4/26
In class.

Session 2, Lecture 2, Mechanical behavior of soft tissue

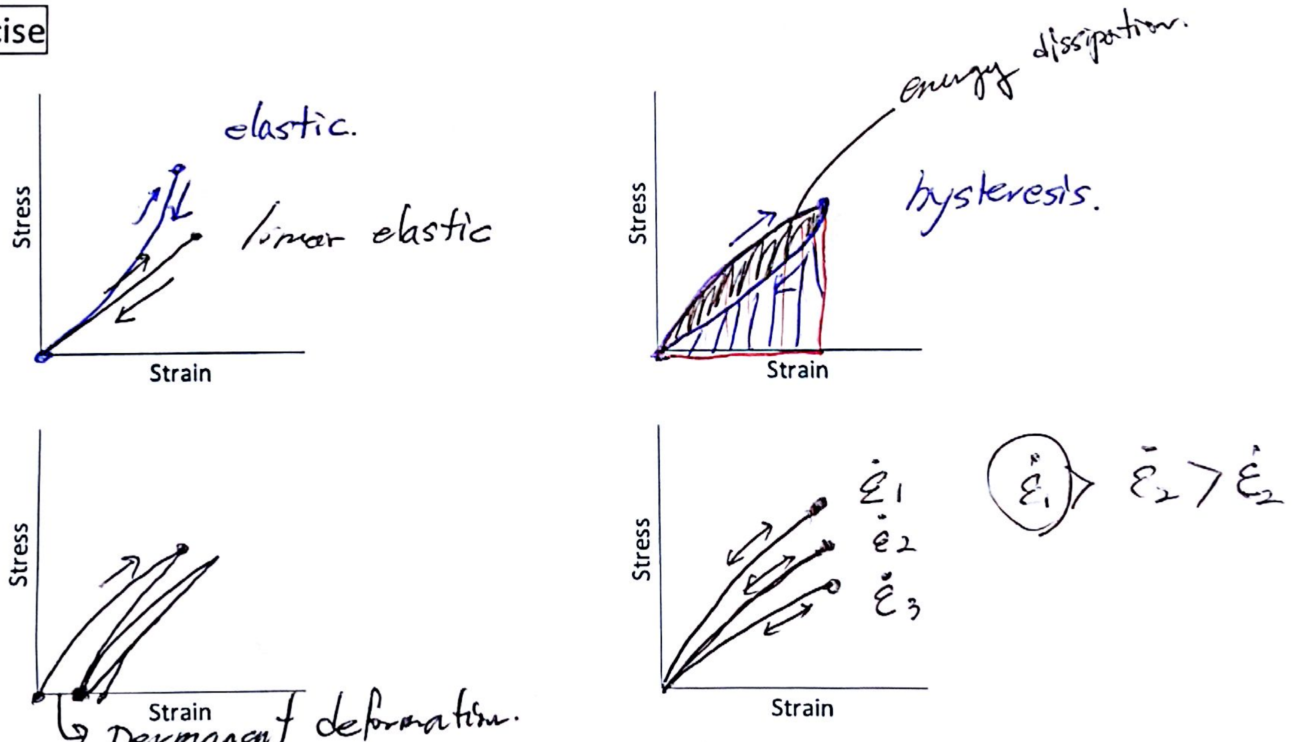
Soft tissue

: Most solid tissues are soft (unlike bone)

- **Structural Properties**

1. highly deformable, non-linear stress-strain curves.
2. Viscoelastic, incompressible, anisotropic
3. hydrated - 65-85% water
4. ~~Compo~~ Complex composites - cells, ECM, vasculature, lymphatics.
5. ECM: Elastin, Collagen. ground substance.

Exercise



- **Elastic material**

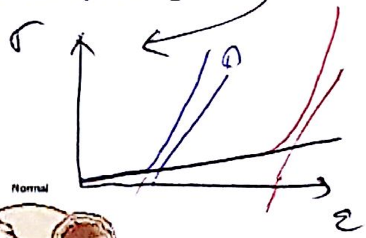
1. No dependence on the rate of loading or unloading.
2. Stress-strain ~~curve~~ path is same on loading and unloading (reversible)
3. No permanent deformation.

Elastic behavior of tissue

- The main fibrous ECM proteins are collagen, elastin, fibronectin, and laminin

Elastin

- Highly elastic (remain elastic up to 60% stretch), stable proteins, low stiffness
- Provides recoil to tissues that undergo stretch
- Elastin stretch is limited by collagen
- ligamentum nuchae (noo-kee), lungs



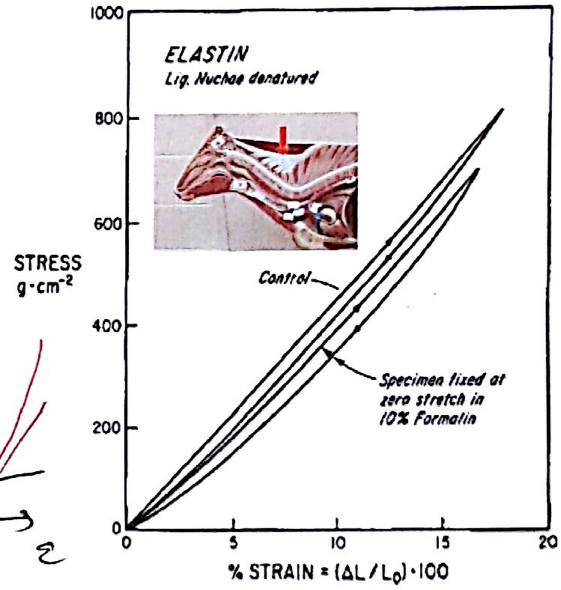


Figure 1 The stress-strain curve of elastin. The material is the ligamentum nuchae if cattle, which contains a small amount of collagen that was denatured by heating at 100°C for an hour. Such heating does not change the mechanical properties of elastin. The specimen is cylindrical with rectangular cross-section. Loading is uniaxial.

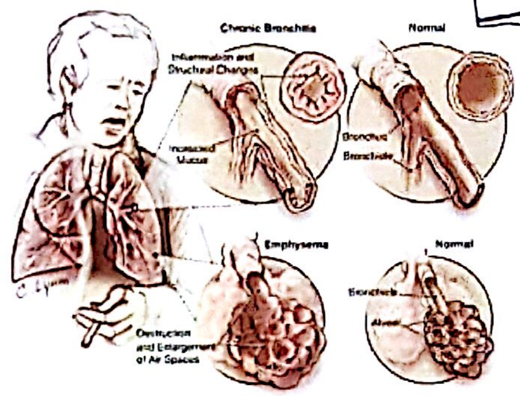


Figure 2. Emphysema

Lung

elastin (with alveolus) is very important determinant of lung elasticity.

Elastin is susceptible to injury through tobacco smoke. Smoking causes a loss of elasticity of the lung primarily to the destruction of elastin resulting in the loss of pressure and enlarged lungs.

In normal aging, the elastin become fragmented and discontinuous and the mechanical load is transferred to collagen fibers, which are 100-1000 times stiffer than elastic fibers

In aorta, elastic fibers that damaged during aging or as a result of tissue injury are generally not replaced, because elastin expression is turned off in adult animals. Instead, more collagen is produced, which decreases the amount of elastin compared to collagen and shifts the arterial mechanical properties into the stiffer range of collage fibers.

Collagen

- The most abundant fibrous protein, high stiffness
- Many in vascular tissues and skin
- Tendon : over 85% of dry mass.
- Most ligaments are purely collagenous (except for ligamentum nuchae and ligament flava of the spine)
- 90% of bone matrix - ~~minerized~~. mineralized.

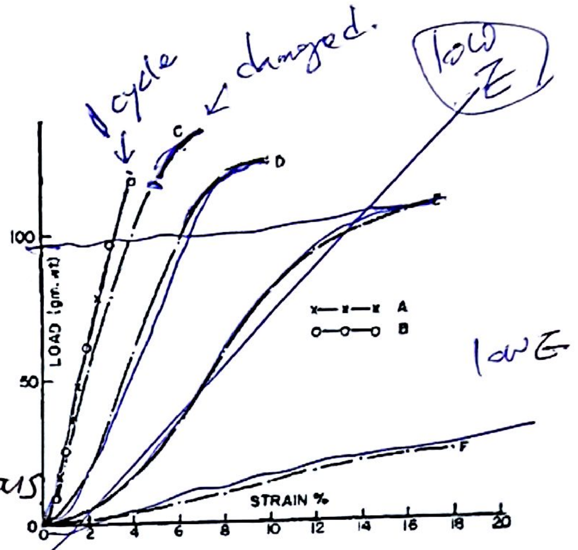


Figure 3. A typical set of load-strain cures showing the effect of a series of successive stretches on the behavior of the rat tail tendon. The rate of straining was 2 %/min, the temperature was 21°C. (A) the tendon returned to its original length. (B) extended past the "safe limit" (C) the tendon has become weaker

elastin : rubber band

collagen : rope (may or may not be straight)

Viscoelastic behavior of tissue

- In other connective tissue, elastin and collagen together form a unit of composite material. The straight elastic fibers attached to the bent collagen fibers can have the mechanical properties exhibited by the composite material
- Skin: 75% collagen, elastin 4%
- Blood vessel: the ratio of elastin and collagen is 2 in thoracic aorta(d=1.16cm) and ½ for elsewhere

- **Viscoelastic material**

1. Soild material with some 'fluid-like' characteristics
2. Polymer plastics and most biological material
3. Dependence on the rate of straining
4. Loading and unloading curves do not coincide (hysteresis loop)
5. Some permanent deformation may occur

Basically the relationship between stress and strain depends on time or frequency

elastic : $\sigma = \sigma(\varepsilon)$

vis : $\sigma = \sigma(\varepsilon, \dot{\varepsilon}, f)$

$= \sigma(\varepsilon, t \text{ or } f)$

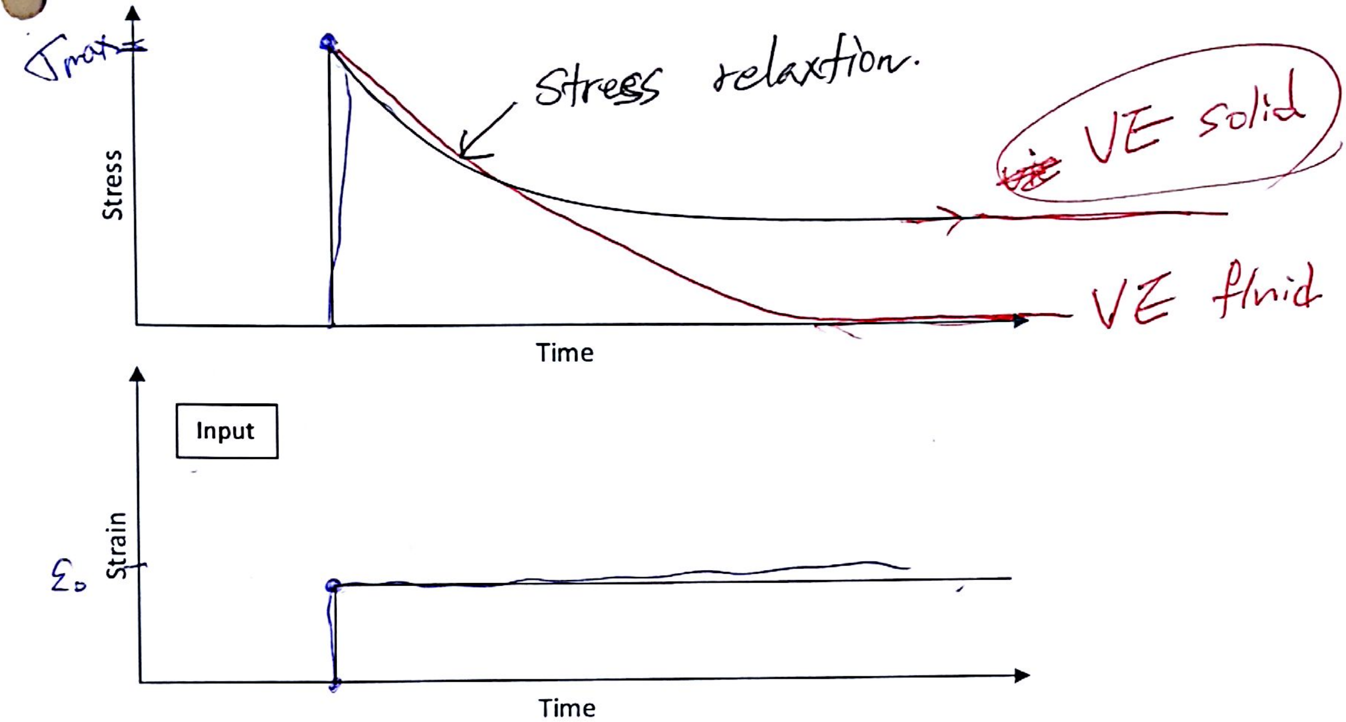
Viscoelastic Testing

1. Stress & stain curve (elasticity) → E. G
2. Stress relaxation and Creep. → τ.
3. Dynamic modulus responses. → ~~G', G''~~ E' E'' → E. G / (K)

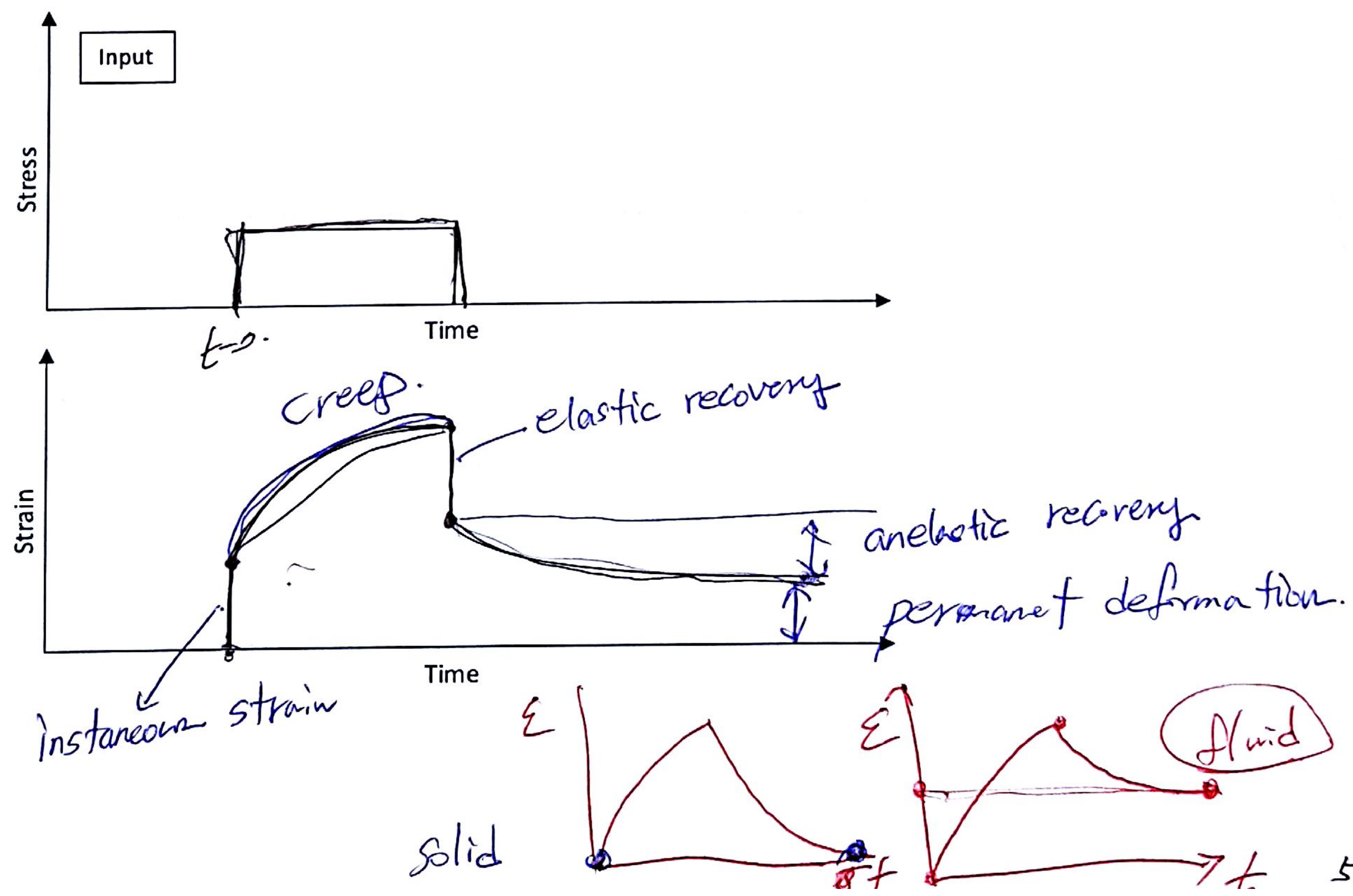
E' ↙ storage Modulus

E'' ↙ loss modulus.

1. Stress relaxation – straining a material at constant strain

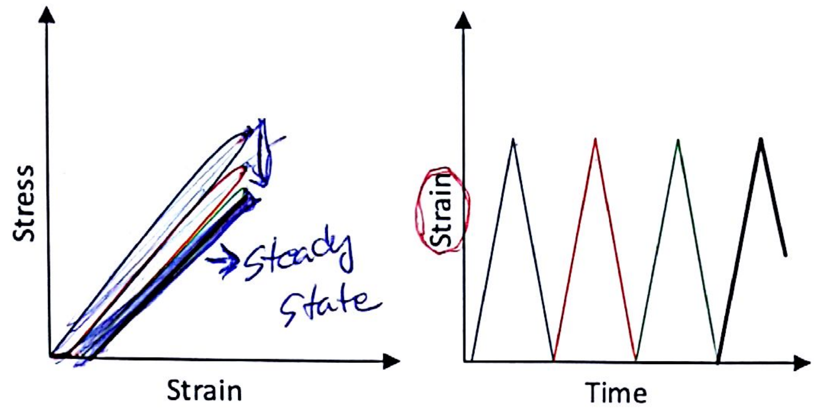


2. Creep – loading a material at a constant stress (compliance test)



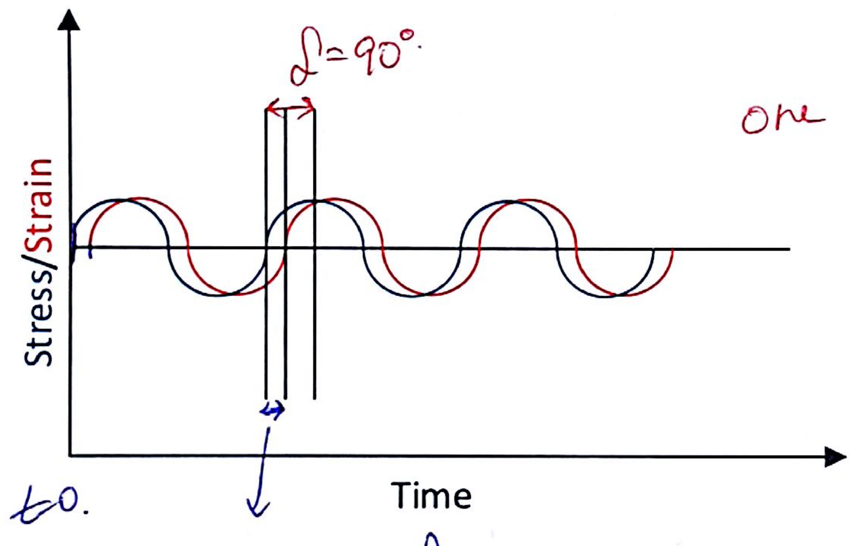
3. Oscillatory Response Test (Dynamic Mechanical Analysis)

a. time dependence – removed by preconditioning – a procedure to load and unloading the tissue before testing, until steady state.



fixed frequency

b. frequency sweep



one frequency

phase lag, δ.

- $\delta = 0°$. "Solid"
- $\delta = 90°$. "fluid"
- "$0 < \delta < 90$"

$\delta = \delta(f)$

⇒ you can evaluate E′ (storage modulus), E″ (loss modulus)

→ (E, G) → G′, G″

Examples

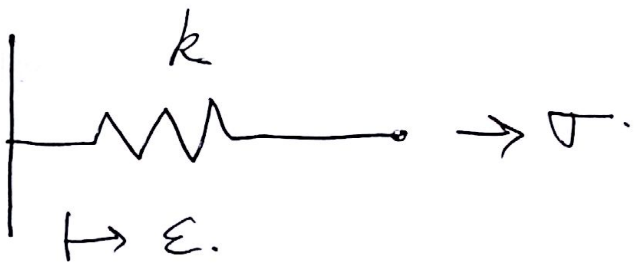
(1) Spinal Disks: The disks creep under the body weight, that is they shorter with time. Lying down allows the spinal disks to recover and this means the most people are taller in the morning than in the evening.

(2) Skin tissue: This can be seen by pinching the skin of the hand. It takes time to recover back to its original flat position. The longer the skin is held in the pinched position, the longer it takes the recover. The more rapidly it is pinched, the less it takes to recover. Also, skin is aging material, so its physical properties change over time. Younger skin recovers more rapidly than older skin.

Lumped Parameter Models (Linear viscoelastic models)

- Lumped representations

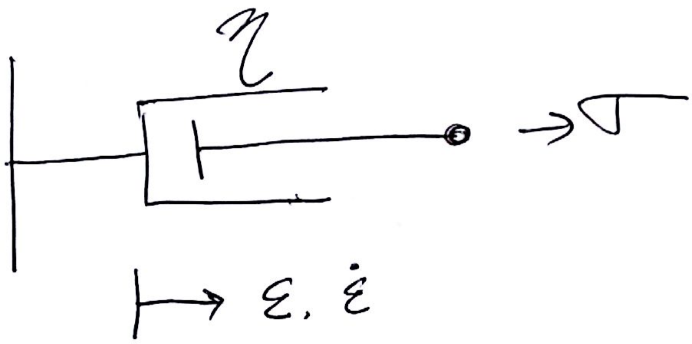
(1) Linear spring - the elastic solid behavior



Hooke's Law

$$\sigma = k\varepsilon = E\varepsilon$$

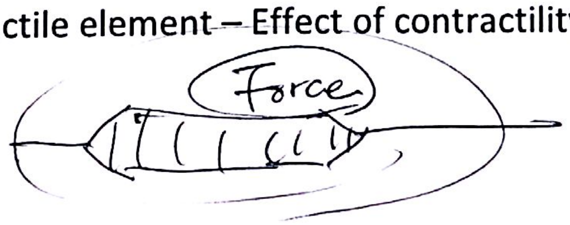
(2) Linear dashpot – the viscous fluid behavior



$$\sigma = \eta \cdot \dot{\varepsilon}$$

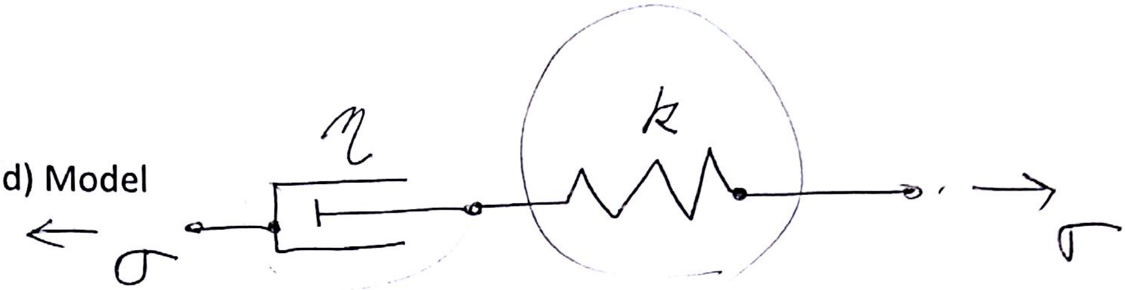
$$\dot{\varepsilon} = \frac{d\varepsilon}{dt}$$

(3) Contractile element – Effect of contractility of a muscle



Hill's model

- Maxwell (fluid) Model



ε_2 $\quad$ ε_1

$\sigma_{tot} = \sigma_1 = \sigma_2$

$\varepsilon_{tot} = \varepsilon_1 + \varepsilon_2$

$\sigma_1 = k\varepsilon_1 \rightarrow \dot{\sigma}_1 = k\dot{\varepsilon}_1$

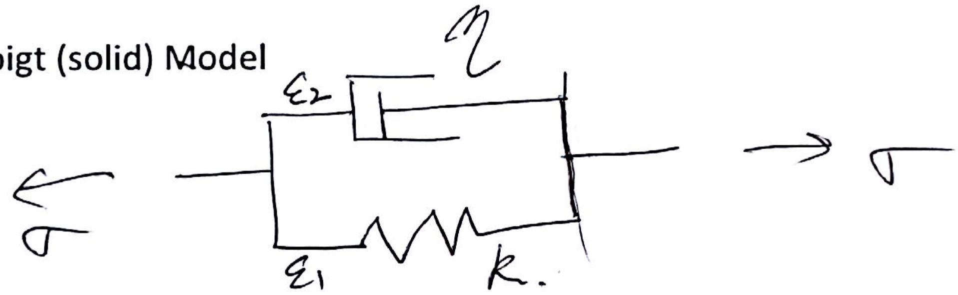
$\sigma_2 = \eta\dot{\varepsilon}_2$

$$\dot{\varepsilon}_{tot} = \frac{\sigma}{\eta} + \frac{\dot{\sigma}}{k}$$

linear 1st order ODE.

$(\sigma = T, \ k = E)$

- Voigt (solid) Model



ε

$\sigma_{tot} = \sigma_1 + \sigma_2$

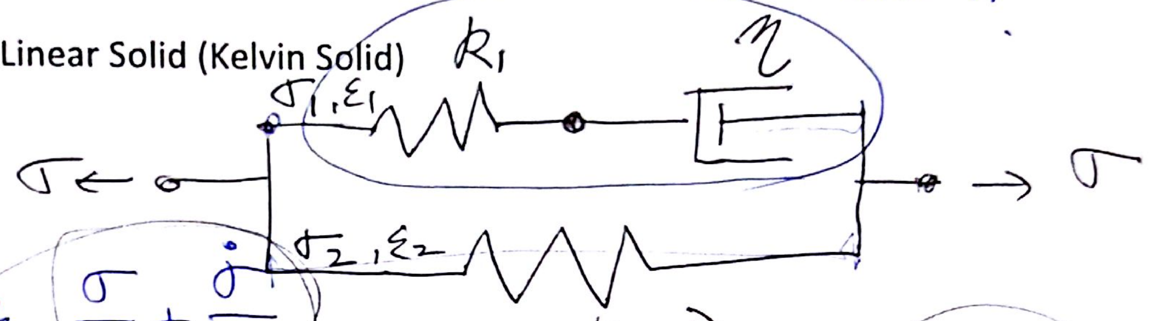
$\varepsilon_{tot} = \varepsilon_1 = \varepsilon_2$

$\sigma_{tot} = k\varepsilon_1 + \eta\dot{\varepsilon}_2$

$$\sigma = k\varepsilon + \eta\dot{\varepsilon}$$

Maxwell

- **Standard Linear Solid (Kelvin Solid)**



Maxwell: $\dot{\varepsilon} = \frac{\sigma}{\eta} + \frac{\dot{\sigma}}{k_1}$

$\sigma_2 = k_2 \varepsilon$

$\sigma_{tot} = \sigma_1 + \sigma_2$

$\varepsilon_{tot} = \varepsilon_1 = \varepsilon_2 \Rightarrow \dot{\varepsilon} = \frac{\sigma_1}{\eta} + \frac{\dot{\sigma}_1}{k_1}$

$\sigma_1 = \sigma - \sigma_2$

$= \sigma - k_2 \varepsilon$

$\dot{\sigma}_1 = \dot{\sigma} - k_2 \dot{\varepsilon}$

$$\Rightarrow \dot{\varepsilon} = \frac{\sigma - k_2 \varepsilon}{\eta} + \frac{\dot{\sigma} - k_2 \dot{\varepsilon}}{k_1}$$

[Stress] = [Strain] : Standard form

$$\sigma + \frac{\eta}{k_1}\dot{\sigma} = \eta\dot{\varepsilon} + k_2 \varepsilon + \frac{\eta k_2}{k_1}\dot{\varepsilon}$$

$$= k_2 \varepsilon + \eta\left[1 + \frac{k_2}{k_1}\right]\dot{\varepsilon}$$

- **Another three-parameter model (Homework 5)**