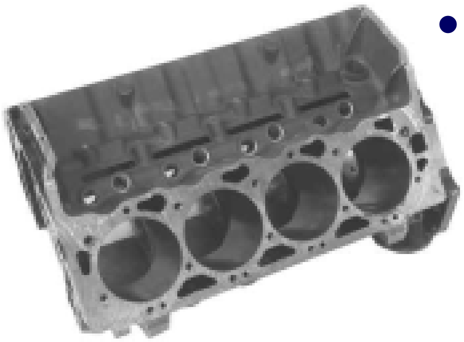
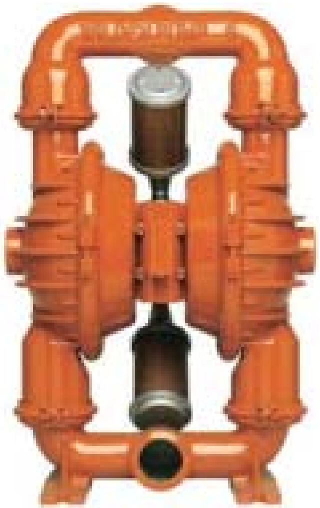
Cast Iron Plasticity

Classification of Cast Iron



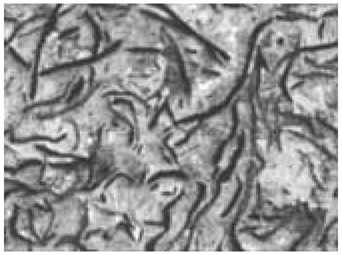
Example of Cast Iron Engine Block



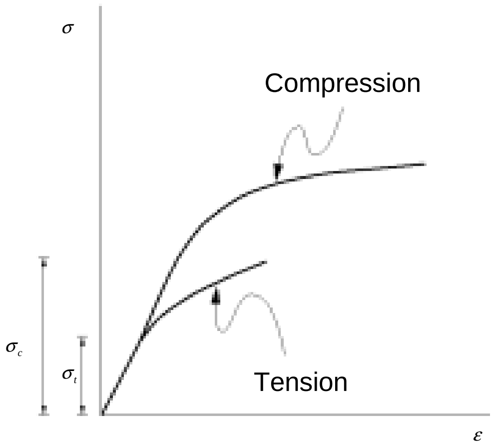
Example of Cast Iron Pump

- *Cast iron* includes a wide range of iron alloys
  - Contains appreciable amount of carbon and silicon in alloy (silicon for softening affect), which affect mechanical behavior
  - Cooling rate also affects properties
  - Cast iron has many advantages, including low cost, ability to cast into complex shapes, good damping capabilities, etc.
  - Cast iron includes *gray cast iron, nodular (ductile) cast iron, white cast iron, malleable cast iron,* etc. Each has specific characteristics and microstructure. Subsequent discussion will focus on *gray cast iron*.

Background on Gray Cast Iron



Graphite flakes in steel matrix



- Gray cast iron is comprised of graphite flakes in a pearlite/ferrite matrix.
  - Unlike steels, which usually have < 1% carbon, gray cast iron contains > 2% carbon. The excess carbon precipitate forms graphite flakes in the steel matrix during solidification.
  - In compression, graphite flakes do not have a significant effect on material behavior, and inelastic response is dominated by ductile steel.
  - In tension, these graphite flakes act as stress raisers which cause localized plastic flow at low stresses (1/3 - 1/5 of compressive strength) and can eventually initiate fracture (i.e., low strength in tension). The cracks also result in inelastic volume change.

Cast Iron Plasticity Assumptions

- In 6.1, the cast iron plasticity model was introduced to model gray cast iron behavior with the following assumptions:
  - Supported by 18x series of elements.
  - Model is for plastic, not brittle response. Does not fracture/fail like SOLID65 concrete model.
  - Elastic behavior (MP) isotropic, so it is assumed to be same in tension and compression.
  - Different yield strength, flow, and hardening in tension and compression. Cast iron exhibits *nonassociative flow* (discussed later).

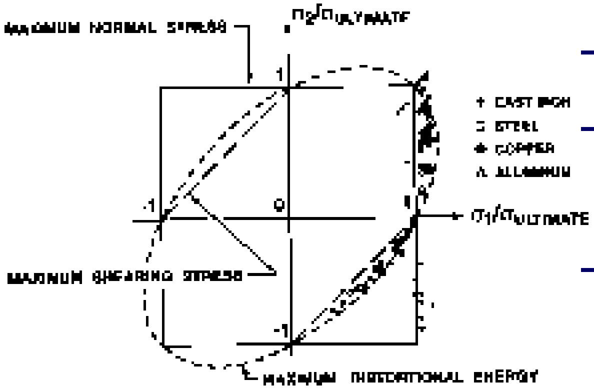


Chart of test data on Rankine and von Mises yield surfaces for different metals. This figure illustrates that cast iron (+) is not well-represented by either criterion alone.

Cast Iron Assumptions (cont'd)

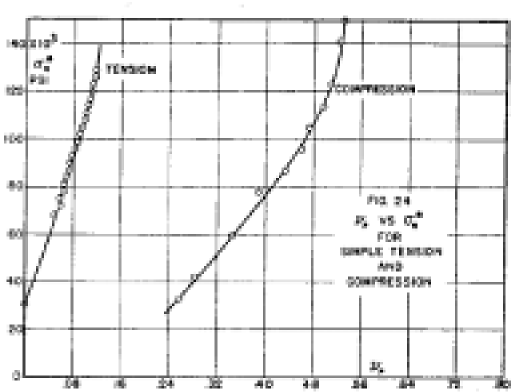
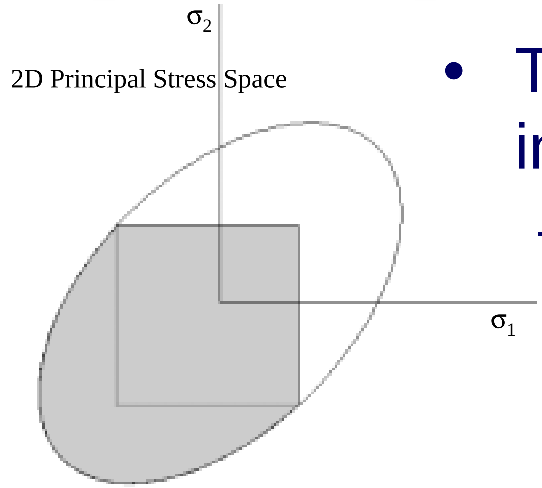
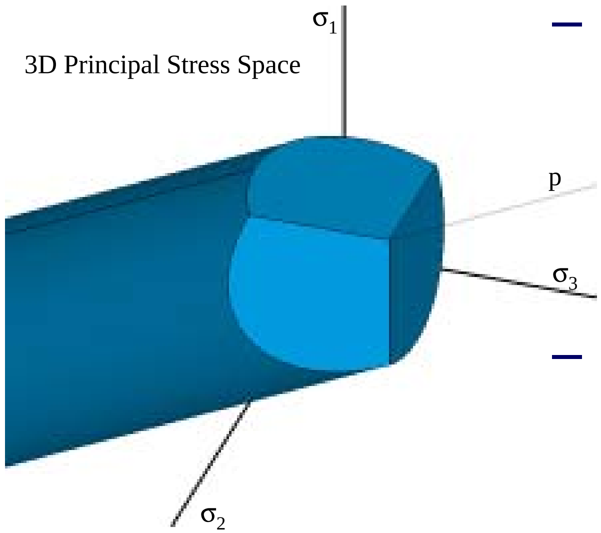


Chart of plastic Poisson's ratio in tension vs. compression for gray cast iron (Coffin). Note the difference and variation in values of plastic ν.

- Assumptions (cont'd):
  - Inelastic strains assumed to be incompressible in compression ($\nu_{pl} = 0.5$).
  - User-input plastic Poisson's ratio defines inelastic volume change in tension. Although plastic Poisson's ratio in tension can vary with stress, ANSYS assumes plastic Poisson's ratio only varies with temperature.
  - Intended for monotonic loading only.
  - Cannot be combined with any other model.

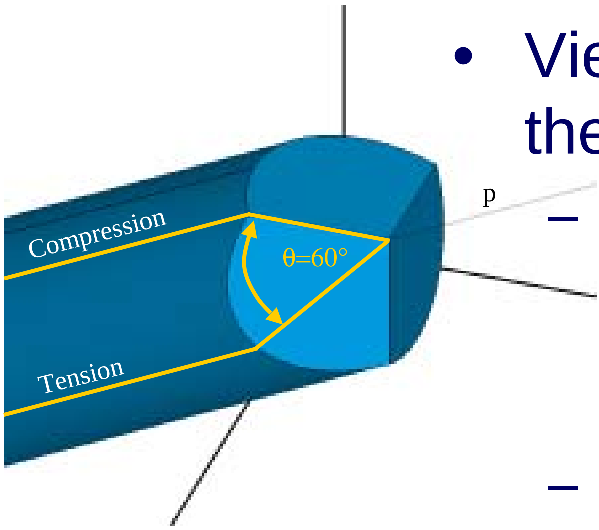
Cast Iron Yield Criterion

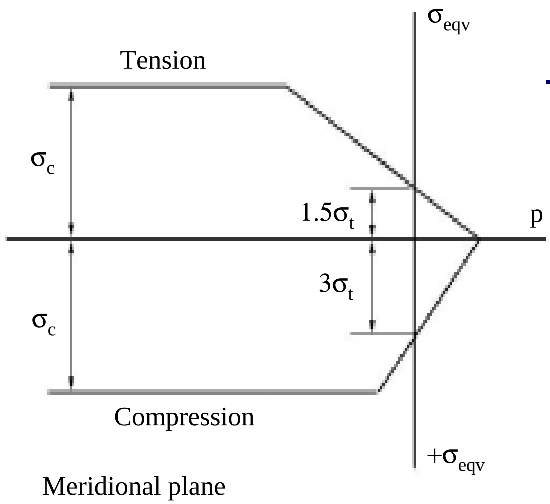




- The yield criterion is a Mises cylinder intersected with a Rankine cube
  - The octahedral shear stress yield criterion (Mises) is a cylinder in 3D principal stress space (an ellipse in 2D). Since only deviatoric stresses are assumed to cause yielding in compression, there is no hydrostatic pressure dependence.
  - The maximum normal stress yield criterion (Rankine) is a box in 3D principal stress space (rectangle in 2D). Yielding in tension is assumed to occur when $\sigma_{1,2,3} = \sigma_y$. There is hydrostatic dependence with this yield surface.
  - Cast iron is assumed to have Mises yield criterion in compression, Rankine yield criterion in tension. This forms a *composite yield surface*

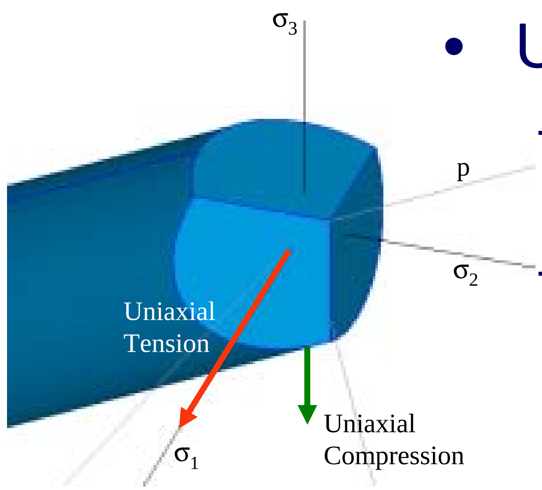
Cast Iron Yield Criterion (cont'd)

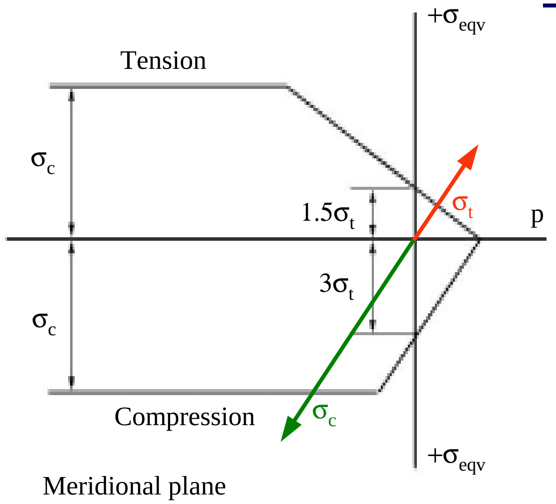




- Viewing the composite yield surface from the meridional plane provides addt'l insight
  - The figure on the left shows that if one goes from the tip of the composite yield surface along the outside (parallel to the axis of the cylinder), the two orange lines will differ.
  - The meridional plane is a slice along the axis of the cylinder ($\sigma_1=\sigma_2=\sigma_3=$p axis).
  - The slope along the tension line is 1.5, whereas the slope along the compression line is 3.0. Both lines intersect with $\sigma_{eqv}=\sigma_c$ as hydrostatic pressure (-p) increases.
    - The "tension line" is called as such because it is in the direction of $+\sigma_1$. Conversely, the "compression line" is aligned with direction of $-\sigma_3$.

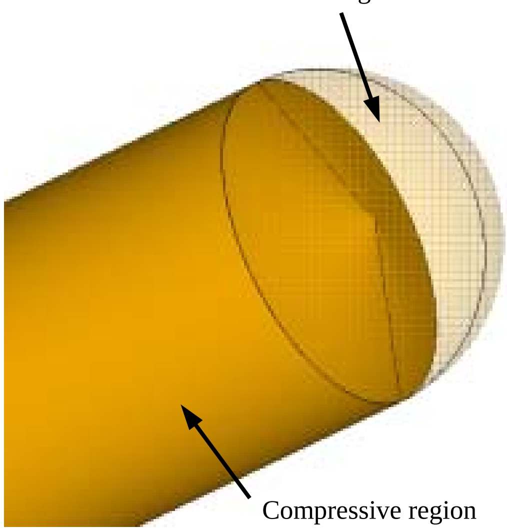
Cast Iron Yield Criterion (cont'd)





- Understanding uniaxial behavior:
  - The meridional plane is oriented at an angle from the principal axes.
  - If a specimen is loaded in *uniaxial tension* (travel along $+\sigma_1$ axis), it will follow the red path shown on the left in principal stress space and in the meridional plane.
  - Likewise, a specimen loaded in *uniaxial compression* (travel along $-\sigma_3$ axis) will follow the dark green path.

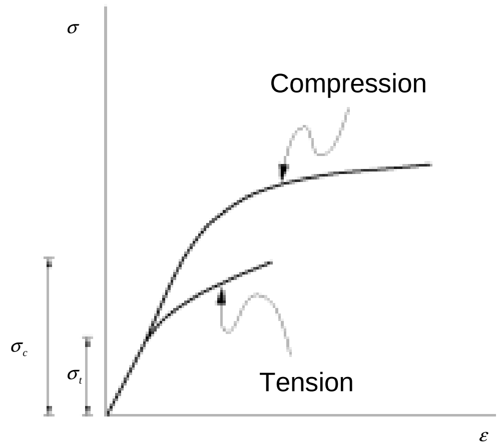
Cast Iron Flow Rule



Flow potential in 3D principal stress space

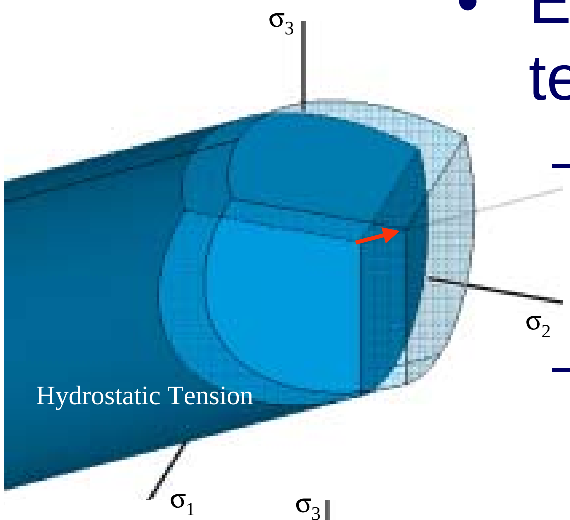
- The flow potential is different for tension and compression.
  - A cylinder with a conical cap represents the compressive region in 3D principal stress space, as shown on the left.
  - An ellipsoidal cap represents the tensile region (transparent volume on left), where the shape of the ellipsoid is dependent on the amount of inelastic volume change (plastic Poisson's ratio).
  - Plastic strains develop normal to flow potential
  - Because of the fact that the flow potential is different from the yield surface, this is an example of *nonassociated flow*. Hence, the stiffness matrix is *unsymmetric,* and NROPT,UNSYM should be used.

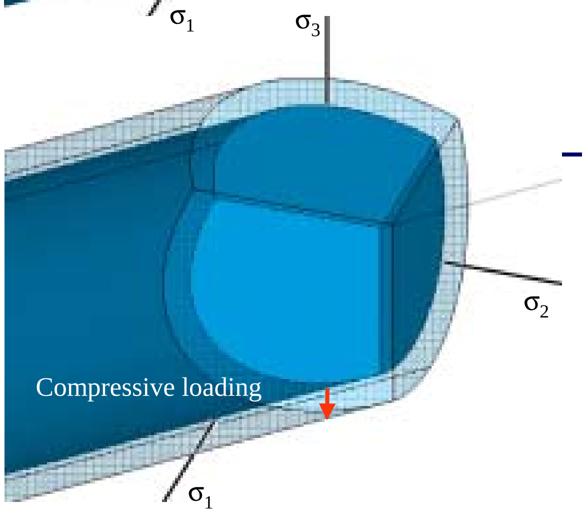
Cast Iron Hardening



- The cast iron constitutive model uses isotropic hardening.
  - Cast iron, being a brittle material, does not exhibit a distinct yield point, as shown on the left
  - This model is suitable for monotonic loading situations only.
  - In cyclic loading, gray cast iron would exhibit the Bauschinger effect to some degree because of the steel matrix.
  - However, the yield surface under load reversal would change due to the behavior of the graphite flakes, and this effect is not captured with this material model.

Cast Iron Hardening (cont'd)

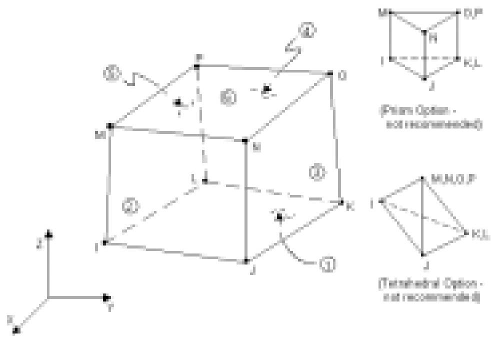




- Evolution of the yield surface is different in tension and compression.
  - In *hydrostatic tension* (travel along +p axis), σ_t evolves, as shown on the top left figure. On the other hand, σ_c does not change.
  - In *compression*, the yield surface expands, though not uniformly. σ_c varies, based on deviatoric inelastic strains. σ_t is updated, based on deviatoric and volumetric inelastic strains.
  - The opaque areas on left show the original yield surface, and the transparent areas show the evolution of that yield surface under the aforementioned loading conditions.

Cast Iron Procedure

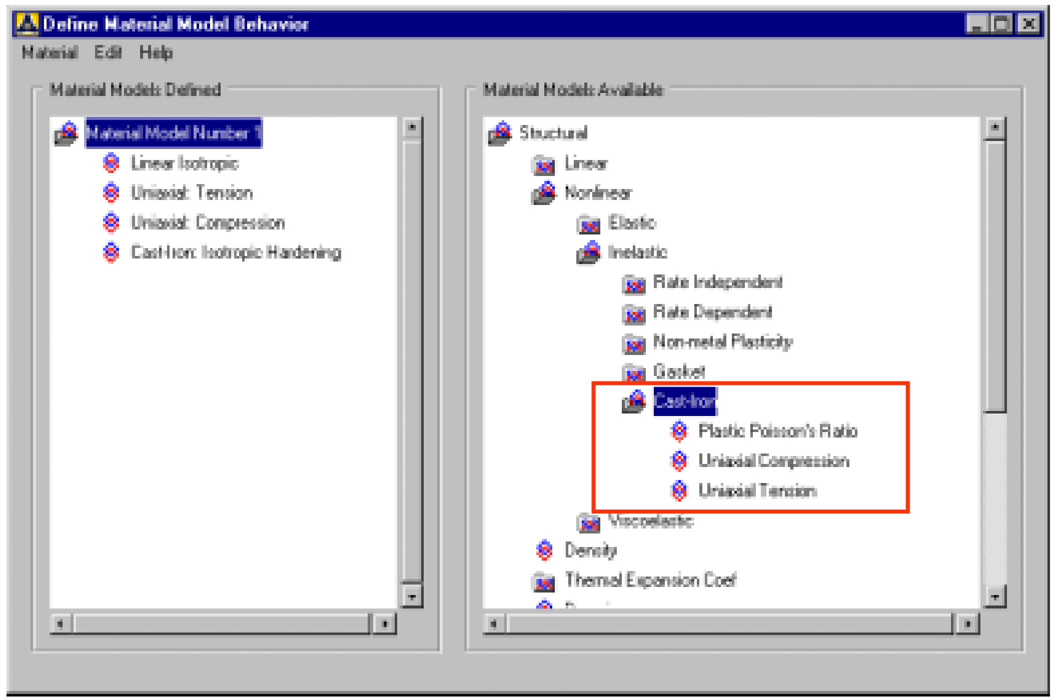
1. Supported Element Types



- All of the 18x elements support cast iron plasticity
  - LINK180, SHELL181, PLANE182-183, SOLID185-187, and BEAM188-189.
- Points to keep in mind:
  - If large compressive strains are expected, use of B-Bar with lower-order 182, 185 is recommended
  - Currently, cast iron plasticity cannot be combined with any other material model

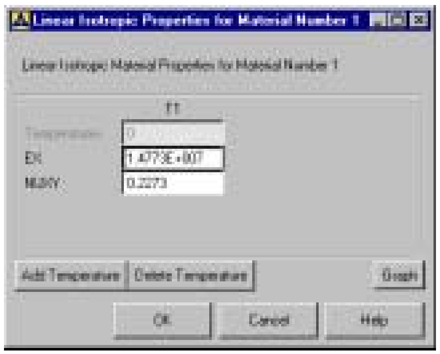
2. Procedure for Cast Iron Input

- The Materials GUI allows specification of cast iron material parameters.



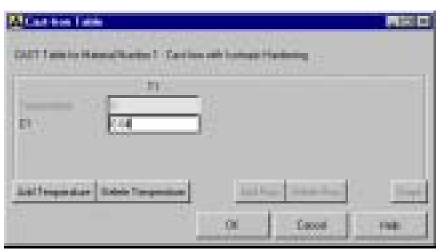
Main Menu > Preprocessor > Material Props > Material Models…
Materials GUI > Structural > Nonlinear > Inelastic > Cast-Iron

Procedure for Cast Iron Input (cont'd)




```
MP,EX   ,1,14.773e6
MP,NUXY,1,0.2273
```

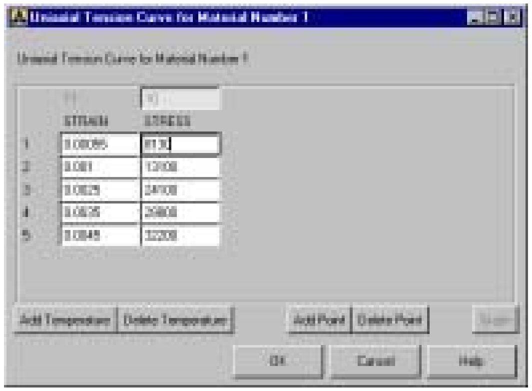
1. Linear elastic materials (EX, NUXY) must be input first. If not input, user will be prompted to input values when entering cast iron data.
   - Isotropic elastic behavior is assumed.
   - Values can be temperature-dependent




```
TB,CAST,1,,,ISOTROPIC
TBTEMP,0
TBDATA,1,0.04
```

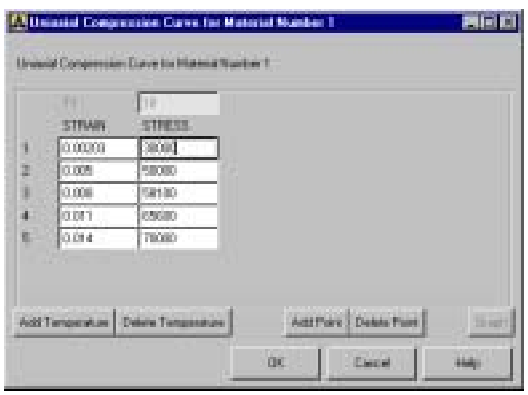
2. Under "Plastic Poisson's Ratio," input the value under the "C1" constant.
   - Up to 10 temperature-dependent values can be input

Procedure for Cast Iron Input (cont'd)




```
TB,UNIAXIAL,1,1,5,TENSION
TBTEMP,10
TBPT,,0.550e-03,0.813e+04
```

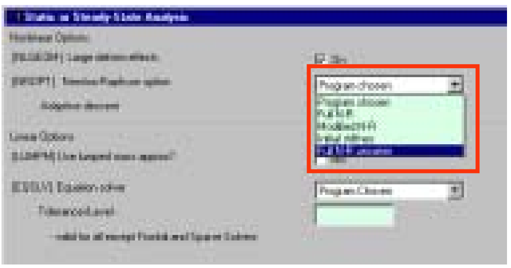
3. Under "Uniaxial Tension", input true stress vs. strain values. This defines σ_t data.
   - Up to 20 data points can be defined
   - Up to 10 temperature-dependent sets of data can be input
   - Values cannot currently be plotted (TBPLOT)



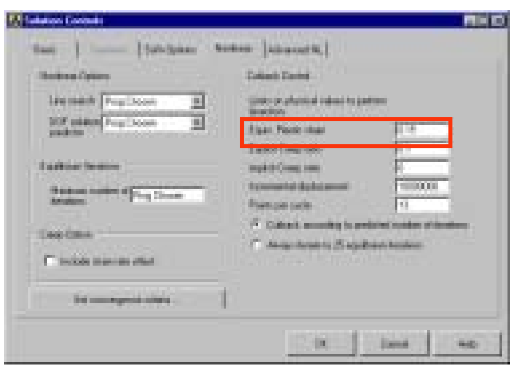

```
TB,UNIAXIAL,1,1,5,COMPRESSION
TBTEMP,10
TBPT,,0.203e-02,0.300e+05
```

4. Under "Uniaxial Compression", input true stress vs. strain values. This defines σ_c data.
   - Up to 20 data points can be defined
   - Up to 10 temperature-dependent sets of data can be input
   - Values cannot currently be plotted (TBPLOT)

3. Solving the Model



- Because cast iron plasticity is an example of *nonassociative flow*, use of unsymmetric solver will aid convergence.
  - GUI: Main Menu > Solution (Unabridged) > Analysis Type > Analysis Options
  - Command: NROPT,UNSYM
  - The unsymmetric option will require more memory and will be slower *per iteration* but should require less total iterations.



- As with all cases of inelastic strains, user can control max plastic strain increment
  - GUI: Main Menu > Solution > Sol’n Controls...
  - Command: CUTCON,PLSLIMIT,value
  - The monitor file (jobname.mntr) will list plastic strain increment per substep in last column.

4. Postprocessing Considerations

- When viewing equivalent plastic strains, note that ANSYS assumes that ν_{pl}=0.5.
  - In compression, plastic strains are assumed to be incompressible, so this is fine
  - In tension, plastic strains have compressibility, as specified by the plastic Poisson's ratio input with TB,CAST. Hence, the user should be aware of this and postprocess plastic and total equivalent strains with either one of the following methods:
    - Select areas in tension and use $\nu' = \nu_{pl}$ via AVRES,,ν' command
    - Use a macro to recalculate equivalent plastic and total strains