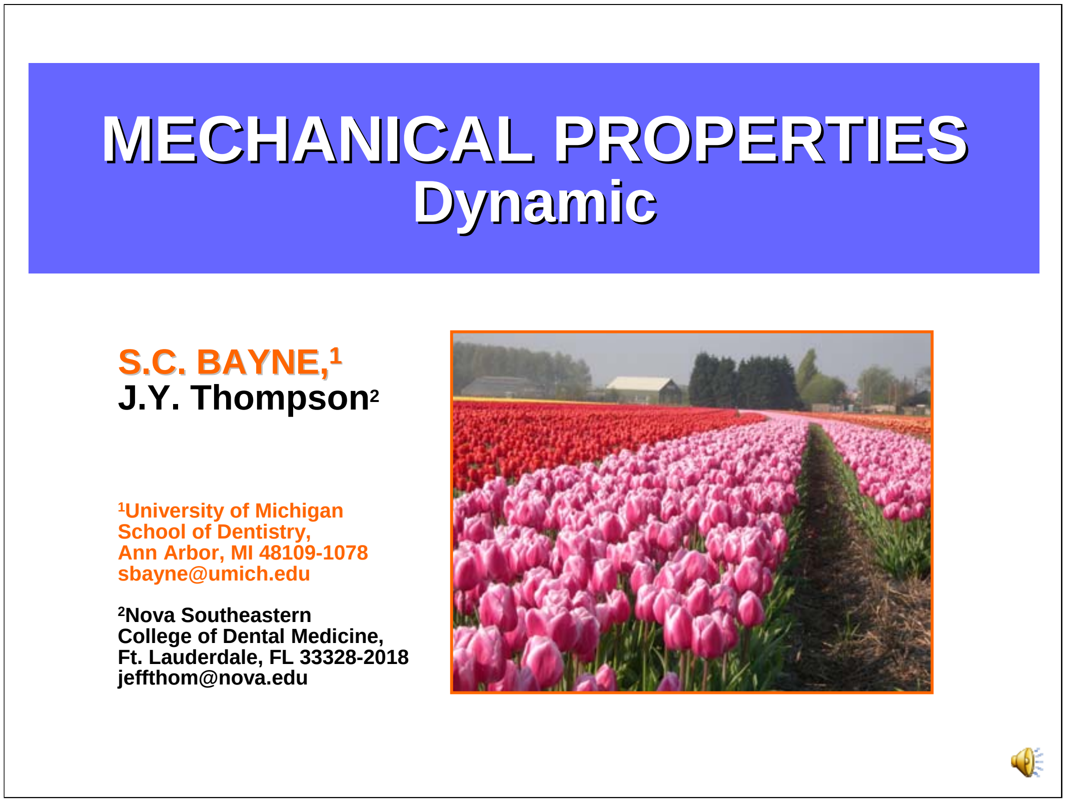

MECHANICAL PROPERTIES

Dynamic

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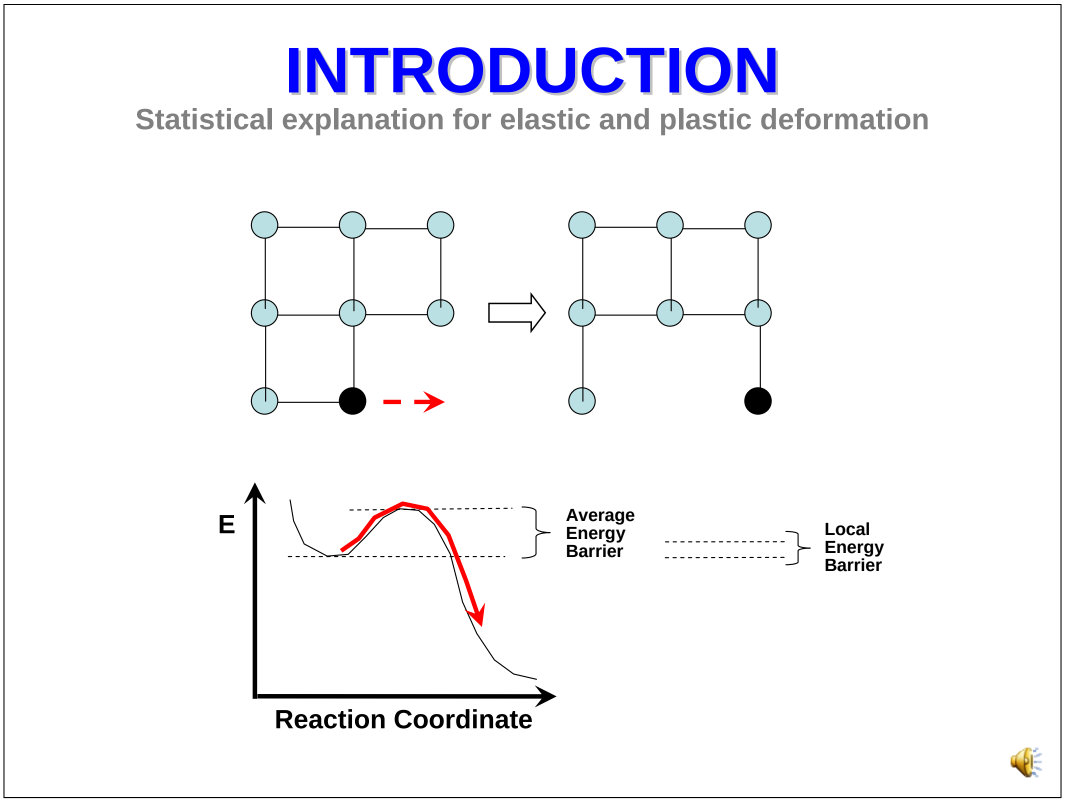
Some interesting new things emerge when we look closely at dynamic mechanical properties.



INTRODUCTION

Statistical explanation for elastic and plastic deformation

E

Average
Energy
Barrier

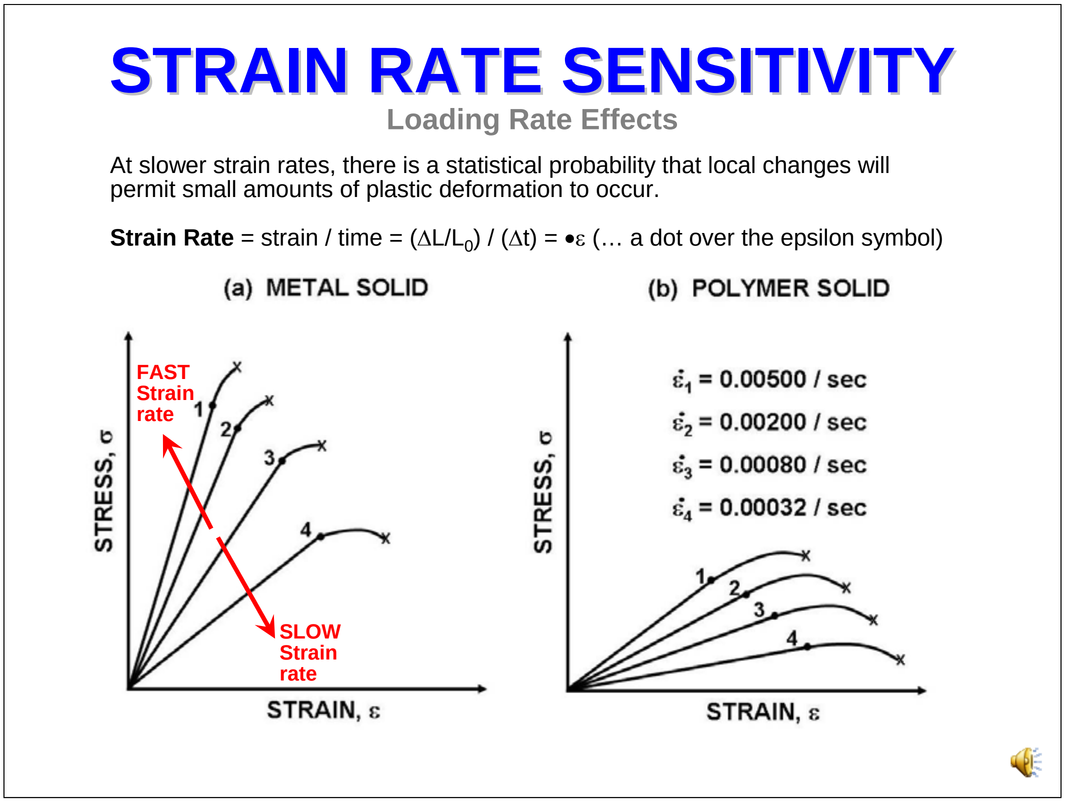
Local
Energy
Barrier

Reaction Coordinate

In the example shown here, **[CLICK]** the black atom is trying to diffuse to a new location. **[CLICK]** There’ss an energy barrier for that change. On average, that energy barrier might be high **[CLICK]** , but locally the energy barrier may fluctuate, and the barrier may briefly be low -- and the change may actually occur. **[CLICK]**

When mechanical properties were originally introduced, we stated that the first response of strain to stress was elastic only. However, very, very small amounts of plastic strain actually are possible below the elastic limit, for the statistical reasons just explained. These plastic strains are so small that they can effectively be ignored for loading and unloading for a limited number of cycles of stress. However, if you wait around for long times (TIME) or increase the available thermal energy (TEMPERATURE) then you will encounter measureable amounts of plastic deformation below the elastic limit.

The following sequence demonstrates the effects of small amounts of plastic strain events in terms of (1) strain-rate sensitivity, (2) creep and stress relaxation, (3) fatigue, and (4) different temperatures.



STRAIN RATE SENSITIVITY

Loading Rate Effects

At slower strain rates, there is a statistical probability that local changes will permit small amounts of plastic deformation to occur.

Strain Rate = strain / time = $(\Delta L/L_0) / (\Delta t)$ = •ε (… a dot over the epsilon symbol)

When stress is applied to a material, it can be applied at different speeds (i.e., different rates). You can push or pull quickly -- or slowly. **[CLICK]** If you push very quickly, there is little chance for small amounts of plastic deformation to occur. If you push slowly, however, small amounts of plastic deformation have a much great chance of showing up. Imagine pushing over many minutes, or hours, or days, or even years.

[CLICK] Because the strain changes in response to the stressing rate, we say materials are strain-rate sensitive. We indicate the fact that time is involved or that we mean rate -- by putting a dot over the symbol for strain. **[CLICK]** On the left is an example of 4 different stress-strain curves for a metal being stressed at 4 different strain rates. **[CLICK]** Fast stressing produces curves with steeper slopes, higher elastic limits, and more brittle behavior. **[CLICK]** Slower stressing has the opposite effects. **[CLICK]** On the right is an example for a polymer. Generally, ceramics are the least strain-rate sensitive and polymers are the most strain-rate sensitive. Note that the units for strain rate are reciprocal seconds (i.e., strain/sec).

SNICKER'S BAR

Taking advantage of strain-rate sensitivity.

Dividing a Candy Bar

FAST Strain Rate

SLOW Strain Rate

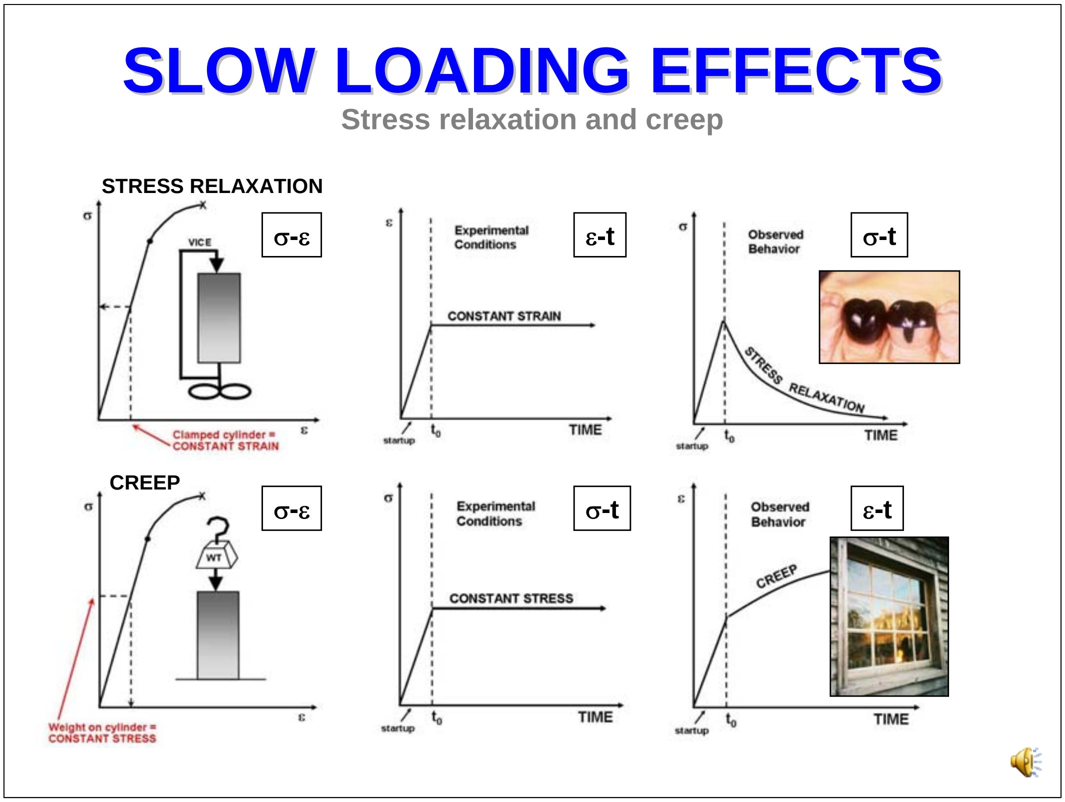
Brittle failure – with almost no plastic deformation.

Ductile failure -- with extensive plastic deformation.

Now let's examine a very simple but dramatic example of strain rate sensitivity in action. You need a SNICKERS BAR to do this for yourself. It works better with a bigger piece of candy. You are going to break the bar into 2 pieces, first at a slow rate, and then at a fast rate. **[CLICK]** Slowly bend and tear the bar to create 2 pieces, and you will immediately note that it undergoes considerable plastic deformation. Now, start with a new piece of candy, and this time, quickly break it into 2 pieces. The easiest way to do this is to position it half way off of the edge of a table, Hold the table side with one hand, and karate chop the other piece to cause the break. **[CLICK]** It should produce a nice clean brittle fracture. Your reward for a successful experiment is to eat the candy bar. ☺

Another example of the same thing is "silly putty." At slow strain rates it behaves like moldable clay. If you deform it slowly by rolling it in your hand, you can easily create a ball. Now throw it at the wall. When it encounters the wall, it will be strained at a very high rate and behave totally elastically, bouncing off of the wall.

A dental example of taking advantage of this property is the removal of an impression from a patients mouth. You care trying to capture the details and dimensions of the hard and soft tissues of a dental arch. The material is rubbery and elastic. If you remove it slowly, it will be more likely to undergo some plastic deformation in heavily undercut areas. If you remove it with a snap, the fast rate, guarantees that the material will behave totally elastically.



SLOW LOADING EFFECTS

Stress relaxation and creep

Both elastic and plastic strain demonstrate time-dependent responses. Recovery from elastic strain may not always occur quickly. In complex materials, the microstructure it may require time to move molecules back to their original positions. For elastic strain this is called “anelastic” or “viscoelastic” behavior.

For plastic deformation, time dependent responses are observed as stress relaxation and/or creep. These two events are extremes on a spectrum of responses. Each will be explained separately, but quite often components of both are occurring. For each situation, we will examine the stress-strain curve, strain or stress versus time, and then stress or strain versus time.

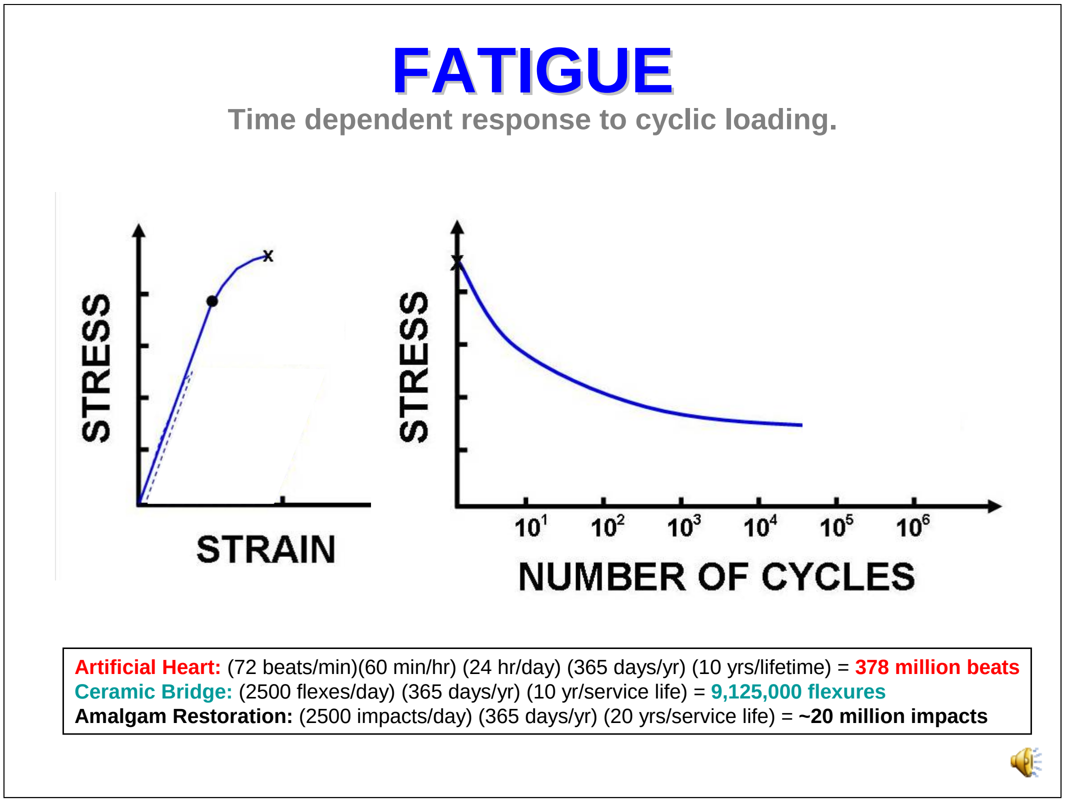
STRESS RELAXATION: Consider the example shown of a cylinder being clamped and placed under fixed strain. **[CLICK]** Graphing the strain versus time, you can see that it is constant. **[CLICK]** It starts out behaving as though the strain is elastic, yet slowly events occur that allow some plastic deformation by converting elastic strain into plastic behavior – and that concomitantly reduces the actual stress. In the end, the original stress values decay to zero. All the original elastic strain will have been converted into plastic strain.

Remember when you were waxing up teeth in your dental anatomy class? **[CLICK]** If you cooled the wax too quickly, you created built-in stresses. Over time, the elastic strain of the built-in stress was converted into plastic strain – deforming the wax pattern. To avoid this event, remember that anything you have waxed needs to be used as quickly as possible.

CREEP: **[CLICK]** Now envision the same cylinder under a constant weight (i.e., constant stress). **[CLICK]** This creates an elastic strain. **[CLICK]** Over time, components of the elastic strain are converted into plastic strain. Since the weight remains in place, it continues to re-establish the original elastic strain level. Over time, more and more plastic strain is added to the original elastic strain. The material creeps. As plastic deformation increases the cross-sectional area, it reduces the stress caused by the weight and the process slows down.

Consider the example of an old window pane in a 200 year-old farm house. **[CLICK]** The weight of the top of the pane on the bottom, produces a constant elastic strain. Over many years, the glass slowly flows and the pane becomes larger at the bottom than the top also causing ripples to appear in the glass. While glass is normally considered very brittle, it is capable of slow flow over many years.

Because it is often difficult to dissect out the exact events, we will refer to the combination of processes simply as stress-relaxation and creep.



FATIGUE

Time dependent response to cyclic loading.

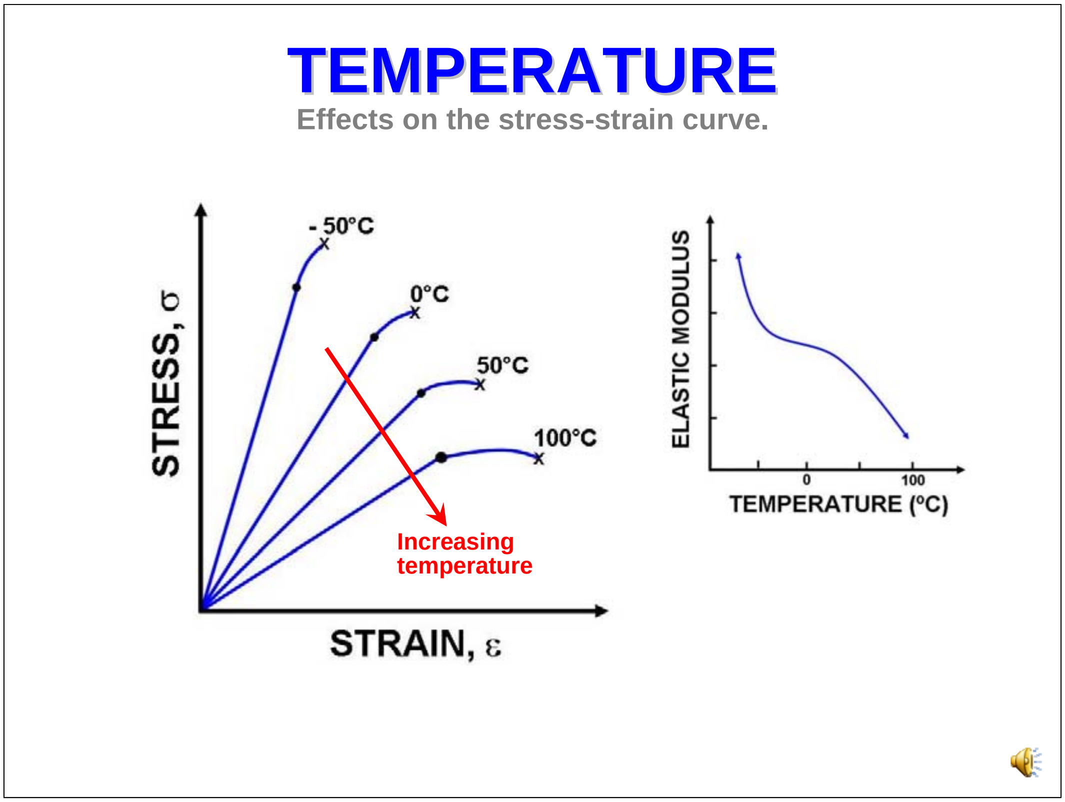
Artificial Heart: (72 beats/min)(60 min/hr) (24 hr/day) (365 days/yr) (10 yrs/lifetime) = **378 million beats**
Ceramic Bridge: (2500 flexes/day) (365 days/yr) (10 yr/service life) = **9,125,000 flexures**
Amalgam Restoration: (2500 impacts/day) (365 days/yr) (20 yrs/service life) = **~20 million impacts**

Another way that small amounts of plastic strain can accumulate into meaningful quantities is through continual stress cycling. Imagine continually cycling stress on-and-off of a restoration. **[CLICK]** Even though the plastic strain is extremely small for one cycle, you get lots of total strain after one million cycles. With continual additions of plastic deformation, the material ultimately fails well below the predicted stress for a single cycle. **[CLICK]** You can keep track of the failure stress and number of cycles with a FATIGUE CURVE or S/N (i.e., Stress vs Log of Number of Cycles) curve as shown on the right. Because the number of cycles is large, the graph is usually plotted versus the log of the number of cycles.

For most materials the fatigue curve is shaped like the one shown to the right – and with an asymptotic approach to a lower limit value -- below which no failure occurs. This is called the ENDURANCE LIMIT. **[CLICK]** Ideally, one would like to choose a material so that the level of stress in service is below the endurance limit. Then the material will never fail. Every combination of stress and number of cycles below the curve represents success.

Now let's look at a couple of practical situations **[CLICK]** and see how many cycles might be important. **[CLICK]** First, consider an artificial heart that you want to succeed for a minimum of 10 years. How many beats (or cycles of stress) must it sustain? 378 million! **[CLICK]** Second, how many flexures must a ceramic bridge endure in 10 years? ~10 million! **[CLICK]** Third, how many impacts an amalgam restoration must survive in 20 years? ~20 million.

As you can see, knowing something about fatigue is very important. It is difficult to collect all of this information experimentally, so often we make estimates of what the curve might look like. A first approximation is that the endurance limit is about 10-20% of the failure stress. If you choose the material so that stresses only occur below the endurance limit, then the material will survive forever.

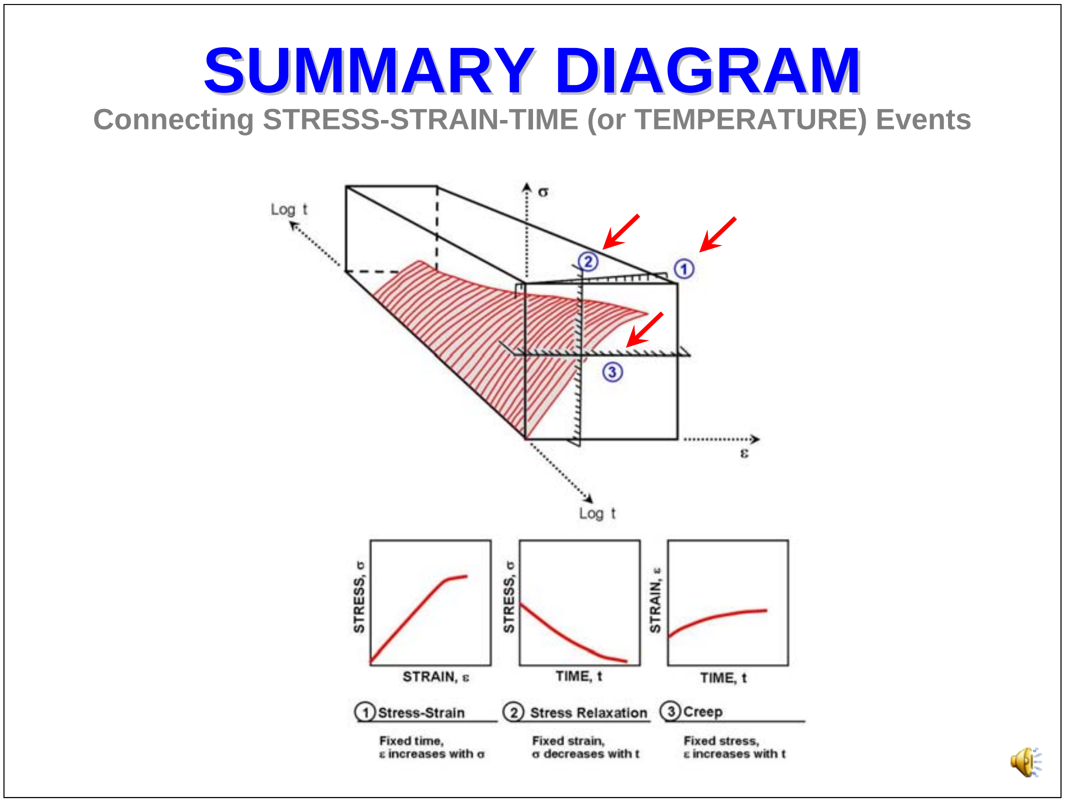


TEMPERATURE

Effects on the stress-strain curve.

Just as we observed that the stress-strain curve shifted in response to strain rates, a similar thing happens with temperature. We normally assume that the temperature of interest is room temperature (25 C) or body temperature (37 C). Materials are less strong as the temperature increases, **[CLICK]** and more strong as it decreases, although they may become more brittle at the same time. The curves shown above are representative of polymers.

[CLICK] The exact relationship of any specific part of the stress-strain curve will not necessarily show a linear response to changing TEMPERATURE (T) but does follow the trend we just talked about. Above is the change in elastic modulus with temperature.

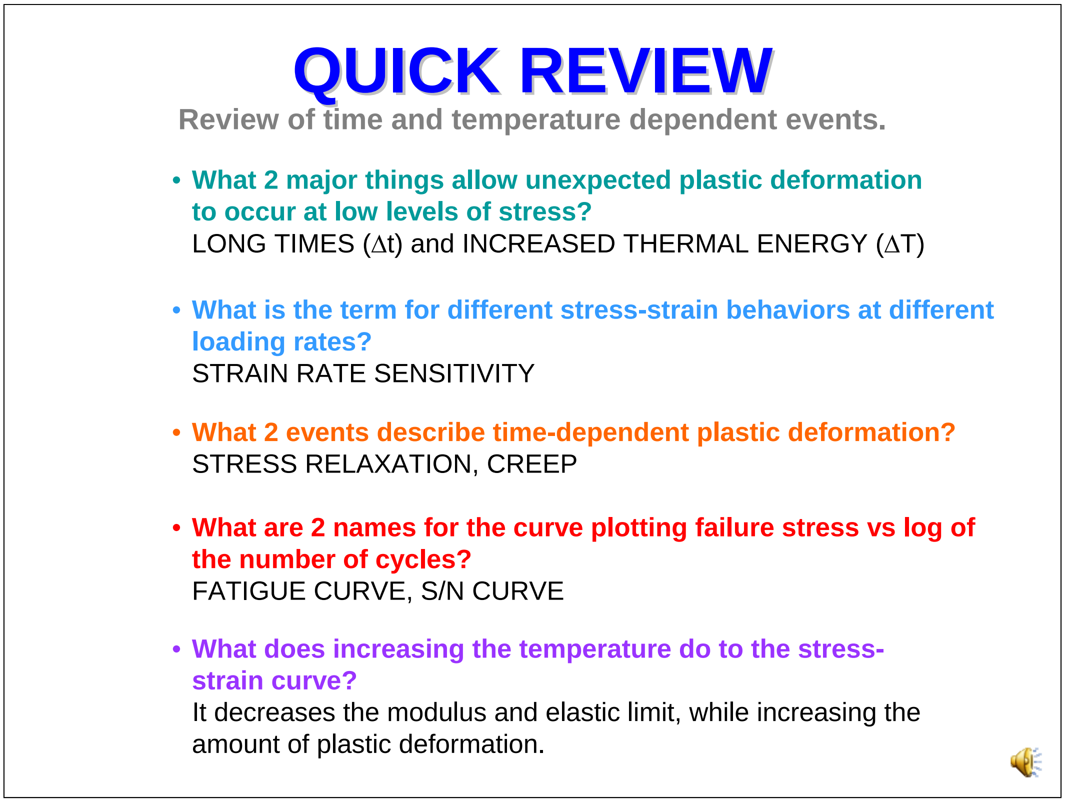


SUMMARY DIAGRAM

Connecting STRESS-STRAIN-TIME (or TEMPERATURE) Events

Finally, it is theoretically possible to pull together all of this information into a single diagram. If you find this confusing, just ignore this explanation.

Imagine a 3D graph of STRESS-vs-STRAIN-vs-LOG-of-TIME. Instead of a line, there is a surface containing all the relevant information. **[CLICK]** Depending on how you cut through it, **[CLICK]** you get stress-strain, stress-relaxation, or creep curves. Temperature and time are related to each other in their effects. Knowing the TIME-TEMPERATURE-TRANSFORMATION relationship, allows you to include temperature as well.



QUICK REVIEW

Review of time and temperature dependent events.

- **What 2 major things allow unexpected plastic deformation to occur at low levels of stress?**
  LONG TIMES (Δt) and INCREASED THERMAL ENERGY (ΔT)
- **What is the term for different stress-strain behaviors at different loading rates?**
  STRAIN RATE SENSITIVITY
- **What 2 events describe time-dependent plastic deformation?**
  STRESS RELAXATION, CREEP
- **What are 2 names for the curve plotting failure stress vs log of the number of cycles?**
  FATIGUE CURVE, S/N CURVE
- **What does increasing the temperature do to the stress-strain curve?**
  It decreases the modulus and elastic limit, while increasing the amount of plastic deformation.

Here is a quick review of the concepts from this module.

[CLICK] (1) What 2 major things allow unexpected plastic deformation to occur at low levels of stress?

[CLICK]

[CLICK] (2) What is the term for different stress-strain behaviors at different loading rates?

[CLICK]

[CLICK] (3) What 2 events describe time-dependent plastic deformation?

[CLICK]

[CLICK] (4) What are 2 names for the curve which graphs failure stress versus log of number of cycles?

[CLICK]

[CLICK] (5) What does increasing the temperature do to the stress-strain curve?

[CLICK]

THANK YOU

THANK YOU.