PennState
College of Engineering

ME 563: Nonlinear Finite Elements

Application and Exploration of Nonlinear Finite Elements

Charpy Impact Simulation - Johnson-Cook Plasticity + Damage

The Pennsylvania State University

Table of Contents

1. Introduction

Why Johnson Cook Material model ?

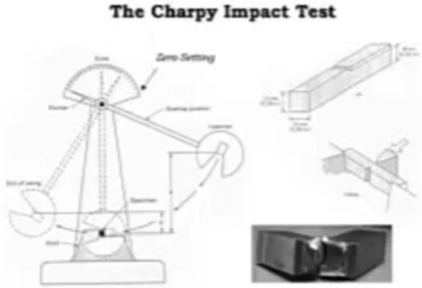
- Under dynamic impact material/object experience
  - High strain rates
  - Large strain
  - Elevated temperature

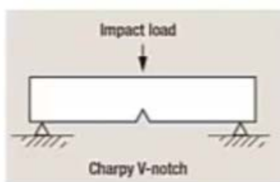
- The behavior **differs significantly** under impact loading putting material to Quasi-static loading approach
- Researchers have **proposed several material** model case by case
- **No universal model** catering to large variety of materials which can account all above parameters for impact simulations
- **Reliable prediction** in response to impact loading is critical for accurate design
- **Johnson Cook** is popular constitutive material model for metals widely used in simulation of impact and penetration related problems

Examples:
- Automotive applications
- High speed machinery
- Defense applications such as battle tanks
- High speed project impact on armour

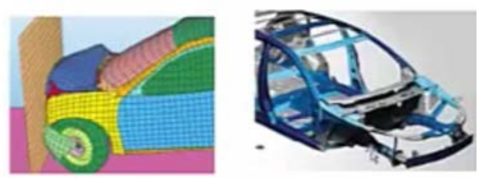
Dynamic Impact Simulations

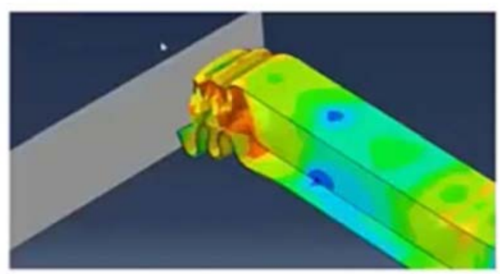
The Charpy Impact Test





Vehicle Crash Explicit model





Armor Steel

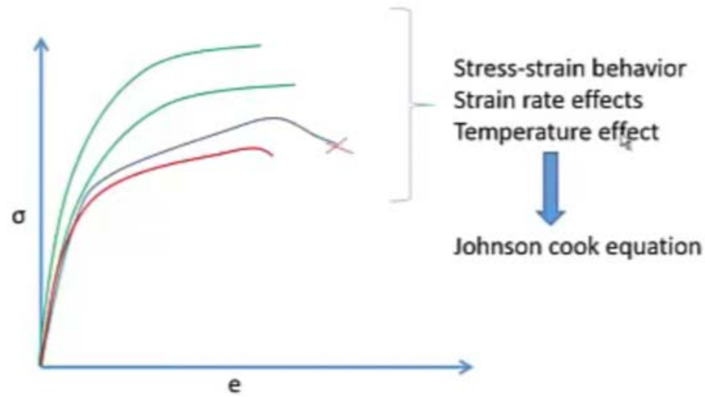
Bullet impact

Johnson cook constitutive equation

$$\sigma_{eq} = \underbrace{[A + B\varepsilon_p{}^n]}_{\text{hardening law/ power law}}\underbrace{[1 + c\ln(\dot{\varepsilon}^*)]}_{\text{Strain Rate}}\underbrace{[1 - T^{*m}]}_{\text{Temperature effect}}$$

- Yield stress, A (MPa)
- Strain hardening parameter, B (MPa)
- Strain hardening exponent, n
- Strain rate sensitivity parameter, c
- Temperature exponent, m

- ε_p is the accumulated plastic strain,
- $\varepsilon\bullet^* = (\varepsilon\bullet_p / \varepsilon\bullet_0)$ is a dimensionless strain rate,
- $\varepsilon\bullet_0$ is the reference strain rate
- $T^* = (T - T_0)/(T_m - T_0)$; T, T_0 and T_m being the working temperature, room temperature and melting temperature respectively.



Johnson–Cook failure/damage model

$$\varepsilon_f = \underbrace{\left[D_1 + D_2\exp(D_3\sigma^*)\right]}_{\text{stress triaxiality}}\underbrace{\left[1 + D_4 \ln\left(\dot{\varepsilon}_p{}^*\right)\right]}_{\text{strain rate}}\underbrace{[1 + D_5T^*]}_{\text{temperature}}$$

- ε_f the fracture strain
- D1 to D5 are material constants
- $\sigma^* = \sigma_m/\sigma_{eq}$ is the stress tri-axiality ratio and σm is the mean stress or hydrostatics stress
-

- *Material damage is accounted*
- *Fracture strength is calculated*

Johnson Cook Parameters for Abaqus simulation (Literature)

Table 2: Input parameters for the Johnson-Cook plasticity model, [5, 6, 7]

Material	A, [MPa]	B, [MPa]	n	θ_{melt} [K]	$\theta_{transition}$ [K]	m	C	$\dot{\varepsilon}_0$ [1/s]
Aluminum 6061 -T6	324.1	113.8	0.42	925	293.2	1.34	0.002	1.0
Steel 4340, C-30	792	510	0.26	1793	293.2	1.03	0.014	1.0

Table 4: Input parameters for the Johnson-Cook dynamic failure model, [5, 6, 7]

Material	d_1	d_2	d_3	d_4	d_5
Aluminum 6061 -T6	-0.77	1.45	0.47	0.0	1.6
Steel 4340, C-30	0.05	3.44	2.12	0.002	0.61

Materials Science & Engineering A 640 (2015) 200–209

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

ELSEVIER

Determination of Johnson cook material and failure model constants and numerical modelling of Charpy impact test of armour steel

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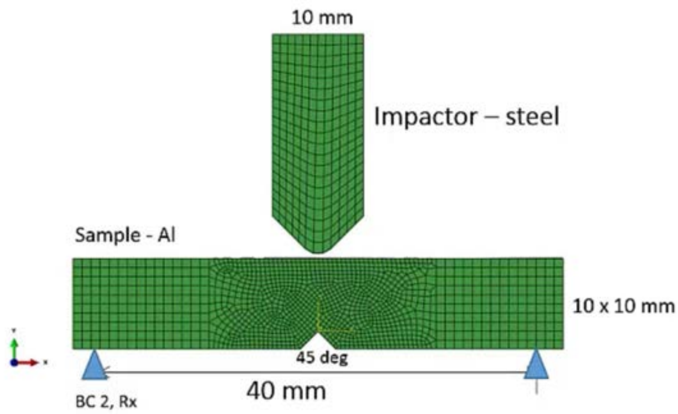
ARTICLE INFO

Article history:
Received 13 December 2014
Received in revised form
15 May 2015
Accepted 23 May 2015
Available online 27 May 2015

Keywords:
Johnson–Cook material and failure models
Charpy test
Armour steel
Finite Element analysis
Numerical simulation

ABSTRACT

The behaviour of typical armour steel material under large strains, high strain rates and elevated temperatures needs to be investigated to analyse and reliably predict its response to various types of dynamic loading like impact. An empirical constitutive relation developed by Johnson and Cook (J–C) is widely used to capture strain rate sensitivity of the metals. A failure model proposed by Johnson and Cook is used to model the damage evolution and predict failure in many engineering materials. In this work, model constants of J–C constitutive relation and damage parameters of J–C failure model for a typical armour steel material have been determined experimentally from four types of uniaxial tensile test. Some modifications in the J–C damage model have been suggested and Finite Element simulation of three different tensile tests on armour steel specimens under dynamic strain rate ($10^{-1}\,s^{-1}$), high triaxiality and elevated temperature respectively has been done in ABAQUS platform using the modified J–C failure model as user material sub-routine. The simulation results are validated by the experimental data. Thereafter, a moderately high strain rate event viz. Charpy impact test on armour steel specimen has been simulated using J–C material and failure models with the same material parameters. Reasonable agreement between the simulation and experimental results has been achieved.



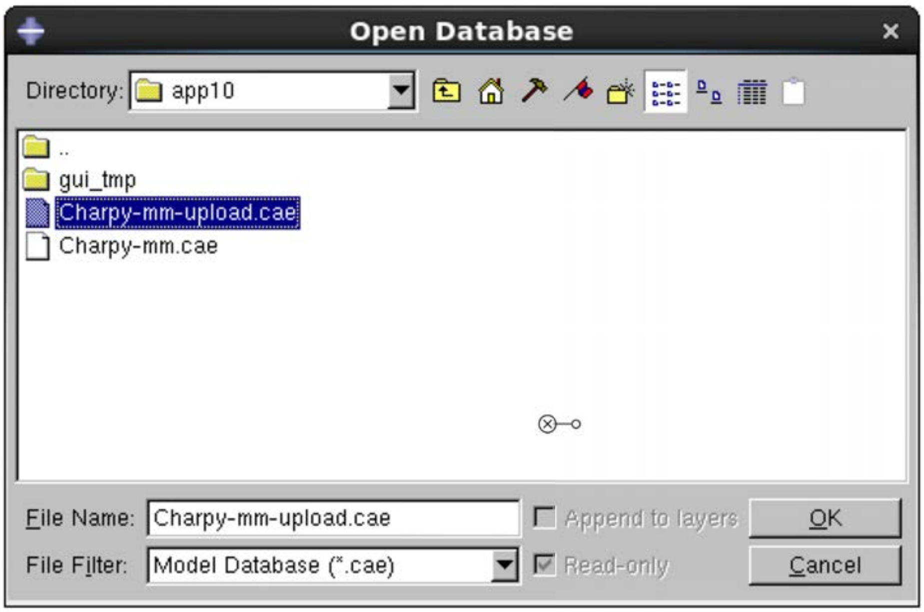
Unit System: N, Tonne, mm, S
Impactor Velocity: -2500 mm/s
Impactor Mass: Density 1E-6 t/mm3 (1.5 kg)

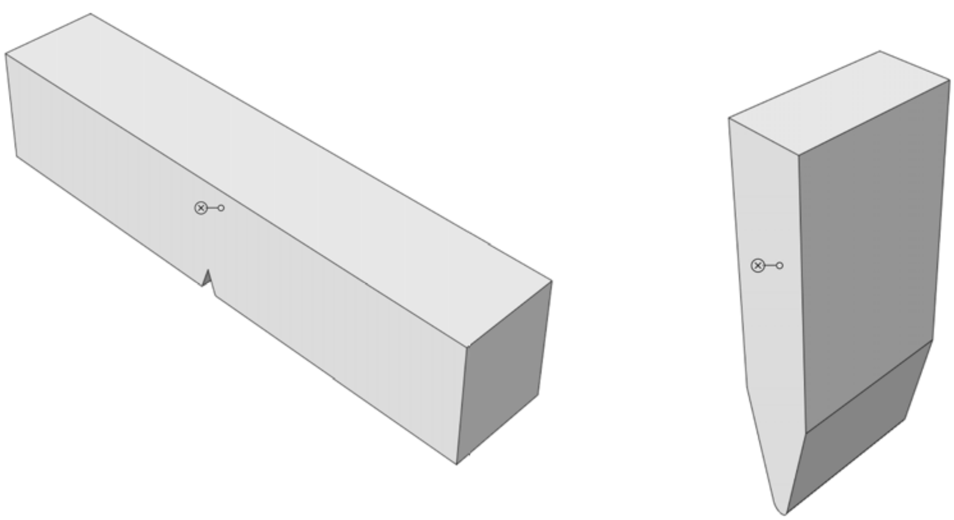
Tonne is unit of mass

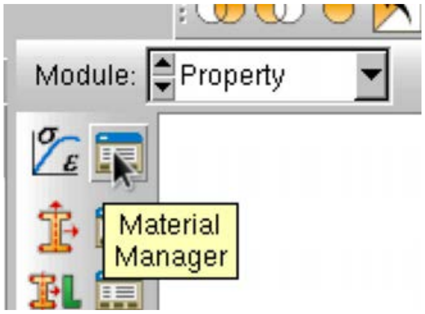
2. Simulation

Download Charpy-mm-upload.cae from Github and load into Abaqus:

git clone https://github.com/rhk12/CharpyJC



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Material Manager


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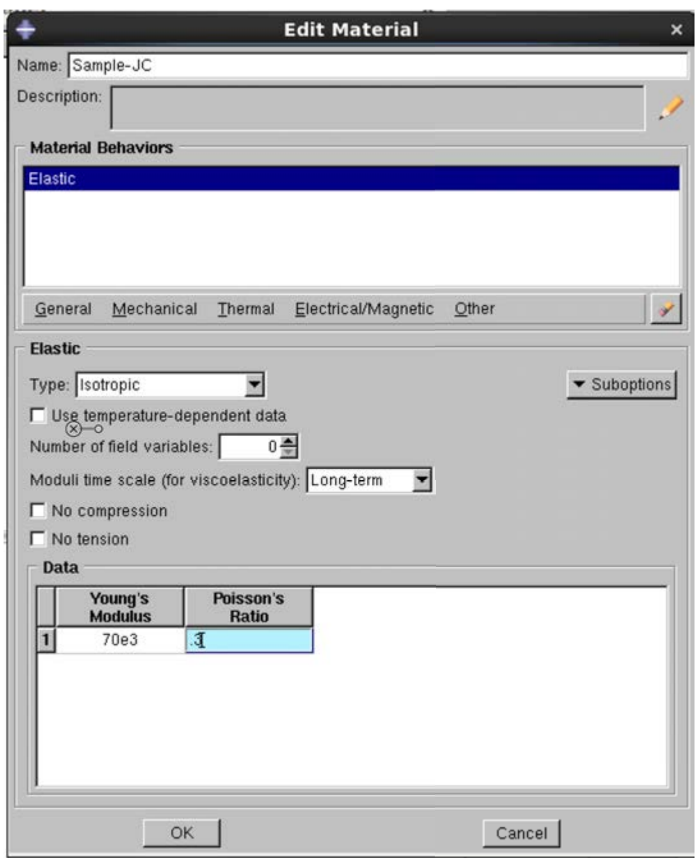
Edit...
Copy...
Rename...
Delete...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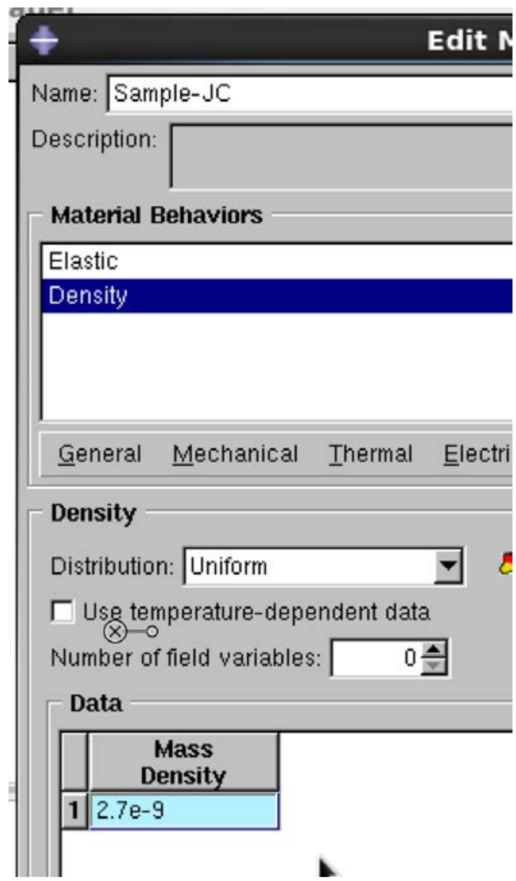
Description:
Material Behaviors
Elastic
General Mechanical Thermal Electrical/Magnetic Other
Elastic
Type: Isotropic
Suboptions
Use temperature-dependent data
Number of field variables: 0
Moduli time scale (for viscoelasticity): Long-term
No compression
No tension
Data
Young's Modulus
Poisson's Ratio
1 70e3 .3
OK
Cancel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Density
General Mechanical Thermal Electri
Density
Distribution: Uniform
Use temperature-dependent data
Number of field variables: 0
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Mass Density
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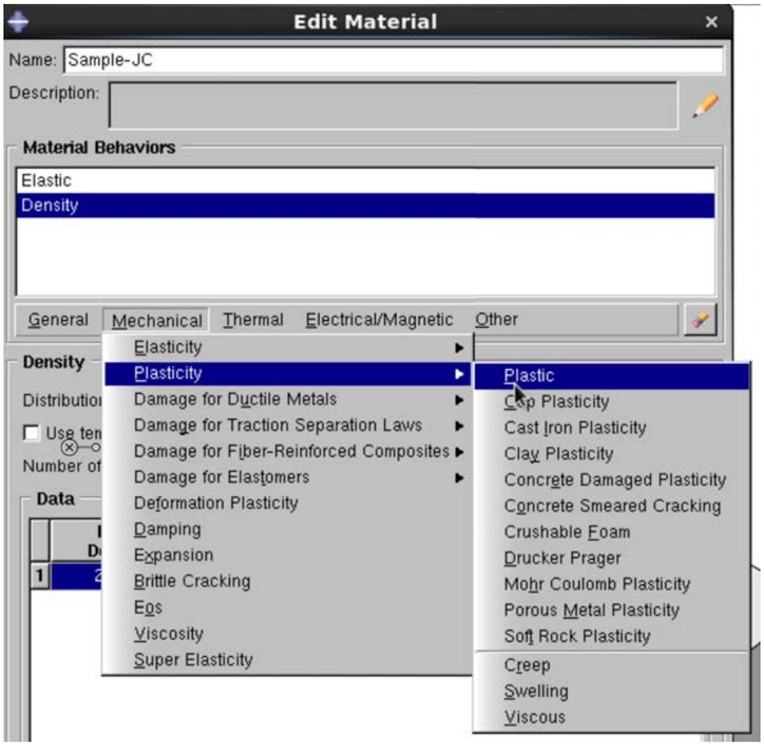
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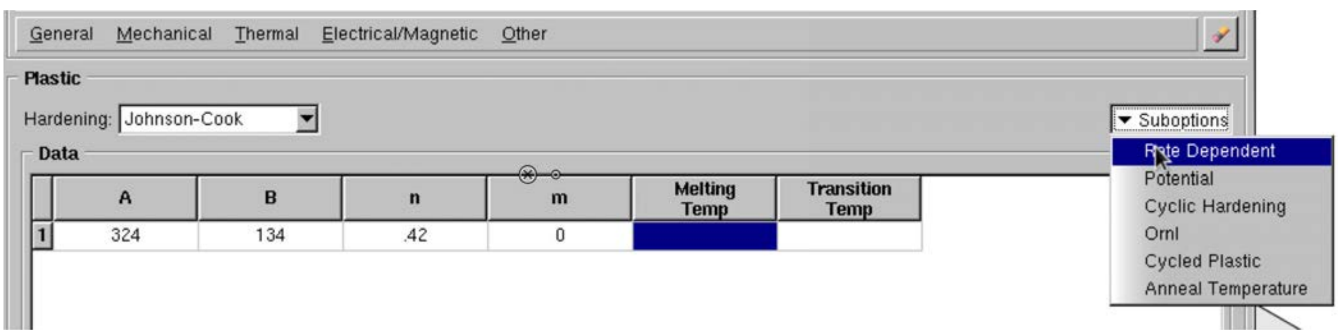
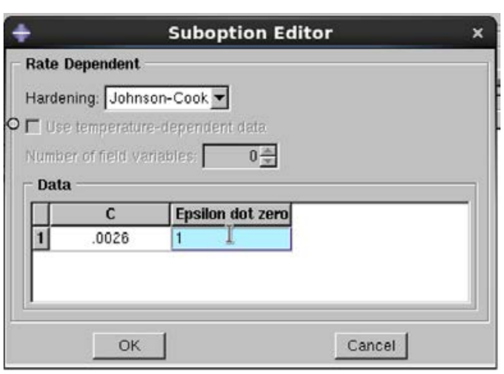
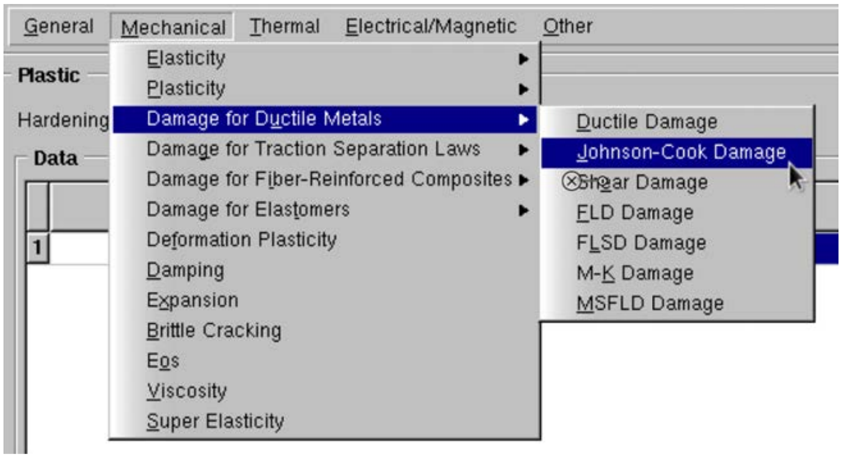
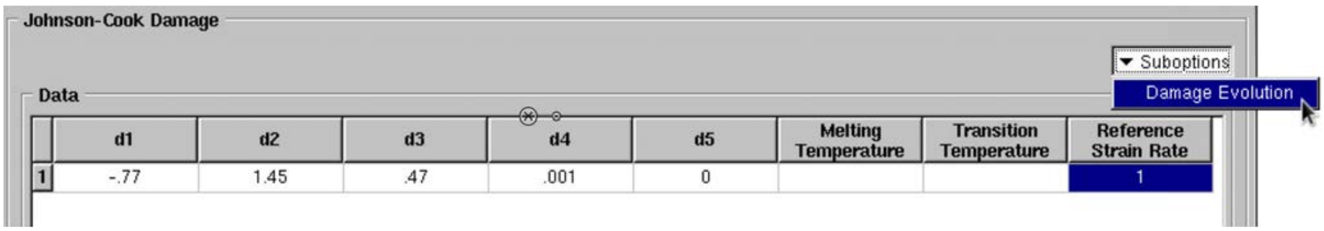
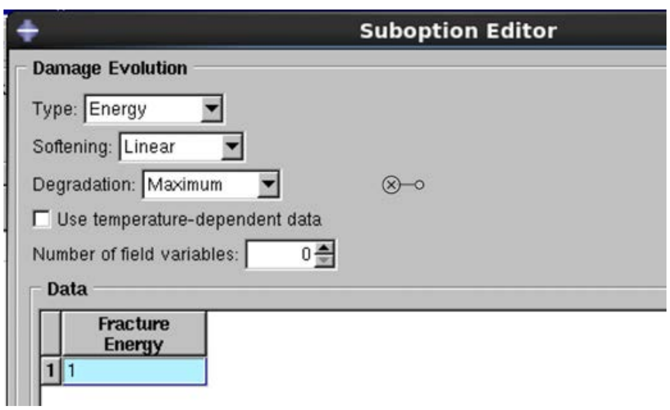
Name: Sample-JC
Description:
Material Behaviors
Elastic
Density
General
Mechanical
Thermal
Electrical/Magnetic
Other
Density
Elasticity
Plasticity
Damage for Ductile Metals
Damage for Traction Separation Laws
Damage for Fiber-Reinforced Composites
Damage for Elastomers
Deformation Plasticity
Damping
Expansion
Brittle Cracking
Eos
Viscosity
Super Elasticity
Plastic
Cap Plasticity
Cast Iron Plasticity
Clay Plasticity
Concrete Damaged Plasticity
Concrete Smeared Cracking
Crushable Foam
Drucker Prager
Mohr Coulomb Plasticity
Porous Metal Plasticity
Soft Rock Plasticity
Creep
Swelling
Viscous
Data


General
Mechanical
Thermal
Electrical/Magnetic
Other
Plastic
Hardening: Johnson-Cook
Suboptions
Rate Dependent
Potential
Cyclic Hardening
Ornl
Cycled Plastic
Anneal Temperature
Data
A
B
n
m
Melting Temp
Transition Temp
1
324
134
.42
0

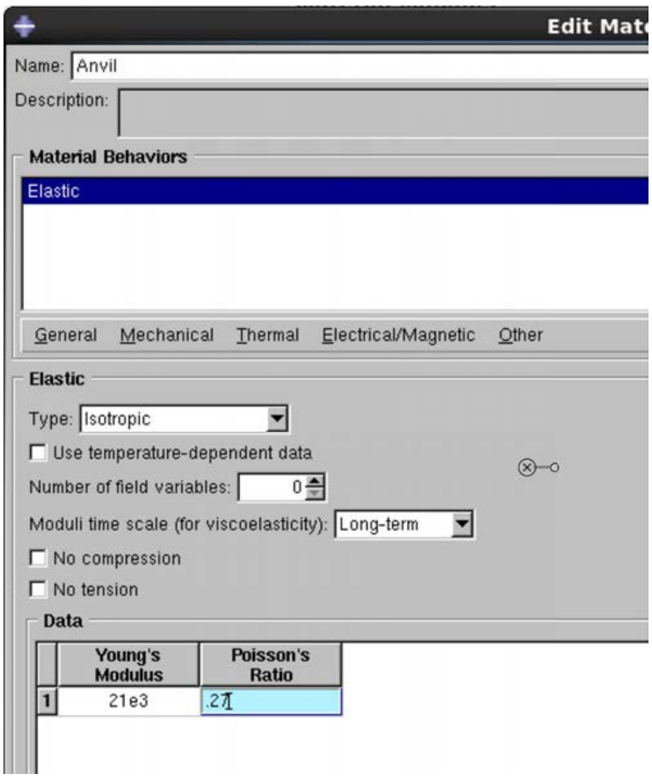

Suboption Editor
Rate Dependent
Hardening: Johnson-Cook
Use temperature-dependent data
Number of field variables: 0
Data
C
Epsilon dot zero
1
.0026
1
OK
Cancel







Add new material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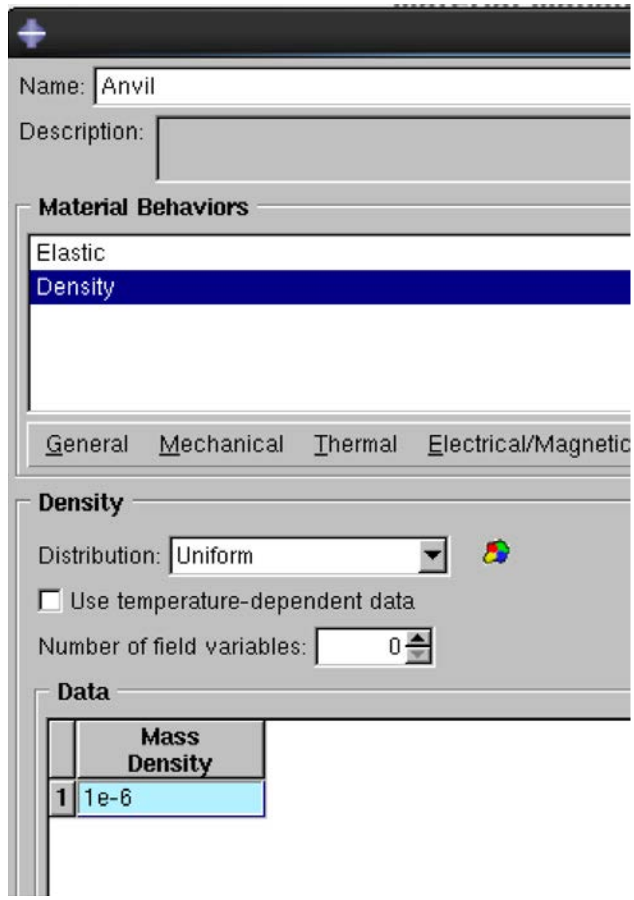
Name: Anvil
Description:
Material Behaviors
Elastic
General Mechanical Thermal Electrical/Magnetic Other
Elastic
Type: Isotropic
Use temperature-dependent data
Number of field variables: 0
Moduli time scale (for viscoelasticity): Long-term
No compression
No tension
Data
Young's Modulus
Poisson's Ratio
1
21e3
.27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Description:
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Density
General Mechanical Thermal Electrical/Magnetic
Density
Distribution: Uniform
Use temperature-dependent data
Number of field variables: 0
Data
Mass Density
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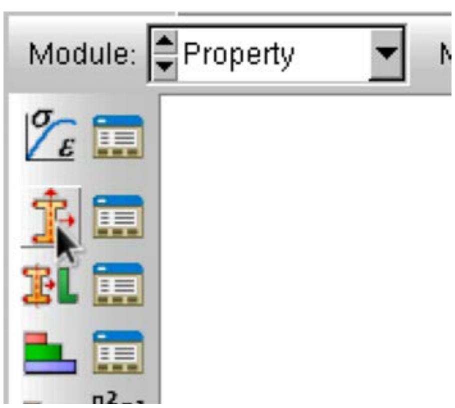
1e-6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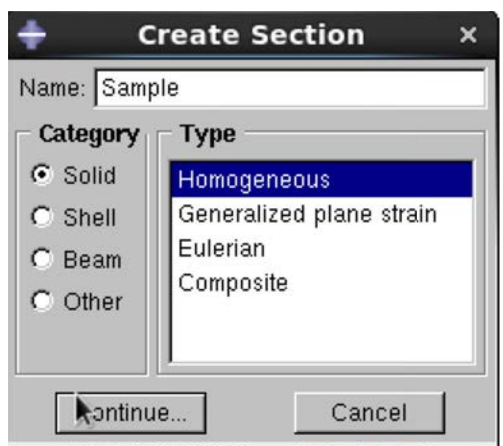
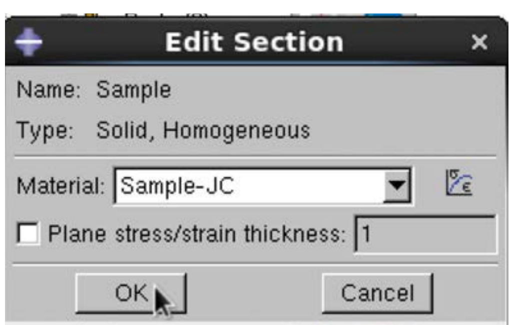
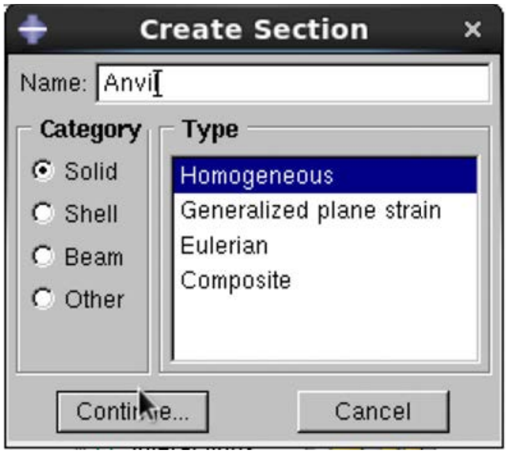
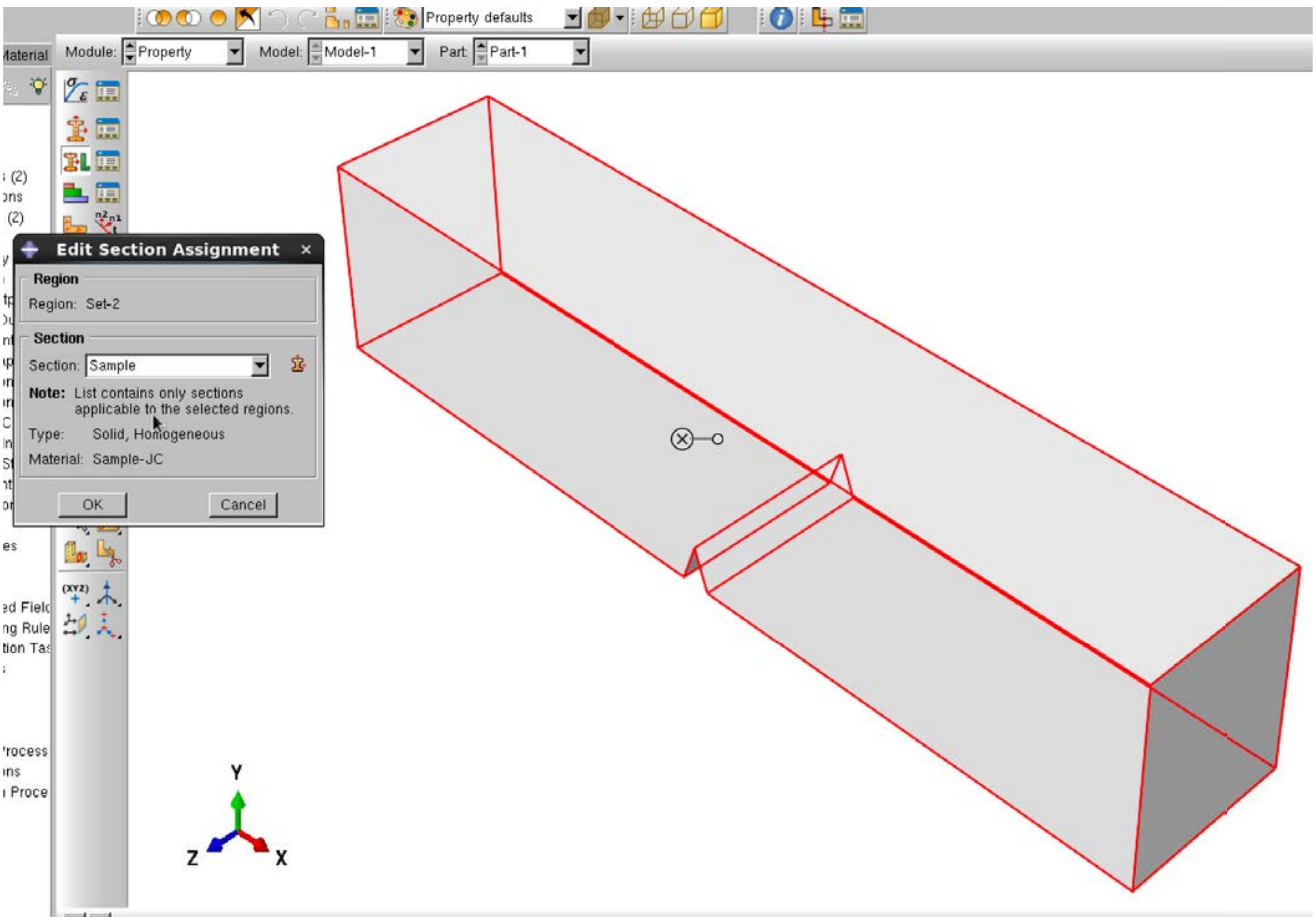
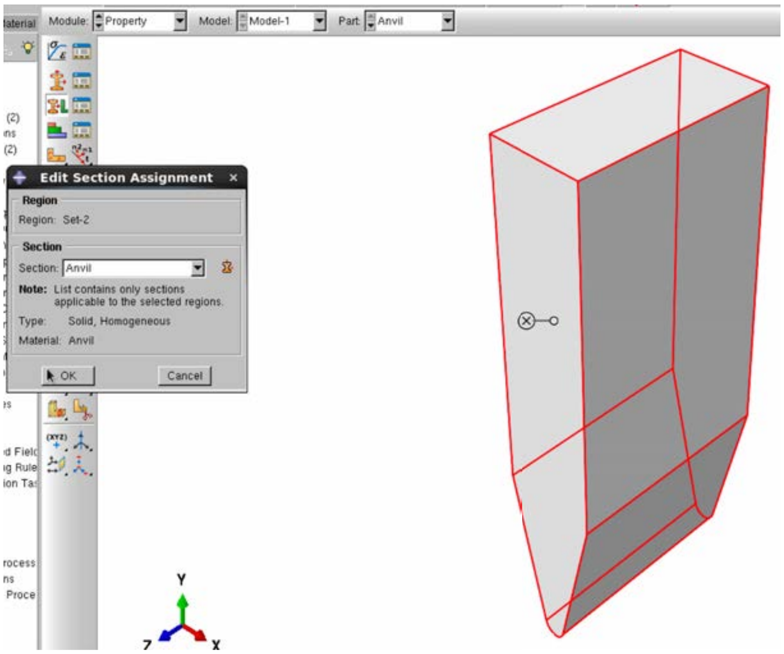

Create Section
Name: Sample
Category
Solid
Shell
Beam
Other
Type
Homogeneous
Generalized plane strain
Eulerian
Composite
Continue...
Cancel

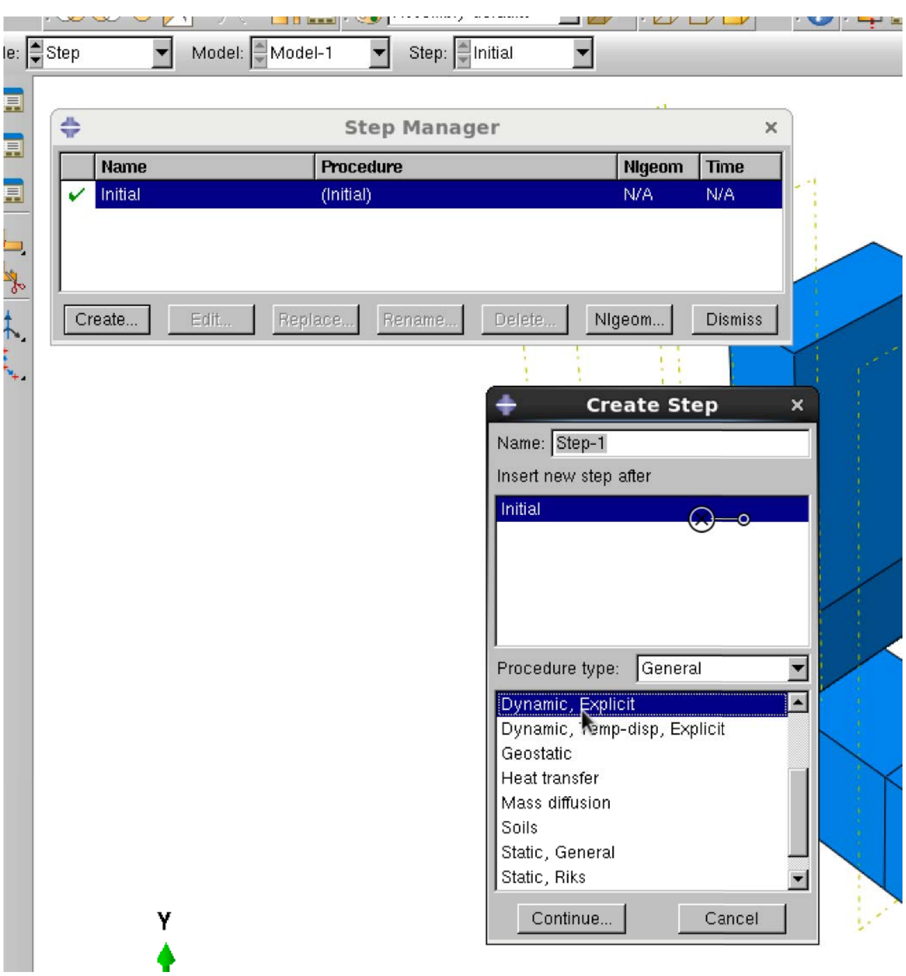

Edit Section
Name: Sample
Type: Solid, Homogeneous
Material: Sample-JC
Plane stress/strain thickness: 1
OK
Cancel

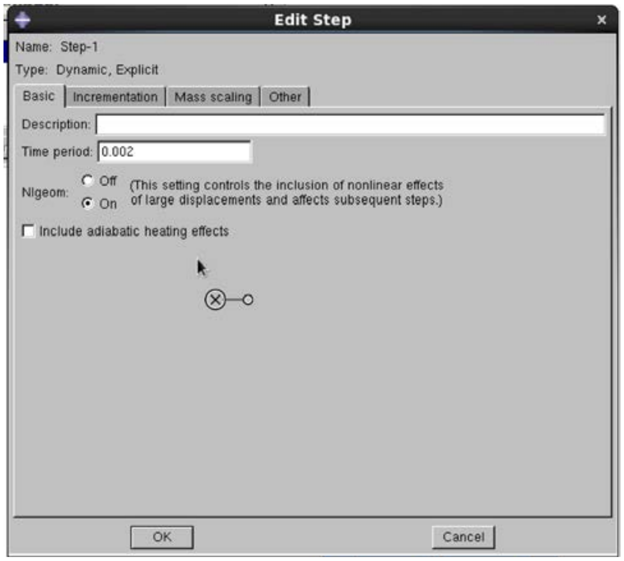

Create Section
Name: Anvil
Category
Solid
Shell
Beam
Other
Type
Homogeneous
Generalized plane strain
Eulerian
Composite
Continue...
Cancel

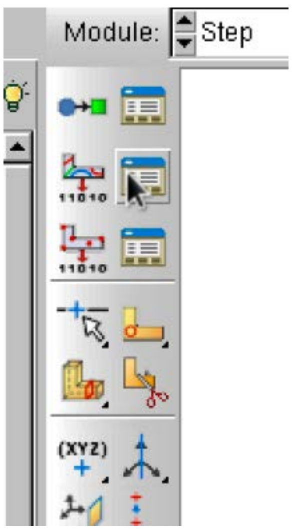

Edit Section
Name: Anvil
Type: Solid, Homogeneous
Material: Anvil
Plane stress/strain thickness: 1
OK
Cancel


Property defaults
Module: Property
Model: Model-1
Part: Part-1
Edit Section Assignment
Region
Region: Set-2
Section
Section: Sample
Note: List contains only sections applicable to the selected regions.
Type: Solid, Homogeneous
Material: Sample-JC
OK
Cancel
Y
Z
X

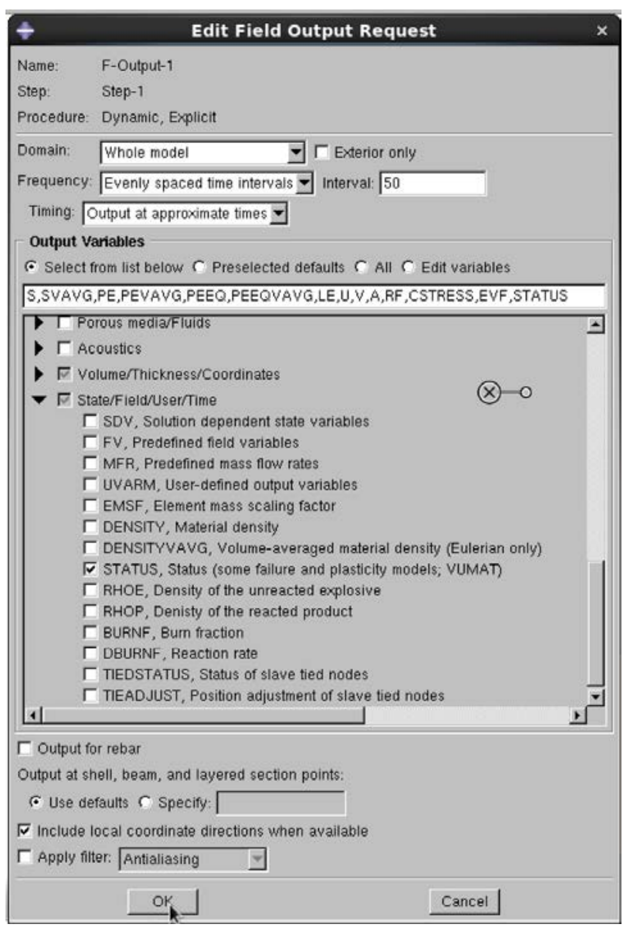

Module: Property
Model: Model-1
Part: Anvil
Edit Section Assignment
Region
Region: Set-2
Section
Section: Anvil
Note: List contains only sections applicable to the selected regions.
Type: Solid, Homogeneous
Material: Anvil
OK
Cancel

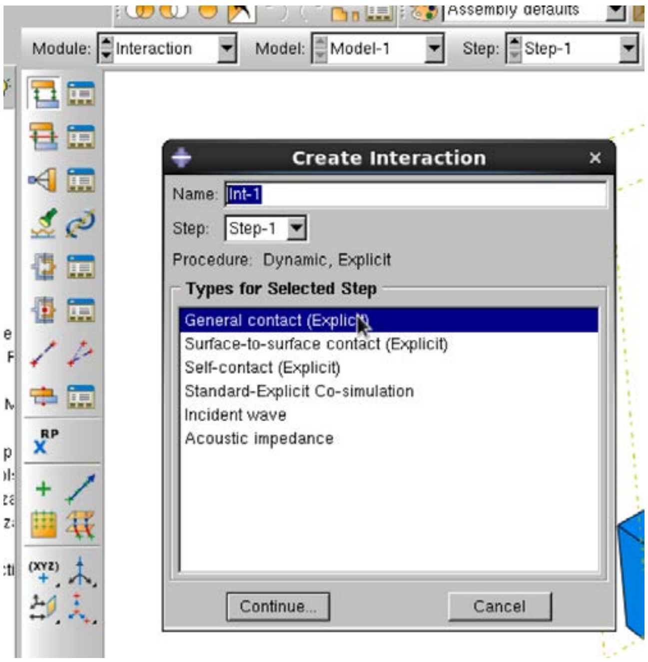

Step
Model: Model-1
Step: Initial
Step Manager
Name
Procedure
Nlgeom
Time
Initial
(Initial)
N/A
N/A
Create...
Edit...
Replace...
Rename...
Delete...
Nlgeom...
Dismiss
Create Step
Name: Step-1
Insert new step after
Initial
Procedure type: General
Dynamic, Explicit
Dynamic, Temp-disp, Explicit
Geostatic
Heat transfer
Mass diffusion
Soils
Static, General
Static, Riks
Continue...
Cancel

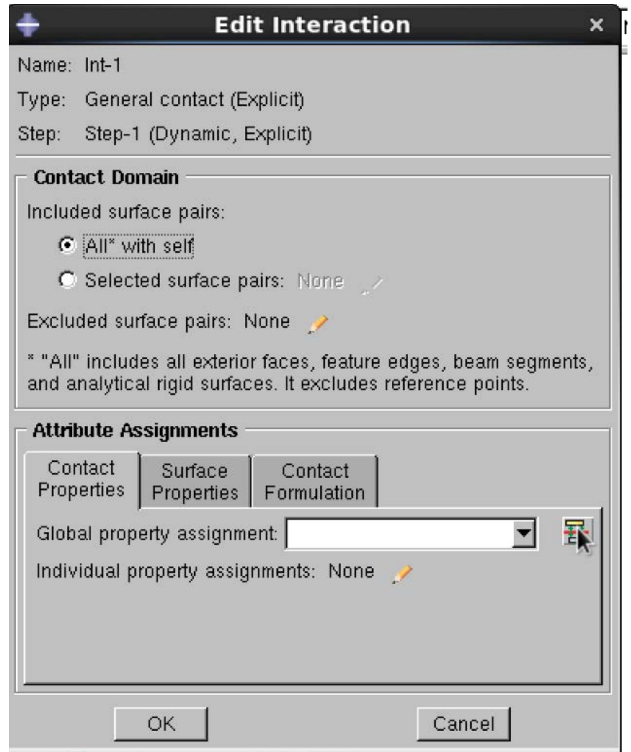

Edit Step
Name: Step-1
Type: Dynamic, Explicit
Basic
Incrementation
Mass scaling
Other
Description:
Time period: 0.002
Nlgeom:
Off
On
(This setting controls the inclusion of nonlinear effects of large displacements and affects subsequent steps.)
Include adiabatic heating effects
OK
Cancel

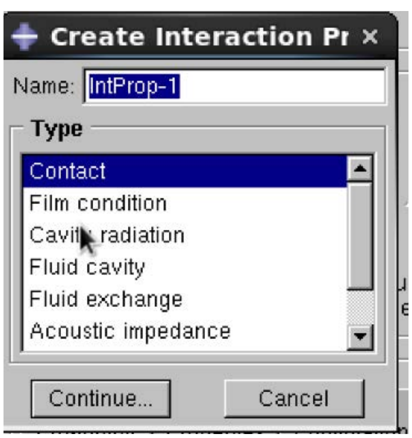

Module:
Step

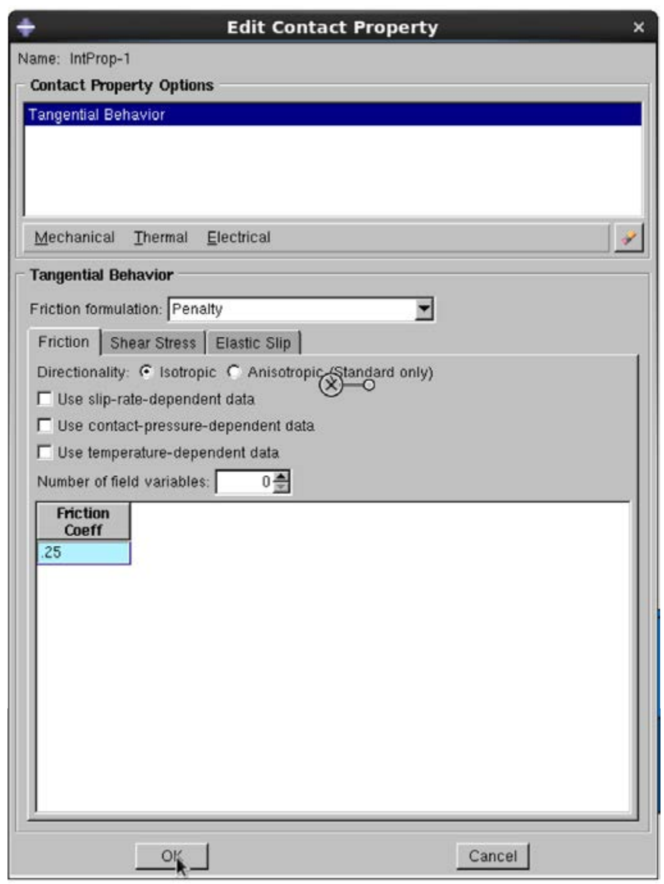

Field Output Requests Manager
Name
Step-1
F-Output-1
Created
Step procedure: Dynamic, Explicit
Variables: Preselected defaults
Status: Created in this step
Create...
Copy...
Rename...
Delete...
Dismiss

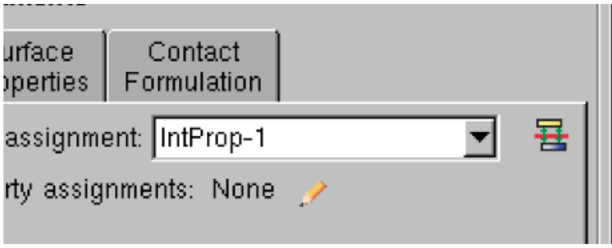

Edit Field Output Request
Name: F-Output-1
Step: Step-1
Procedure: Dynamic, Explicit
Domain: Whole model
Exterior only
Frequency: Evenly spaced time intervals
Interval: 50
Timing: Output at approximate times
Output Variables
Select from list below
Preselected defaults
All
Edit variables
S,SVAVG,PE,PEVAVG,PEEQ,PEEQVAVG,LE,U,V,A,RF,CSTRESS,EVF,STATUS
Porous media/Fluids
Acoustics
Volume/Thickness/Coordinates
State/Field/User/Time
SDV, Solution dependent state variables
FV, Predefined field variables
MFR, Predefined mass flow rates
UVARM, User-defined output variables
EMSF, Element mass scaling factor
DENSITY, Material density
DENSITYVAVG, Volume-averaged material density (Eulerian only)
STATUS, Status (some failure and plasticity models; VUMAT)
RHOE, Density of the unreacted explosive
RHOP, Denisty of the reacted product
BURNF, Burn fraction
DBURNF, Reaction rate
TIEDSTATUS, Status of slave tied nodes
TIEADJUST, Position adjustment of slave tied nodes
Output for rebar
Output at shell, beam, and layered section points:
Use defaults
Specify:
Include local coordinate directions when available
Apply filter:
Antialiasing
OK
Cancel

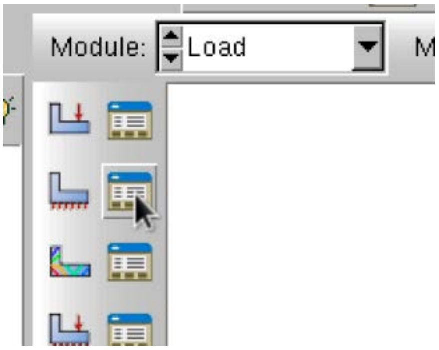

Module: Interaction
Model: Model-1
Step: Step-1
Create Interaction
Name: Int-1
Step: Step-1
Procedure: Dynamic, Explicit
Types for Selected Step
General contact (Explicit)
Surface-to-surface contact (Explicit)
Self-contact (Explicit)
Standard-Explicit Co-simulation
Incident wave
Acoustic impedance
Continue...
Cancel

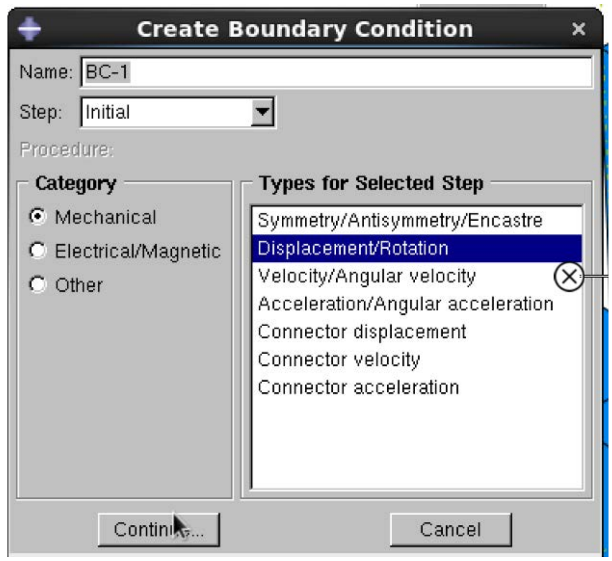

Edit Interaction
Name: Int-1
Type: General contact (Explicit)
Step: Step-1 (Dynamic, Explicit)
Contact Domain
Included surface pairs:
All* with self
Selected surface pairs: None
Excluded surface pairs: None
* "All" includes all exterior faces, feature edges, beam segments, and analytical rigid surfaces. It excludes reference points.
Attribute Assignments
Contact Properties
Surface Properties
Contact Formulation
Global property assignment:
Individual property assignments: None
OK
Cancel

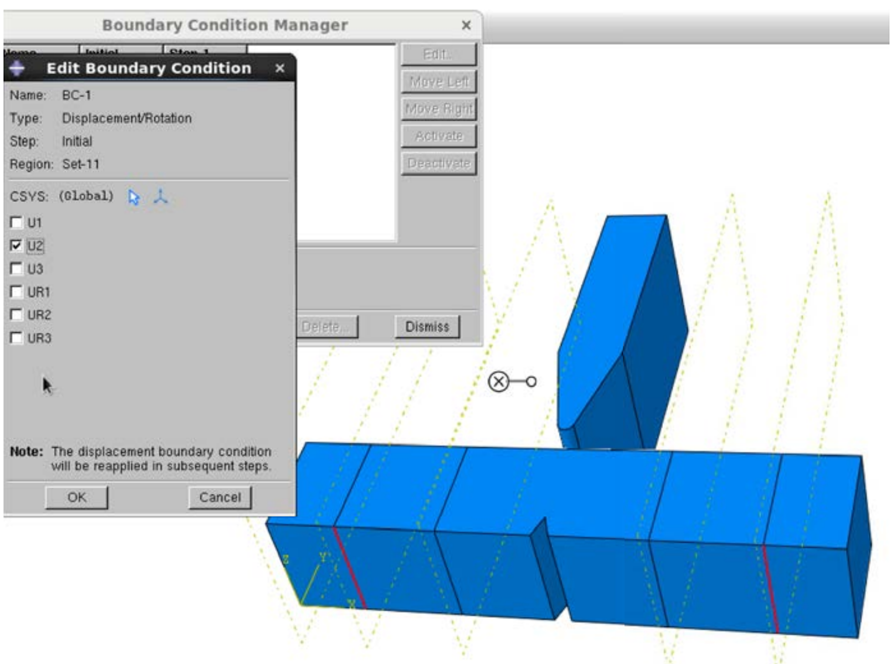

Create Interaction Pr
Name: IntProp-1
Type
Contact
Film condition
Cavity radiation
Fluid cavity
Fluid exchange
Acoustic impedance
Continue...
Cancel

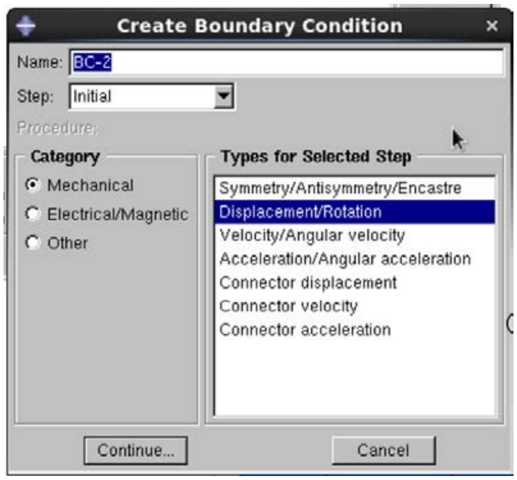

Edit Contact Property
Name: IntProp-1
Contact Property Options
Tangential Behavior
Mechanical Thermal Electrical
Tangential Behavior
Friction formulation: Penalty
Friction Shear Stress Elastic Slip
Directionality: Isotropic Anisotropic (Standard only)
Use slip-rate-dependent data
Use contact-pressure-dependent data
Use temperature-dependent data
Number of field variables: 0
Friction Coeff
.25
OK
Cancel

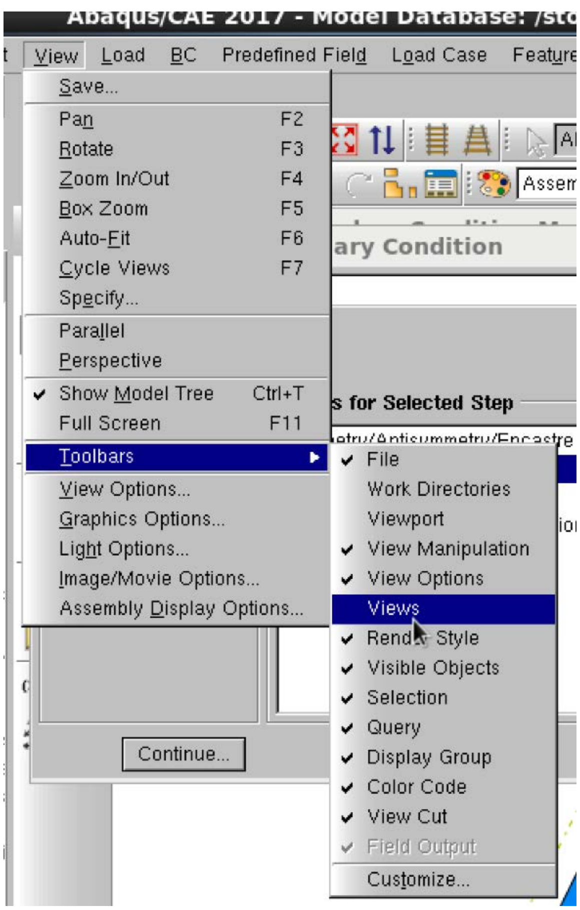

urface
perties
Contact
Formulation
assignment: IntProp-1
rty assignments: None

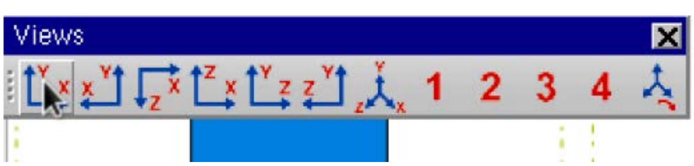

Module: Load

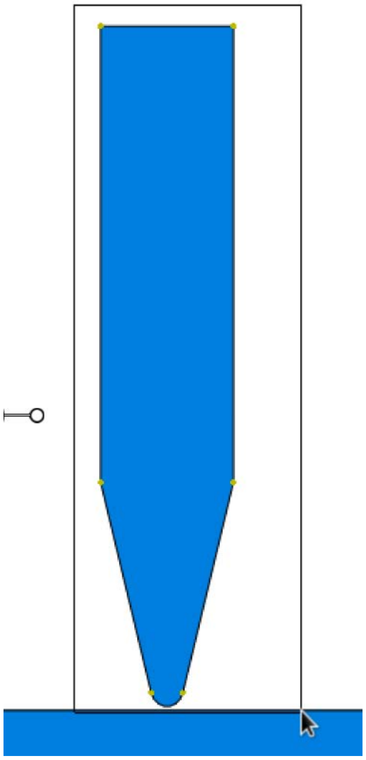

Create Boundary Condition
Name: BC-1
Step: Initial
Procedure:
Category
Mechanical
Electrical/Magnetic
Other
Types for Selected Step
Symmetry/Antisymmetry/Encastre
Displacement/Rotation
Velocity/Angular velocity
Acceleration/Angular acceleration
Connector displacement
Connector velocity
Connector acceleration
Cancel

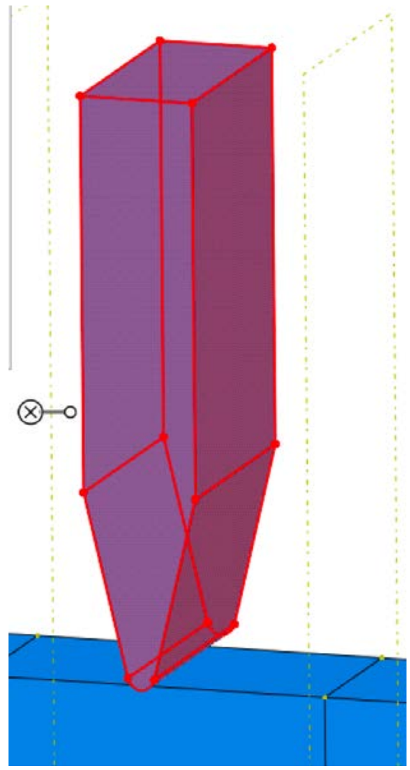

Boundary Condition Manager
Edit Boundary Condition
Name: BC-1
Type: Displacement/Rotation
Step: Initial
Region: Set-11
CSYS: (Global)
U1
U2
U3
UR1
UR2
UR3
Note: The displacement boundary condition will be reapplied in subsequent steps.
OK
Cancel
Dismiss

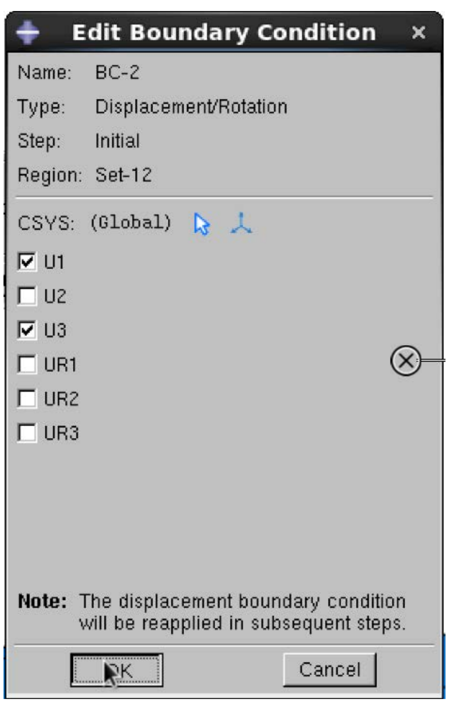

Create Boundary Condition
Name: BC-2
Step: Initial
Procedure:
Category
Mechanical
Electrical/Magnetic
Other
Types for Selected Step
Symmetry/Antisymmetry/Encastre
Displacement/Rotation
Velocity/Angular velocity
Acceleration/Angular acceleration
Connector displacement
Connector velocity
Connector acceleration
Continue...
Cancel

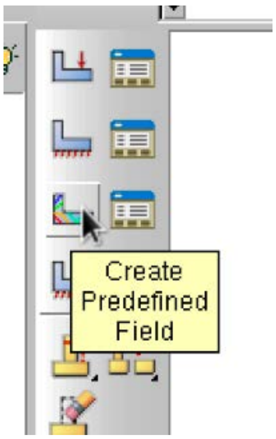

View Load BC Predefined Field Load Case Feature
Save...
Pan F2
Rotate F3
Zoom In/Out F4
Box Zoom F5
Auto-Fit F6
Cycle Views F7
Specify...
Parallel
Perspective
Show Model Tree Ctrl+T
Full Screen F11
Toolbars
View Options...
Graphics Options...
Light Options...
Image/Movie Options...
Assembly Display Options...
File
Work Directories
Viewport
View Manipulation
View Options
Views
Visible Objects
Selection
Query
Display Group
Color Code
View Cut
Field Output
Customize...
s for Selected Step
Continue...

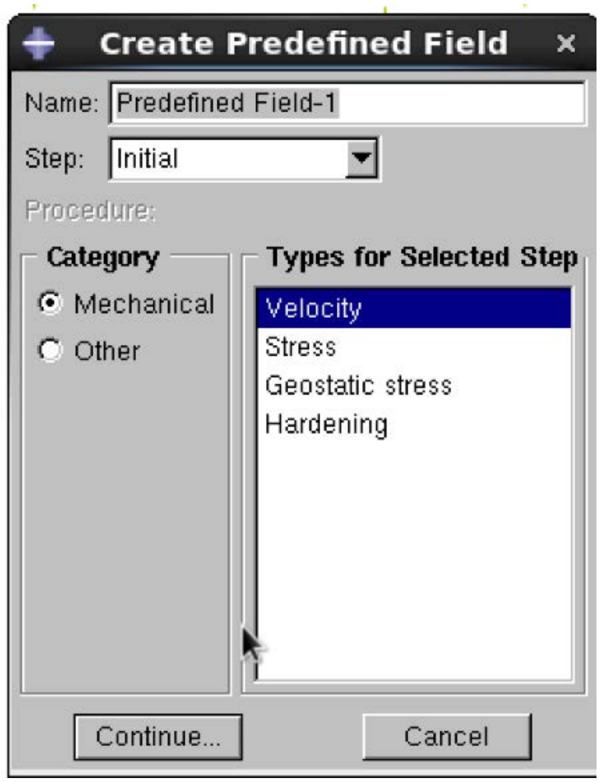

Views
1 2 3 4

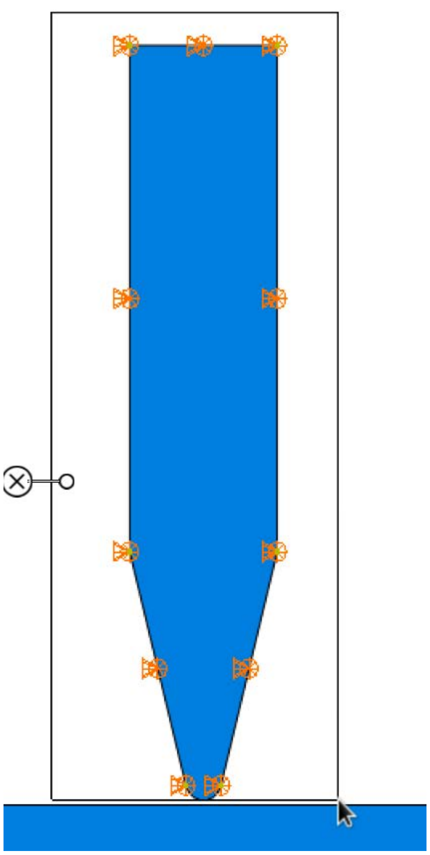


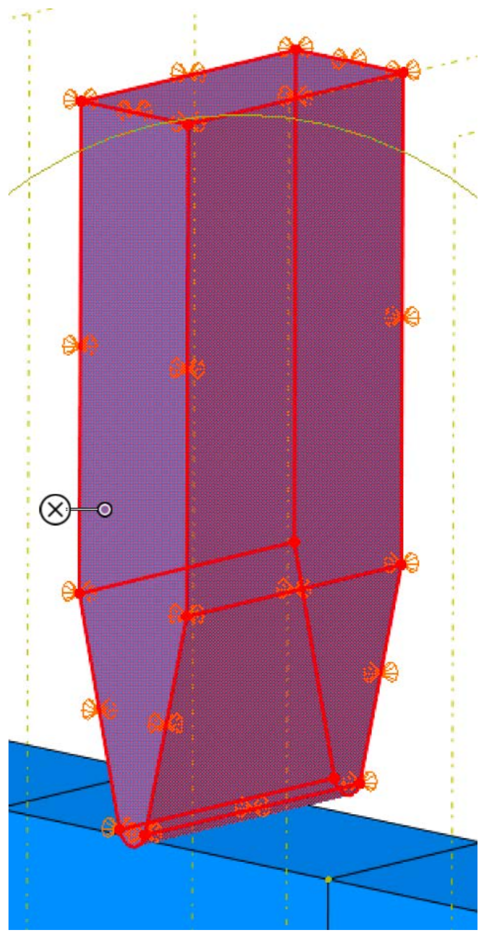


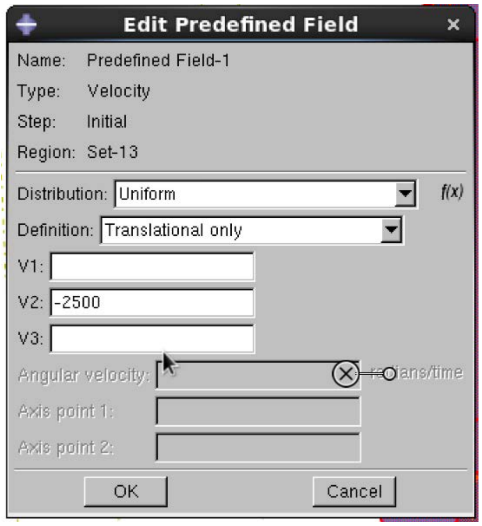

Edit Boundary Condition
Name: BC-2
Type: Displacement/Rotation
Step: Initial
Region: Set-12
CSYS: (Global)
U1
U2
U3
UR1
UR2
UR3
Note: The displacement boundary condition will be reapplied in subsequent steps.
OK
Cancel

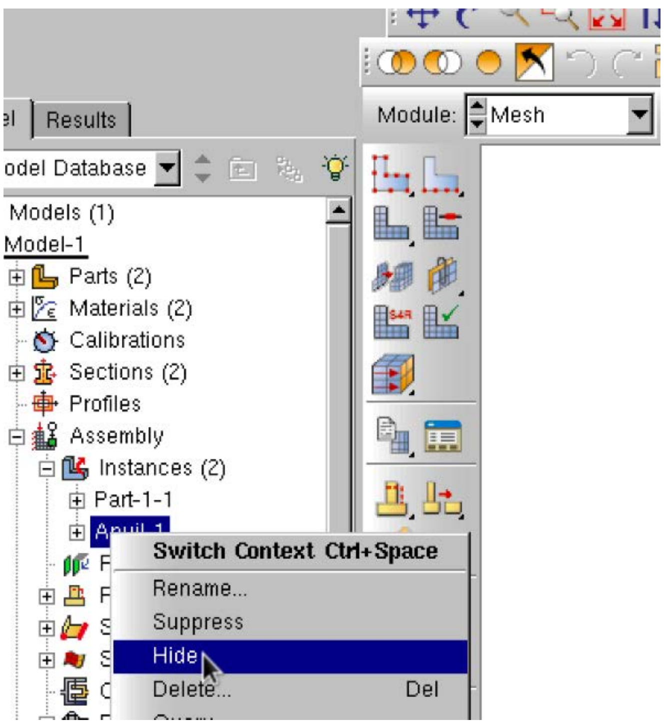

Create
Predefined
Field

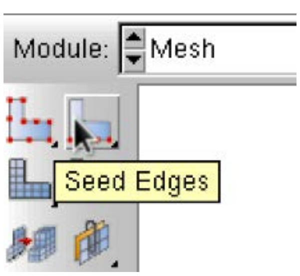

Create Predefined Field
Name: Predefined Field-1
Step: Initial
Procedure:
Category
Mechanical
Other
Types for Selected Step
Velocity
Stress
Geostatic stress
Hardening
Continue...
Cancel

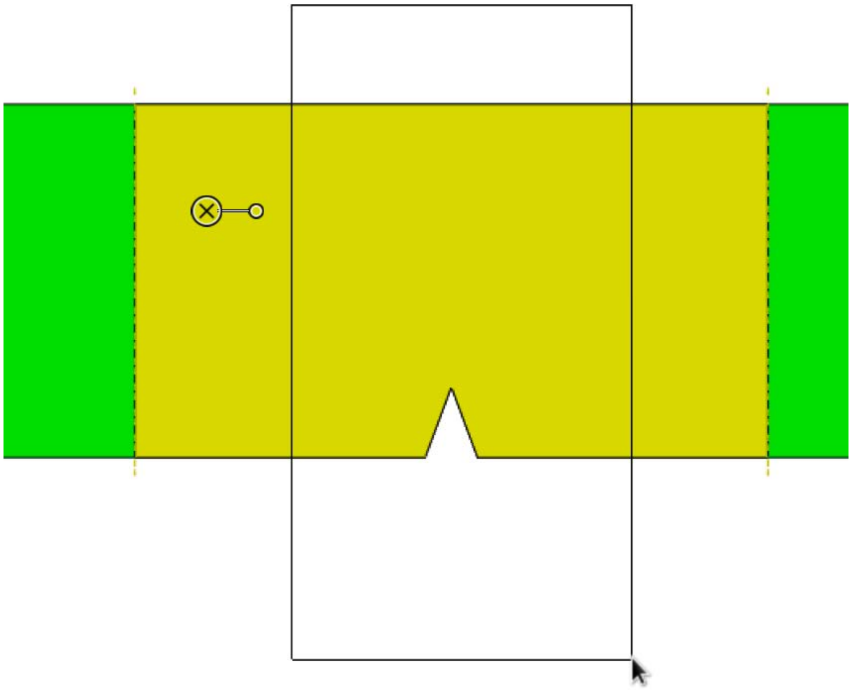


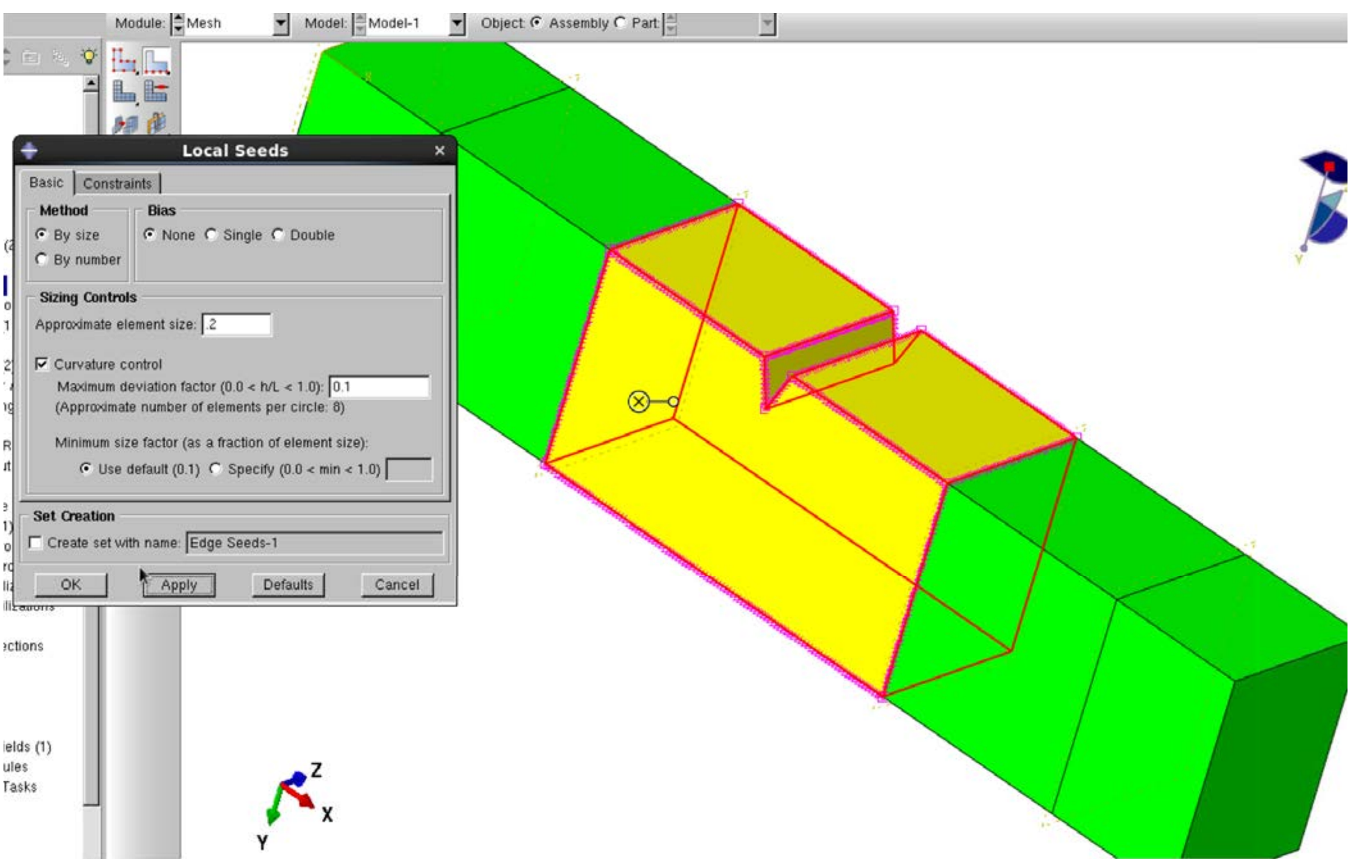


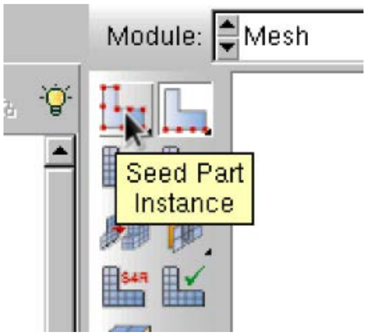

Edit Predefined Field
Name: Predefined Field-1
Type: Velocity
Step: Initial
Region: Set-13
Distribution: Uniform
f(x)
Definition: Translational only
V1:
V2: -2500
V3:
Angular velocity:
Axis point 1:
Axis point 2:
OK
Cancel

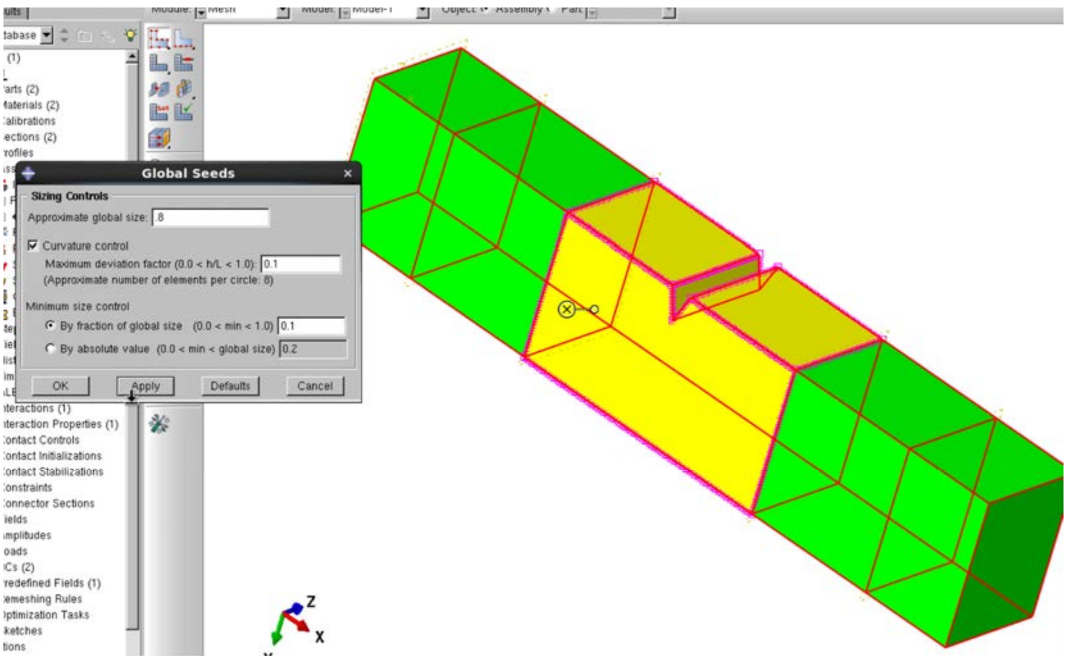

Results
Module: Mesh
Models (1)
Model-1
Parts (2)
Materials (2)
Calibrations
Sections (2)
Profiles
Assembly
Instances (2)
Part-1-1
Switch Context Ctrl+Space
Rename...
Suppress
Hide
Delete... Del

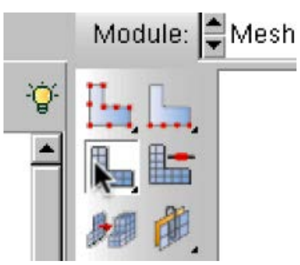

Module: Mesh
Seed Edges

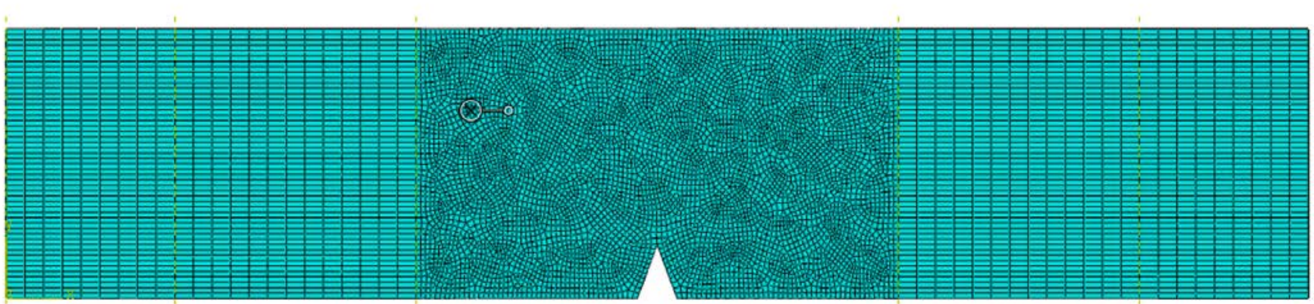


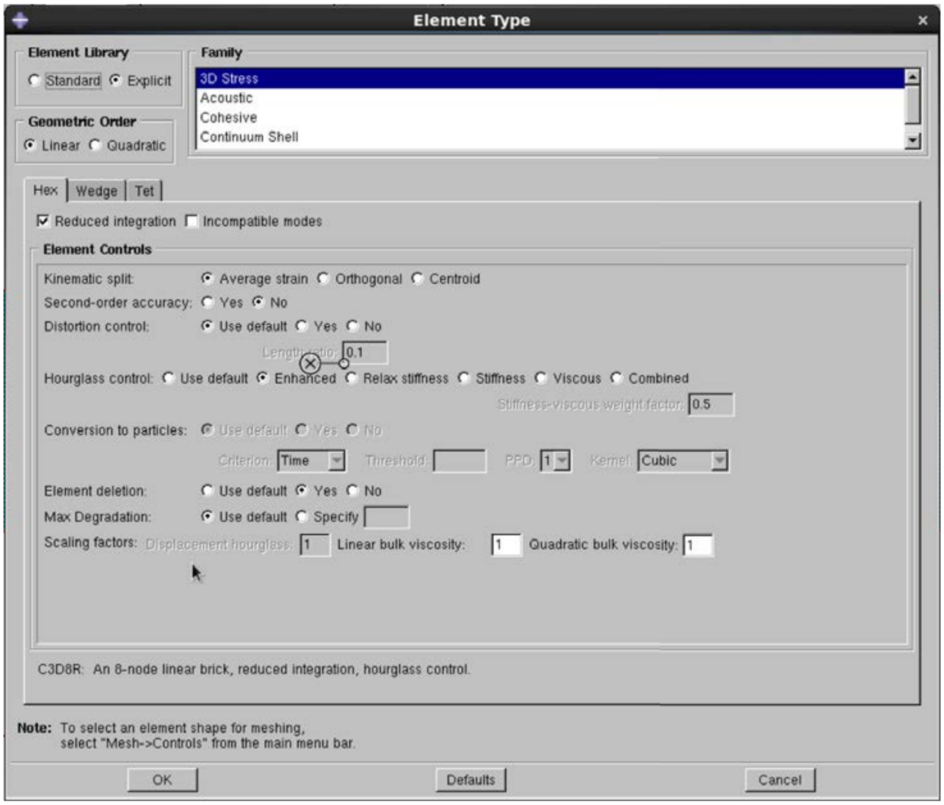

Module: Mesh
Model: Model-1
Object: Assembly Part:
Local Seeds
Basic
Constraints
Method
By size
By number
Bias
None
Single
Double
Sizing Controls
Approximate element size: .2
Curvature control
Maximum deviation factor (0.0 < h/L < 1.0): 0.1
(Approximate number of elements per circle: 8)
Minimum size factor (as a fraction of element size):
Use default (0.1)
Specify (0.0 < min < 1.0)
Set Creation
Create set with name: Edge Seeds-1
OK
Apply
Defaults
Cancel
Z
X
Y

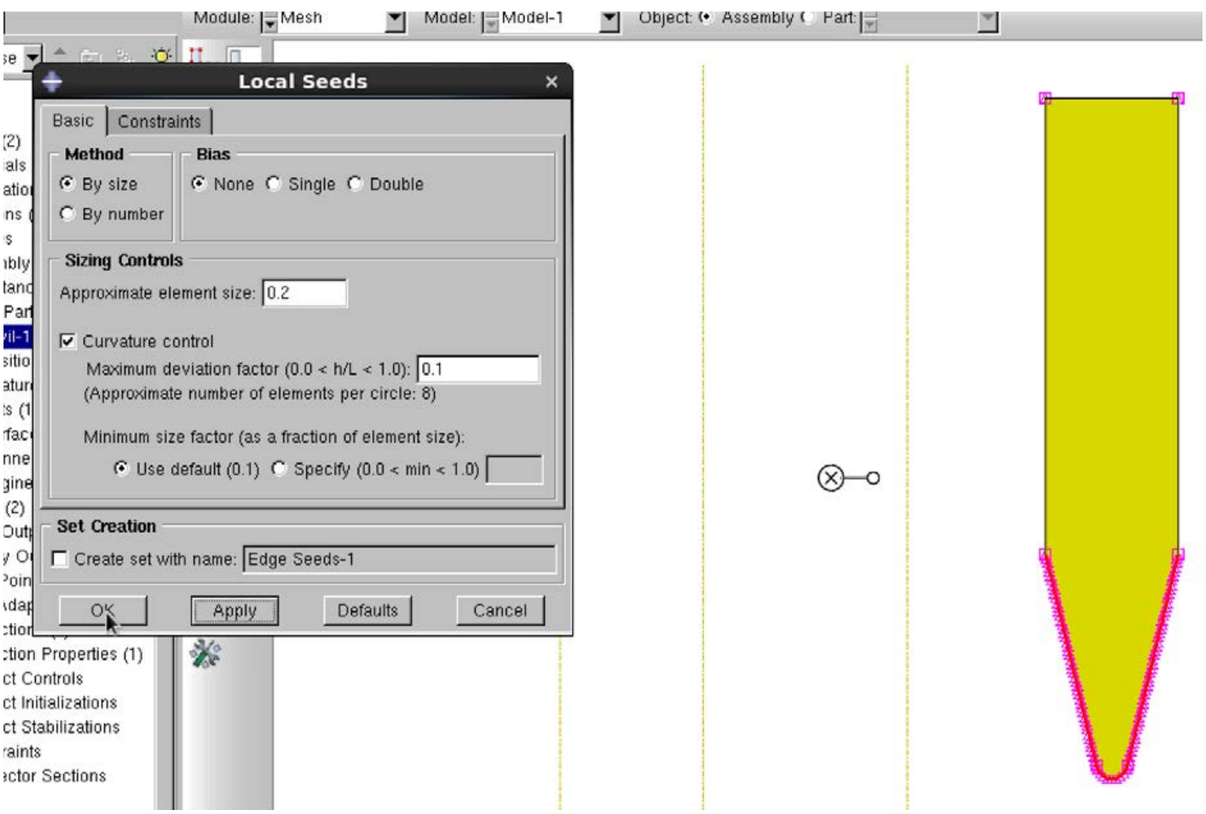

Module:
Mesh
Seed Part Instance

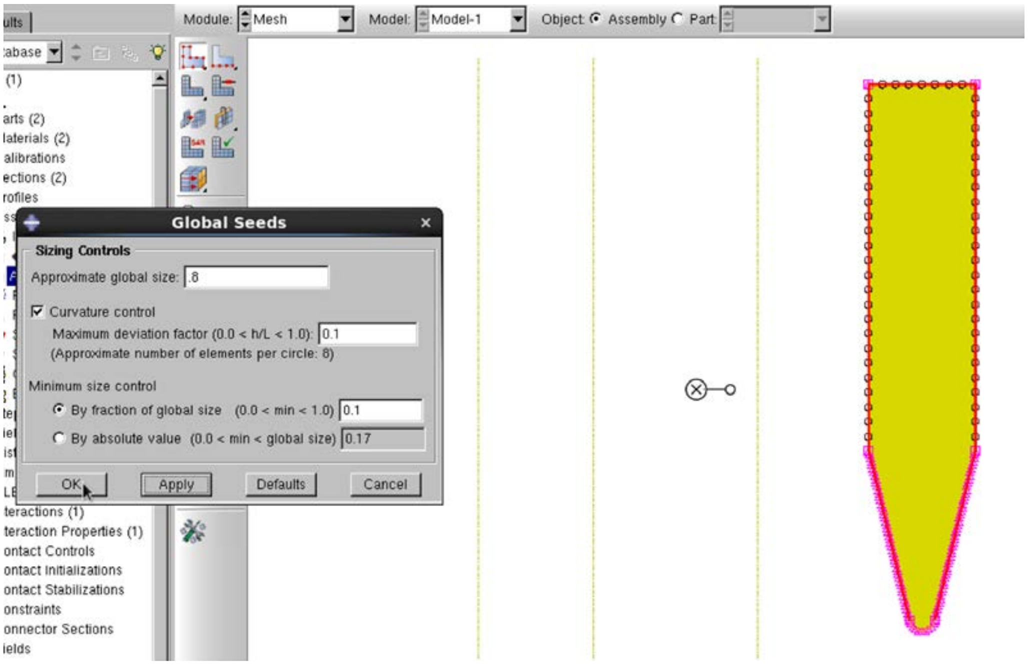

Global Seeds
Sizing Controls
Approximate global size: .8
Curvature control
Maximum deviation factor (0.0 < h/L < 1.0): 0.1
(Approximate number of elements per circle: 8)
Minimum size control
By fraction of global size (0.0 < min < 1.0) 0.1
By absolute value (0.0 < min < global size) 0.2
OK
Apply
Defaults
Cancel

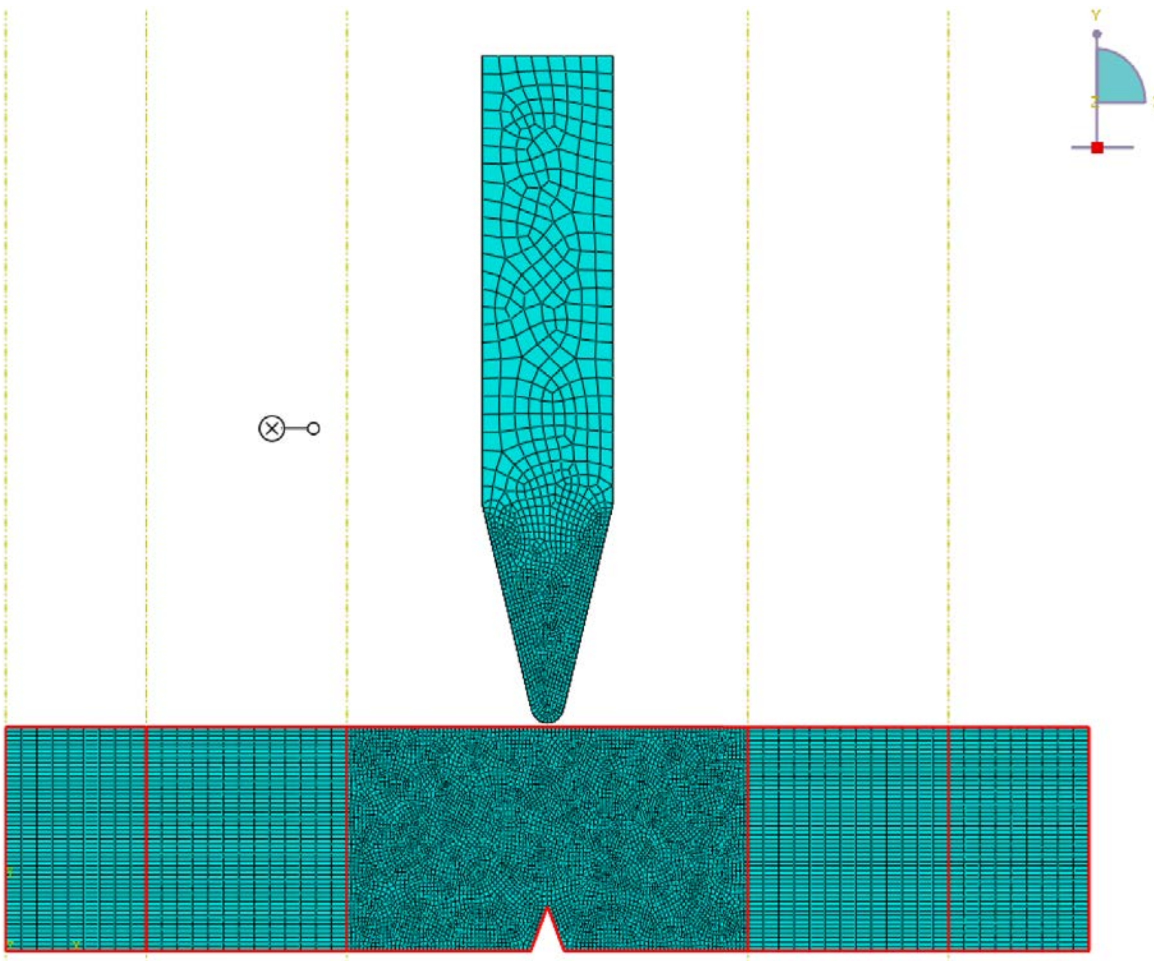

Module:
Mesh

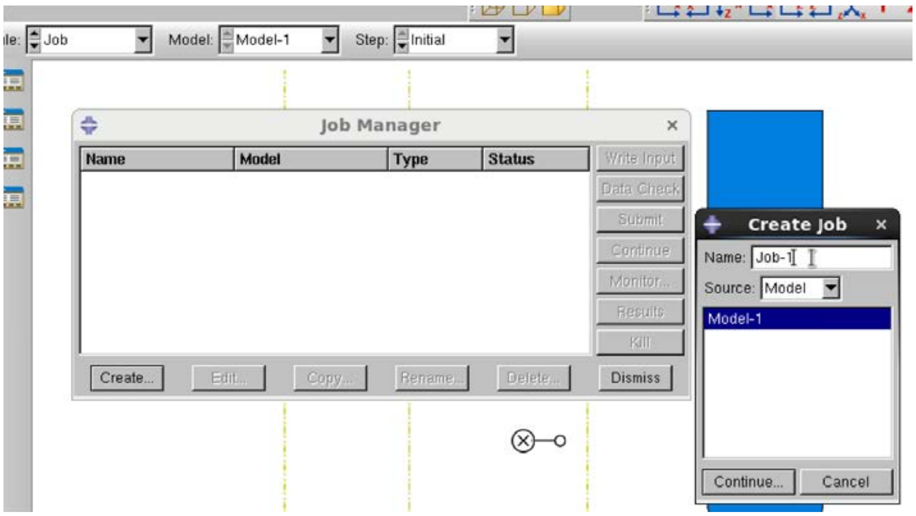


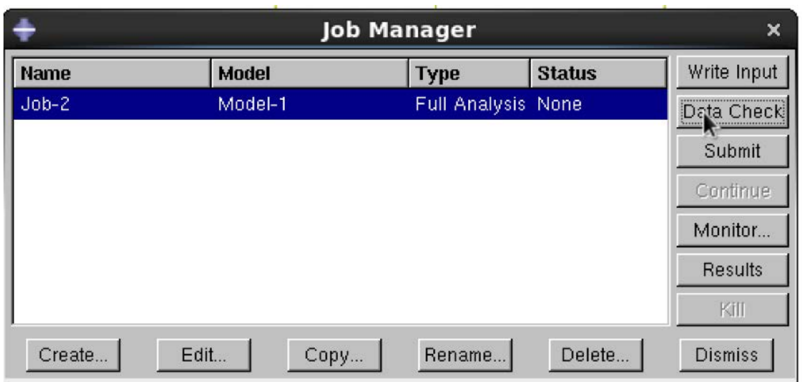

Element Type
Element Library
Standard
Explicit
Family
3D Stress
Acoustic
Cohesive
Continuum Shell
Geometric Order
Linear
Quadratic
Hex
Wedge
Tet
Reduced integration
Incompatible modes
Element Controls
Kinematic split: Average strain Orthogonal Centroid
Second-order accuracy: Yes No
Distortion control: Use default Yes No
Length ratio: 0.1
Hourglass control: Use default Enhanced Relax stiffness Stiffness Viscous Combined
Stiffness-viscous weight factor: 0.5
Conversion to particles: Use default Yes No
Criterion: Time Threshold: PPD: 1 Kernel: Cubic
Element deletion: Use default Yes No
Max Degradation: Use default Specify
Scaling factors: Displacement hourglass: 1 Linear bulk viscosity: 1 Quadratic bulk viscosity: 1
C3D8R: An 8-node linear brick, reduced integration, hourglass control.
Note: To select an element shape for meshing, select "Mesh->Controls" from the main menu bar.
OK
Defaults
Cancel

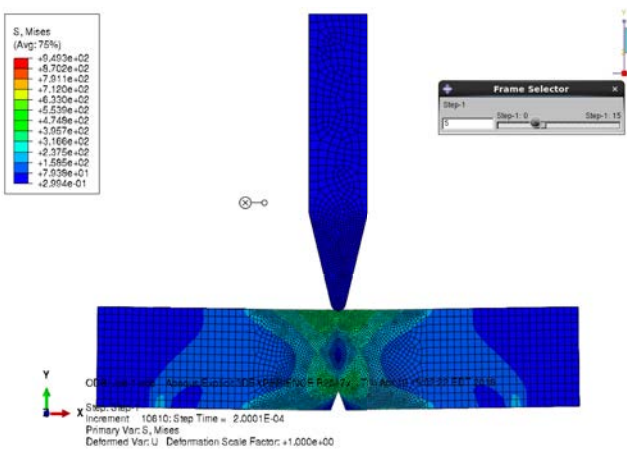

Module: Mesh
Model: Model-1
Object: Assembly Part:
Local Seeds
Basic
Constraints
Method
By size
By number
Bias
None
Single
Double
Sizing Controls
Approximate element size: 0.2
Curvature control
Maximum deviation factor (0.0 < h/L < 1.0): 0.1
(Approximate number of elements per circle: 8)
Minimum size factor (as a fraction of element size):
Use default (0.1)
Specify (0.0 < min < 1.0)
Set Creation
Create set with name: Edge Seeds-1
OK
Apply
Defaults
Cancel

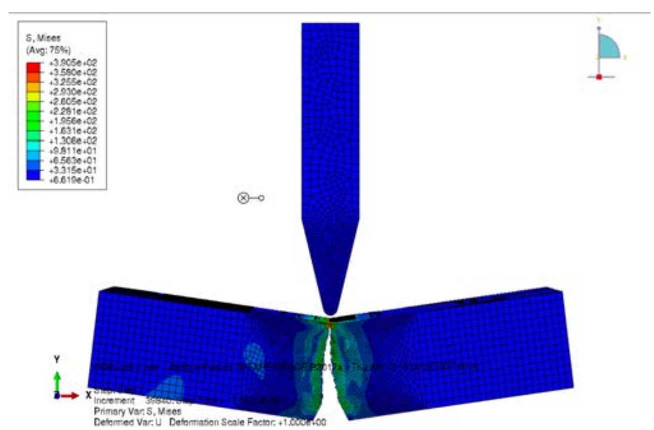

Module: Mesh
Model: Model-1
Object: Assembly Part:
Global Seeds
Sizing Controls
Approximate global size: .8
Curvature control
Maximum deviation factor (0.0 < h/L < 1.0): 0.1
(Approximate number of elements per circle: 8)
Minimum size control
By fraction of global size (0.0 < min < 1.0) 0.1
By absolute value (0.0 < min < global size) 0.17
OK
Apply
Defaults
Cancel

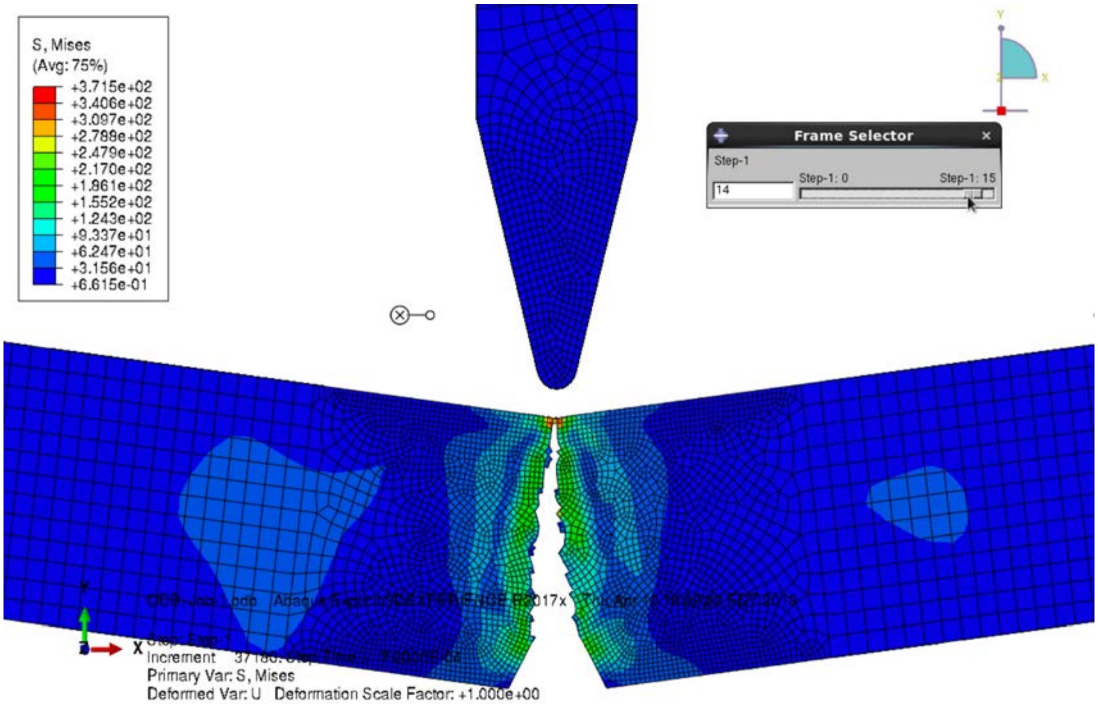

Y
X


Module: Job
Model: Model-1
Step: Initial
Job Manager
Name
Model
Type
Status
Write Input
Data Check
Submit
Continue
Monitor...
Results
Kill
Create...
Edit...
Copy...
Rename...
Delete...
Dismiss
Create Job
Name: Job-1
Source: Model
Model-1
Continue...
Cancel


Job Manager
Name
Model
Type
Status
Job-2
Model-1
Full Analysis
None
Write Input
Data Check
Submit
Continue
Monitor...
Results
Kill
Create...
Edit...
Copy...
Rename...
Delete...
Dismiss






S, Mises
(Avg: 75%)
+3.715e+02
+3.406e+02
+3.097e+02
+2.788e+02
+2.479e+02
+2.170e+02
+1.861e+02
+1.552e+02
+1.243e+02
+9.337e+01
+6.247e+01
+3.156e+01
+6.615e-01
Frame Selector
Step-1
14
Step-1: 0
Step-1: 15
Increment
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +1.000e+00