynamics: Stable time increment

- Stable time increment
  - It is the *minimum* time that a dilatational wave takes to move across any element in the model
  - For each element it can be expressed as $\Delta t = \left(\frac{L^e}{c_d}\right)$, where L^e is the characteristic length of the element and c_d is the dilatational wave speed.
  - For a linear elastic material with a Poisson's ratio of zero: $c_d = \sqrt{\frac{E}{\rho}}$, where E is the Young's modulus and ρ is the material density.
  - *Larger elements, a softer material and a larger material density* are frequently used to increase the size of the stable time increment.

Tip 01

Explicit can be used for quasi-static events

- At first glance it appears the implicit solver would be the appropriate choice for modeling highly nonlinear static problems.
  - However, explicit dynamics solvers are more efficient for this class of problems.
  - This is especially true for three-dimensional problems involving contact and very large deformations.

- Artificially increasing the speed of the process in the simulation is necessary to obtain an economical solution.

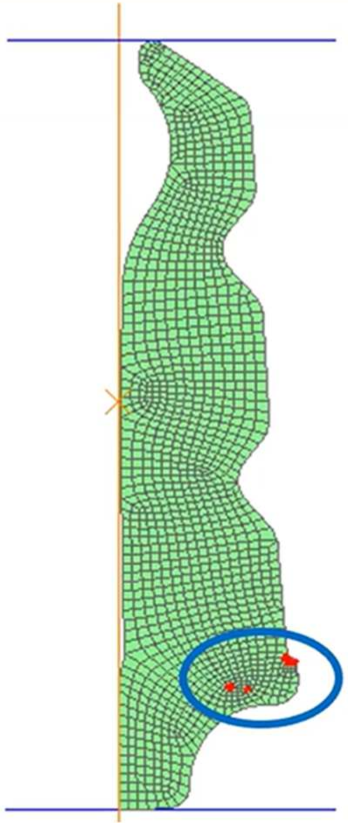
Note: In general you can almost always get results, but are these results appropriate for the event you are trying to simulate?

Tip 02

Put effort into generating good meshes

- Since the element with the smallest stable time increment controls the increment size for the entire model, having a uniformly sized mesh helps increase Δt.

- Try to generate regular meshes and uniform elements
  - Regular elements will handle distortion better
- Work to eliminate tiny elements and sliver elements – *these will kill your minimum time increment!*
- Clean up and idealize geometry
  - *The Age Old battle: geometry data can be acceptable for CAD but make life more difficult for simulation and mesh generation*
- Simplify geometry and eliminate small features where it makes sense



Tip 02

Put effort into generating good meshes

- Run time went from 40 hours to 3 hours
  - Cleaned up surface geometry and produced a better tet mesh
    - More regular elements allowed for an increase in minimum time increment
    - Reduced the total number of elements (900,000 to 300,000)

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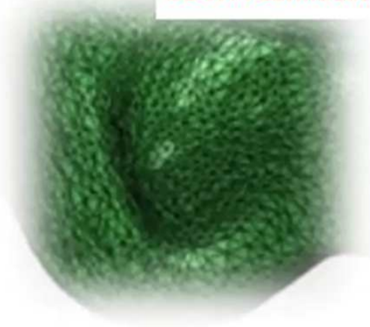
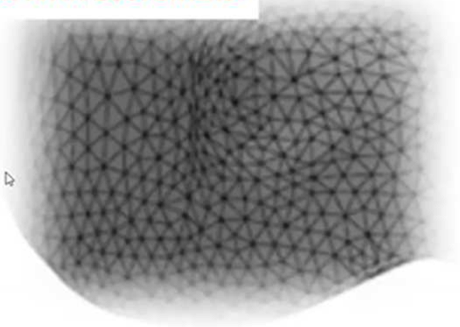
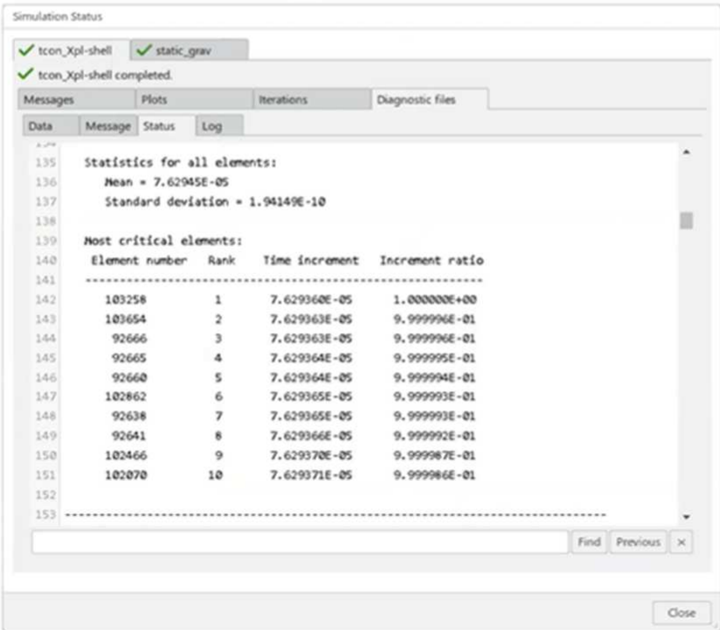




Tip 03

Check for the critical elements

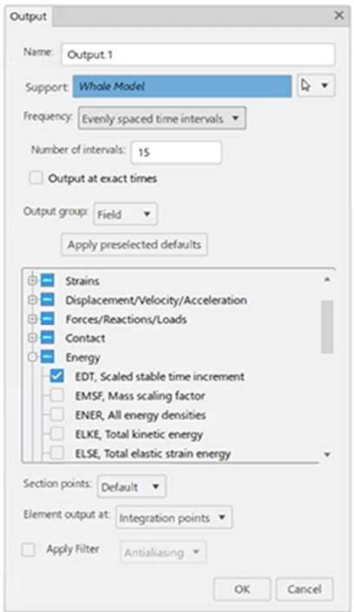
- The most critical elements are reported to the status (.sta) file during the datacheck phase of the analysis
- Also check out the Field Output variable EDT

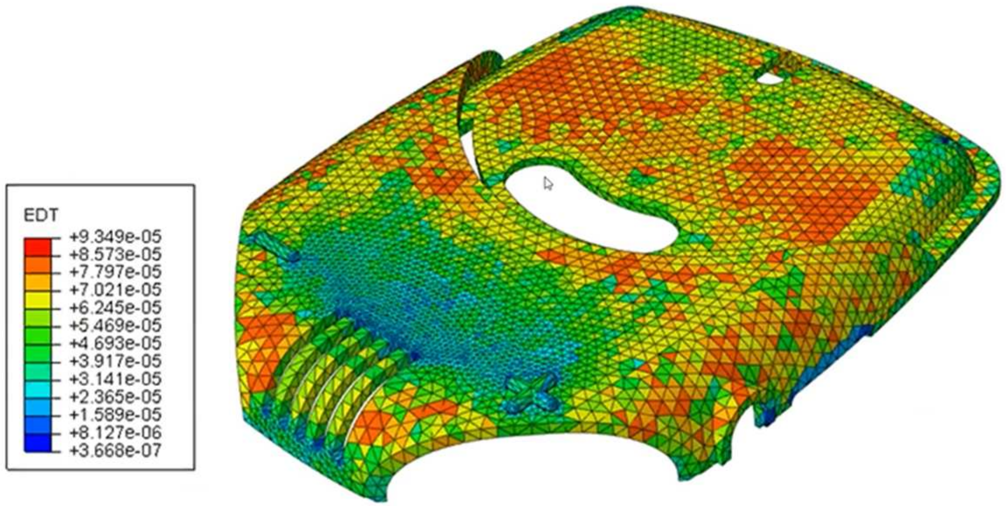


Tip 03

Check for the critical elements

- The 10 most critical elements are reported to the status (.sta) file during the datacheck phase of the analysis
- Also check out the Field Output variable EDT





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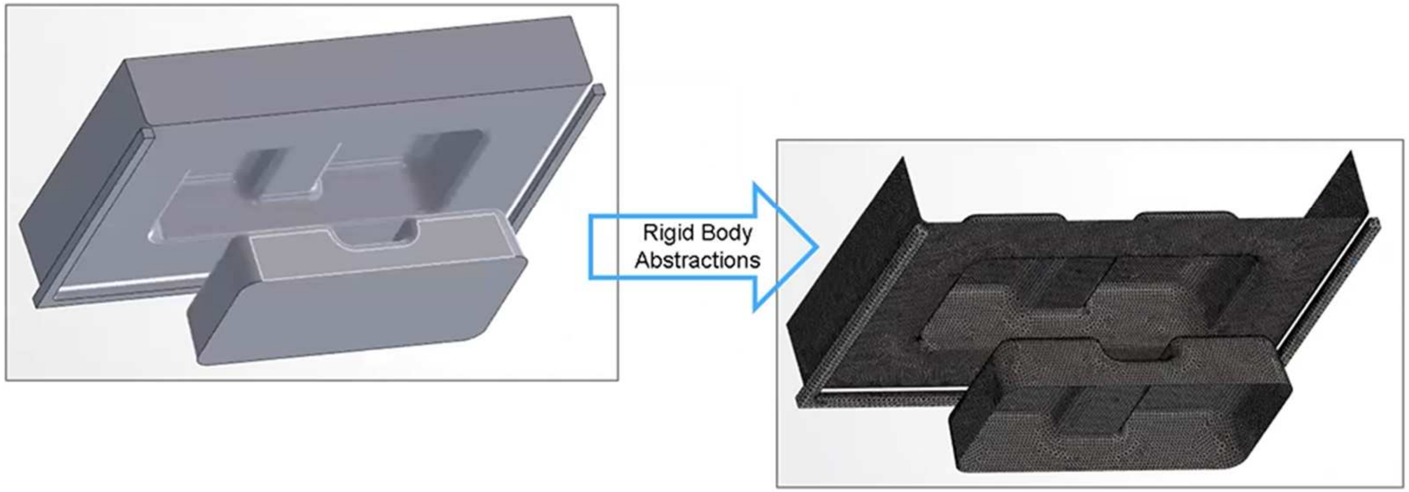
Tip 04

Use Rigid Body abstractions when possible

- Since the element with the smallest stable time increment controls the increment size for the entire model, having a uniformly sized mesh helps increase Δt.

- ▶ The elements of the rigid body abstractions won't affect smallest stable time increment
  - ▷ Note: sections containing materials with densities are still necessary for these elements



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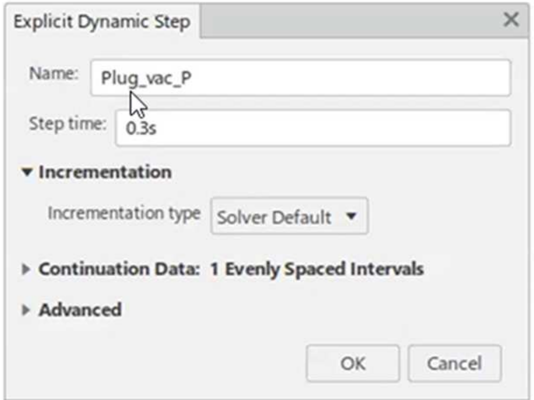
Tip 05

Stick with solver default for incrementation

- For most analysis the default automatic global estimation method is appropriate.
  - Occasionally, experienced users may choose an alternative time incrementation method.
    - For example, to use a more conservative stable time increment.



Tip 06

Adjust time scale for quasi-static simulations

- Artificially increase the speed of the process in the simulation
  - Increase the load rate for simulation (reducing the time scale of the process)

For quasi-static you don't have to match the actual time duration of the event

- Modify (reduce) the step time or increase velocity of load
  - Fewer increments needed to complete the job
- Don't overdo it, or you will lose your static response as the simulation becomes dynamic

  - As the speed of the process is increased, a state of static equilibrium evolves into a state of dynamic equilibrium.
    - Inertia forces become more dominant.
  - *The goal is to model the process in the shortest time period (or with the most mass scaling) in which inertia forces are still insignificant.*

Tip 07

Check Energies for quasi-static simulation

- Energy balances

  - An energy balance equation can be used to help evaluate whether an Abaqus/Explicit simulation is yielding an appropriate response.

  - In Abaqus/Explicit the energy balance equation is written as

$$E_I + E_{VD} + E_{FD} + E_{KE} - E_W = E_{TOT} = constant$$

where:

	Description	Output variable
E_I	internal energy (elastic, inelastic, "artificial" strain energy),	ALLIE
E_{VD}	energy absorbed by viscous dissipation	ALLVD
E_{FD}	frictional dissipation energy	ALLFD
E_{KE}	kinetic energy	ALLKE
E_{AE}	artificial strain energy due to hourglass	ALLAE
E_W	work of external forces (including constraint penalties and propelling mass added by mass scaling),	ALLWK
E_{TOT}	total energy in the system	ETOTAL

  - These energies can be requested for the entire model or for subsets of the model.

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Tip 07

Check Energies for quasi-static simulation

- Indicators of problems when reviewing the energy balance are:
  - Excessive "artificial" strain energy (ALLAE) that is used to suppress hourglass modes.
    - It should be less than 1–2% of internal energy (ALLIE) for all but the enhanced hourglass control method.
  - Excessive kinetic energy (ALLKE) in a quasi-static simulation.
    - Th kinetic energy (ALLKE) should be a small fraction (typically 5–10%) of work (ALLWK) or internal energy (ALLIE).
    - Remember that rigid bodies with mass contribute to the total kinetic energy in the model and thus should not be considered in the above assessment.
    - It is generally not possible to achieve this in early stages of the analysis since the deformable body will be moving before it develops any significant deformation.

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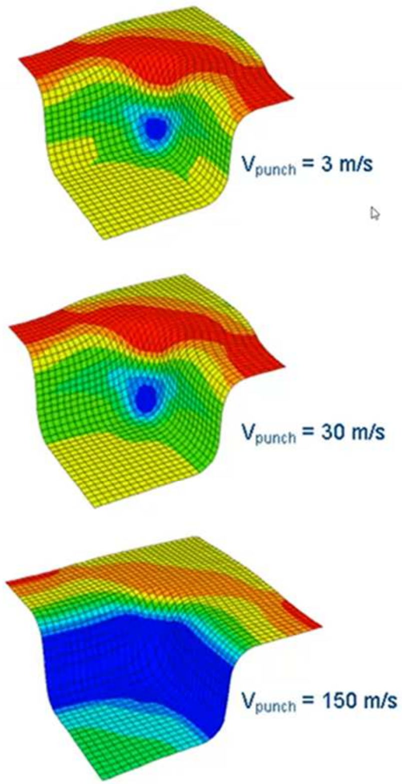
Tip 07

Check Energies for quasi-static simulations

- We examine three different punch speeds:
  - 3 m/s
  - 30 m/s
  - 150 m/s
- Contours of blank thickness in final formed configuration
  - Excessive punch speeds lead to results that do not correspond to the physics. At 150 m/s unrealistic thinning of the blank is predicted.
  - Results obtained at 30 m/s and 3 m/s are very similar, even though the difference in computation cost is a factor of 10.

Punch speed (m/s)	Time increments	Normalized CPU time
3 (1×)	27929	1.0
30 (10×)	2704	0.097
150 (50×)	529	0.019



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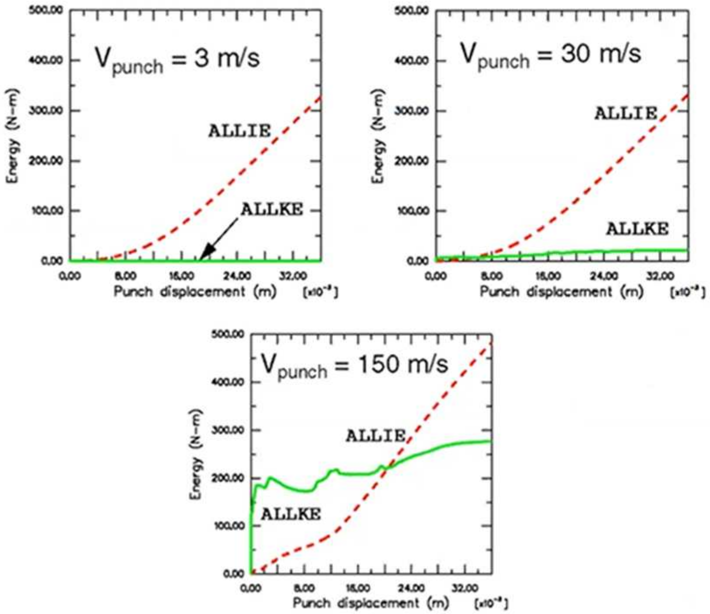
Tip 07

Check Energies for quasi-static simulations

- Comparison of internal and kinetic energies
  - At a punch speed of 150 m/s the kinetic energy of the blank is a significant fraction of its internal energy.
  - At punch speeds of 3 m/s and 30 m/s the kinetic energy is only a small fraction of the internal energy over the majority of the forming process history.



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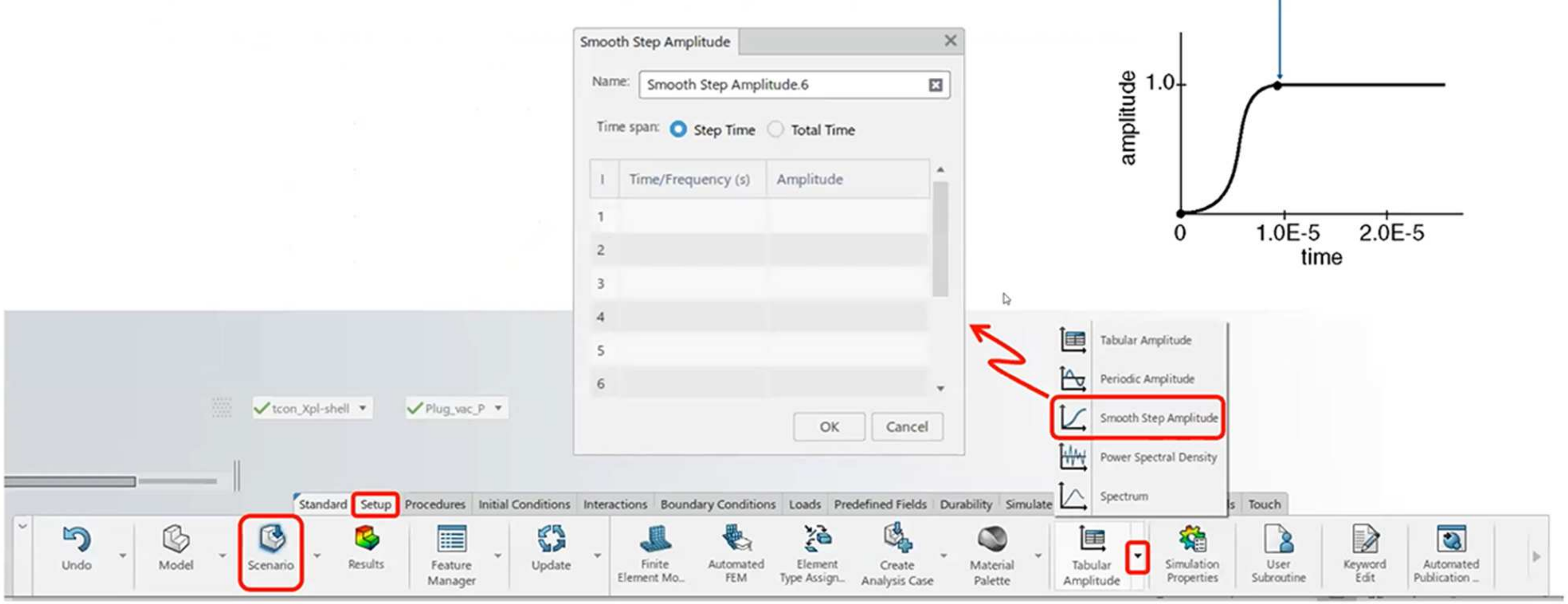
Tip 08

Use Smooth Step amplitude curve for loading

- Instantaneous loading may induce the propagation of a stress wave through the model, producing undesired results

A fifth-order polynomial transition is created: the first and second time derivatives are zero at the beginning and the end of the transition



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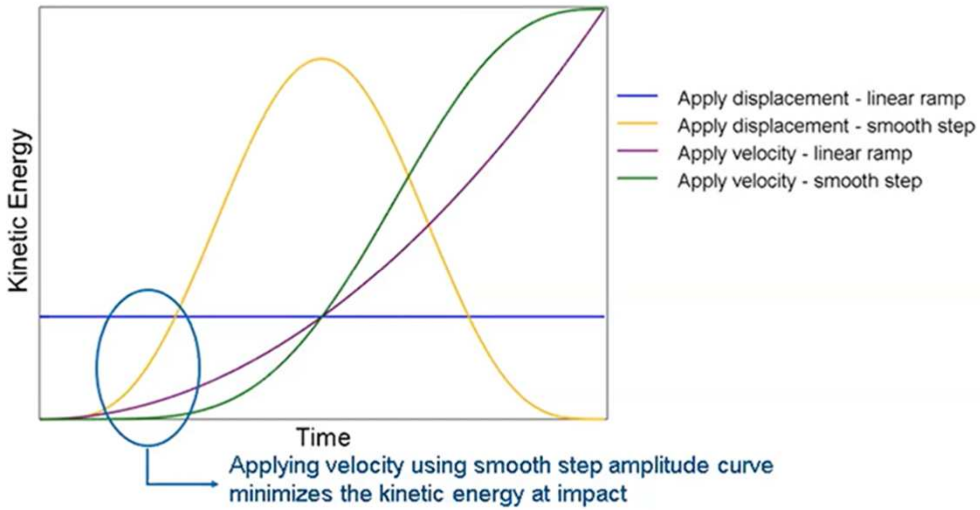
Tip 09

Consider using Velocity instead of Displacement

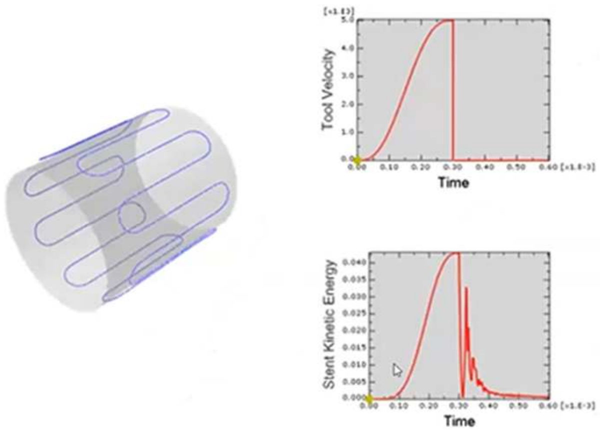
- High energy impact between the stent and the tools could increase the dynamic effect
  - By gradually increasing the velocity of the tools, the impact at the beginning of the step is minimized



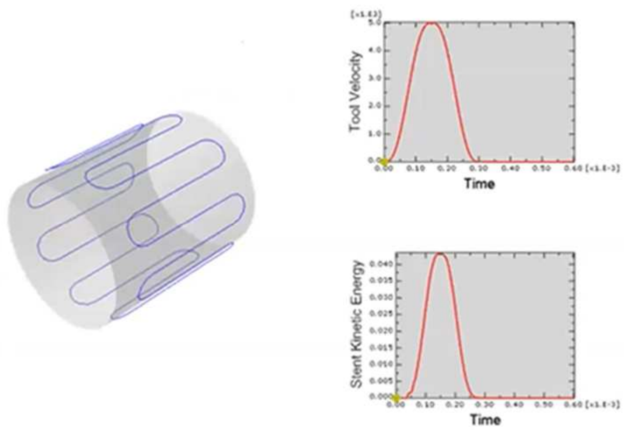
Tip 09

Consider using Velocity instead of Displacement

- Ramp tool velocity to zero at the end of the step
  - Ramping the tool velocity to zero brings the stent close to a state of static equilibrium
  - Otherwise, the stent will vibrate after the tool suddenly stops



Without ramping down the velocity



With ramping down the velocity

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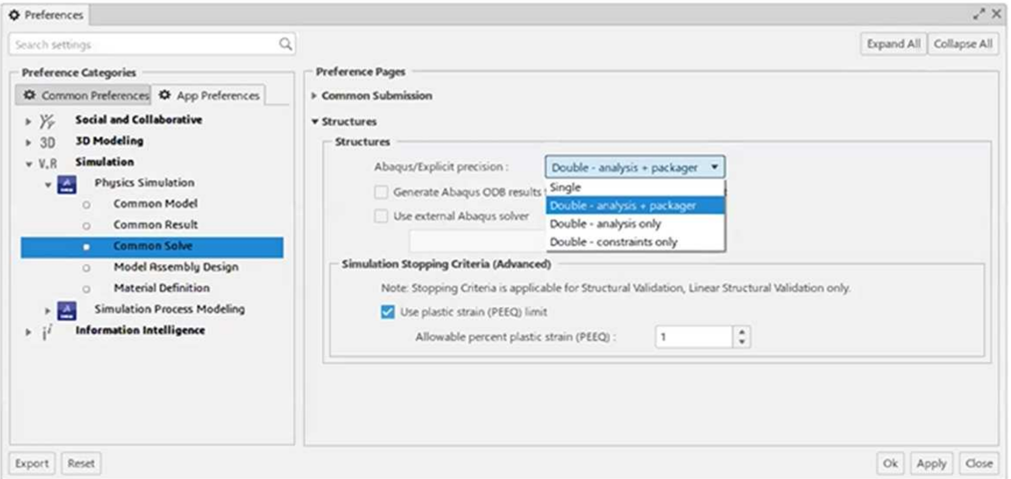
Tip 10

About Parallelization and Double Precision

- Explicit parallelizes very well with additional compute cores, especially for larger models
  - RAM is not nearly as big of a factor for Explicit as it is for the Implicit solver
- Double precision may be important
  - Larger models, more increments, rotating components etc.
  - User needs to be mindful when not using this
  - Single precision will run faster



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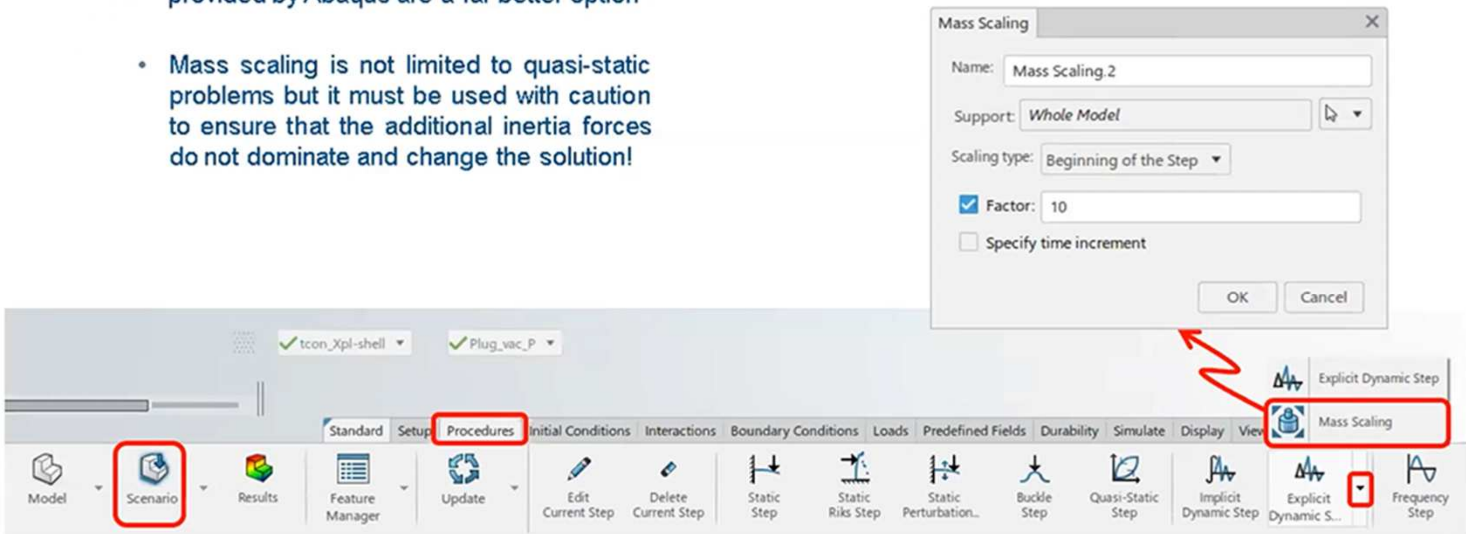
Tip 11

Use Mass Scaling when appropriate

$$\Delta t_{critical} \approx \frac{L_{min}}{\sqrt{E/\rho}} = \frac{L_{min}\sqrt{\rho}}{\sqrt{E}}$$

- Mass scaling can be accomplished by increasing the material density; however, the *variable mass scaling* capabilities provided by Abaqus are a far better option
- Mass scaling is not limited to quasi-static problems but it must be used with caution to ensure that the additional inertia forces do not dominate and change the solution!



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Tip 11

Use Mass Scaling when appropriate

- Mass scaling
  - If strain rate sensitivity is being modeled, erroneous solutions can result if the load rates are increased.
  - Mass scaling allows you to model processes in their natural time scale when considering rate-sensitive materials.

    Artificially increasing the material density by a factor of f^2 increases the stable time increment by a factor of f.

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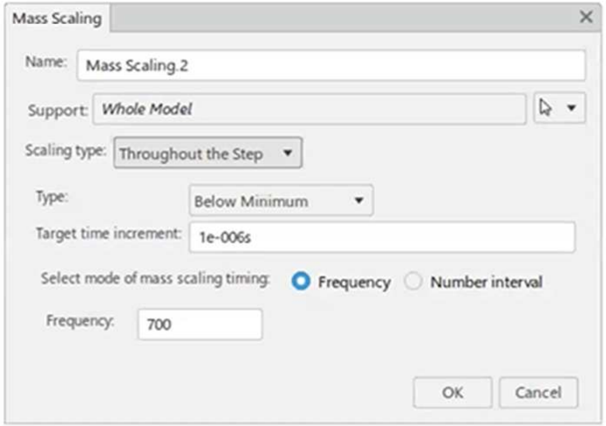
Tip 11

Use Mass Scaling when appropriate

- Variable mass scaling
  - There are situations in which it is desirable to mass scale elements periodically during a step in quasi-static analyses.
    - This might be the case if some elements experience such large deformation that their stable time increment is drastically reduced.
  - The variable mass scaling option provides this capability.
    - Mass scaling calculations are performed periodically during the step.
      You specify how frequently the mass matrices are updated.
  - Typically, variable mass scaling is defined by specifying a target stable time increment.
    - As with fixed mass scaling you can choose to scale all the elements (uniformly or nonuniformly) or only the elements below the target.



Tip 11

Use Mass Scaling when appropriate

Simulation Status

Solving Structural Analysis Case.1 ... 54%

Messages | Licensing Messages | Plots | Iterations | Diagnostic files

Step	Inc	Tot Time (s)	Wall Time (s)	Step Time (s)	Stable Inc (s)	Kin Engy (J)	Tot Engy (J)	Total Mass Change (%)
Explicit ...ic Step.1	0	0	1	0	7e-007	11.55	11.55	9.167
Explicit ...ic Step.1	358	2.506e-004	6	2.506e-004	7e-007	0.015	11.546	9.167
Explicit ...ic Step.1	715	5.005e-004	11	5.005e-004	7e-007	0.111	11.544	9.167
Explicit ...ic Step.1	1072	7.504e-004	16	7.504e-004	7e-007	0.494	11.543	9.167
Explicit ...ic Step.1	1429	0.001	21	0.001	7e-007	1.362	11.543	9.167
Explicit ...ic Step.1	1803	0.001	27	0.001	6.667e-007	3.164	11.544	9.167
Explicit ...ic Step.1	2177	0.002	32	0.002	6.668e-007	5.896	11.546	9.169
Explicit ...ic Step.1	2552	0.002	39	0.002	6.669e-007	10.051	11.555	9.173
Explicit ...ic Step.1	2927	0.002	44	0.002	6.669e-007	15.037	11.568	9.173
Explicit ...ic Step.1	3303	0.002	50	0.002	6.594e-007	20.96	11.577	9.175
Explicit ...ic Step.1	3682	0.003	57	0.003	6.623e-007	28.002	11.584	9.176
Explicit ...ic Step.1	4059	0.003	63	0.003	6.626e-007	35.704	11.613	9.177
Explicit ...ic Step.1	4436	0.003	69	0.003	6.63e-007	44.039	11.655	9.177
Explicit ...ic Step.1	4814	0.003	76	0.003	6.623e-007	52.847	11.681	9.177
Explicit ...ic Step.1	5199	0.004	82	0.004	6.604e-007	61.509	11.704	9.182
Explicit ...ic Step.1	5586	0.004	89	0.004	6.44e-007	70.293	11.71	9.191
Explicit ...ic Step.1	6016	0.004	97	0.004	6.219e-007	77.127	11.713	9.204
Explicit ...ic Step.1	6468	0.004	105	0.004	5.296e-007	83.433	11.717	9.204

Close | Stop

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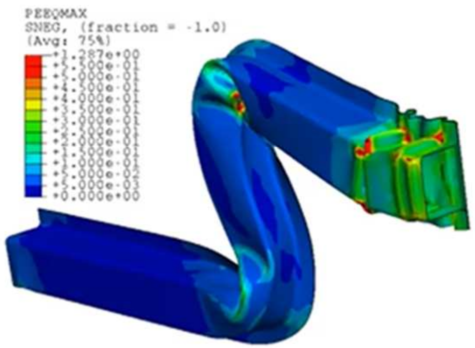
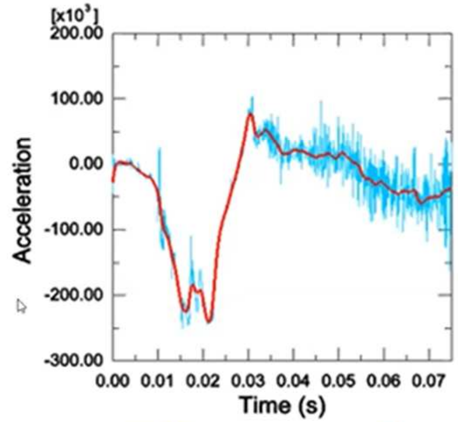
About output

- Output to the output database file
  - Two types of output data: *field* and *history* data.
    - Field data are used for model (deformed, contour, etc.) and *X–Y* plots.
      ***OUTPUT, FIELD**
    - History data are used for *X–Y* plots.
      ***OUTPUT, HISTORY**



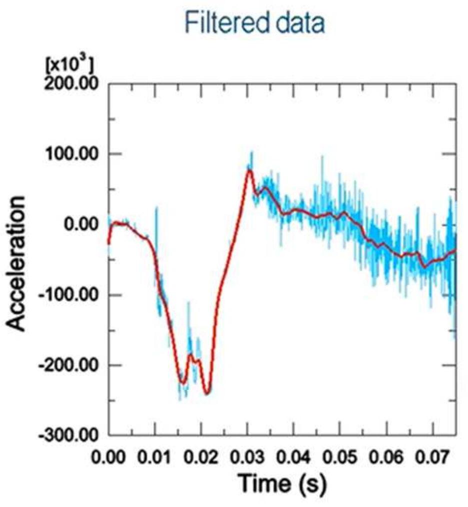
Contour plot generated from
field output

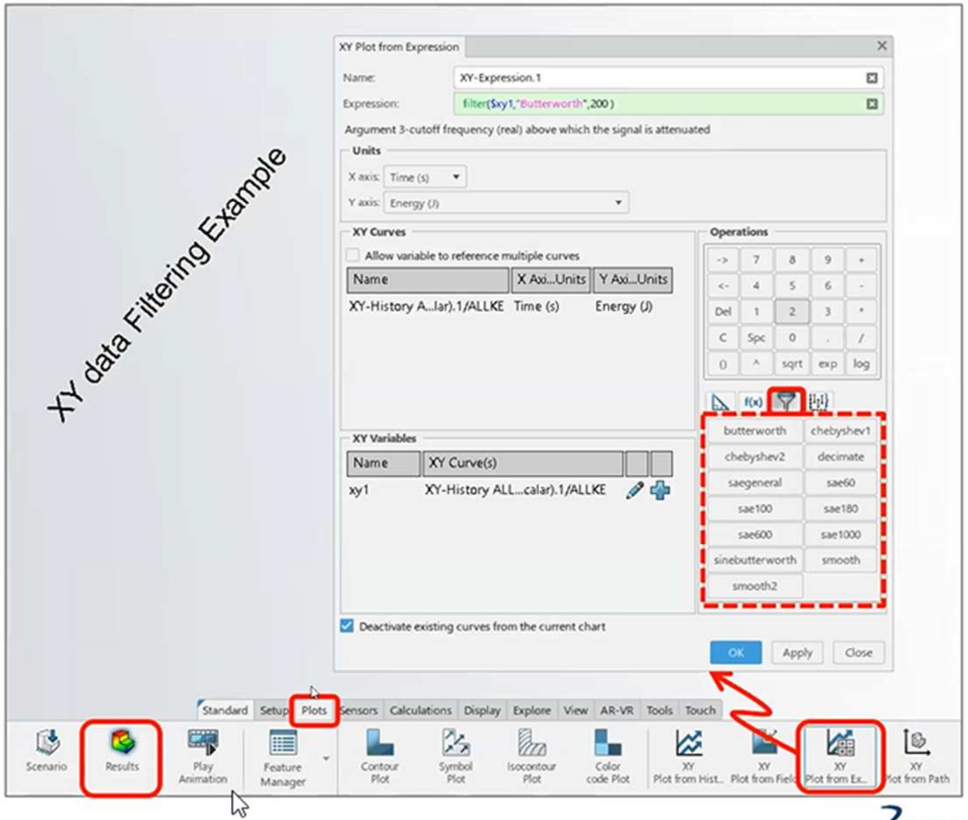


X–Y plot generated from

Tip 12

About output





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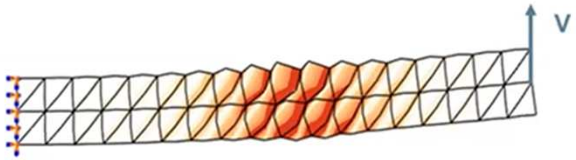
Tip 13

Troubleshooting

- **Excessive wave speed**
  - This error indicates that something in the model has caused an element (or elements) to deform dramatically in a single increment.
  - Most likely associated with some event that occurred shortly before the first warning message appears.
  - Potential causes include: *contact*, *unstable time increment* (user scaling of the time increment, direct user control, etc.), *mesh distortion*, and *hourglassing*



***WARNING: In element 21 of instance BEAM-1 the ratio of deformation speed to wave speed is 0.30353 at increment 32444.

***ERROR: The ratio of deformation speed to wave speed exceeds 1.0000 in at least one element. This usually indicates an error with the model definition.

- Warped surface warnings indicate that the contact surfaces are so distorted that contact tracking may fail

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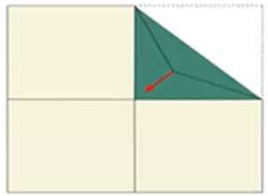
Tip 13

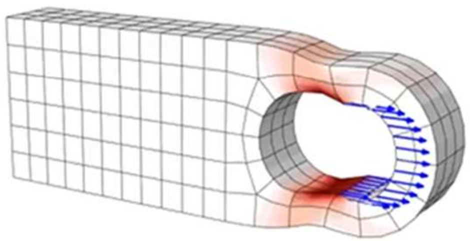
Troubleshooting

- **Element distortion**
  - These messages are issued when the volume at an integration point of an element becomes negative
  - Often associated with incorrect material properties, loads, and/or boundary conditions. May require additional mesh refinement



***WARNING: EXCESSIVE DISTORTION AT A TOTAL OF 1 INTEGRATION POINTS IN SOLID (CONTINUUM) ELEMENTS

- **Excessive yielding**
  - Relatively large deformations in a problem in which the material model has some form of plasticity
  - Usually related to:
    - *Loading*: is the magnitude of loading realistic?
    - *Material data*: perfectly plastic at too low a strain?
    - *Mesh refinement*: meshes that are adequate for linear elasticity may not be adequate for large-strain plasticity problems



***WARNING: THE STRAIN INCREMENT HAS EXCEEDED FIFTY TIMES THE STRAIN TO CAUSE FIRST YIELD AT 48 POINTS

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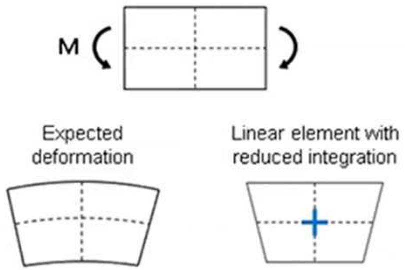
Tip 13

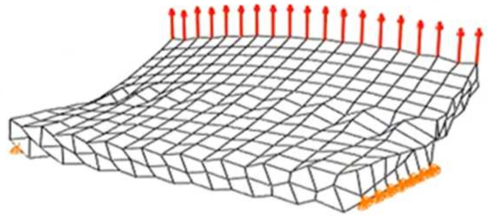
Troubleshooting

Hourglassing

- Is a mesh instability that affects *first-order reduced-integration* continuum elements and reduced-integration shell elements.
- Because of the numerical discretization of the problem, certain deformations of these elements cause no strain energy.
- It behaves in a manner that is similar to that of a rigid body mode.
  Unless these nonphysical deformations are controlled, they will dominate the solution
- Alternatives to address hourglassing:
  - Refine the mesh
  - Change the element type
  - Use non-default hourglass controls



The edges of a linear element are unable to curve (formulation restriction). No changes in length or angle at the integration point. All components of stress are zero!



Simply supported plate showing clear signs of hourglassing

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