Lecture 5

Quasi-Static Analyses

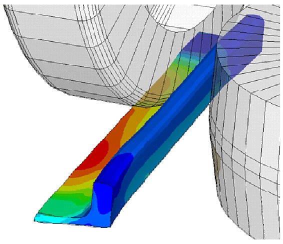
Overview

- Introduction
- Quasi-Static Simulations Using Explicit Dynamics
- Loading Rates
- Energy Balance in Quasi-Static Analyses
- Mass Scaling
- Viscous Pressure
- Summary

Introduction

Introduction

- **Challenging nonlinear quasi-static problems often involve:**
  - Very complex contact conditions
  - Very large deformations
    - Mesh distortion possible
- **Applications:**
  - Metal forming simulations:
    - Bulk forming (drawing, rolling, extrusion, upsetting, etc.)
    - Sheet metal forming (stretching, drawing)

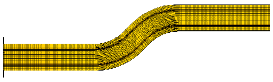


Rolling of a symmetric I-section

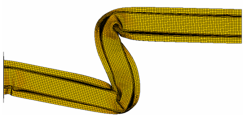
Video Clip

Introduction

- **Applications (cont'd):**
  - Quasi-static collapse analyses
    - Example: Collapse of a curved beam:

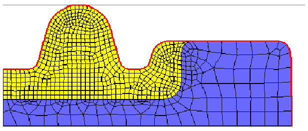


undeformed shape

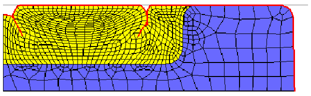


final deformed shape

  - Quasi-static loading of flexible rubber components (seals, bushings, etc.)
    - Example: Compression of a rubber gasket



undeformed shape



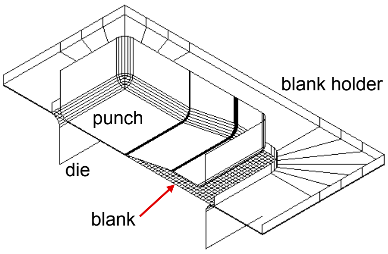
final deformed shape

Introduction

- **ABAQUS offers two solvers:**
  - Implicit solver (ABAQUS/Standard)
    - Solves for true static equilibrium.
  - Explicit solver (ABAQUS/Explicit)
    - Solves for true dynamic equilibrium.
- **At first glance it appears the implicit solver would be the appropriate choice for modeling highly nonlinear static problems.**
  - However, explicit solvers are more efficient for this class of problems.
  - This is especially true for three-dimensional problems involving contact and very large deformations.

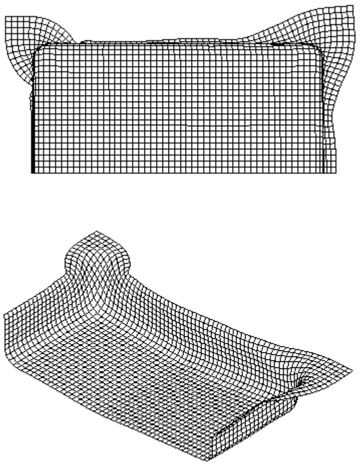
Introduction

- **Example: Simulation of a deep drawing process used to form an oil pan**
  - The pan is formed by displacing the punch downward while holding the die and blank holder fixed.
  - The blank is modeled with shell elements; the tools are assumed rigid.
  - Analysis performed with both implicit (ABAQUS/Standard) and explicit (ABAQUS/Explicit) solvers.



Introduction

- The final deformed configuration is shown at right.
  - Near the end of the punch stroke, the blank pulls through the blank holder and begins to wrinkle.
- The ABAQUS/Standard job was about 20 times more expensive than the ABAQUS/Explicit job (CPU cost).
- ABAQUS/Standard fails to converge at the point where the blank begins to wrinkle.



ABAQUS

Quasi-Static Simulations Using Explicit Dynamics

Quasi-Static Simulations Using Explicit Dynamics

- **Introduction**
  - The explicit dynamics procedure is a true dynamic procedure.
    - It was originally developed to model high-speed impact events.
    - Explicit dynamics solves for the state of dynamic equilibrium where inertia can play a dominant role in the solution.
  - Application of explicit dynamics to model quasi-static events requires special consideration:
    - It is computationally impractical to model the process in its natural time period.
      - Literally millions of time increments would be required.
    - Artificially increasing the speed of the process in the simulation is necessary to obtain an economical solution.

ABAQUS

Quasi-Static Simulations Using Explicit Dynamics

- **Two approaches to obtaining economical quasi-static solutions with an explicit dynamics solver**
  - Increased load rates
    - Artificially reduce the time scale of the process by increasing the loading rate.
    - Material strain rates calculated in the simulation are artificially high by the same factor applied to increase the loading rate.
      - This is irrelevant if the material is rate insensitive.
  - Mass scaling
    - 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.

Quasi-Static Simulations Using Explicit Dynamics

- **How much can I increase the load rate or scale the mass?**
  - Increased load rates and mass scaling achieve the same effect:
    - Increased load rates reduce the time scale of the simulation.
      - Fewer increments are needed to complete the job.
    - Mass scaling increases the size of the stable time increment.
      - Fewer increments are needed to complete the job.
  - 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.**

ABAQUS

Loading Rates

Loading Rates

- **The dominant response of a quasi-static analysis will be the first structural mode.**
- **The frequency of this mode is used to estimate the impact velocity.**
  - Estimate the first natural frequency of the model.
  - Calculate the corresponding time period (T) using the first natural frequency of the model.
  - Estimate the global deflection (D) in the impact direction of the model
  - Calculate the impact velocity (V) by using the formula $V=D/T$
  - A **general recommendation** is to limit the impact velocity to less than 1% of the wave speed of the material
    - Typical wave speed in metals is 5000 m/sec.

ABAQUS

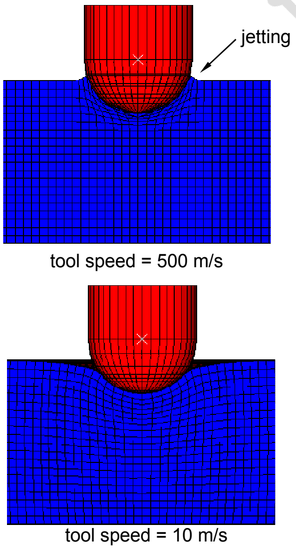
Loading Rates

- **Suggested approach**
  - **Run a series of simulations** in the order from the fastest load rate to the slowest, since the analysis time is greater for slower load rates.
  - Examine the results (deformed shapes, stresses, strains, energies) to get an understanding for the effects of varying the model.
    - For example, excessive tool speeds in explicit sheet metal forming simulations tend to suppress wrinkling and to promote unrealistic localized stretching.
    - Excessive tool speeds in explicit bulk forming simulations cause “jetting”—hydrodynamic-type response.
    - Excessive loading rates in a quasi-static collapse analysis can result in
      - a steep initial slope of the load versus displacement curve
        - inertial effects cause increased (non-structural) resistance to initial deformation
      - localized buckling near the applied load

Loading Rates

- **Jetting**
  - Consider the following bulk forming process (180° section of an axisymmetric model).
  - When the tool speed is too large, highly localized deformation develops (jetting).

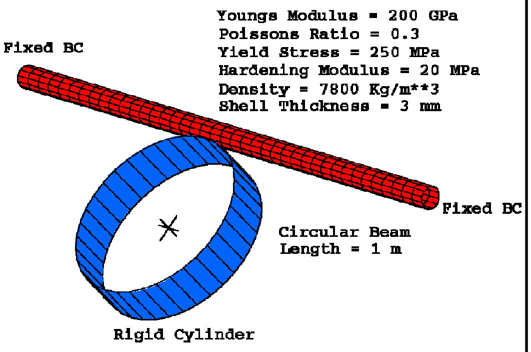
Video Clip



Effect of tool speed on deformed shape

Loading Rates

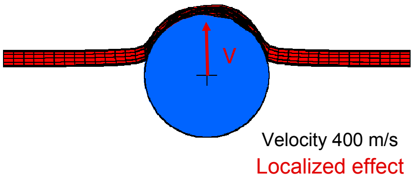
- **Example: Door beam intrusion test**
  - A simple model of a standard door beam intrusion test for an automobile door is shown.
    - The circular beam is fixed at each end, and the beam is deformed by a rigid cylinder.
    - The actual test is quasi-static.



Rigid cylinder impacting a deformable beam

Loading Rates

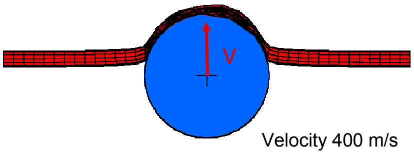
- **Example (cont’d) : Door beam intrusion test**
  - An initial analysis is run with an extremely high impact velocity, 400 m/sec.
  - The final deformed shape indicates a dynamic event rather than a static one:
    - There is highly localized deformation
    - No structural response by the beam



Final deformed shape

Loading Rates

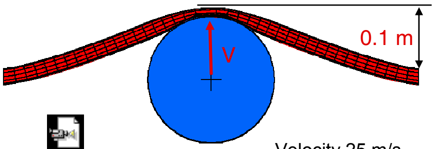
- **Example (cont'd) : Door beam intrusion test**
  - The dominant response in a static test will be in the first structural mode of the beam.
  - The frequency of this mode is used to estimate the impact velocity.
    - The frequency of the first mode is approximately 250 Hz.
    - This rate corresponds to a period of 4 milliseconds.
    - Using a velocity of 25 m/sec, the cylinder will be pushed into the beam 0.1 m in 4 milliseconds.



Velocity 400 m/s

Localized effect

Final deformed shapes



Video Clip

Velocity 25 m/s

Good global result

Loading Rates

- **Why is the velocity 25 m/sec appropriate?**
  - The frequency (f) of the first mode is approximately 250 Hz.
  - This corresponds to a period t=0.004 seconds.
  - During this period, the rigid cylinder is pushed into the beam d=0.1 m.
    - Thus, the velocity v is estimated to be $v = d / t = 0.1/0.004$=25 m/sec.
  - Recall, the wave speed of metals is about 5000 m/sec, so the impact velocity 25 m/sec is about 0.5% of the wave speed.
    - The impact velocity should be limited to less than 1% of the wave speed of the material.
  - A more accurate solution could be obtained by ramping up the velocity **smoothly** from zero over the analysis step.

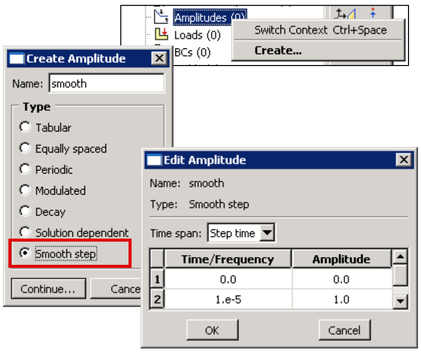
Loading Rates

- **Use the SMOOTH STEP amplitude curve**
  - A quasi-static solution is also promoted by applying loads gradually:
    - Instantaneous loading may induce the propagation of a stress wave through the model, producing undesired results.
      - By default, ABAQUS/Explicit loads applied immediately and remain constant throughout the step.
      - Constant velocity boundary conditions also result in a sudden impact load onto a deformable body.
    - Ramping up the loading gradually from zero minimizes these adverse effects.
    - Ramping down the loading to zero is also recommended for the same reasons.

Loading Rates

–Syntax example (single step):

```
*AMPLITUDE, NAME=SMOOTH, DEFINITION=SMOOTH STEP
0.0, 0.0, 1.e-5, 1.0
*BOUNDARY, TYPE=DISPLACEMENT, AMP=SMOOTH
12, 2, 2, 2.5
```



Create Amplitude

Name: smooth

Type: ● Smooth step

Edit Amplitude

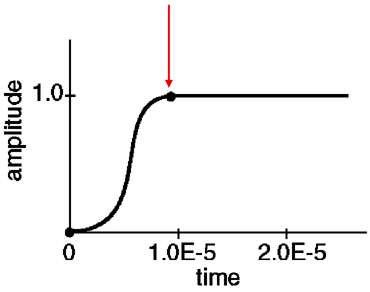
Name: smooth

Type: Smooth step

Time span: Step time

	Time/Frequency	Amplitude
1	0.0	0.0
2	1.e-5	1.0

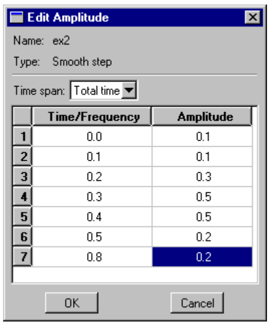
A fifth-order polynomial transition between two amplitude values is created such that the first and second time derivatives are zero at the beginning and the end of the transition.



Loading Rates

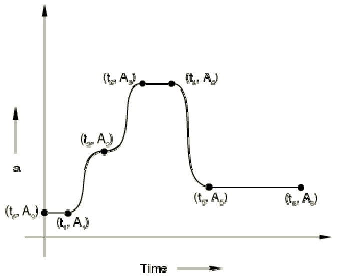
– Syntax example (multiple steps):

```
*AMPLITUDE, NAME=ex2,
DEFINITION=SMOOTH STEP, TIME=TOTAL TIME
0.0, 0.1, 0.1, 0.1, 0.2, 0.3, 0.3, 0.5
0.4, 0.5, 0.5, 0.2, 0.8, 0.2
```



Name: ex2
Type: Smooth step
Time span: Total time

	Time/Frequency	Amplitude
1	0.0	0.1
2	0.1	0.1
3	0.2	0.3
4	0.3	0.5
5	0.4	0.5
6	0.5	0.2
7	0.8	0.2



$t_0 = 0.0$ $A_0 = 0.1$ $t_1 = 0.1$ $A_1 = 0.1$ $t_2 = 0.2$ $A_2 = 0.3$ $t_3 = 0.3$ $A_3 = 0.5$

$t_4 = 0.4$ $A_4 = 0.5$ $t_5 = 0.5$ $A_5 = 0.2$ $t_6 = 0.8$ $A_6 = 0.2$

$$a = A_0 \quad \text{for} \quad t \le t_0$$

$$= A_6 \quad \text{for} \quad t \ge t_6$$

Amplitude, a, between any two consecutive data points (t_i, A_i) and (t_{i+1}, A_{i+1}) is

$$a = A_i + (A_{i+1} - A_i)\,\xi^3 (10 - 15\xi + 6\xi^2)$$

$$\text{where } \xi = \frac{t - t_i}{t_{i+1} - t_i}$$

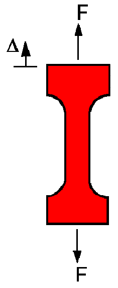
Energy Balance in Quasi-Static Analyses

Energy Balance in Quasi-Static Analyses

- **An energy balance equation can be used to help evaluate whether a simulation is yielding an appropriate quasi-static response.**

Consider a pull test applied to a uniaxial tensile specimen.

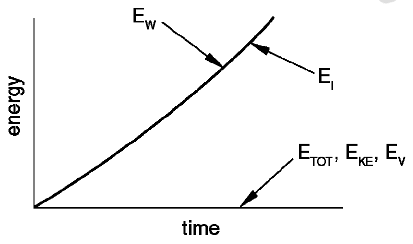
If the physical test is quasi-static, the work applied by the external forces in stretching the specimen equals the internal energy in the specimen.



Uniaxial pull test

Energy Balance in Quasi-Static Analyses

- The energy history for the quasi-static test would appear as shown in the figure at right:
  - Inertia forces are negligible.
  - The velocity of material in the test specimen is very small.
  - Kinetic energy is negligible.
- As the speed of the test increases:
  - The response of the specimen becomes less static, more dynamic.
  - Material velocities and, therefore, kinetic energy become more significant.



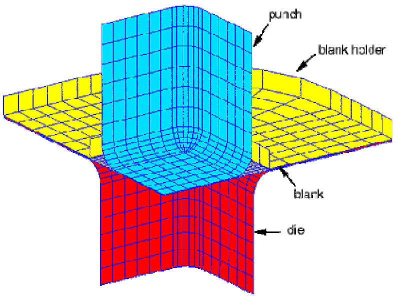
Energy history for quasi-static pull test

Energy Balance in Quasi-Static Analyses

- Hence, examination of the energy content provides another measure to evaluate whether the results from an ABAQUS/Explicit simulation reflect a quasi-static solution.
- The kinetic energy of the **deforming** material should not exceed a small fraction of its internal energy throughout the majority of a quasi-static analysis.
  - A small fraction typically means 1–5%.
    - 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.
    - Use smooth step amplitude curves to improve early response.
  - Not interested in kinetic energy of rigid bodies.
    - Subtract their contribution from global model kinetic energy or restrict energy output to deforming components.

Energy Balance in Quasi-Static Analyses

- **Example: Deep drawing of a square box**
  - The quarter-symmetric finite element model is shown in the figure.
  - Friction is modeled along all contact interfaces:
    - Punch and blank: $\mu = 0.25$.
    - Die and blank: $\mu = 0.125$.
    - Blank holder and blank: $\mu = 0$.
  - The deep drawing simulation is conducted by applying a downward force of 22.87 kN to the blank holder, then displacing the punch downward 36 mm.



Initial configuration for square box deep drawing

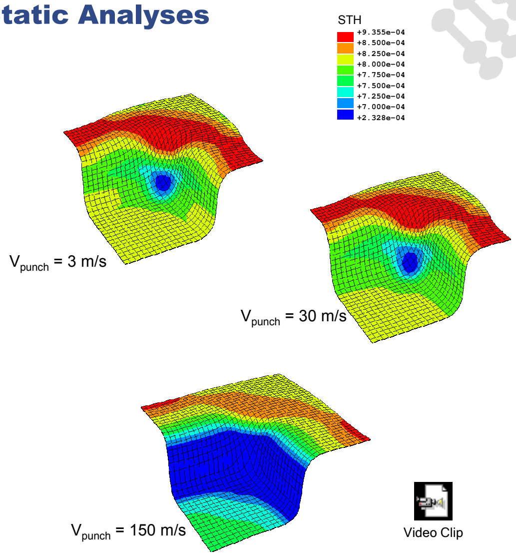
Energy Balance in Quasi-Static Analyses

- We examine three different punch speeds:
  - 3 m/s
  - 30 m/s
  - 150 m/s
- The computation cost of each deep drawing simulation is summarized in the following table:

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

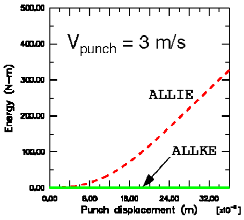
Energy Balance in Quasi-Static Analyses

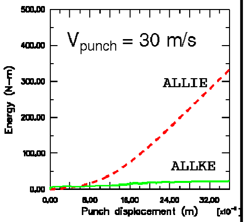
- Contours of blank thickness in final formed configuration
- Excessive punch speeds lead to results that do not correspond to the physics.
  - At 150 m/s unrealistic thinning of the blank is predicted.
- Results obtained at 30 m/s and 3 m/s are very similar, even though the difference in computation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

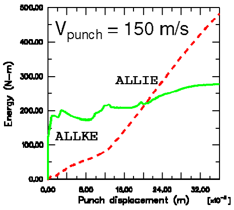


Energy Balance in Quasi-Static Analyses

– 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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Mass Scaling

Mass Scaling

- **Introduction**
  - When the loading rates is increased to efficiently model a quasi-static problem, the material strain rates calculated in the simulation are artificially high by the same factor applied to increase the loading rate.
    - This is irrelevant if the material is rate insensitive.
    - If strain rate sensitivity is being modeled, erroneous solutions can result.
  - It is generally desirable to analyze a model in its natural time period if rate dependency is being considered.
  - This can be accomplished through mass scaling.

Mass Scaling

- As shown in Lecture 1, an estimate of the stability limit in the explicit dynamics procedure can be expressed as

$$\Delta t = \left(\frac{L^e}{c_d} \right),$$

where L^e is the smallest characteristic element length and c_d is the dilatational wave speed of the material.

- The dilatational wave speed in a linear elastic material (with Poisson’s ratio equal to zero) is

$$c_d = \sqrt{\frac{E}{\rho}},$$

where E is the elastic modulus and ρ is the material density.

- If we artificially increase the material density by a factor of f^2:
  - The wave speed decreases by a factor of f.
  - The stable time increment increases by a factor of f.

Mass Scaling

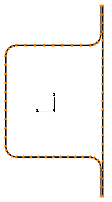
  - By artificially increasing the stable time increment through mass scaling, we can analyze the model in its natural time period.
  - Mass scaling has the same influence on inertia effects as artificially increasing the loading rates.
    - Therefore, excessive mass scaling can lead to erroneous solutions.
- **Fixed mass scaling**
  - Mass scaling for quasi-static analyses is usually performed on the entire model once at the beginning of the step.
  - One way to define fixed mass scaling is through the specification of a mass scaling factor.
    - Specify f^2 such that the density of every element in the model is increased by f^2.
      - The element stable time increment, thus, increases by f.

Mass Scaling

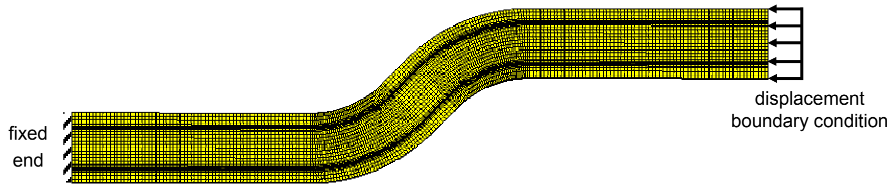
- **Items affected by mass scaling**
  - Mass, rotary inertia, rigid, and infinite elements
  - Rotary inertia in beams and shells
  - Bulk viscosity and mass proportional damping
- **Items not affected by mass scaling**
  - Gravity loads
  - Adiabatic heat calculations
  - Thermal solution response in a fully coupled thermal-stress analysis
  - Equation of state materials
  - Fluid and fluid link properties
  - Spring and dashpot elements

Mass Scaling

- **Example: Quasi-static collapse of a curved beam.**
  - A curved beam is compressed to 70% of it’s original length.
  - Shell elements (S4R) with the constitutive behavior of a mild steel are used to model beam.



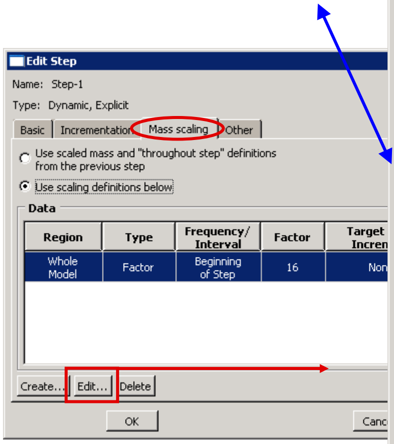
beam cross-section



45° curved beam

Mass Scaling

```
*FIXED MASS SCALING, FACTOR=16
```



Edit Step

Name: Step-1

Type: Dynamic, Explicit

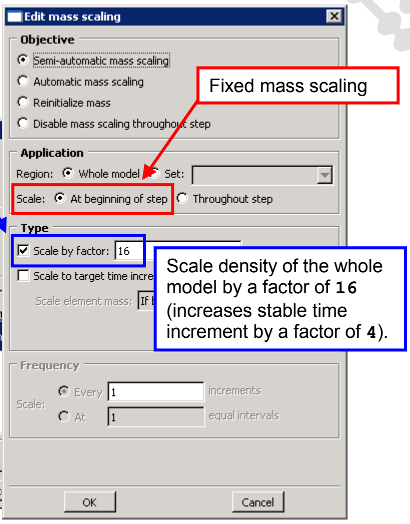
○ Use scaled mass and "throughout step" definitions from the previous step

● Use scaling definitions below

Data

Region	Type	Frequency/ Interval	Factor	Target Incren
Whole Model	Factor	Beginning of Step	16	Non

Edit Step dialog box



Edit mass scaling

Objective

● Semi-automatic mass scaling

○ Automatic mass scaling

○ Reinitialize mass

○ Disable mass scaling throughout step

Fixed mass scaling

Application

Region: ● Whole model ○ Set:

Scale: ● At beginning of step ○ Throughout step

Type

☑ Scale by factor: 16

☐ Scale to target time incre

Scale element mass: If

Scale density of the whole model by a factor of `16` (increases stable time increment by a factor of `4`).

Frequency

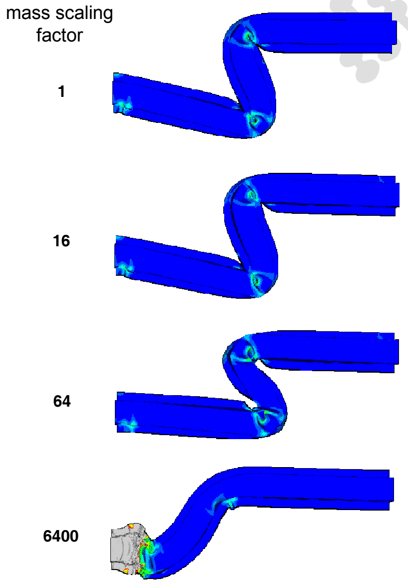
Scale: ● Every 1 increments

○ At 1 equal intervals

Edit Mass Scaling dialog box

Mass Scaling

- **This figure shows the results of four different analyses (contours of PEEQ).**
  - The top two results are almost identical.
    - The solution for the results in the second plot requires one-fourth the computer time of the first solution.
  - The last two solutions are essentially meaningless compared to the original static solution.



Video Clip

Mass Scaling

- **Results**
  - ABAQUS results exhibit very good correlation with experimental study

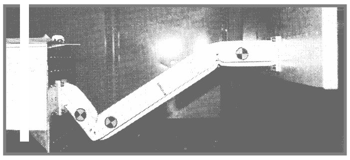
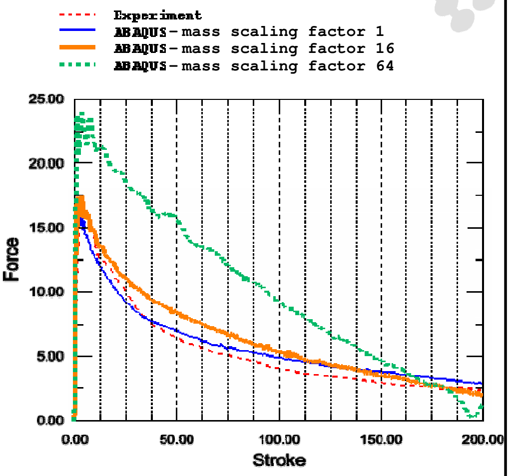


Photo of 15° curved beam static test

Courtesy: Honda R&D



45° static test results

Mass Scaling

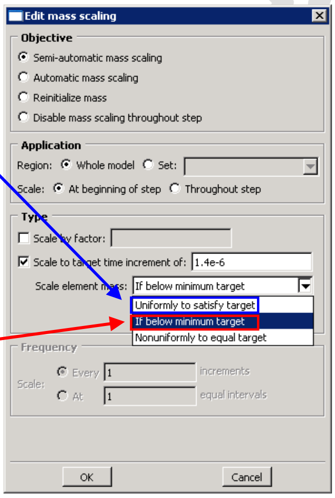
- **There are three alternatives to specifying the scaling factor directly:**

① `*FIXED MASS SCALING, TYPE=UNIFORM, DT=dt`

- Scales all elements by a single factor so that the minimum stable time increment of the specified elements becomes equal to *dt*.
- Similar to the FACTOR parameter.
- Applicable to quasi-static analyses.

② `*FIXED MASS SCALING, TYPE=BELOW MIN, DT=dt`

- Scales only elements whose stable time increment is below the value assigned to DT so that their stable time increment equals *dt*.
- Applicable to quasi-static and dynamic analyses.



Edit mass scaling

Objective
● Semi-automatic mass scaling
○ Automatic mass scaling
○ Reinitialize mass
○ Disable mass scaling throughout step

Application
Region: ● Whole model ○ Set:
Scale: ● At beginning of step ○ Throughout step

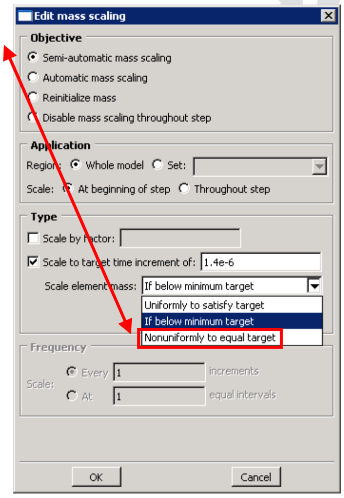
Type
☐ Scale by factor:
☑ Scale to target time increment of: 1.4e-6
Scale element mass: If below minimum target
Uniformly to satisfy target
If below minimum target
Nonuniformly to equal target

Frequency
Scale: ● Every 1 increments
○ At 1 equal intervals

Mass Scaling

③ `*FIXED MASS SCALING, TYPE=SET EQUAL DT, DT=dt`

- Scales all specified elements to have the same stable time increment equal to *dt*.
- Applicable to quasi-static analyses.



Edit mass scaling

Objective
● Semi-automatic mass scaling
○ Automatic mass scaling
○ Reinitialize mass
○ Disable mass scaling throughout step

Application
Region: ● Whole model ○ Set:
Scale: ● At beginning of step ○ Throughout step

Type
☐ Scale by factor:
☑ Scale to target time increment of: 1.4e-6
Scale element mass: If below minimum target
Uniformly to satisfy target
If below minimum target
Nonuniformly to equal target

Frequency
Scale: ● Every 1 increments
○ At 1 equal intervals

Mass Scaling

- **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 deformations 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.

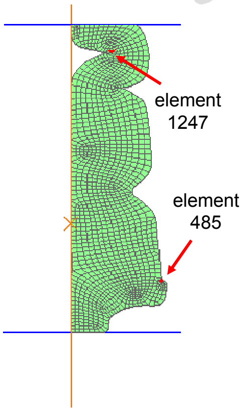
Mass Scaling

- Variable mass scaling can be used to scale the mass matrix above and beyond that done with fixed mass scaling.
- 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.
- Alternatively, fully-automatic variable mass scaling is available for bulk metal rolling problems.
  - The mass scaling factor is computed based on mesh geometry and initial conditions and is adjusted throughout the analysis.

Mass Scaling

- Example: Compression of a jounce bumper
  - Recall from Lecture 1 that the stable time increment for the jounce bumper analysis decreased due to element deformation.
  - Excerpt from status (.sta) file:

```
STEP        TOTAL        STABLE     CRITICAL   KINETIC
INCREMENT   TIME    ...  INCREMENT  ELEMENT    ENERGY
   ⋮
  5892  3.000E+00  ... 5.087E-04  485       2.457E+02
  6876  3.500E+00  ... 5.074E-04  485       2.730E+02
  7861  4.000E+00  ... 5.070E-04  485       3.581E+02
  8876  4.500E+00  ... 3.120E-04  1247      4.106E+02
 10702  5.000E+00  ... 2.739E-04  1247      4.208E+02
 12890  5.500E+00  ... 2.065E-04  1247      3.859E+02
   ⋮
```



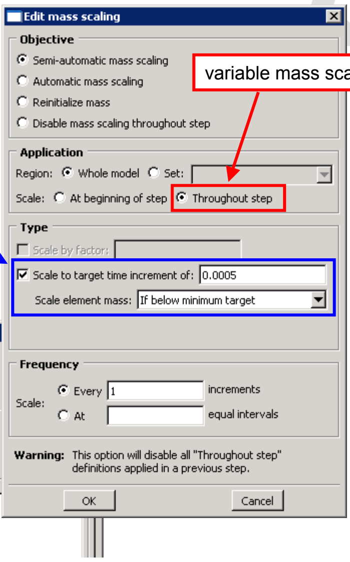
jounce bumper at time 5.0 seconds

Mass Scaling

- Example (cont'd): Compression of a jounce bumper

```
*VARIABLE MASS SCALING, FREQUENCY=1,
 DT=0.0005, TYPE=BELOW MIN
```

Scale density of elements whose stable time increment is less than .0005 s



Edit mass scaling

Objective
- ● Semi-automatic mass scaling
- ○ Automatic mass scaling
- ○ Reinitialize mass
- ○ Disable mass scaling throughout step

Application

Region: ● Whole model ○ Set:

Scale: ○ At beginning of step ● Throughout step

Type

☐ Scale by factor:

☑ Scale to target time increment of: 0.0005

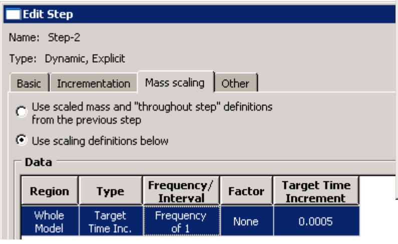
Scale element mass: If below minimum target

Frequency

Scale: ● Every 1 increments ○ At equal intervals

Warning: This option will disable all "Throughout step" definitions applied in a previous step.

variable mass scaling



Edit Step

Name: Step-2

Type: Dynamic, Explicit

○ Use scaled mass and "throughout step" definitions from the previous step

● Use scaling definitions below

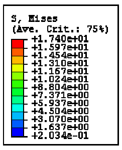
Data

Region	Type	Frequency/ Interval	Factor	Target Time Increment
Whole Model	Target Time Inc.	Frequency of 1	None	0.0005

Mass Scaling

- Example (cont'd): Compression of a jounce bumper
  - Excerpt from status (`.sta`) file of analysis with mass scaling:

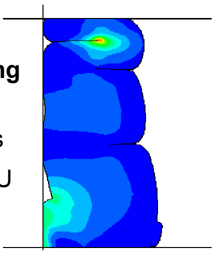
```
  STEP      TOTAL      STABLE     CRITICAL   KINETIC    PERCENT
INCREMENT   TIME    ...INCREMENT  ELEMENT    ENERGY     CHNG MASS
   :
17846  9.000E+00 ...5.000E-04   1061   1.184E+01  6.534E-01
18847  9.501E+00 ...5.000E-04   1108   1.427E+00  6.779E-01
19846  1.000E+01 ...5.000E-04   1051   4.621E-01  6.816E-01
ODB Field Frame Number 10 of 10 requested intervals
  THE ANALYSIS HAS COMPLETED SUCCESSFULLY
```



without mass scaling

34,743 increments

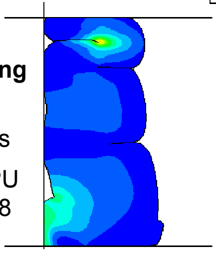
relative CPU time =1



with mass scaling

19,846 increments

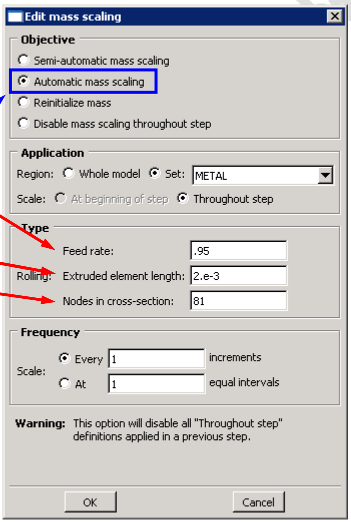
relative CPU time = 0.58



Mass Scaling

- Example: Rolling of a thick plate
  - Automatic mass scaling based on mesh geometry and initial conditions.

```
*VARIABLE MASS SCALING, TYPE=ROLLING,
 ELSET=METAL, FREQUENCY=1, FEED RATE=.95,
 EXTRUDED LENGTH=2.0E-3,
 CROSS SECTION=81
```



Objective

- ○ Semi-automatic mass scaling
- ● Automatic mass scaling
- ○ Reinitialize mass
- ○ Disable mass scaling throughout step

Application

Region: ○ Whole model ● Set: METAL

Scale: ○ At beginning of step ● Throughout step

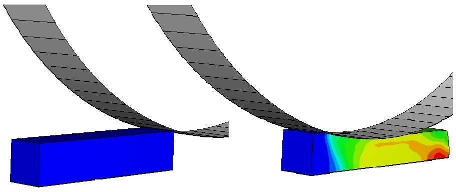
Type

Rolling:
- Feed rate: .95
- Extruded element length: 2.e-3
- Nodes in cross-section: 81

Frequency

Scale:
- ● Every 1 increments
- ○ At 1 equal intervals

Warning: This option will disable all "Throughout step" definitions applied in a previous step.



Undeformed shape

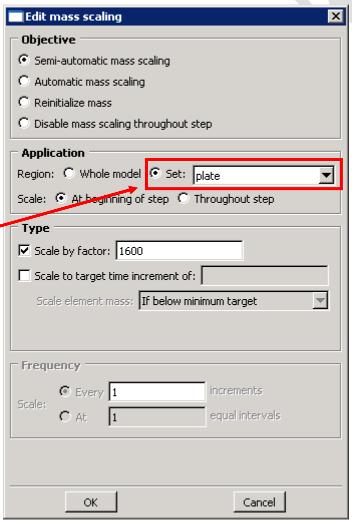
Deformed shape with contours of equivalent plastic strain

Mass Scaling

- **Selected regions of the model can be scaled independently.**
  - Useful when different regions of the model have different stiffness and mass properties
  - Example:

```
*FIXED MASS SCALING, ELSET=plate,
FACTOR=1600
```

  - Only one fixed and one variable mass scaling factor definition is allowed per element set.
    - An element that has multiple fixed or variable mass scaling definitions results in an error message.



Edit mass scaling

Objective

● Semi-automatic mass scaling
○ Automatic mass scaling
○ Reinitialize mass
○ Disable mass scaling throughout step

Application

Region: ○ Whole model ● Set: plate

Scale: ● At beginning of step ○ Throughout step

Type

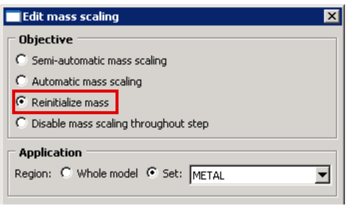
☑ Scale by factor: 1600
☐ Scale to target time increment of:
Scale element mass: If below minimum target

Frequency

Scale: ● Every 1 increments
○ At 1 equal intervals

Mass Scaling

- **Mass scaling in multistep analysis**
  - Fixed mass scaling definitions are not retained from step to step, but the scaled mass matrix is retained.
    - Using the ∗FIXED MASS SCALING option with no parameters resets the entire mass matrix.



Edit mass scaling

Objective

○ Semi-automatic mass scaling
○ Automatic mass scaling
● Reinitialize mass
○ Disable mass scaling throughout step

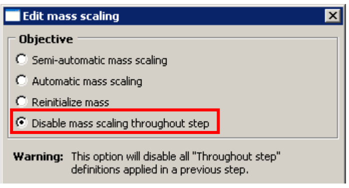
Application

Region: ○ Whole model ● Set: METAL

  - This is particularly useful when a quasi-static step is followed by a dynamic event.

Mass Scaling

- Variable mass scaling definitions are retained from step to step.
  - Any variable mass scaling definition in the current step causes all variable mass scaling definitions from previous steps to be removed.
    - To remove variable mass scaling from previous steps, use the *VARIABLE MASS SCALING option with no parameters.



Edit mass scaling

Objective

○ Semi-automatic mass scaling
○ Automatic mass scaling
○ Reinitialize mass
● Disable mass scaling throughout step

Warning: This option will disable all "Throughout step" definitions applied in a previous step.

- Deactivating variable mass scaling does not prevent scaled masses from being carried forward to subsequent steps.
  - To return to the initial mass matrix, the mass must also be reinitialized (i.e., include the *FIXED MASS SCALING option with no parameters).

Mass Scaling

- Avoid very large changes in element mass due to mass scaling at the start of a step that is not the first step in a multiple step analysis.
  - The resulting precision problems in the mass calculations may give rise to erroneous or misleading results.
- If a large change is desired, do the following:

① Insert a new step to reinitialize the element masses to their original values.

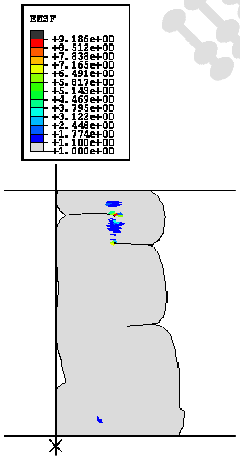
② In a subsequent step add mass scaling definitions to scale the element masses to their desired values.

Mass Scaling

- **Output variables**
  - The following mass scaling output variables are available:

EMSF	Element mass scaling factor.
EDT	Element stable time increment.
DT	Time increment
DMASS	Percent change in mass caused by mass scaling.

- ABAQUS/Viewer can be used to create history plots of all four output variables;
  - in addition, contour plots of EMSF and EDT can be created.
- The time increment and percent change in mass are also printed to the status (`.sta`) file.



Mass scaling factor for jounce bumper with variable mass scaling

---

Viscous Pressure

Viscous Pressure

- Viscous pressure (VP) loading is a very effective way to damp out dynamic effects quickly, and thus reach quasi-static equilibrium in a minimal number of increments.
  - It is commonly used to damp out kinetic energy associated with structural motion (usually on the exterior surface of a body).
- The viscous pressure load is defined through:

$$p = -c_v \boldsymbol{v} \cdot \boldsymbol{n}.$$

  - The effect of the load is that pressure waves crossing the free surface are absorbed; there is no reflection of energy back into the interior of the model.
- Note that viscous pressure applies damping at the surface of the body.
  - Damping in the interior of the body is introduced through material damping.

Viscous Pressure

- The choice of viscous pressure coefficient (c_v) is critical for using the technique effectively.
  - The value of c_v is problem dependent.
  - Typically c_v is set equal to a small percentage (1 or 2%) of $\rho\, c_d$.
- Usage:

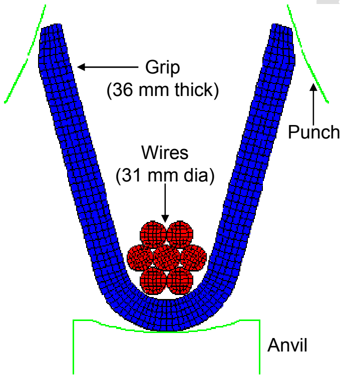
```
*DLOAD
element_set, VPn, cv
```

or

```
*DSLOAD
surface_name, VP, cv
```

Viscous Pressure

- **Example: Crimp forming**
  - A variation on the crimp forming problem discussed previously (Lecture 4, *Contact Modeling*)
  - As before, the rigid punch undergoes a downward stroke to complete the crimp forming.
    - The anvil is held fixed.



Solid grip section;
free extrusion model

Viscous Pressure

- **Even though the intended simulation is quasi-static, an explicit dynamic simulation is used.**
  - The following aspects would present difficulties for a static analysis with ABAQUS/Standard:
    - The model has no static stability due to the free rigid body motion of the grip and wires.
    - During crimping the grip arms buckle as they are turned by the punch downward into the bundle.
    - There is complex multi-body contact in the analysis: between the grip arms and the wires, between each combination of two wires, and between the two grip arms.
  - The punch is moved downward in such a way as to conduct the analysis efficiently without having inertia effects significantly influence the solution.
    - **Viscous pressure** is used to damp out dynamic effects quickly.

Viscous Pressure

```
*Heading
:
*Material, Name=copper
*Density
8.5e-3,
*Elastic
17.8e+03,0.34
:
*Step
*Dynamic,explicit
,.2
**
** Punch Velocity of ~ 36 M/sec
**
*Boundary,amplitude=ramp
PunchRef,2,2,-7.163
```

All exterior faces of wires →

```
**
**   Viscous Pressure on Wires
**
*Dsload,amplitude=ramp4
wires, vp, 0.12
:
*End step
```

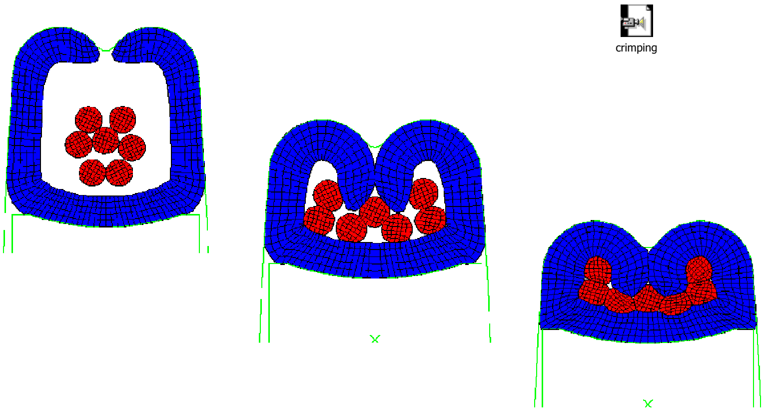
$$\rho c_d = \rho\sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \approx 15$$

$$c_v / \rho c_d \approx 0.8\%$$

Viscous Pressure

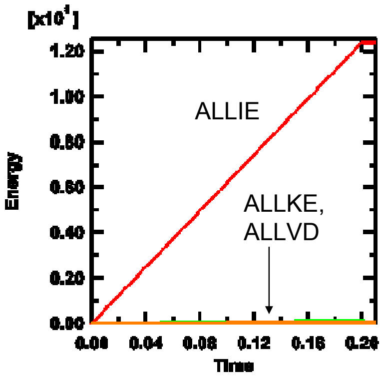
- **Deformed configuration**

crimping



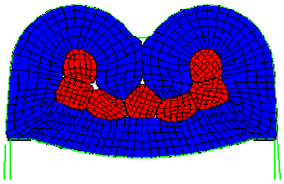
Viscous Pressure

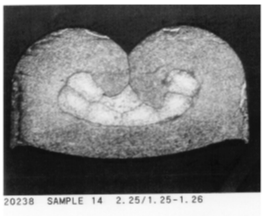
- **Comparison of viscous and internal energy**
  - The plot reveals that ALLKE and ALLVD stay a very low fraction of the ALLIE in the stamping process, so this is indeed a quasi-static problem.



Viscous Pressure

- **Experimental verification**
  - The solution is verified by experimental results.





Summary

Summary

- Excessive loading rates can produce solutions with significant inertia effects.
- A general guideline is to restrict loading rates to less than 1% of the material wave speed.
  - Ramping applied loads and boundary conditions from zero also promotes a quasi-static response.
    - Use the SMOOTH STEP amplitude definition.
- Mass scaling can be used to treat rate-dependent material behavior, allowing the process to be modeled in its natural time period.

Summary

- The energy balance can be used to assist in evaluating whether a given solution represents a quasi-static response to applied loads.
- Since results can depend strongly on the process speed (real or artificially adjusted by mass scaling), it is vital to ensure that unrealistic results are not being generated by excessive artificial process speed scaling.
  - To confirm that the ABAQUS/Explicit results are realistic, it may be useful to study a simplified version of the problem as a static analysis in ABAQUS/Standard for comparison.
  - The easiest way to create a suitable simplified test case for this purpose is often to define a two-dimensional version of part of the problem.