Implicit Creep

Background on Creep

- In crystalline materials, such as metals, creep mechanism is linked to diffusional flow of vacancies and dislocation movement.
  - Vacancies are point defects, and they tend to favor grain boundaries that are normal, rather than parallel, to the applied stress. Vacancies tend to move from regions of high to low concentrations. Diffusional flow can occur at low stresses but usually require high temperatures.
  - Dislocations in grains are line defects. The movement of dislocations (climb, glide, deviation) tend to be activated by high stresses, although it may also occur at intermediate temperatures.
  - Grain boundary sliding is sometimes considered as a separate mechanism which also contributes to creep deformation.

Although a detailed discussion of material science is beyond the scope of this seminar, it may suffice to say that the aforementioned physical mechanics contribute to creep. The dependency of creep deformation on stress, strain, time, and temperature are generally modeled with a form similar to the following:

$$\dot{\varepsilon}_{cr} = f_1(\sigma) f_2(\varepsilon) f_3(t) f_4(T)$$

- The functions $f_{1\text{-}4}$ are dependent on the creep law selected.
  - Associated creep constants are usually obtained through various tensile tests at different strain rates and temperatures.
- Assuming isotropic behavior, the von Mises equation is used to compute the effective stress, and the equivalent strain is used in the creep strain rate equation (similar to rate-independent plasticity).
  - At 6.0, we can use HILL potential along with implicit creep to model anisotropic creep behavior.

Background on Creep (cont'd)

- ANSYS uses the additive strain decomposition when calculating elastic, plastic, and creep strain:

  Stress-strain $$\dot{\sigma} = D : \dot{\varepsilon}_{el}$$

  Additive decomposition $$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{pl} + \dot{\varepsilon}_{cr}$$

  Creep strains are evaluated based on the creep strain rate equations, specific forms of which will be discussed later.

- The elastic, creep, and plastic strains are all evaluated on the (current) stress state, but they are calculated independently (not based on each other).
  - Note that there is a difference between calculations performed using implicit creep vs. explicit creep.

Background on Creep (cont'd)

- Creep, like plasticity, is an irreversible (inelastic) strain which is based on deviatoric behavior. The material is assumed to be incompressible under creep flow.

- On the other hand, creep, unlike rate-independent plasticity, has no yield surface at which inelastic strains occur.
  - Hence, creep does not require a higher stress value for more creep strain to occur. Creep strains are assumed to develop at all non-zero stress values.

- Creep and viscoplasticity are the same from a material standpoint.
  - In engineering usage, creep is generally used to describe a thermally-activated process with a low strain rate. Rate-independent plastic and implicit creep strains are treated in a weakly coupled manner.
  - Conversely, viscoplasticity constitutive models in ANSYS are used to describe high-strain-rate applications (e.g., impact loading). Inelastic strains are treated in a strongly coupled manner.

Definition of Terms

- ## Three stages of creep:

  - Under constant load, the uniaxial strain vs. time behavior of creep is shown below.

  - In the *primary stage*, the strain rate decreases with time. This tends to occur over a short period. The *secondary stage* has a constant strain rate associated with it. In the *tertiary stage*, the strain rate increases rapidly until failure (rupture).

ε

Rupture

Primary | **Secondary**

Tertiary

t

6
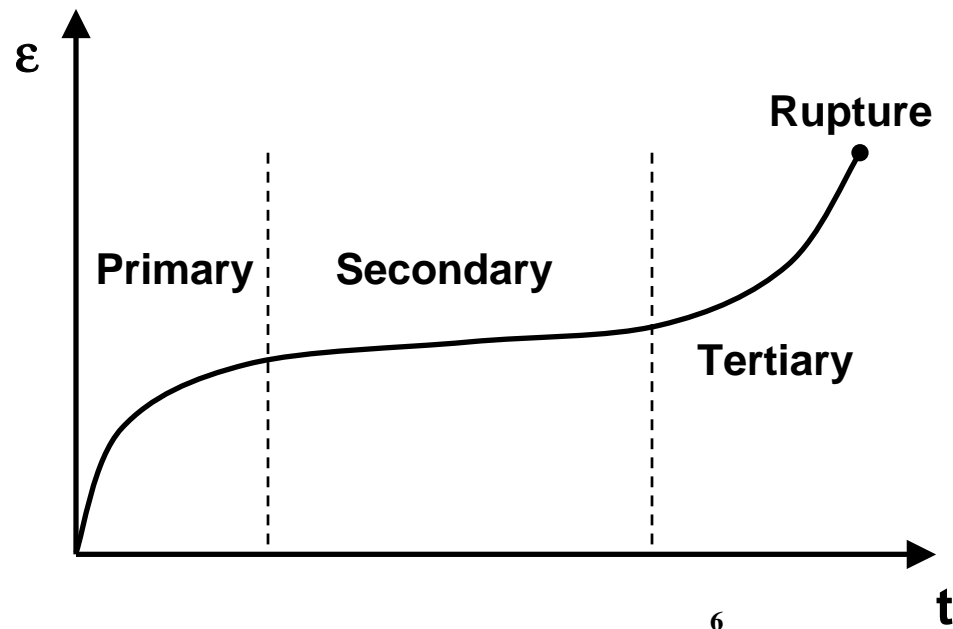
Definition of Terms (cont'd)

- Three stages of creep (cont'd):
  - The creep strain rate may be a function of stress, strain, temperature, and/or time.
  - For engineering analysis, the primary and secondary stages of creep are usually of greatest interest. Tertiary creep is usually associated with the onset of failure (necking, damage) and is short-lived. Hence, tertiary creep is not modeled in ANSYS.
  - The strain rate associated with primary creep is usually much greater than those associated with secondary creep. However, the strain rate is decreasing in the primary stage whereas it is usually nearly constant in the secondary stage (for the aforementioned uniaxial test case at constant stress and temperature). Also, primary creep tends to be of a shorter period than secondary creep.
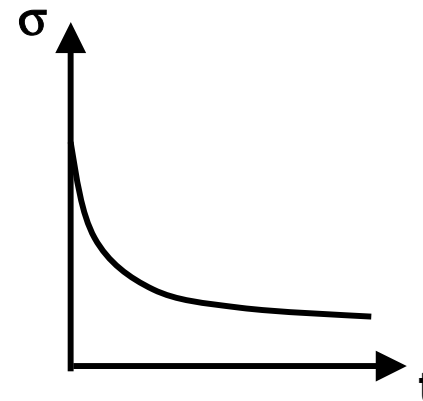
Definition of Terms (cont'd)

- *Creep*
  - Under constant applied stress, creep strain increases.
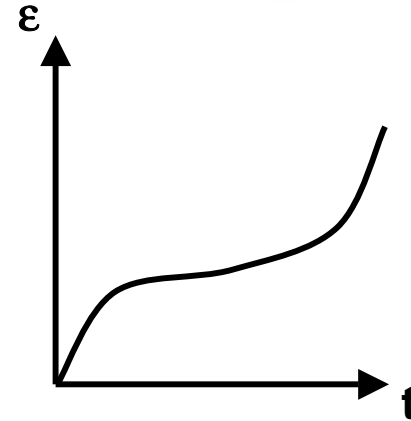
- *Stress Relaxation*
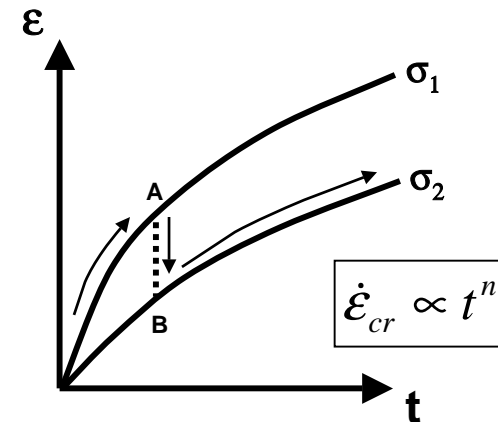 - Under constant applied strain, stress decreases.
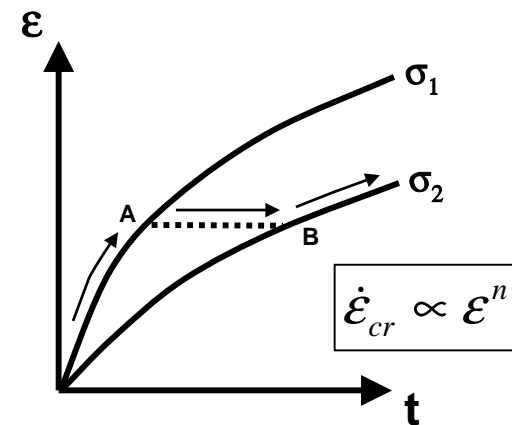
Definition of Terms (cont'd)

- *Time-hardening*
  - Assumes that the creep strain rate depends only upon the time from the beginning of the creep process. In other words, the curve shifts up/down. As stress changes from σ_1 to σ_2, the different creep rates are calculated at points A to B.

$$\dot{\varepsilon}_{cr} \propto t^n$$

- *Strain-hardening*
  - Assumes that the creep rate depends only on the existing strain of the material. In other words, the curve shifts left/right. As stress changes from σ_1 to σ_2, the different creep strain rates are calculated at points A to B.

$$\dot{\varepsilon}_{cr} \propto \varepsilon^n$$

Definition of Terms (cont'd)

- *Explicit creep*
    - Explicit creep means that the forward Euler method is used for the calculation of creep strain evolution. The creep strain rate used at each time step corresponds to the rate at the beginning of the time step and is assumed to be constant throughout that time step Δt. Because of this, very small time steps are required to minimize error.

$$\dot{\varepsilon}_{cr} = f\left(\sigma^t, \varepsilon^t, T^{t+\Delta t}, \cdots\right)$$

    - For explicit creep with plasticity, plasticity correction is performed first followed by creep correction. These two corrections occur at different stress values; therefore, it may be less accurate.

- *Implicit creep*
  - Implicit creep refers to the use of backward Euler integration for creep strains. This method is numerically unconditionally stable. This means that it does not require as small a time-step as the explicit creep method, so it is much faster overall.

$$\dot{\varepsilon}_{cr} = f\left(\sigma^{t+\Delta t}, \varepsilon^{t+\Delta t}, T^{t+\Delta t}, \cdots\right)$$

  - For implicit creep plus rate-independent plasticity, the plasticity correction and creep correction done at the same time, not independently. Consequently, implicit creep is generally more accurate than explicit creep, but it is still dependent on the time-step size. A small enough time-step must be used to capture the path-dependent behavior accurately.

- Implicit creep is the recommended method in ANSYS for the reasons stated above (efficiency, accuracy).

Implicit vs. Explicit Creep

The table below summarizes differences between implicit and explicit creep:

	Implicit Creep	Explicit Creep
	Recommended	
Integration Scheme	Backward Euler (More Efficent, Less Substeps)	Forward Euler (Less Efficient, More Substeps)
Plasticity Calculations	Simultaenous (More Accurate)	Superposition (Less accurate)
Plasticity Models Supported	BISO, MISO, NLISO, BKIN, HILL	Most models supported (no restrictions)
Temperature-Dependency	Through Arrhenius function. Temperature-dependent constants	Through creep equations (Arrhenius function). No temperature-dependent constants.
Elements Supported	Core and 18x elements	Core and Misc elements
Turn on/off creep effects	Through RATE command	None available[1]
Creep limit control	CUTCON,CRPLIMIT,crvalue,1 No default value, although values of 1-10 are recommended.	CUTCON,CRPLIMIT,crvalue,0 By default, 10%. Stability limit requires < 25%.

[1]For explicit creep, the creep calculations are bypassed if T+TOFFSET < 0.0, time step < 1e-6, or C1 < 0.0 (for primary creep)

General Creep Equation

- As noted earlier, the creep equations are usually of a rate form similar to the one below:

$$\dot{\varepsilon}_{cr} = f_1(\sigma) f_2(\varepsilon) f_3(t) f_4(T)$$

- However, the type of material being analyzed determines the choice of a specific creep equation. Some general characteristics will be discussed presently. Specific models will be covered in the implicit and explicit creep sections.

  - The implicit and explicit creep equations are also covered in the Elements Manual, Ch. 2.5.

General Creep Equation (cont'd)

<u>Temperature-dependency</u>

- Creep effects are thermally activated, and its temperature dependence is usually expressed through the Arrhenius law:

$$\dot{\varepsilon}_{cr} \propto e^{-\frac{Q}{RT}}$$

where Q is the activation energy, R is the universal gas constant, and T is absolute temperature.

<u>Stress dependency</u>

- Creep strain is also usually stress-dependent, especially with dislocation creep. Norton's law is:

$$\dot{\varepsilon}_{cr} \propto \sigma^{n}$$

A common modification to the above power law is as follows:

$$\dot{\varepsilon}_{cr} \propto e^{C\sigma}$$

General Creep Equation (cont'd)

<u>Primary creep usually exhibits either *time- or strain-hardening*.</u>

- Time-hardening is the inclusion of a time-dependent term:

$$\dot{\varepsilon}_{cr} \propto t^m$$

- Strain-hardening is the inclusion of a strain-dependent term:

$$\dot{\varepsilon}_{cr} \propto \varepsilon^n$$

- Determination of which to use (strain- or time-hardening) is based upon material data available.
- Secondary creep does not exhibit time- or strain-hardening. Creep strain rate is usually constant for secondary stage.

General Creep Equation (cont'd)

- Below is a summary of creep laws available in ANSYS:

Creep Equation Description	Type	Explicit C6/C12 value	Implicit TBOPT value
Strain Hardening	Primary	C6=0	1
Time Hardening	Primary	C6=1	2
Generalized Exponential	Primary	C6=2	3
Generalized Graham	Primary	-	4
Generalized Blackburn	Primary	-	5
Modified Time Hardening	Primary	-	6
Modified Strain Hardening	Primary	-	7
Generalized Garofalo (Hyperbolic sine)	Secondary	-	8
Exponential Form	Secondary	C12=0	9
Norton	Secondary	C12=1	10
Time Hardening	Both	-	11
Rational Polynomial	Both	C6=15	12
Generalized Time Hardening	Primary	-	13
User Creep		C6=100	100
Annealed 304 Stainless Steel	Both	C6=9	-
Annealed 316 Stainless Steel	Both	C6=10	-
Annealed 2.25 Cr - 1 Mo Low Alloy Steel	Both	C6=11	-
Power Function Creep Law	Primary	C6=12	-
Sterling Power Function Creep Law	Both	C6=13	-
Annealed 316 Stainless Steel	Both	C6=14	-
20% Cold Worked 316 SS (Irradiation-Induced)	Both	C66=5	-

As noted earlier, implicit creep is the recommended method to use, whenever possible.

Example of Creep in Solder Ball
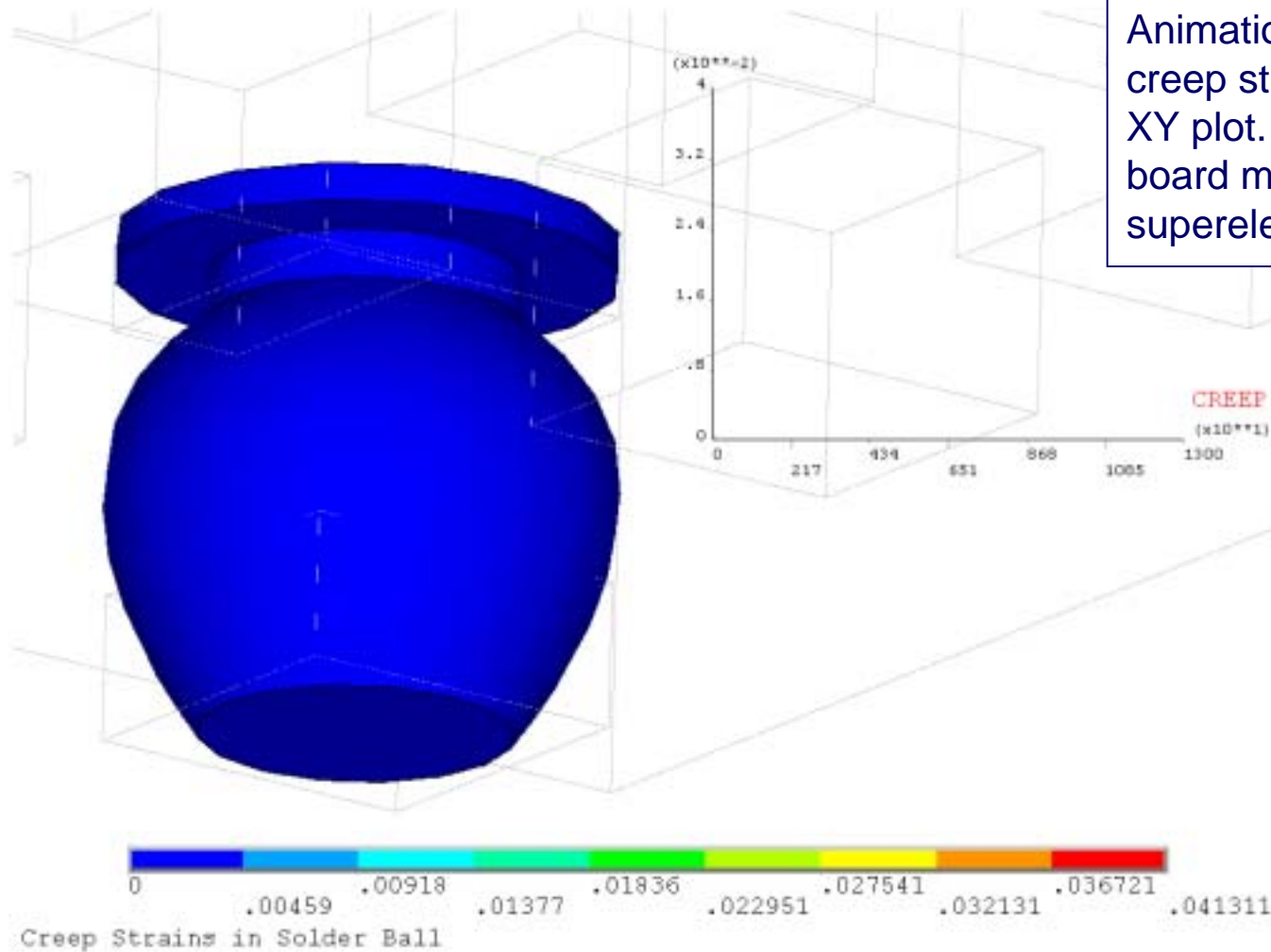
Animation of equivalent creep strain contours and XY plot. Rest of chip and board modeled with superelements.

Creep Strains in Solder Ball

ANSYS model courtesy of Bret Zahn, ChipPAC (http://www.chippac.com/)

Implicit Creep Procedure

Supported Element Types

- Element types supported for implicit creep material:
  - Core elements: PLANE42, SOLID45, PLANE82, SOLID92, and SOLID95
  - 18x family of elements: LINK180, SHELL181, PLANE182, PLANE183, SOLID185, SOLID186, SOLID187, BEAM188, and BEAM189.

- The 18x family of elements are the recommended choice for implicit creep analyses.
  - Because of the wide range of element technology available in the 18x series, these elements offer greater flexibility and power. These formulations include B-Bar, URI, Enhanced Strain, and Mixed U-P.
  - The 18x series also support more constitutive models than the core elements, including hyperelasticity.

Plasticity Models Supported

- Recall that creep is decoupled with rate-independent plasticity. Implicit creep allows combinations with the following rate-independent plasticity models:
  - BISO, MISO, and NLISO with CREEP
    (creep with isotropic hardening)
  - BKIN with CREEP
    (creep with kinematic hardening)
  - HILL and CREEP
    (anisotropic creep)
  - BISO, MISO, and NLISO with HILL and CREEP
    (anisotropic creep with isotropic hardening)
  - BKIN with HILL and CREEP
    (anisotropic creep with kinematic hardening)

Defining Implicit Creep

- To define an implicit creep model, you can use commands or through the GUI (discussed on next slide).

- For implicit creep, temperature-dependency can be defined in two ways:
  - Temperature-dependent constants may be defined through TBDATA (or Materials GUI)
  - Many creep equations include the aforementioned Arrhenius equation

$$\dot{\varepsilon}_{cr} \propto e^{-\frac{Q}{RT}}$$

  - The choice of either or both methods to include temperature-dependency is determined by the user.

Defining Implicit Creep (cont'd)

- When defining implicit creep through commands, use TB,CREEP with the specific creep model defined as TBOPT.
  - TB, CREEP, mat, ntemp, npts, TBOPT
  - TBTEMP defines temperature-dependent constants
  - TBDATA defines the actual constants.

For the example below, TBOPT = 2 specifies that the time-hardening creep equation will be used. Temperature dependent constants are specified using the TBTEMP command, and the four constants associated with this equation are specified as arguments with the TBDATA command

```
TB,CREEP,1,1,4,2
TBTEMP,100
TBDATA,1,C1,C2,C3,C4
```
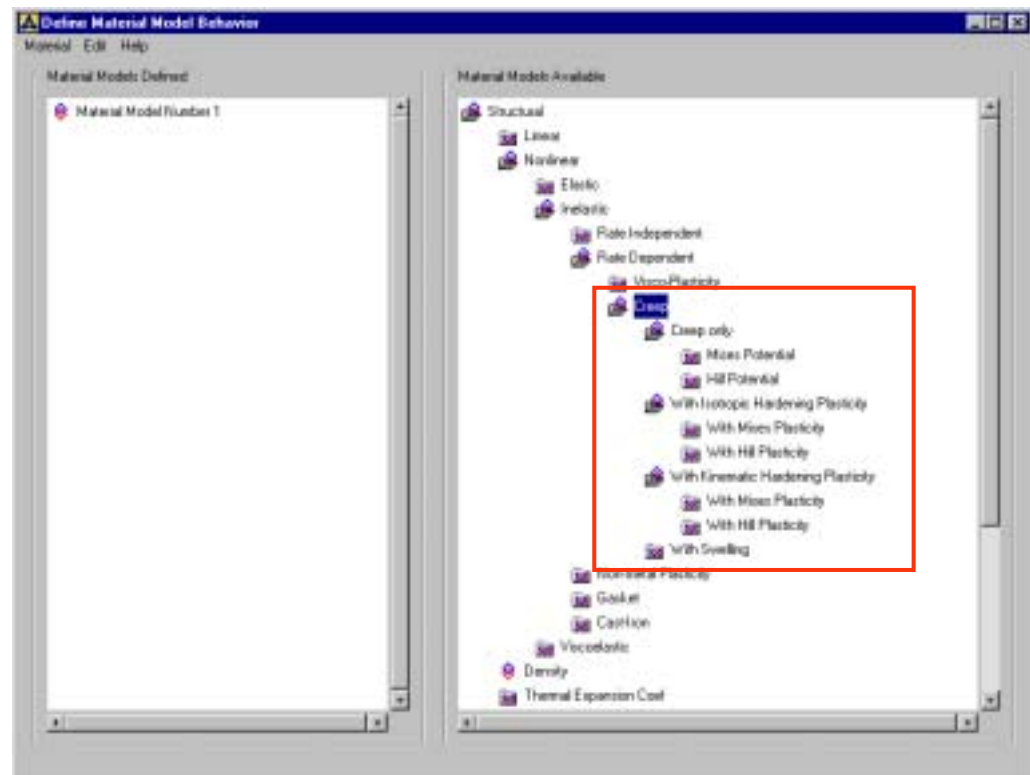
Defining Implicit Creep (cont'd)

All implicit creep models can be selected in the Materials GUI under:

- Structural > Nonlinear > Inelastic > Rate Dependent > Creep

1. Choose whether material will use creep only or creep with plasticity.
2. Selection of Hill or Mises potential is required.
3. Specific creep law can then be chosen.

   Make sure to define the necessary linear elastic material properties first (EX and PRXY).

Defining Implicit Creep (cont'd)

- After selecting the appropriate implicit creep model, a separate dialog box will appear with the required input.
  - In the example below, a primary creep equation has been defined, and the user is prompted to input four creep constants.
  - Temperature-dependent constants may also be input.
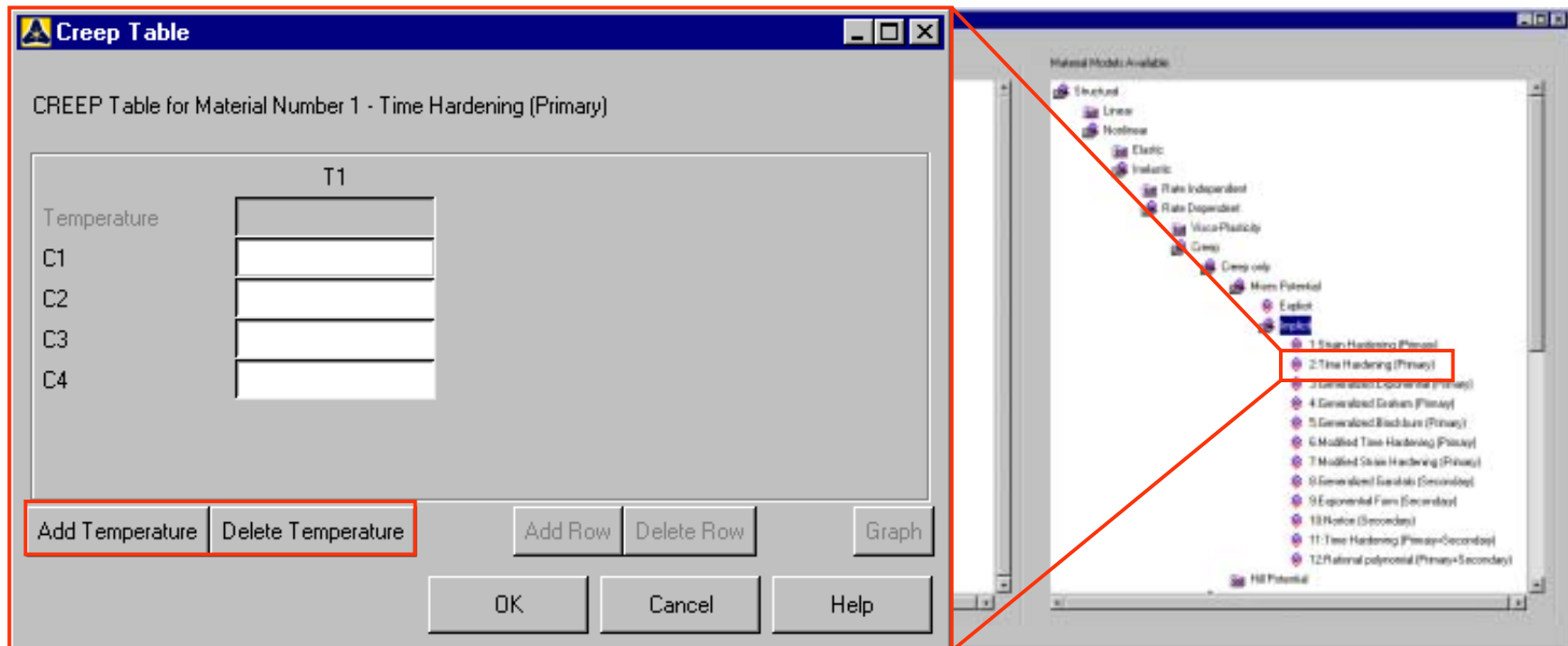
Solution Options

- The solution of models containing creep materials is similar to other nonlinear problems, but there are some special considerations when solving problems with creep.

    – Creep can be large or small strain, depending on the problem.

    – Unlike other static nonlinear analyses with rate-independent materials, "time" has significance in creep analyses.

        • Make sure that the ending time is appropriate for the model and time domain of interest

        • Note that the analysis does not have to be a *transient* analysis. Inertial effects (TIMINT) may be on or off, depending on the problem.

        • Generally speaking, however, creep analyses do not consider inertial effects (ANTYPE,STATIC or TIMINT,OFF) because the time domain is long.

Solution Options (cont'd)

– For *implicit creep* only, the RATE ("Include strain rate effect") command can be used to turn creep effects on or off during an analysis.

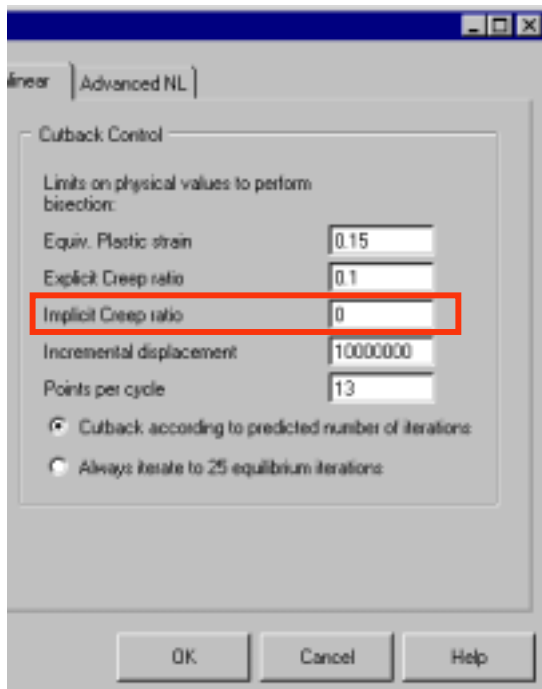Main Menu > Solution > Analysis Type > Sol'n Controls > -Nonlinear Tab- Creep Option
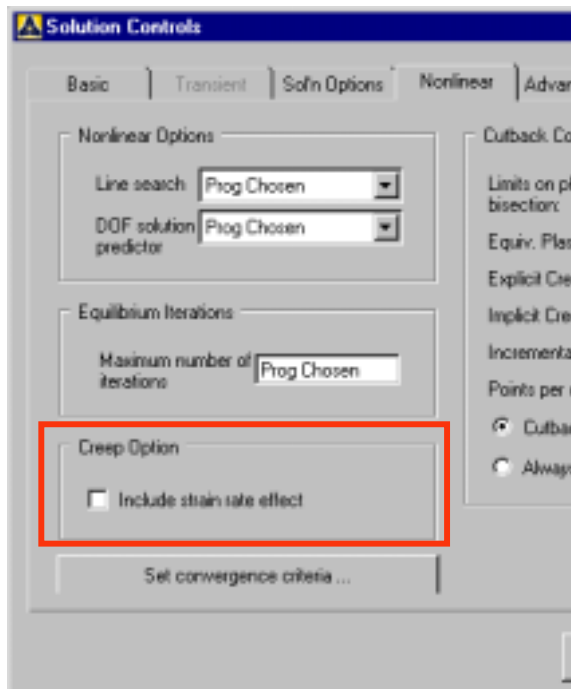
• This is useful to establish initial conditions. In this situation, a very small ending TIME value (e.g., 1e-8) should be set, and rate effects turned off (RATE,OFF). Solve as usual. Then, to turn creep effects on, use RATE,ON and specify the real end time.

• The RATE command is only applicable for the following cases:

– Implicit creep with 18x elements (von Mises potential)

– Anisotropic implicit creep with 18x or core elements (Hill potential)

Solution Options (cont'd)

Since creep is path-dependent, it is important to ensure that the response is adequately captured. One measure of this which ANSYS uses is the creep ratio C_s, defined as: $C_s = \dfrac{\Delta \varepsilon^{cr}}{\varepsilon^{et}}$

– Use Cutback Control (CUTCONTROL) to specify a maximum equivalent creep strain ratio, if desired.

  Main Menu > Solution > Analysis Type > Sol'n Controls > -Nonlinear Tab- Cutback Control

  • CUTCONTROL,CRPLIMIT,*crvalue*,1 will impose a maximum creep ratio of *crvalue* for implicit creep. By default, no implicit creep limit control is specified.

  • If, during a timestep, ANSYS calculates a creep strain ratio larger than *crvalue*, then the solution is automatically bisected until the creep limit is satisfied or the minimum time step is reached.
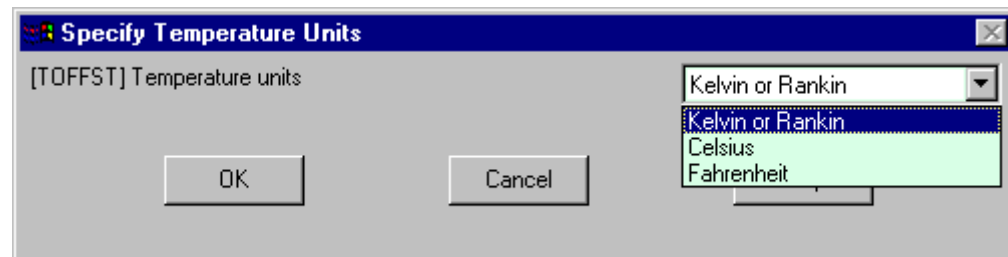
Solution Options (cont'd)

- – Specify an absolute temperature offset with TOFFST.

    Main Menu > Preprocessor > Material Props > Temperature Units

    - Oftentimes, thermal loads may be in ⁰C or ⁰F. TOFFST can be used to have ANSYS internally convert to absolute units.

    - Creep equations rely on absolute temperature specification, such as in the Arrhenius function
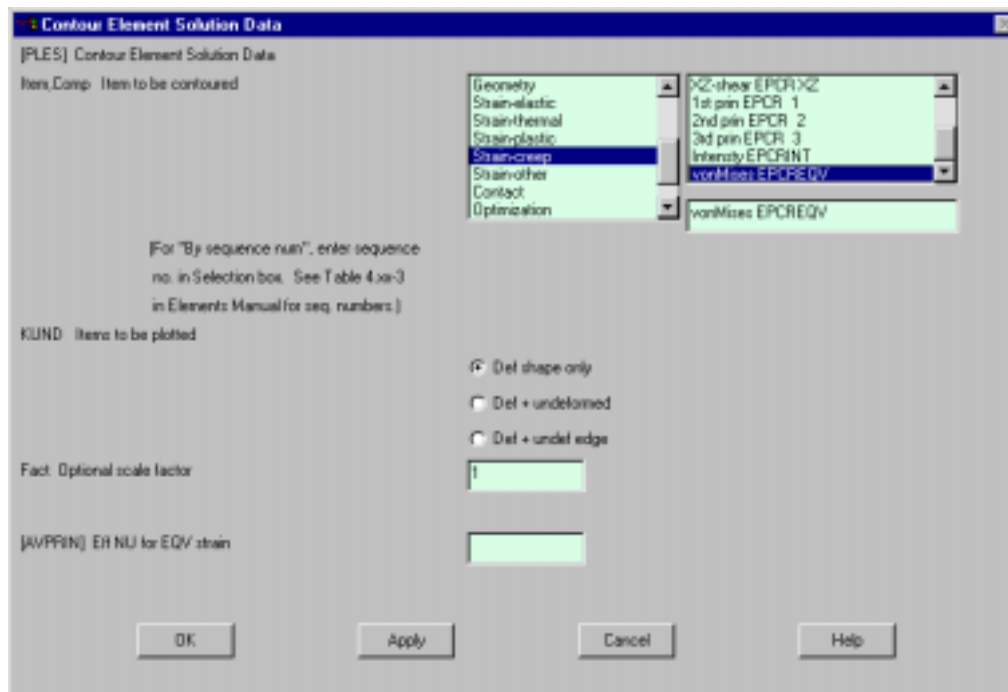
Postprocessing

- **In addition to reviewing elastic, thermal, and plastic strains, one can review creep strains.**

  Main Menu > General Postproc > Plot Results > Nodal Solu …

  Main Menu > General Postproc > Plot Results > Element Solu …

In the dialog box shown on the left, the creep strain category is selected. Components, principal, and effective creep strains can be selected on the right-hand choices.
Note that, at v6.0, Eff Nu is not required. Actual equivalent strains are calculated and stored except for line elements.
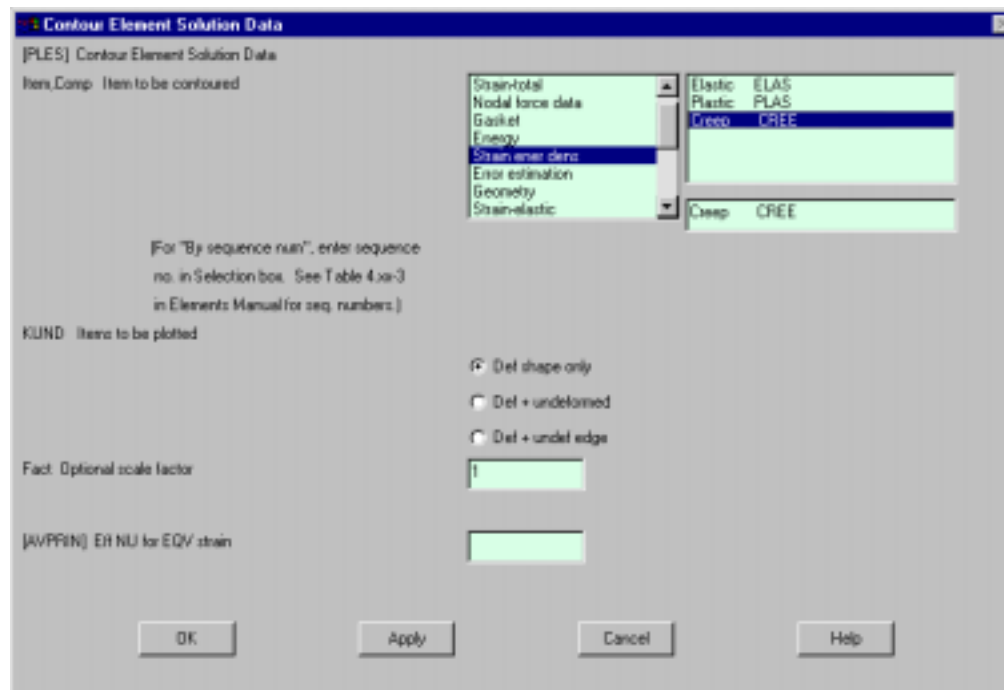
Postprocessing (cont'd)

- Creep strain energy density can also be retrieved and plotted or listed.

  Main Menu > General Postproc > Plot Results > Nodal Solu …

  Main Menu > General Postproc > Plot Results > Element Solu …

Example of Sheet Forming

ELEMENT SOLUTION

STEP=1
SUB =4
TIME=.021848
SMIS17
TOP
DMX =.084747
SMN =.079953
SMX =.079983

ELEMENT SOLUTION

STEP=1
SUB =4
TIME=.021848
EPCREQV (NOAVG)
DMX =.084747
SMN =.296E-05
SMX =.006428

Animation of shell thickness and equivalent creep strain contours. SHELL181 with rigid-deformable contact using power law creep.

.063   .066778   .070556   .074333   .078111
   .064889   .068667   .072444   .076222   .08

0   .152889   .305778   .458667   .611556
   .076444   .229333   .382222   .535111   .688