ABAQUS

Lecture 9

Material Damage and Failure

Overview

- Progressive Damage and Failure
- Damage Initiation for Ductile Metals
- Damage Evolution
- Element Removal
- Failure in Fasteners

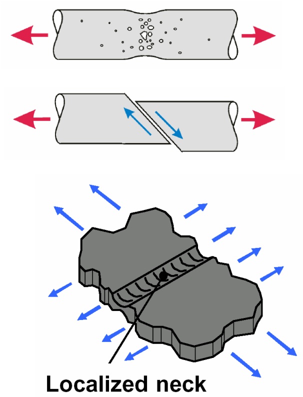
Progressive Damage and Failure

Progressive Damage and Failure

- **ABAQUS offers a general capability for modeling progressive damage and failure in engineering structures.**
  - Material failure refers to the complete loss of load carrying capacity that results from progressive degradation of the material stiffness.
  - Stiffness degradation is modeled using damage mechanics.
- **Progressive damage and failure can be modeled in:**
  - Bulk materials
    - Continuum constitutive behavior
      - used in conjunction with the Mises, Johnson-Cook, Hill, or Drucker-Prager plasticity models
    - This is the primary focus of this lecture.
  - Interface materials
    - Cohesive elements with a traction-separation law
    - This was discussed in Lecture 7, *Constraints and Connections*.

Progressive Damage and Failure

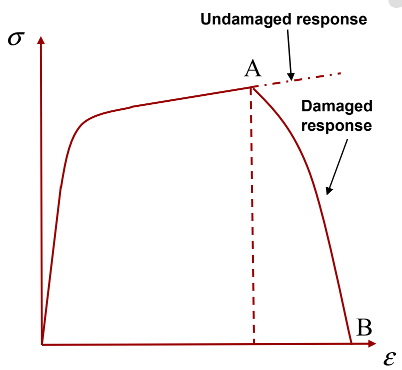
- **Two distinct types of bulk material failure can be modeled with ABAQUS/Explicit**
  - Ductile fracture of metals
    - Void nucleation, coalescence, and growth
    - Shear band localization
  - Necking instability in sheet-metal forming
    - Forming Limit Diagrams
    - Marciniak-Kuczynski (M-K) criterion
  - Damage in sheet metals is not discussed further in this seminar.



ABAQUS

Progressive Damage and Failure

- **Components of material definition**
  - Undamaged constitutive behavior (e.g., elastic-plastic with hardening)
  - Damage initiation (point A)
  - Damage evolution (path A–B)
  - Choice of element removal (point B)



Typical material response showing progressive damage

Keywords

Multiple damage definitions are allowed

```
*MATERIAL
*ELASTIC
*PLASTIC
*DAMAGE INITIATION,CRITERION=criterion
*DAMAGE EVOLUTION
*SECTION CONTROLS, ELEMENT DELETION=YES
```


ABAQUS

ABAQUS

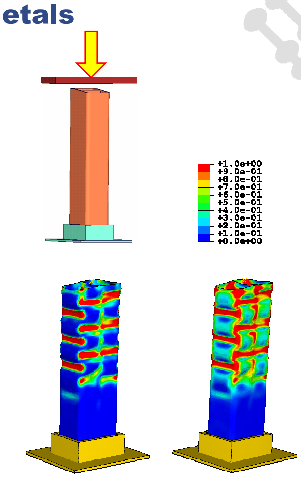
Damage Initiation Criteria for Ductile Metals

Damage Initiation Criteria for Ductile Metals

- **Damage initiation defines the point of initiation of degradation of stiffness**
  - It is based on user-specified criteria
    - Ductile or shear
  - It does not actually lead to damage unless damage evolution is also specified
    - Output variables associated with each criterion
    - Useful for evaluating the severity of current deformation state
  - Output

    DMICRT

    DMICRT ≥ 1 indicates damage has initiated



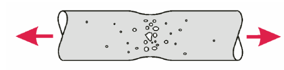
Ductile **Shear**

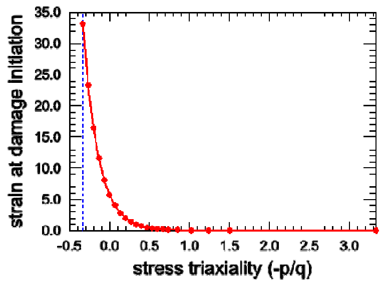
Different damage initiation criteria on an aluminum double-chamber profile

 ABAQUS

Damage Initiation Criteria for Ductile Metals

- **Ductile criterion:**
  - Appropriate for triggering damage due to nucleation, growth, and coalescence of voids
  - The model assumes that the equivalent plastic strain at the onset of damage is a function of stress triaxiality and strain rate.
    - Stress triaxiality $\eta = -p / q$ (Pressure stress: p; Mises stress: q)
  - The ductile criterion can be used with the Mises, Johnson-Cook, Hill, and Drucker-Prager plasticity models, including equation of state.

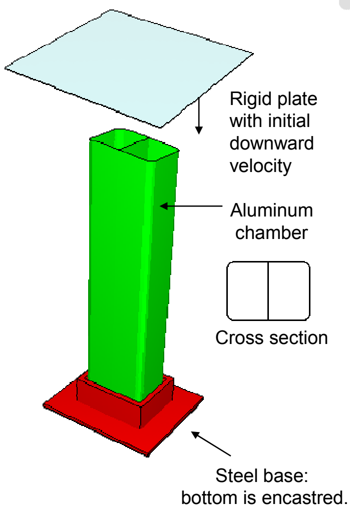




Ductile criterion for Aluminum Alloy AA7108.50-T6 (Courtesy of BMW)

Damage Initiation Criteria for Ductile Metals

- **Example: Axial crushing of an aluminum double-chamber profile**
  - Model details
    - Steel base:
      - C3D8R elements
      - Enhanced hourglass control
      - Elastic-plastic material
    - Aluminum chamber:
      - S4R elements
      - Stiffness hourglass control
      - Rate-dependent plasticity
      - Damage initiation
    - General contact
    - Variable mass scaling



Damage Initiation Criteria for Ductile Metals

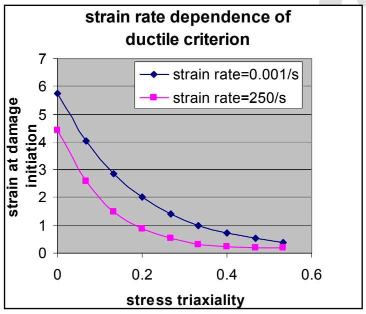
– Specify a damage initiation criterion based on the ductile failure strain.

```
*MATERIAL, NAME=ALUMINUM
*DENSITY
  2.70E-09
*ELASTIC
  7.00E+04,  0.33
*PLASTIC,HARDENING=ISOTROPIC,RATE=0
  :
*DAMAGE INITIATION, CRITERION=DUCTILE
  5.7268, 0.000, 0.001
  4.0303, 0.067, 0.001
  2.8377, 0.133, 0.001
  :
  4.4098, 0.000, 250
  2.5717, 0.067, 250
  1.5018, 0.133, 250
  :
```

Strain rate, $\dot{\bar{\varepsilon}}^{pl}$

Stress triaxiality, η

Equivalent fracture strain at damage initiation, $\bar{\varepsilon}^{pl}$



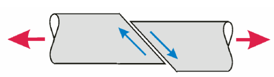
Ductile and shear criteria for Aluminum Alloy AA7108.50-T6 (Courtesy of BMW)

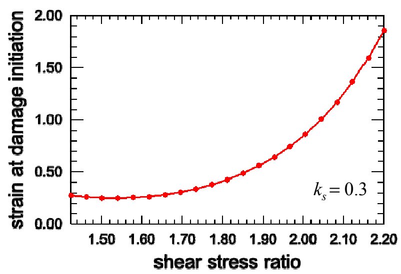
Damage Initiation Criteria for Ductile Metals

- **Shear criterion:**
  - Appropriate for triggering damage due to shear band localization
  - The model assumes that the equivalent plastic strain at the onset of damage is a function of the shear stress ratio and strain rate.
  - Shear stress ratio defined as:

$$\theta_s = (q + k_s\, p) / \tau_{\max}$$

  - The shear criterion can be used with the Mises, Johnson-Cook, Hill, and Drucker-Prager plasticity models, including equation of state.





Shear criterion for Aluminum Alloy AA7108.50-T6 (Courtesy of BMW)

Damage Initiation Criteria for Ductile Metals

- **Example (cont'd): Axial crushing of an aluminum double-chamber profile**
  - Specify a damage initiation criterion based on the ductile failure strain.

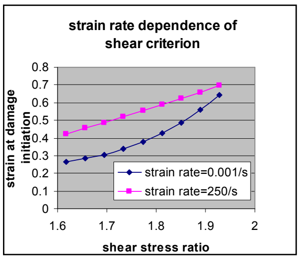
```
*MATERIAL, NAME=ALUMINUM
 :
*DAMAGE INITIATION, CRITERION=DUCTILE
  5.7268, 0.000, 0.001
  4.0303, 0.067, 0.001
 :
*DAMAGE INITIATION, CRITERION=SHEAR, KS=0.3
  0.2761, 1.424, 0.001
  0.2613, 1.463, 0.001
  0.2530, 1.501, 0.001
 :
  0.2731, 1.424, 250
  0.3025, 1.463, 250
  0.3323, 1.501, 250
 :
```

k_s is a material parameter

Strain rate, $\dot{\bar{\varepsilon}}^{pl}$

Shear stress ratio, θ_s

Equivalent fracture strain at damage initiation, $\bar{\varepsilon}^{pl}$



Ductile and shear criteria for Aluminum Alloy AA7108.50-T6 (Courtesy of BMW)

Damage Initiation Criteria for Ductile Metals

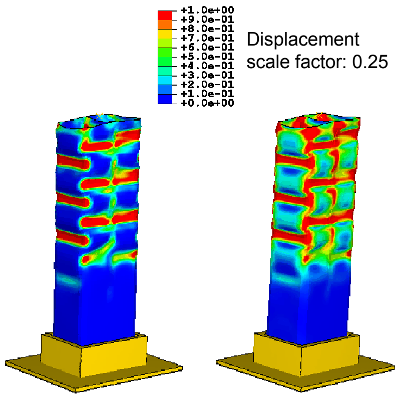
- **Example (cont'd): Axial crushing of an aluminum double-chamber profile**
  - **Ductile** damage initiation criterion output:

    DUCTCRT (ω_D)

    The criterion for damage initiation is met when $\omega_D \geq 1$.
  - **Shear** damage initiation criterion output :

    SHRCRT (ω_S)

    The criterion for damage initiation is met when $\omega_S \geq 1$.

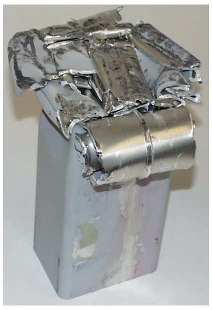


Ductile DUCTCRT

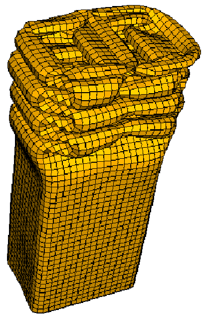
Shear SHRCRT

Damage Initiation Criteria for Ductile Metals

- **Example (cont'd): Axial crushing of an aluminum double-chamber profile**
  - Damage initiation does not actually lead to damage unless damage evolution is also specified.



Aluminum double-chamber after dynamic impact



Analysis results with damage initiation but no damage evolution

Damage Evolution

Damage Evolution

– Damage evolution defines the post damage-initiation material behavior.
  - That is, it describes the rate of degradation of the material stiffness once the initiation criterion is satisfied.

– The formulation is based on scalar damage approach:

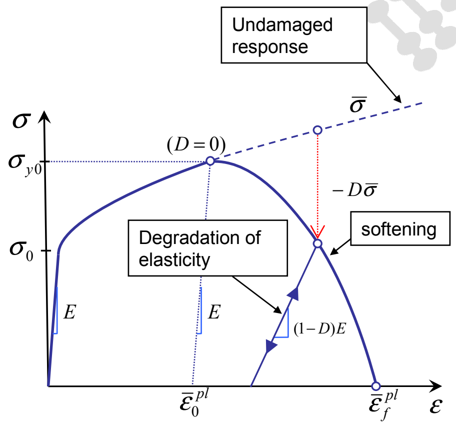
$$\boldsymbol{\sigma} = (1 - D)\bar{\boldsymbol{\sigma}}$$

← Stress due to undamaged response

  - The overall damage variable D captures the combined effect of all active damage mechanisms.
  - When damage variable $D = 1$, material point has completely failed.
    - In other words, fracture occurs when $D = 1$.

Damage Evolution

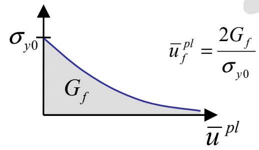
- **Elastic-plastic materials**
  - For a elastic-plastic material, damage manifests in two forms:
    - Softening of the yield stress
    - Degradation of the elasticity



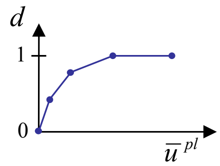
Schematic representation of elastic-plastic material with progressive damage.

Damage Evolution

- The damage evolution law can be specified either in terms of
  - fracture energy (per unit area) or
  - equivalent plastic displacement.
- Both approaches take into account the characteristic length of the element.
- The formulation ensures that mesh-sensitivity is minimized.

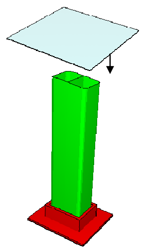


Energy based damaged evolution
(linear or **exponential**)



Displacement based damage evolution
(**tabular**, linear, or exponential)

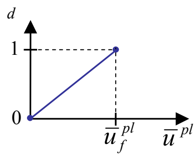
Damage Evolution



- **Example (cont'd): Axial crushing of an aluminum double-chamber profile**
  - Dynamic response with damage evolution

```
*MATERIAL, NAME=ALUMINUM
  :
*DAMAGE INITIATION, CRITERION=DUCTILE
  :
*DAMAGE EVOLUTION, TYPE=DISPLACEMENT, SOFTENING=LINEAR
  0.1,
*DAMAGE INITIATION, CRITERION=SHEAR, KS=0.3
  :
*DAMAGE EVOLUTION, TYPE=DISPLACEMENT, SOFTENING=LINEAR
  0.1,
```

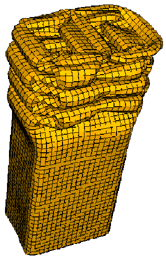
Linear form of damage evolution based on effective plastic **displacement**



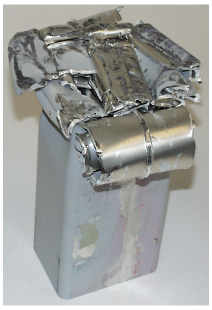
specify the effective plastic displacement, $\bar{u}_f^{pl}$, at the point of failure (full degradation).

Damage Evolution

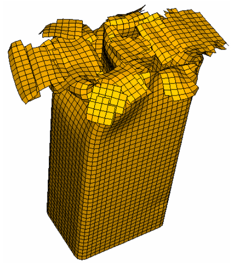
- **Example (cont'd): Axial crushing of an aluminum double-chamber profile**
  - With damage evolution, the simulation response is a good approximation of the physical response.



Simulation without damage evolution



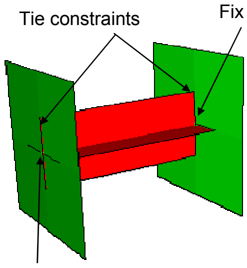
Aluminum double-chamber after dynamic impact

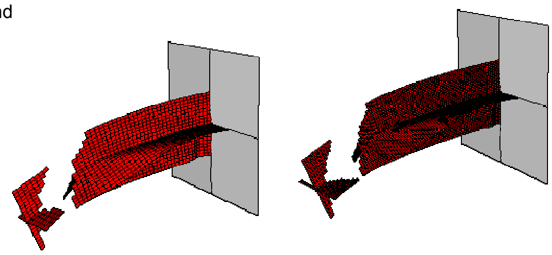


Simulation with damage evolution

Damage Evolution

- **Example: Tearing of an X-shaped cross section**



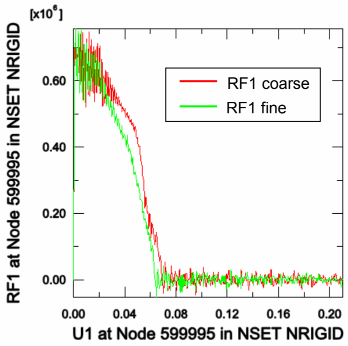


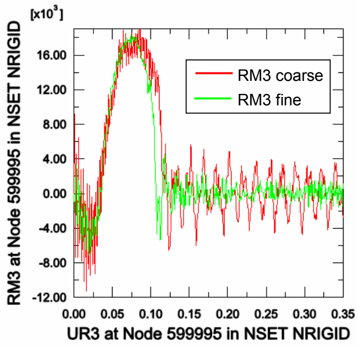
Failure modeled with different mesh densities

Video Clip

Damage Evolution

- **Example (cont'd): Tearing of an X-shaped cross section**
  - Comparison of reaction forces and moments confirms mesh insensitivity of the results.





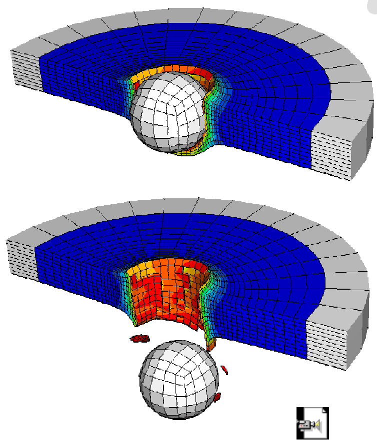
 ABAQUS

ABAQUS

Element Removal

Element Removal

- ABAQUS offers the choice to remove the element from the mesh once the material stiffness is fully degraded (i.e., once the element has failed).
  - An element is said to have failed when all section points at any one integration point have lost their load carrying capacity.
  - By default, failed elements are deleted from the mesh.



Video Clip

Element Removal

- **Removing failed elements before complete degradation**
  - The material point is assumed to fail when the overall damage variable D reaches the critical value D_{max}.
  - You can specify the value for the maximum degradation D_{max}.
    - The default value of D_{max} is 1 if the element is to be removed from the mesh upon failure.

```
*SECTION CONTROLS, NAME=name, ELEMENT DELETION=YES, MAX DEGRADATION=Dmax
```

Refer to the section controls by name on the element section definition, for example:

```
*SOLID SECTION, ELSET=PLATE, MATERIAL=RHA, CONTROLS=RHAControls
```

Element Removal

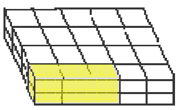
- **Retaining failed elements**
  - You may choose not to remove failed elements from the mesh.

    ```
    *SECTION CONTROLS, ELEMENT DELETION = NO
    ```

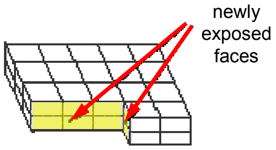
    - In this case the default value of D_{max} is 0.99, which ensures that elements will remain active in the simulation with a residual stiffness of at least 1% of the original stiffness.
      - Here D_{max} represents
        - the maximum degradation of the shear stiffness (three-dimensional),
        - the total stiffness (plane stress), or
        - the uniaxial stiffness (one-dimensional).
    - Failed elements that have not been removed from the mesh can sustain hydrostatic compressive stresses.

Element Removal

- **Contact can occur on both the exterior and interior of regions modeled with material failure and element removal.**
  - The procedure for defining general contact for this type of problem was discussed in Lecture 4, *Contact Modeling*.
    1. Define an element-based surface that includes the exterior and interior faces or define a node based surface that includes all nodes.
    2. Include this surface as part of the general contact definition.
  - When element-based surfaces are used to model eroding contact the contact active contact domain evolves during the analysis as elements fail.



Surface topology before the yellow elements have failed

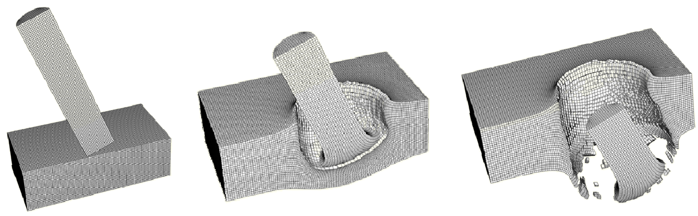


Surface topology after failure

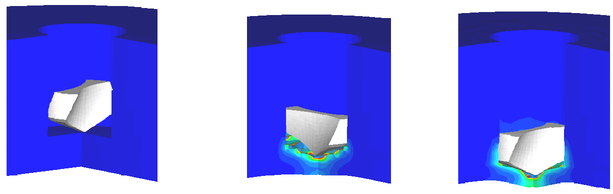
Element Removal

- **Examples of surface erosion in solid elements**

Eroding projectile impacting eroding plate



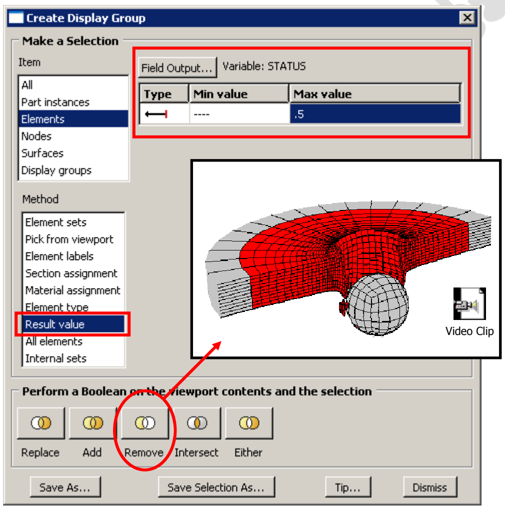
Drilling process

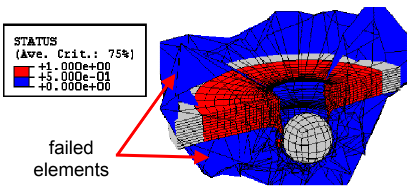


drill

Element Removal

- **Output**
  - The output variable SDEG contains the value of D.
  - The output variable STATUS indicates whether or not an element has failed.
    - STATUS=0 for failed elements
    - STATUS=1 for active elements

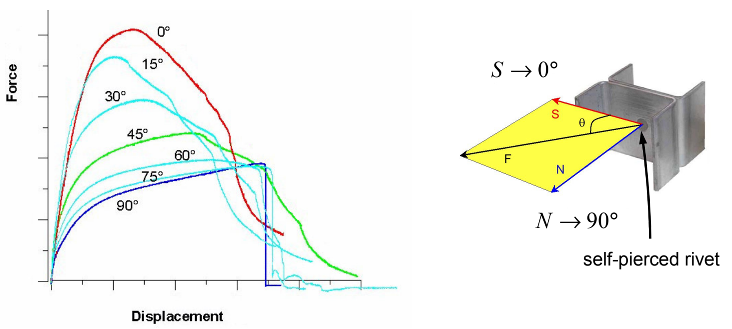




Damage in Fasteners

Damage in Fasteners

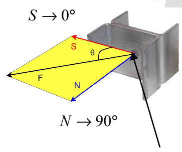
- **Rigid or elastic fasteners may introduce non-physical noise in the solution.**
- **Behavior of fasteners should be modeled based on experimental testing.**

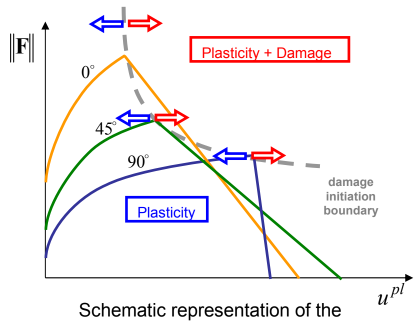


Experimental force-displacement curves for a self-pierced rivet. Response depends on loading angle θ. (***Courtesy of BMW & Fraunhofer Institute, Freiburg***)

Damage in Fasteners

- **Fastener failure implementation is aimed at capturing experimental force-displacement response of fasteners**
  - Model combines plasticity and progressive damage
  - Response depends on loading angle (normal/shear)
  - Stages:
    - Rigid plasticity with variable hardening
    - Damage initiation
    - Progressive damage evolution using fracture energy



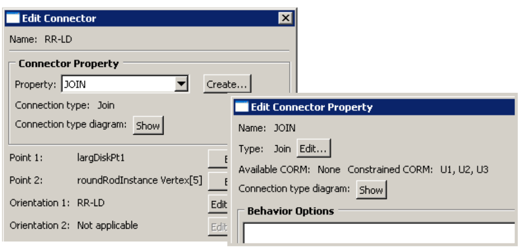


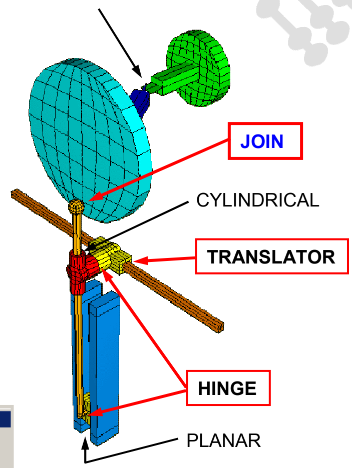
Schematic representation of the predicted numerical response

Damage in Fasteners

- **Example: Multibody mechanism**
  - Damage initiation and evolution are added to the definition of four connectors.
  - Section definition for the original rigid **JOIN** connector:

```
*CONNECTOR SECTION, ELSET=RR-LD
join,
RR-LD
```





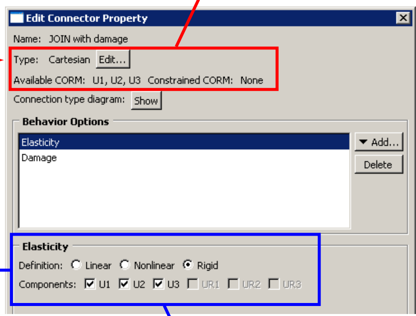
Connector elements in a multibody mechanism

Damage in Fasteners

- **Example (cont'd): Multibody mechanism**
  - Modify section definition to account for damage:

```
*CONNECTOR SECTION, ELSET=RR-LD,
   BEHAVIOR=JOIN_DAM
CARTESIAN
RR-LD,
*CONNECTOR BEHAVIOR, NAME=JOIN_DAM
*CONNECTOR ELASTICITY, RIGID
1,2,3
*CONNECTOR DAMAGE INITIATION
,100000
*CONNECTOR POTENTIAL
1,
2,
3,
*CONNECTOR DAMAGE EVOLUTION, TYPE=ENERGY
100,
```

With the **Cartesian** connection the previously constrained translational components of relative motion are available.

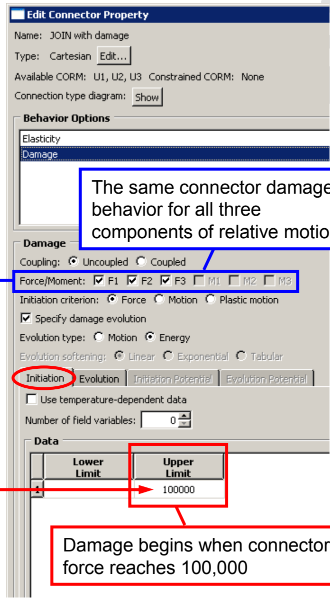


All three translational components of relative motion will behave rigidly before damage initiation.

Damage in Fasteners

- **Example (cont'd): Multibody mechanism**
  - Modify section definition to account for damage:

```
*CONNECTOR SECTION, ELSET=RR-LD,
   BEHAVIOR=JOIN_DAM
CARTESIAN
RR-LD,
*CONNECTOR BEHAVIOR, NAME=JOIN_DAM
*CONNECTOR ELASTICITY, RIGID
1,2,3
*CONNECTOR DAMAGE INITIATION
,100000
*CONNECTOR POTENTIAL
1,
2,
3,
*CONNECTOR DAMAGE EVOLUTION, TYPE=ENERGY
100,
```



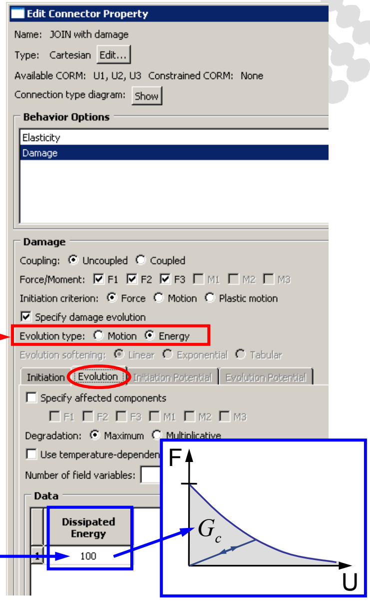
The same connector damage behavior for all three components of relative motion.

Damage begins when connector force reaches 100,000

Damage in Fasteners

- **Example (cont'd): Multibody mechanism**
  - Modify section definition to account for damage:

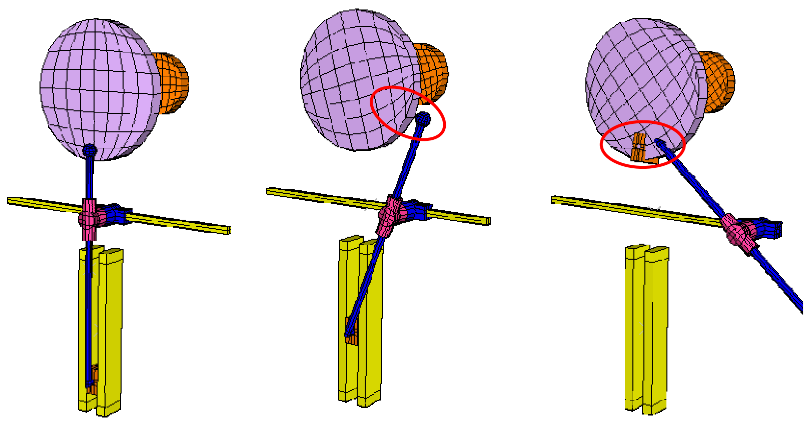
```
*CONNECTOR SECTION, ELSET=RR-LD,
   BEHAVIOR=JOIN_DAM
CARTESIAN
RR-LD,
*CONNECTOR BEHAVIOR, NAME=JOIN_DAM
*CONNECTOR ELASTICITY, RIGID
1,2,3
*CONNECTOR DAMAGE INITIATION
,100000
*CONNECTOR POTENTIAL
1,
2,
3,
*CONNECTOR DAMAGE EVOLUTION, TYPE=ENERGY
100,
```



Damage in Fasteners

Video Clip

- **Example (cont'd): Multibody mechanism**



undeformed **After "JOIN" failure** **After "HINGE" failure**