دانشگاه صنعتی اصفهان

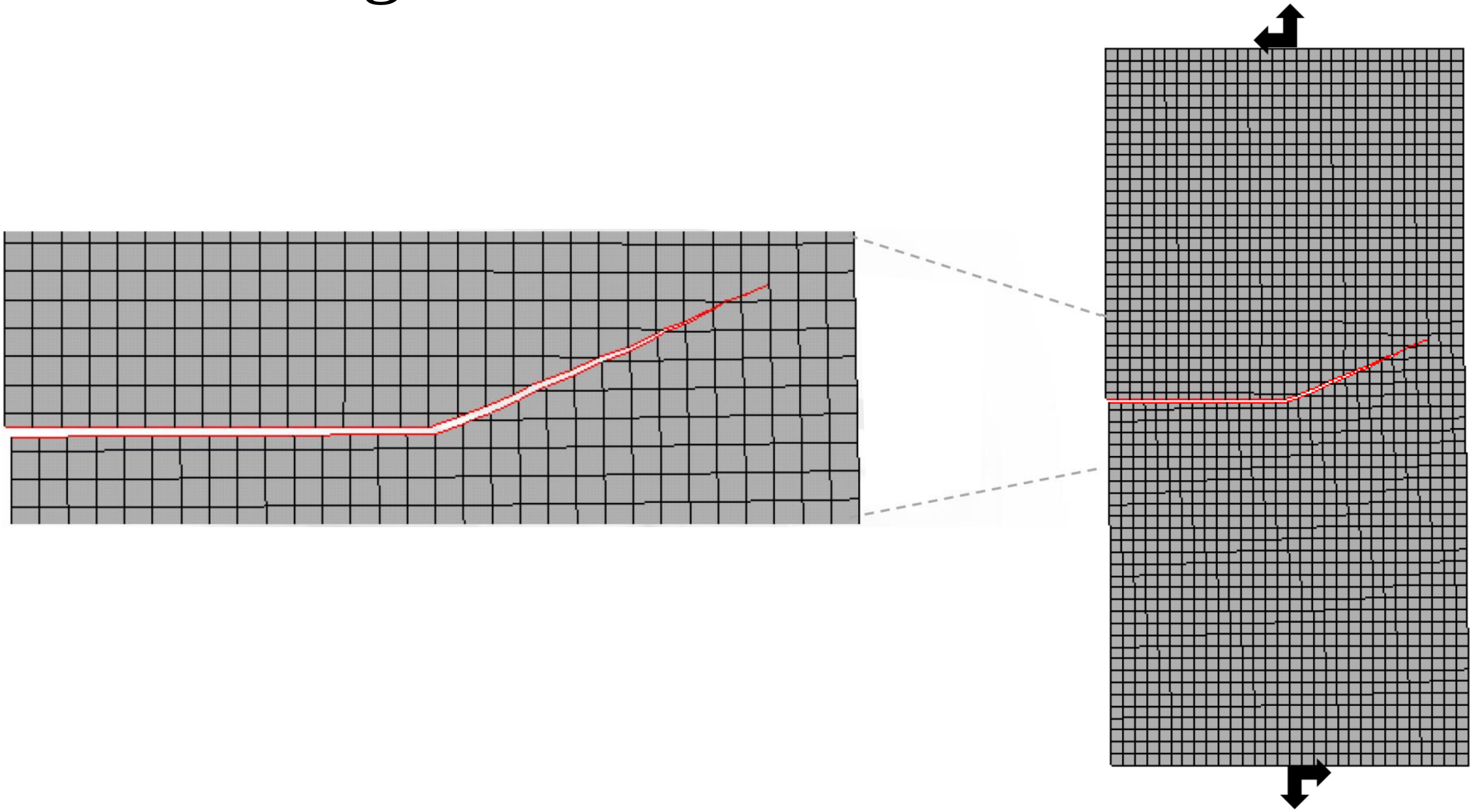
دانشکده مکانیک

Modeling Fracture with Abaqus (2)

Modeling Fracture with Abaqus

- ❖ Modeling Cracks
- ❖ Calculation of Contour Integrals
- ❖ Creating an XFEM Fracture Model

Creating an XFEM Fracture Model



Introduction of XFEM

- The XFEM modeling technique…
  - Can be used in conjunction with the cohesive zone model or the virtual crack closure technique
    - Delamination can be modeled in conjunction with bulk crack propagation
  - Can determine the load carrying capacity of a cracked structure
    - What is the maximum allowable flaw size for safe operation?
- Applications of this technique include the modeling of bulk fracture and the modeling of failure in composites
  - Cracks in pressure vessels or engineering structures
  - Delamination and through-thickness crack modeling in composite plies

Introduction of XFEM

- Some advantages of the method:
  - •Ease of initial crack definition
    - •Mesh is generated independent of crack
    - •Partitioning of geometry not needed as when a crack is represented explicitly
  - •Nonlinear material and nonlinear geometric analysis
  - •Arbitrary solution-dependent crack initiation and propagation path
    - •Crack path does not have to be specified a priori
  - •Mesh refinement studies are much simpler
    - •Reduced remeshing effort
  - •Improved convergence rate for the finite element solution (stationary crack)
    - •Due to the use of singular crack tip enrichment

Introduction of XFEM

- Mesh-independent Crack Modeling –Basic Ingredients

1. Need a way to incorporate discontinuous geometry –the crack –and the discontinuous solution field into the finite element basis functions

    - e**X**tended **F**inite **E**lement **M**ethod (XFEM)

2. Need to quantify the magnitude of the discontinuity –the displacement jump across the crack faces

    - Cohesive zone model (CZM)

3. Need a method to locate the discontinuity

    - Level set method (LSM)

4. Crack initiation and propagation criteria

    - At what level of stress or strain does the crack initiate?
    - What is the direction of propagation?

Basic XFEM Concepts

- XFEM Displacement Interpolation

Heaviside enrichment term

$H(x)$: Heaviside distribution

a_I: Nodal enriched DOF (jump discontinuity)

N_Γ: Nodes belonging to elements cut by crack

$$\mathbf{u}^h(\mathbf{x}) = \sum_{I\in N} N_I(\mathbf{x})\left[\mathbf{u}_I + \underbrace{H(x)a_I}_{I\in N_\Gamma} + \underbrace{\sum_{\alpha=1}^{4} F_\alpha(\mathbf{x})\, b_I^\alpha}_{I\in N_\Lambda}\right]$$

u_I: Nodal DOF for conventional shape functions N_I

Crack tip enrichment term

$F_\alpha(x)$: Crack tip asymptotic functions

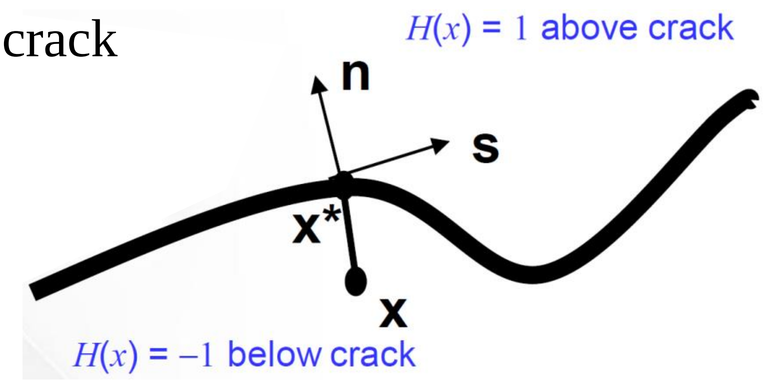
b_I^α: Nodal enriched DOF (jump discontinuity)

N_Λ: Nodes belonging to elements containing crack tip

Basic XFEM Concepts

- The crack tip and Heaviside enrichment functions are multiplied by the conventional shape functions
  - Hence enrichment is local around the crack
  - Sparsity of the resulting matrix equations is preserved
- The crack is located using the level set method (discussed shortly)
- Heaviside function
  - Accounts for displacement jump across crack

$$H(x) = \begin{cases} 1 & \text{if } (\boldsymbol{x} - \boldsymbol{x}^*).\boldsymbol{n} \geq 0 \\ -1 & \text{otherwise} \end{cases}$$



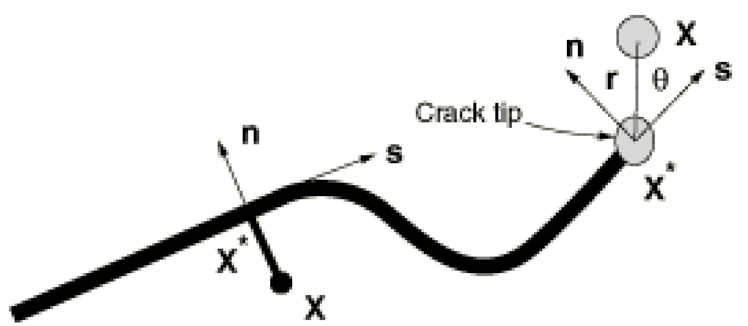
Here $\boldsymbol{x}$ is an integration point, $\boldsymbol{x}^*$ is the closest point to $\boldsymbol{x}$ on the crack face and $\boldsymbol{n}$ is the unit normal at $\boldsymbol{x}^*$

Basic XFEM Concepts

- Crack Tip Enrichment Functions (Stationary Crack Only)
  - Account for crack tip singularity
  - Use displacement field basis functions for sharp crack in an isotropic linear elastic material

$$[F_\alpha(\mathbf{x}), \alpha = 1-4] = [\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\theta\sin\frac{\theta}{2}, \sqrt{r}\sin\theta\cos\frac{\theta}{2}]$$

  - Accounts for displacement jump across crack



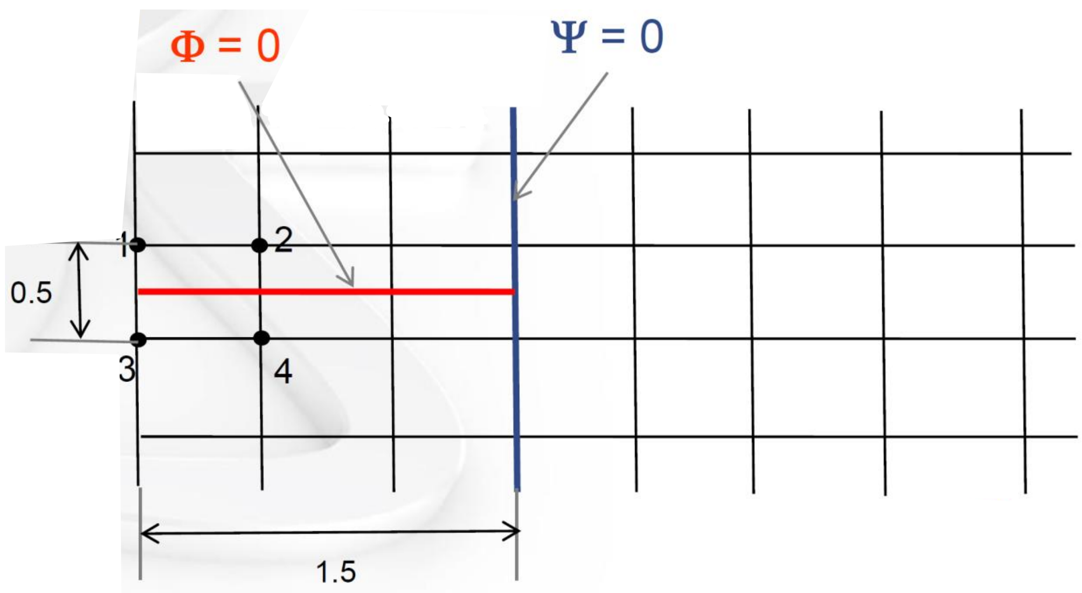
Basic XFEM Concepts

- Level Set Method for Locating a Crack
  - A level set (also called level surface or isosurface) of a real-valued function is the set of all points at which the function attains a specified value
  - Popular technique for representing surfaces in interface tracking problems
  - Two functions Φ and Ψ are used to completely describe the crack
    - The level set Φ= 0 represents the crack face
    - The intersection of level sets Ψ= 0 and Φ= 0 denotes the crack front
    - Functions are defined by nodal values whose spatial variation is determined by the usual finite element shape functions
    - Function values need to be specified only at nodes belonging to elements cut by the crack
  - Uses signed distance functions to describe the crack geometry
  - No explicit representation of the crack is needed and the crack is entirely described by nodal data

Basic XFEM Concepts

- Calculating Φ and Ψ
  - The nodal value of the function Φ is the signed distance of the node from the crack face
    - Positive value on one side of the crack face, negative on the other
  - The nodal value of the function Ψ is the signed distance of the node from an almost-orthogonal surface passing through the crack front
    - The function Ψ has zero value on this surface and is negative on the side towards the crack

Node	Φ	Ψ
1	+0.25	–1.5
2	+0.25	–1.0
3	–0.25	–1.5
4	–0.25	–1.0



Basic XFEM Concepts

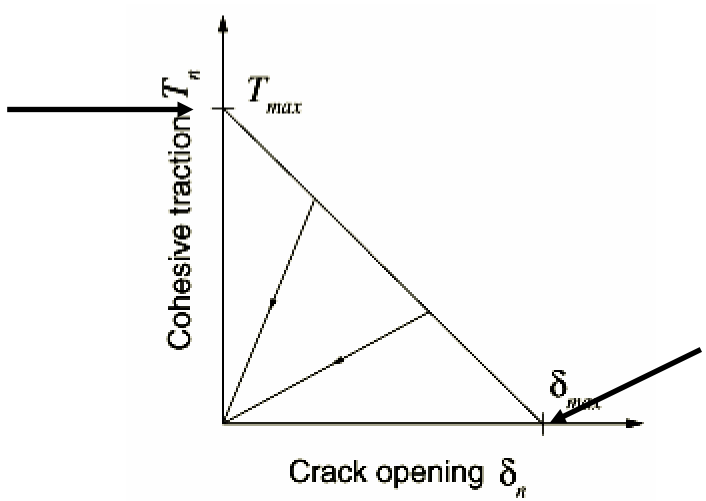
➢ Propagation cracks

- Assumptions
  - Near-tip asymptotic singularity is not considered
  - Crack has to propagate across an entire element at a time to avoid the need to model the stress singularity
  - Effective engineering approach
- Two distinct types of damage modeling within an XFEM framework
  - Cohesive segments approach
  - Linear elastic fracture mechanics (LEFM) approach
- Cohesive segment approach
  - Uses traction-separation laws
  - Follows the general framework for surface based cohesive behavior
  - Damage properties are specified as part of the bulk material definition
- LEFM-based approach
  - Uses the virtual crack closure technique (VCCT)
  - VCCT for XFEM uses the same principles as in VCCT for interfacial debonding
  - Damage properties are specified via an interaction property assigned to the XFEM crack

Damage Modeling

- Damage modeling is achieved through the use of a traction-separation law across the fracture surface
- It follows the general framework:
  - Damage initiation
  - Damage evolution
  - Traction-free crack faces at failure
- Damage properties are specified as part of the bulk material definition

Damage initiation



Failure

Damage Modeling

- Damage Initiation
  - Two criteria available at present
    - Maximum principal stress criterion (MAXPS) $f = \frac{\langle \sigma_{max} \rangle}{\sigma^0_{max}}$

Initiation occurs when the maximum principal stress reaches critical value

    - Maximum principal strain criterion (MAXPE) $f = \frac{\langle \varepsilon_{max} \rangle}{\varepsilon^0_{max}}$

Initiation occurs when the maximum principal strain reaches critical value

- Crack plane is perpendicular to the direction of the maximum principal stress (or strain)
- Crack initiation occurs at the center of the element

However, crack propagation is arbitrary through the mesh

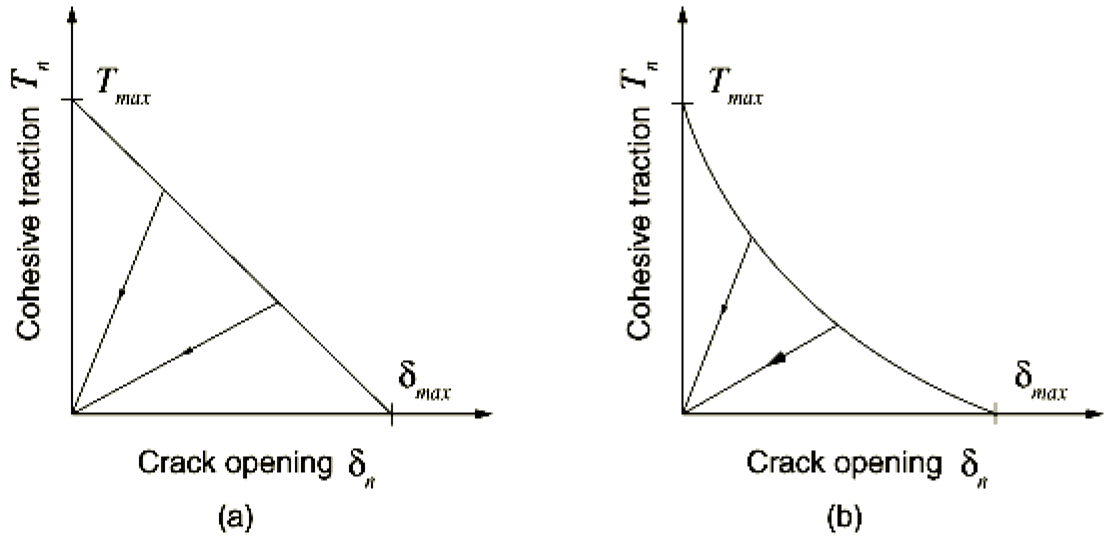
- The damage initiation criterion is satisfied when $1.0 \leq f \leq 1.0 + f_{tol}$ where f is the selected damage criterion and f_{tol} is a user-specified tolerance value

Cohesive segments approach

Damage Modeling

- Damage Evolution

  - Any of the damage evolution models for traction-separation laws
  - However, it is not necessary to specify the undamaged traction-separation response



Damage Modeling

- Damage Stabilization

  - Fracture makes the structural response nonlinear and non-smooth

    Numerical methods have difficulty converging to a solution

  - Using viscous regularization helps with the convergence of the Newton method

  - The stabilization value must be chosen so that the problem definition does not change

    - A small value regularizes the analysis, helping with convergence while having a minimal effect on the response
    - Perform a parametric study to choose appropriate value for a class of problems

Damage Modeling

- User defined damage initiation subroutine UDMGINI
  - Can be used to specify a user-defined damage initiation criterion.
  - Allows the specification of more than one failure mechanisms in an element with the most severe one governing the actual failure.
  - Can be used in combination with several Abaqus built-in damage evolution models, with each model corresponding to a particular failure mechanism.

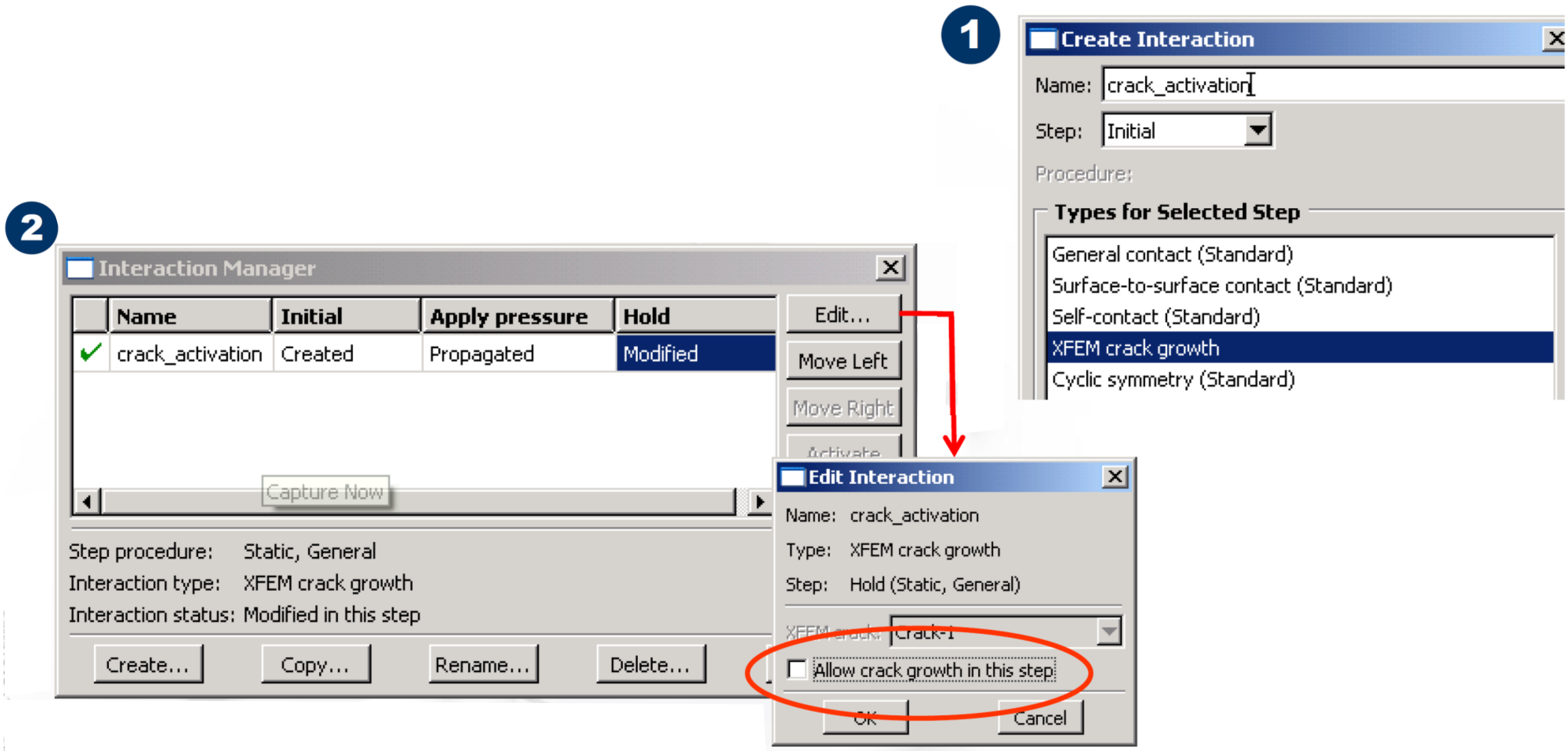
Creating an XFEM Fracture Model

- Steps

1. Define damage criteria in the material model
2. Define an enrichment region (the associated material model should include damage)
    - Crack type –stationary or propagation
3. Define an initial crack, if present
4. If needed, set analysis controls to aid convergence

Creating an XFEM Fracture Model

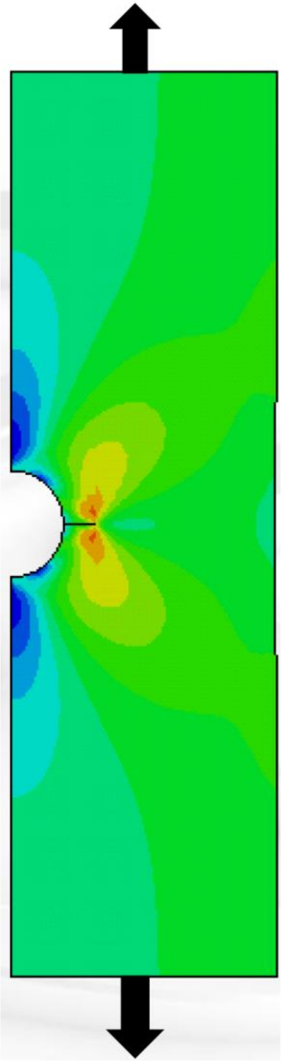
- Step-dependent Enrichment Activation
  - Crack growth can be activated or deactivated in analysis steps



Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

- Model crack initiation and propagation in a plate with a hole
    - Crack initiates at the location of maximum stress concentration
    - Half model is used taking advantage of symmetry

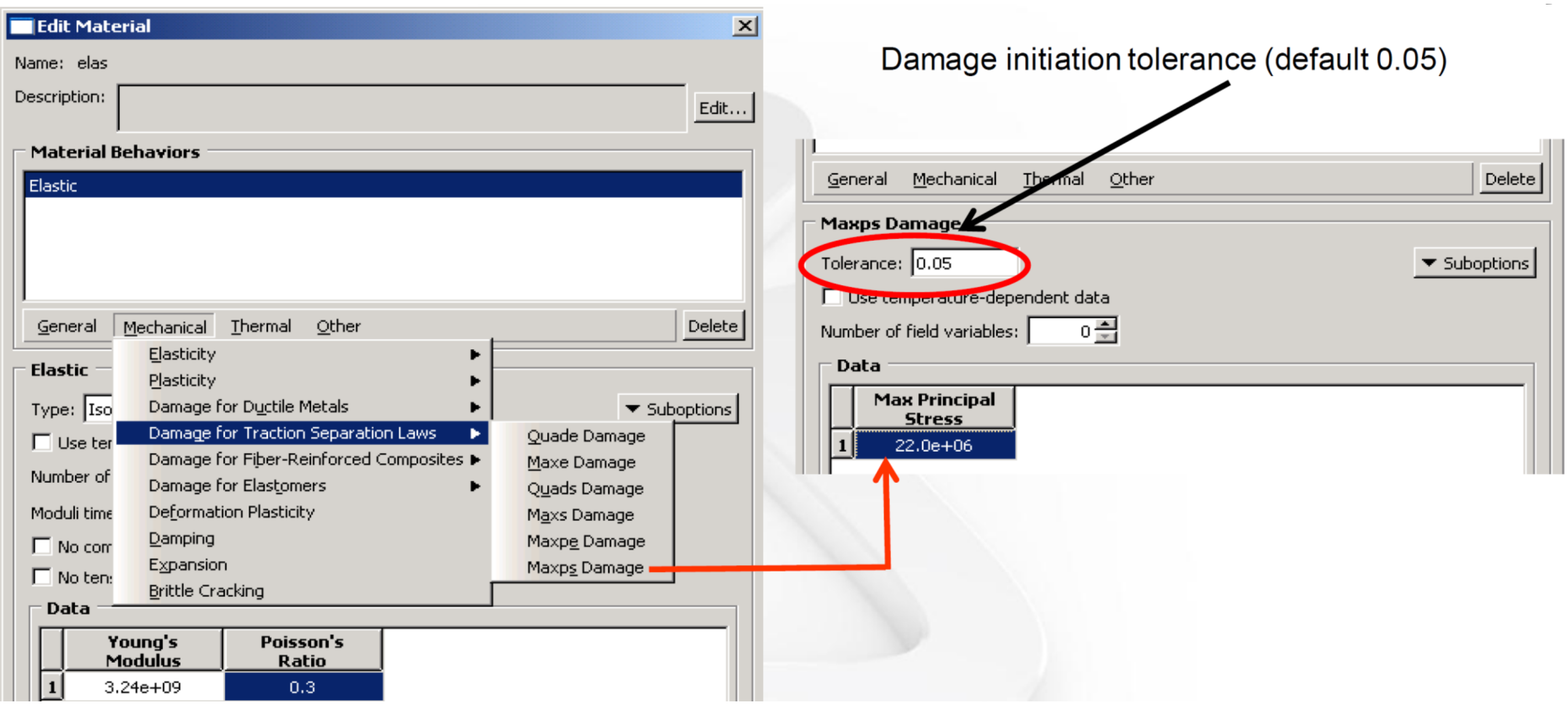


Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

1 Define the damage criteria

- Damage initiation

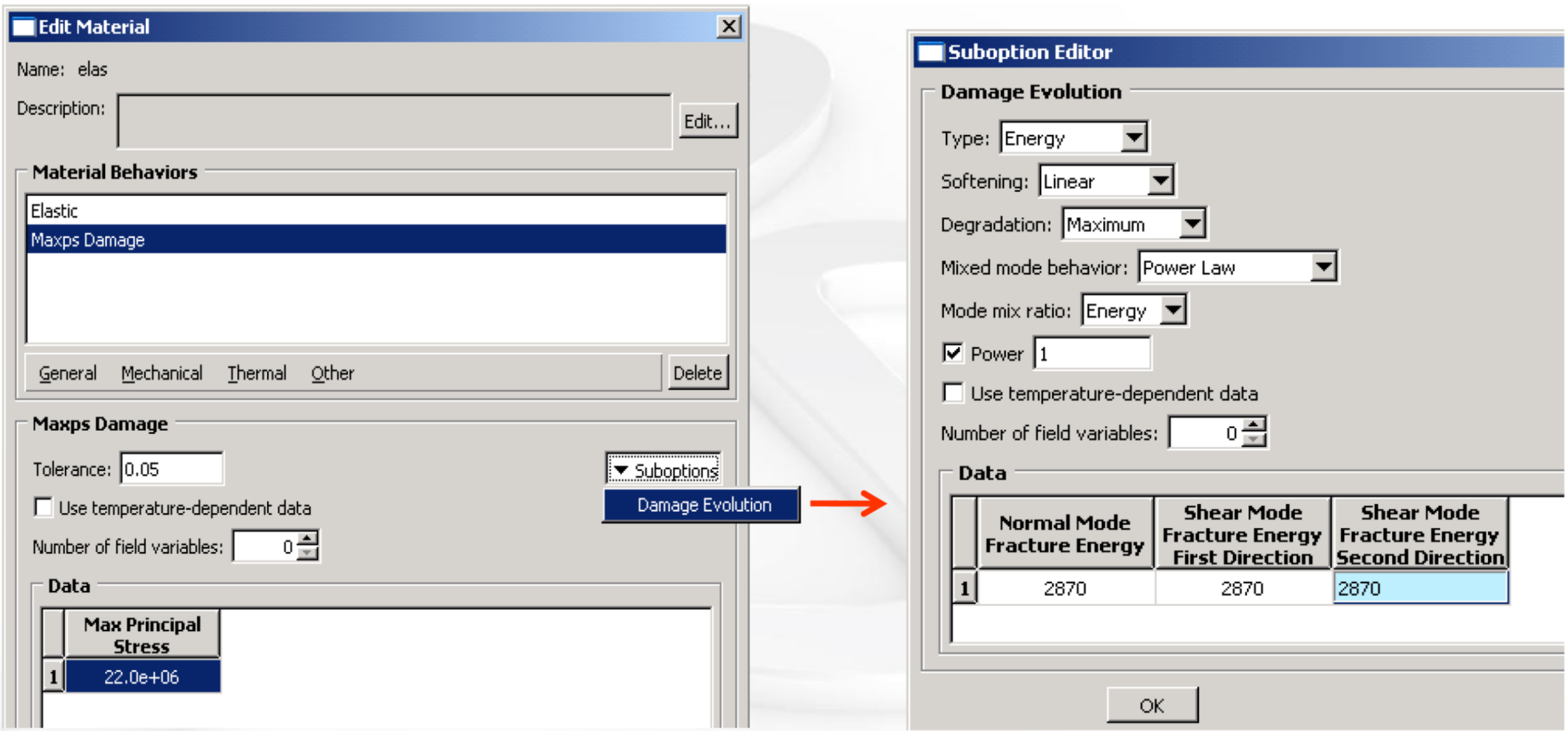


Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

1 Define the damage criteria

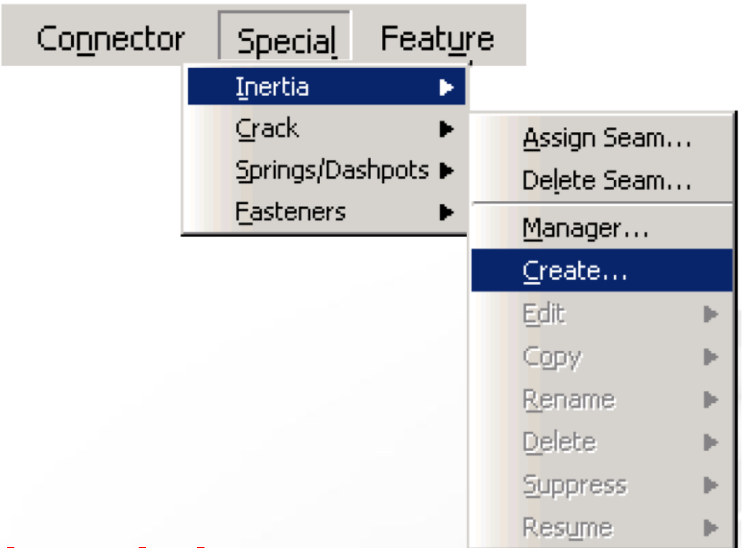
- Damage evolution

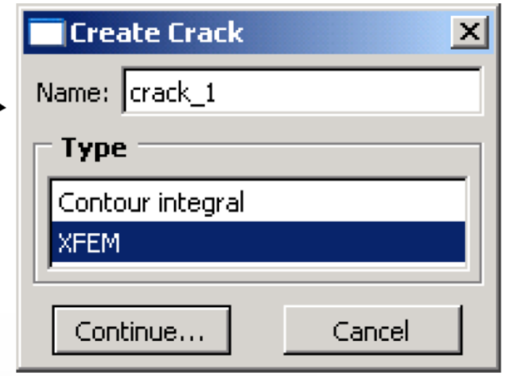


Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

2 Define the enriched region

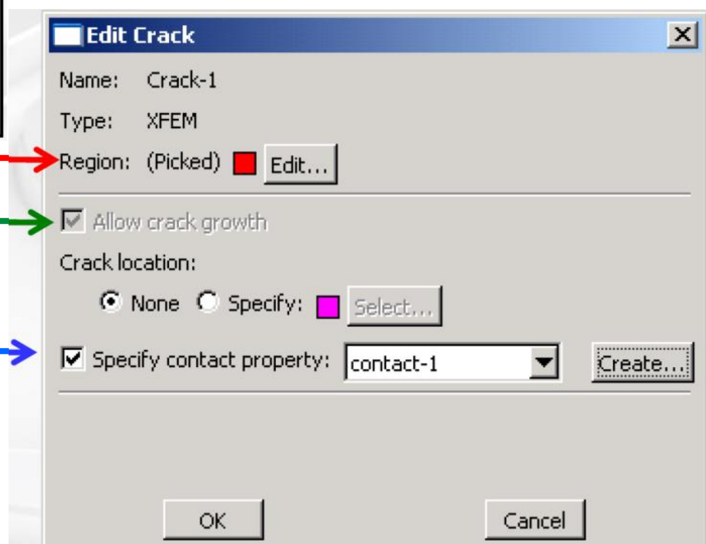


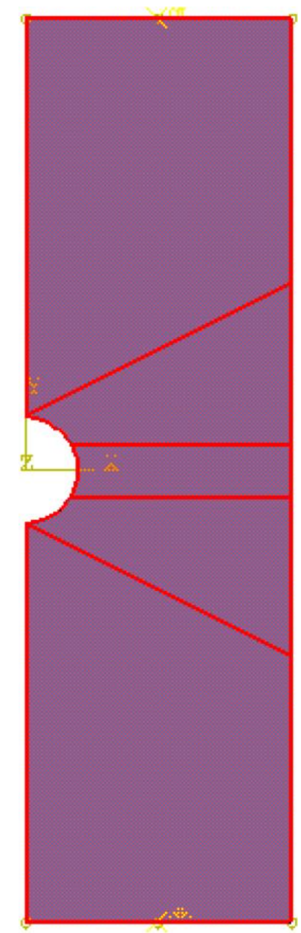


Pick enriched region

Propagating crack

Specify contact interaction
(frictionless small-sliding contact only)





Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

2 Define the enriched region

Keyword interface

```
*ENRICHMENT, TYPE=PROPAGATION CRACK, NAME=CRACK-1,
ELSET=SELECTED_ELEMENTS, INTERACTION=CONTACT-1
```

Frictionless small-sliding contact interaction

3 No initial crack definition is needed

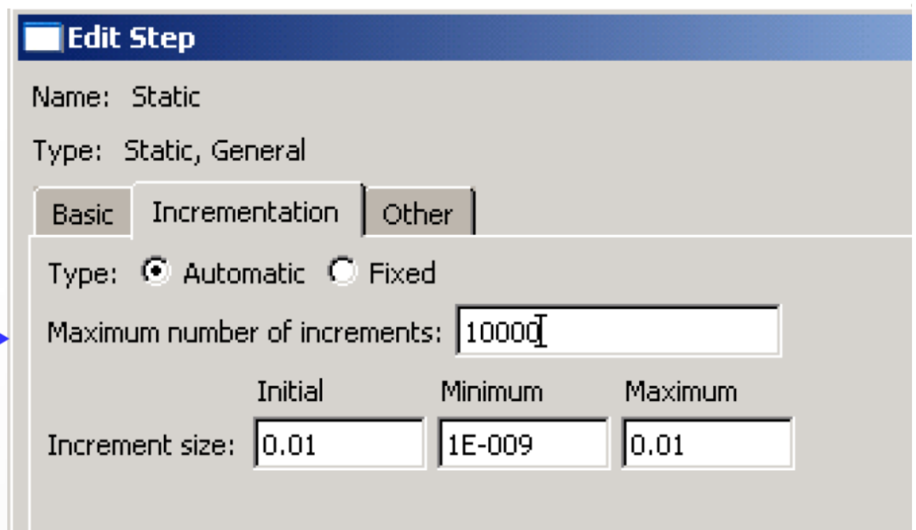
- Crack will initiate based on specified damage criteria

Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

4 Set analysis controls to improve convergence behavior

- Set reasonable minimum and maximum increment sizes for step
- Increase the number of increments for step from the default value of 100

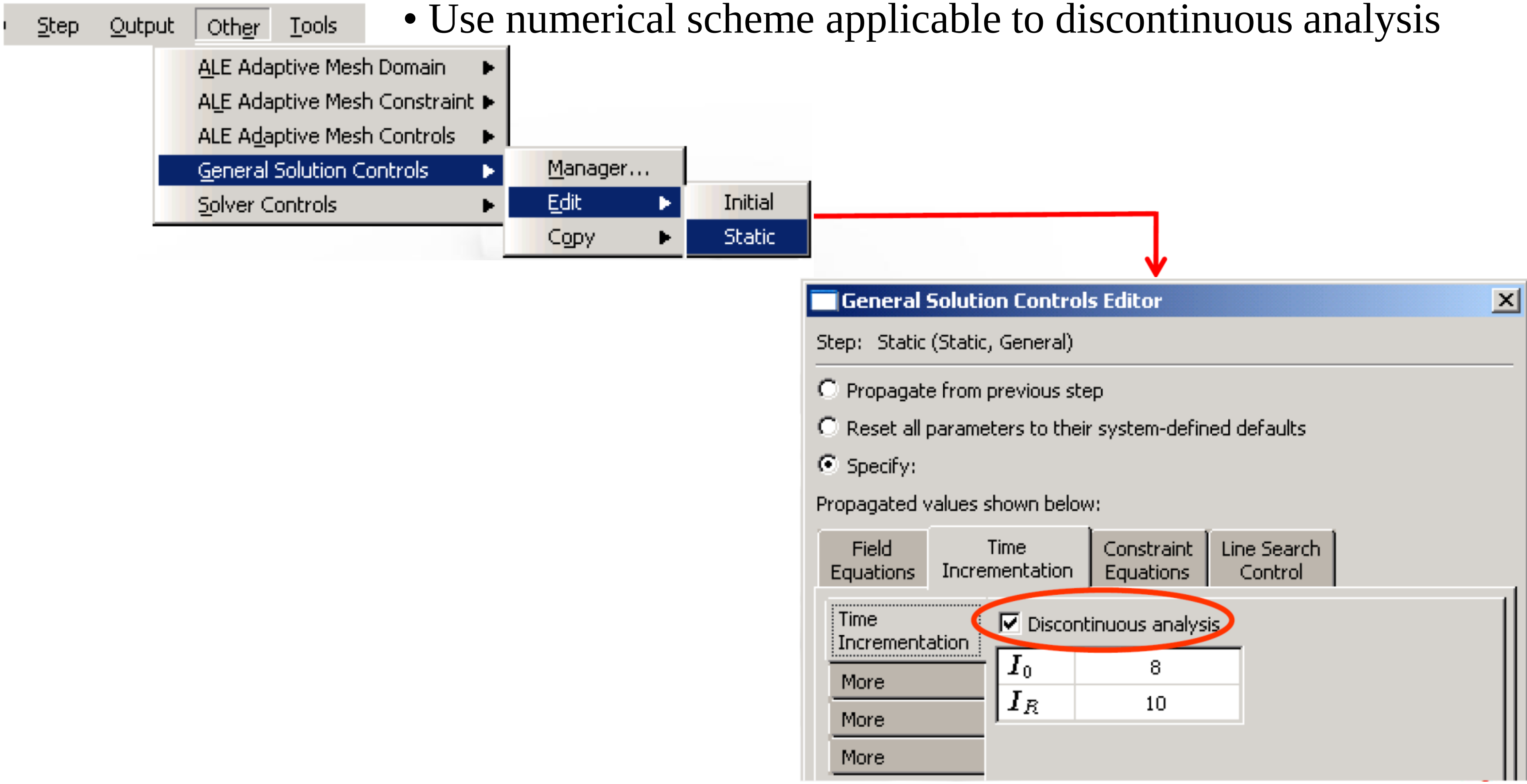


Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

4 Set analysis controls to improve convergence behavior

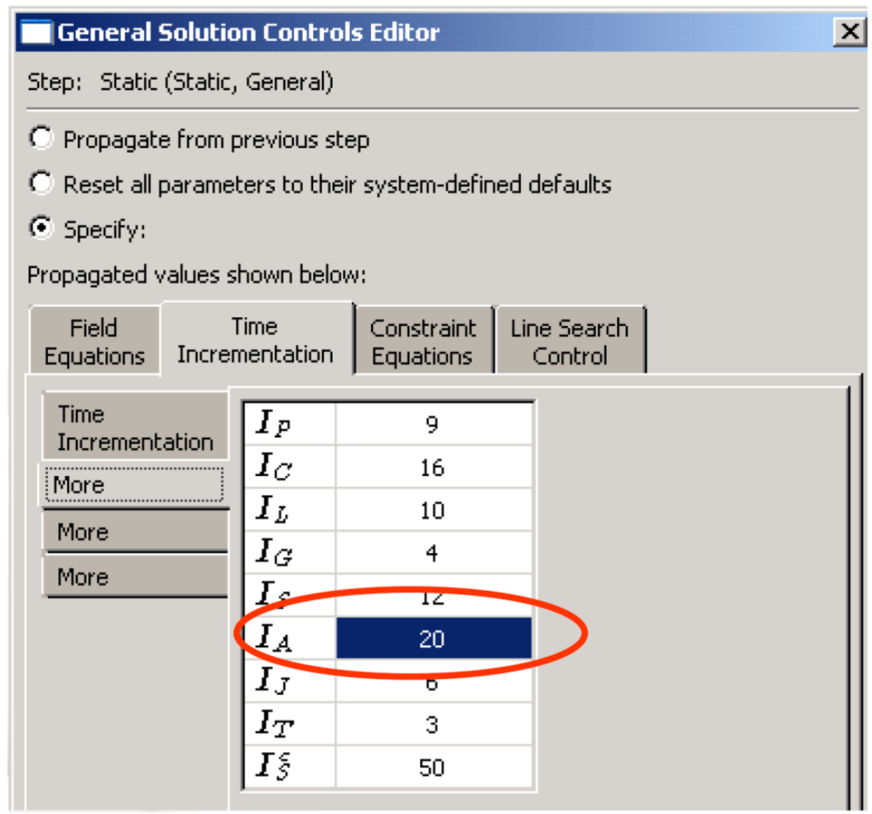
- Use numerical scheme applicable to discontinuous analysis



- Example: Crack Initiation and Propagation

4 Set analysis controls to improve convergence behavior

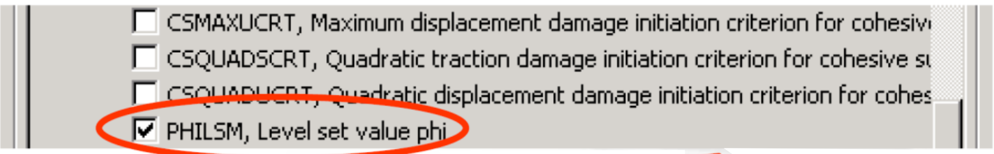
- Increase value of maximum number of attempts before abandoning increment (increased to 20 from the default value of 5)

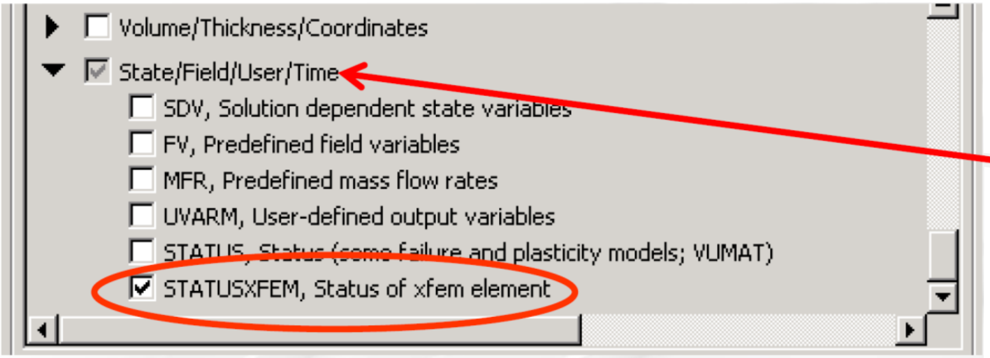


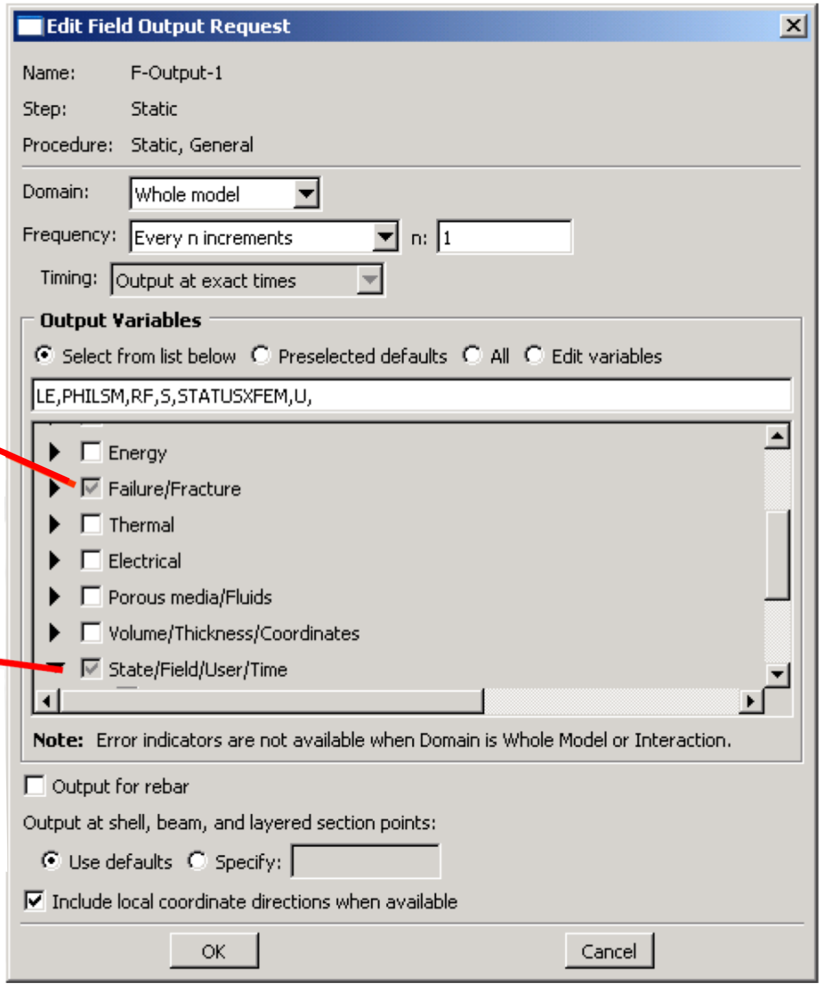
Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

- Output Requests
  - Request PHILSM and STATUSXFEM in addition to the usual output for static analysis



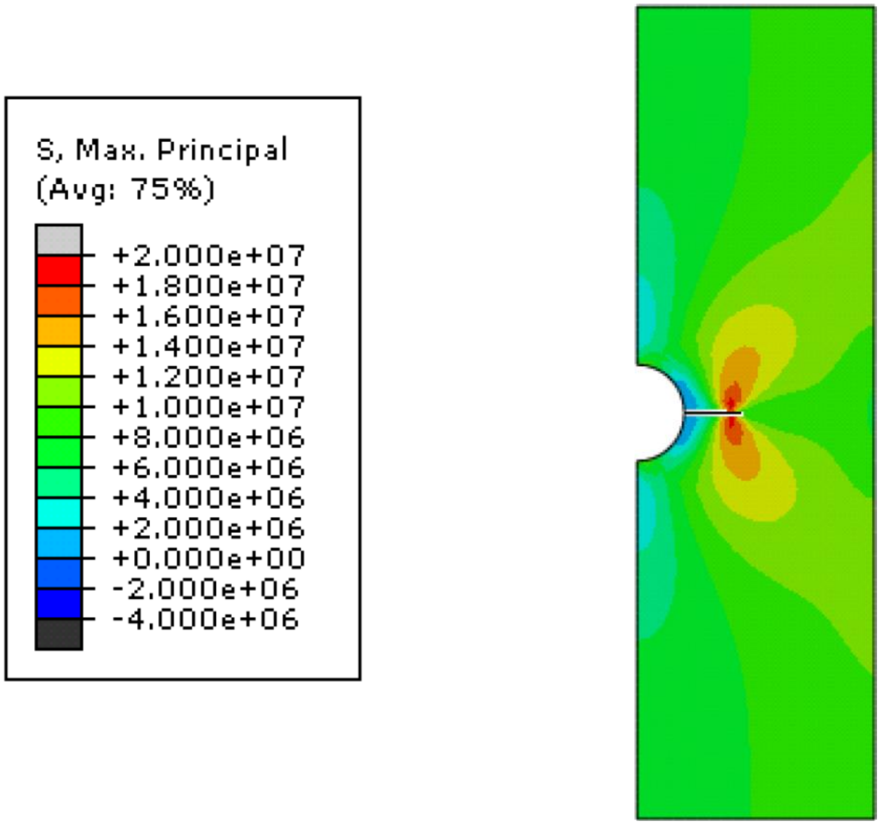


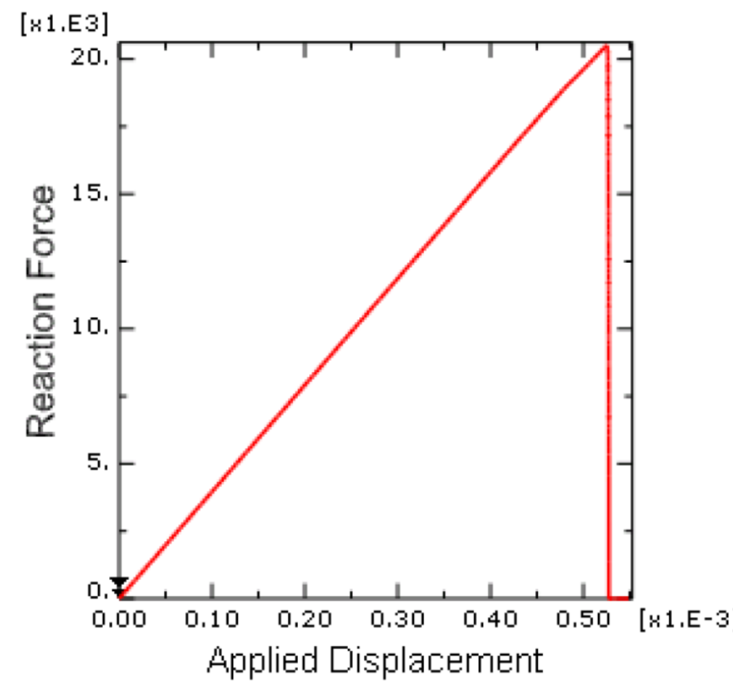


Creating an XFEM Fracture Model

- Example: Crack Initiation and Propagation

- Postprocessing
  - Crack isosurface (Crack_PHILSM) created and displayed automatically
  - Field and history quantities of interest can be plotted and animated as usual





Defining Enriched Feature and its Properties in Abaqus

Category	Keyword	Comments
type of enrichment	*ENRICHMENT, TYPE=PROPAGATION CRACK	The cohesive segments method and linear elastic fracture mechanics approach in conjunction with phantom nodes.
	*ENRICHMENT, TYPE=STATIONARY CRACK	Analysis with stationary cracks requires that the elements around the crack tips are enriched with asymptotic functions
Enriched region	*ENRICHMENT, ELSET=element set name	Elements currently intersected by cracks and those likely to be intersected by cracks
Crack surface	*SURFACE, TYPE=XFEM	Representing both faces of cracked elements
Cracked element surfaces	*ENRICHMENT, INTERACTION =interaction_property_name	Feature such as cohesive behavior can be added as interaction
Crack initiation	*DAMAGE INITIATION, TOLERANCE=f_{tol}	The default value of f_{tol} is 0.05

Defining Enriched Feature and its Properties in Abaqus

Category	Keyword	Comments
Position used to measure the crack initiation criterion	*DAMAGE INITIATION, POSITION=CENTROID (default) *DAMAGE INITIATION, POSITION=CRACKTIP *DAMAGE INITIATION, POSITION=COMBINED	By default, Abaqus uses a Gauss point average of the stress/strain evaluated at the element centroid ahead of the crack tip Alternatively, you can use the stress/strain values extrapolated to the crack tip
Specifying the crack direction	*DAMAGE INITIATION, NORMAL DIRECTION =1 (default) *DAMAGE INITIATION, NORMAL DIRECTION =2	Newly introduced crack is always orthogonal to the maximum principal stress/strain direction you can specify if the newly introduced crack will be orthogonal to the element local 1-direction
Activating and deactivating the enriched feature	*ENRICHMENT ACTIVATION, NAME=name, ACTIVATE=ON *ENRICHMENT ACTIVATION, NAME=name, ACTIVATE=OFF	By default, enrichment is activated and can be deactivated/reactivated in a new step

Fracture Initiation and Extension in Abaqus

Criterion	f	Keyword
Maximum principal stress	$f = \left\{\frac{\langle\sigma_{max}\rangle}{\sigma_{max}^{o}}\right\}$	*DAMAGE INITIATION, CRITERION=MAXPS
Maximum principal strain	$f = \left\{\frac{\langle\varepsilon_{max}\rangle}{\varepsilon_{max}^{o}}\right\}$	*DAMAGE INITIATION, CRITERION=MAXPE
Maximum nominal stress	$f = max\left\{\frac{\langle t_n\rangle}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0}\right\}$ t_n is normal and t_s and t_t are shear components t_n^0 , t_s^0 , t_t^0 represent the peak values of the nominal stress	*DAMAGE INITIATION, CRITERION=MAXS
Maximum nominal strain	$f = max\left\{\frac{\langle\varepsilon_n\rangle}{\varepsilon_n^0}, \frac{\varepsilon_s}{\varepsilon_s^0}, \frac{\varepsilon_t}{\varepsilon_t^0}\right\}$	*DAMAGE INITIATION, CRITERION=MAXE
Quadratic nominal stress	$f = \left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 + \left\{\frac{t_t}{t_t^0}\right\}^2$	*DAMAGE INITIATION, CRITERION=QUADS
Quadratic nominal strain	$f = \left\{\frac{\langle\varepsilon_n\rangle}{\varepsilon_n^0}\right\}^2 + \left\{\frac{\varepsilon_s}{\varepsilon_s^0}\right\}^2 + \left\{\frac{\varepsilon_t}{\varepsilon_t^0}\right\}^2$	*DAMAGE INITIATION, CRITERION=QUADE