



**Mechanical
Characteristics of Fibers**

Fibers Viscoelasticity

**Dynamic Mechanical
Characteristics of Fibers**

**Surface characteristics of
fibers**

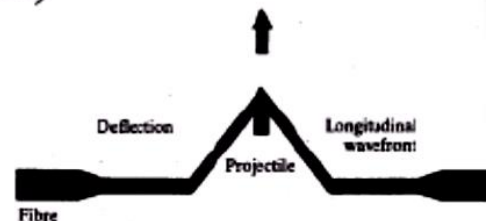
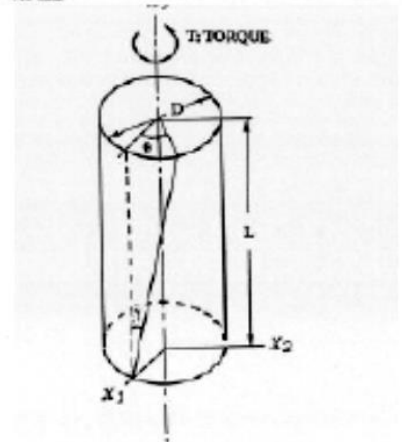
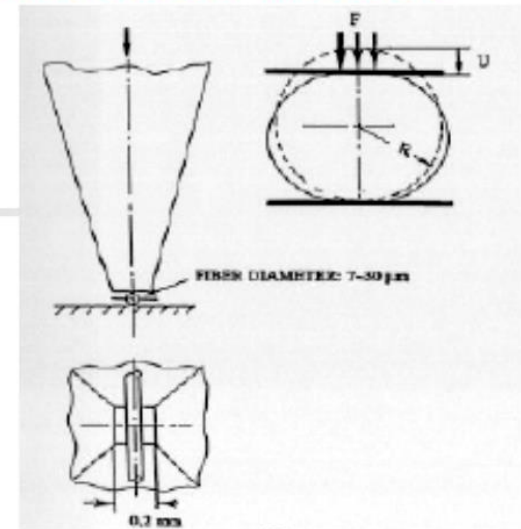




Deformation modes

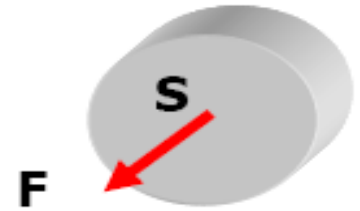
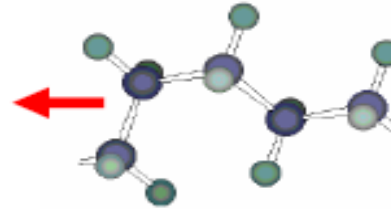
Mechanical properties I

- **Uniaxial** deformation (tensile, compressive)
- **multiaxial** deformation (torsion, bending).
- **Simple** deformation (no cycles)
- **cyclic** deformation
- **Static** (time independent) deformation
- **dynamic** (time dependent)
- **impact** (extreme short time) deformation
- **Ultimate** deformation (to break)
- **non destructive** deformation
- **Isothermal** deformation
- **non isothermal** deformation



- **Range of validity** of linear viscoelasticity is very narrow (deformation limit is less than 1%). Practically all experiments are above this limit. Therefore, the evaluated parameters are not material constants.
- **Under influence of external forces**, the fiber structure permanently changes (change of orientation, crystallinity etc.).
- **Polymeric fibers** – during formation processes subjected to severe temperature and deformation actions. Thermal and deformation history have (due to “memory effects”) certain influence on the results of mechanical experiments.
- **Structural changes** responsible for change of mechanical (viscoelastic) behavior of fibers are often not directly experimentally evaluated.





Stress

- *Stress* is the thermal resistance of a material to the distorting effects of an external load. The total resistance is equal to the external load. This resistance is known as *Stress*.
- *Stress* (σ) can be equated to the load per unit area or the force (F) applied per cross-sectional area (S) perpendicular to the force;

$$\sigma = \frac{F}{S}$$

$\sigma = \text{stress [Pa] i.e. Pascals = Newtons per } m^2; \text{ or [psi] = lbs of force per } in^2$

$F = \text{applied force [Newton] or [lbs of force]}$

$S = \text{cross-sectional area } [m^2] \text{ or } [inch^2]$





Relative load

Relative load (F_r) is load per unit fineness or the force (F) applied per fineness (T) of fiber or yarn

$$F_r = \frac{F}{T} = \frac{F}{S * \rho}$$

T = fineness [Tex]

ρ = fiber density [kg m⁻³]

Mutual relations

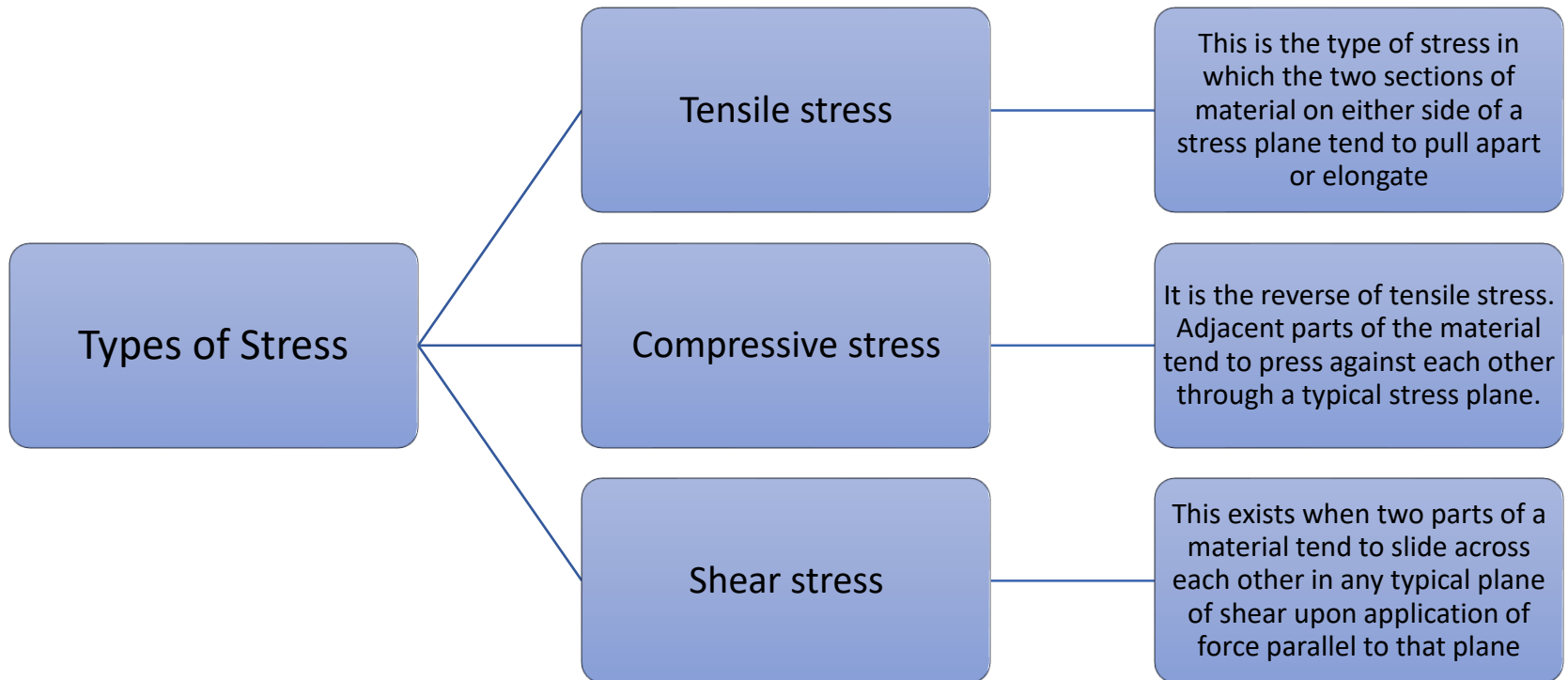
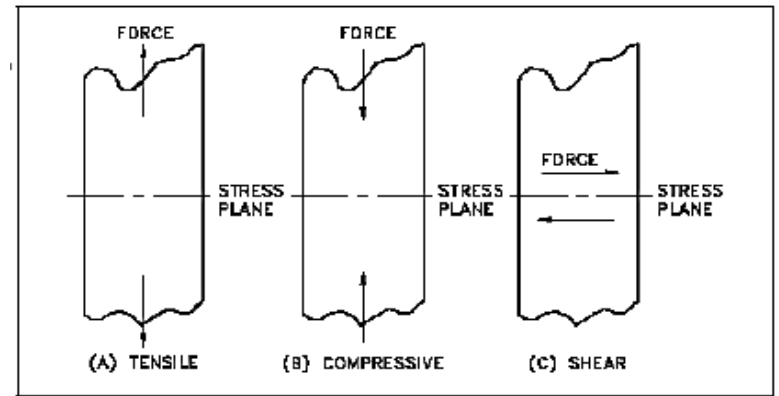
$$\sigma = F_r * \rho \quad [\text{MPa}] = [\text{N/tex}] * [\text{kg/m}^3]$$

$$F_r = \sigma / \rho \quad [\text{N/tex}] = [\text{MPa}] / [\text{kg/m}^3]$$





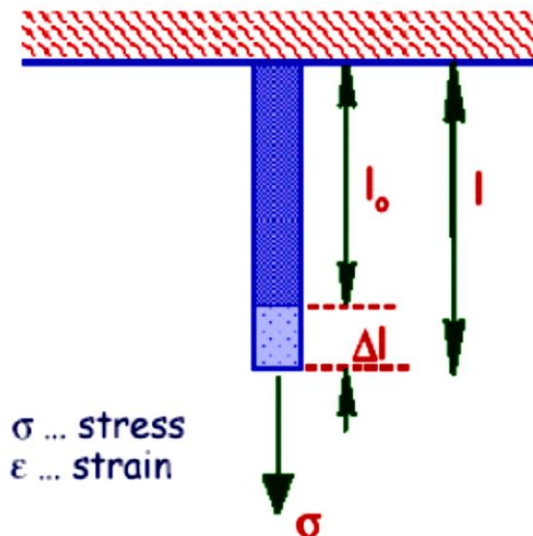
Stress





Strain

- Whenever a stress (no matter how small) is applied to a material. A proportional dimensional change or distortion must take place. Such a proportional dimensional change (intensity or degree of the distortion) is called strain (ε) and is measured as the total elongation (Δl) per unit length of material due to some applied stress.



$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0}$$

ε = strain [-]

Δl = total elongation [m] or [inch]

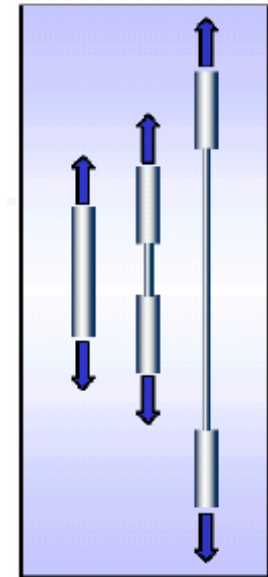
l_0 = original length [m] or [inch]





Draw ratio λ

$$\lambda = \frac{l}{l_0} = \varepsilon + 1$$



True deformation ε^*

$$d\varepsilon^* = \frac{dl}{l}$$

dl = differential elongation

Mutual relations

$$\varepsilon^* = \ln \left(\frac{l}{l_0} \right)$$

$$\varepsilon^* = \ln (\lambda) = \ln (\varepsilon + 1)$$

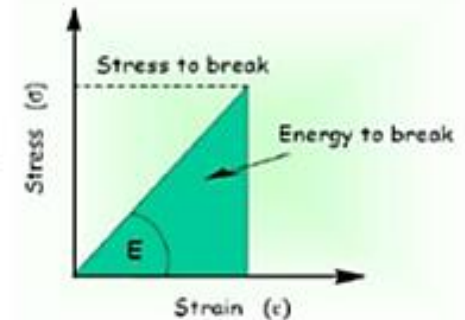
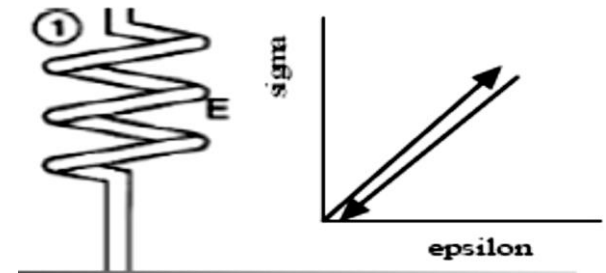
True deformation is always lower than strain





Elastic strain

- Elastic strain (deformation) is dimensional change that exists only while the initiating stress is applied and disappears immediately upon removal of the stress.
- The applied stresses cause the atoms to move from their equilibrium position. All the atoms are displaced the same amount and still maintain their relative geometry.
- When the stresses are removed, all atoms return to their original positions and no permanent deformation occurs. (conformation changes leads to reversible deformation up to 15%).



Hooke's law

$$\sigma = E * \epsilon$$

E= elastic modulus
(stiffness characteristics)

Energy to break (U_e)

$$U_e = 0.5 * E * \epsilon_b^2$$

(toughness characteristics)

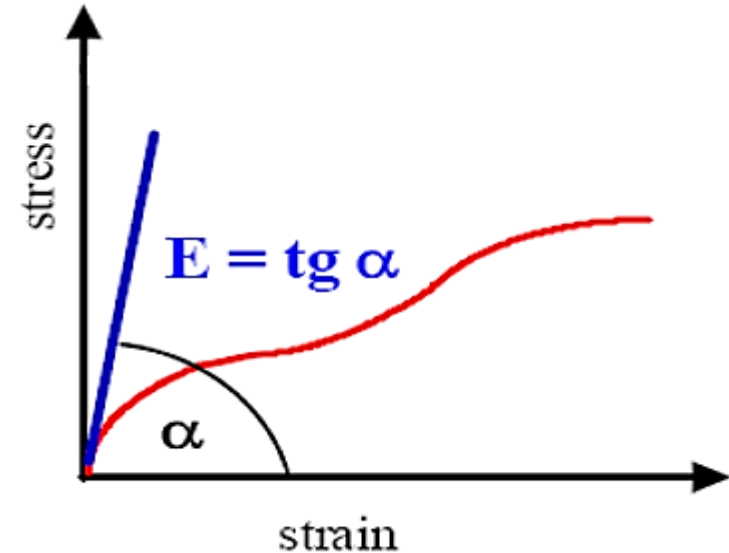


Young's Modulus



$$\sigma = E\varepsilon = E \left(\frac{l-l_0}{l_0} \right)$$

- Young's Modulus** E (or the elastic modulus) is an material characteristic. It is the ratio of stress to strain (the measure of resistance to elastic deformation) for ideal elastic material. In the case of fibers, the modulus is replaced by initial modulus as the straight-line portion of the stress-strain curve.



For isotropic materials, the modulus E connected with shear modulus G and all directional compressive modulus K .

$$K = \frac{E}{3(1 - 2\nu)} \quad G = \frac{E}{2(1 + 2\nu)} \quad \nu = \frac{E}{2G} - 1$$



Poisson's ratio

Poisson's ratio is the ratio of the transverse contraction strain to the longitudinal extension strain in the direction of the stretching force. The definition of poisson's ratio contains a minus sign so that normal materials have a positive ratio:

$$\nu = \frac{\text{transverse contraction}}{\text{longitudinal extension}} = -\frac{\varepsilon_T}{\varepsilon} \quad \text{where} \quad \varepsilon_T = \frac{S - S_o}{S_o}$$

ν – Poisson's ration (for fibers $2.0 \leq \nu \leq 4.05$)

ε – Strain

Fiber volume changes due to deformation are:

$$\frac{V}{V_o} = (1 - \nu * \varepsilon)^2 * (1 + \varepsilon) \approx (1 - 2\nu) * \varepsilon$$

- Poisson's ratio is related to Young's Modulus E and the Shear Modulus G according to; $E = 2G(1+\nu)$.
- For $V/V_o=1$, $\nu=0.5$ – rubber, liquids. For $V>V_o$, $\nu<0.5$.
- Fiber volume increases during deformation. More elongation than lateral contraction.





Shear Modulus

- The shear modulus, G (also known as the **rigidity modulus**) is defined as the ratio of shear stress to engineering shear strain on the loading plane:

$$G = \frac{\tau_{xy}}{\gamma}$$

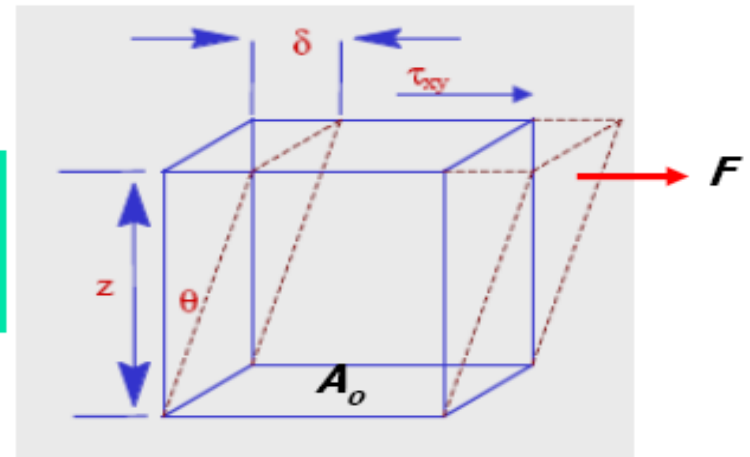
where:

τ_{xy} = shear stress

γ = shear strain

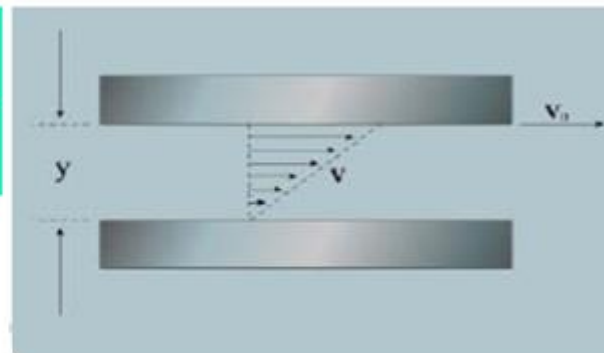
$$\tau_{xy} = \frac{F}{A_o}$$

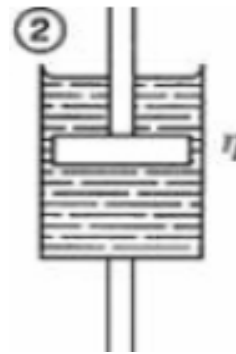
$$\gamma = \frac{\delta}{z} = \tan(\theta)$$



Liquid:

$$d\gamma / dt = \frac{v_o}{y}$$





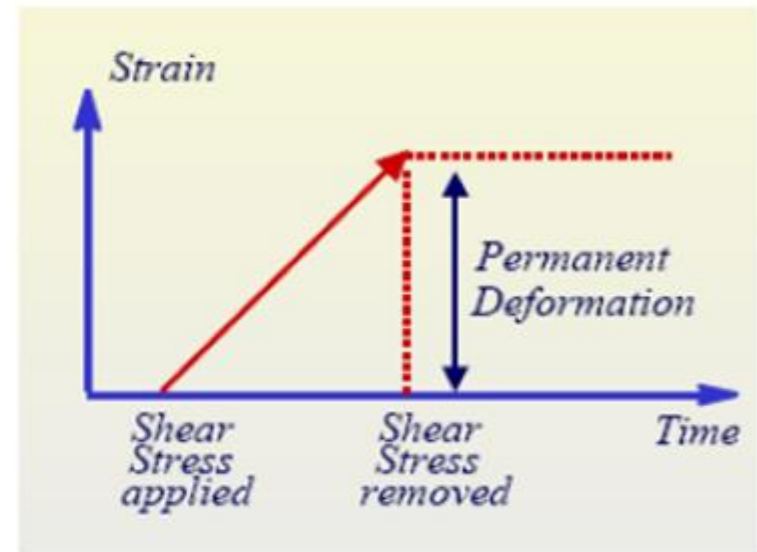
$$\frac{d\varepsilon}{dt} = \frac{\sigma}{\eta}$$

Plastic deformation

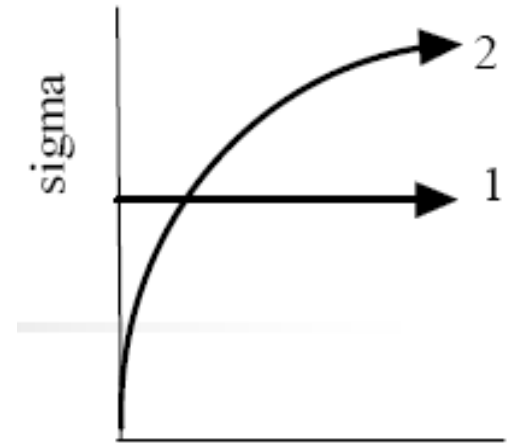
Plastic deformation (or plastic strain) is a dimensional change that does not disappear when the initiating stress is removed.

The state of stress just before plastic strain begins to appear is known as the *proportional limit*, or elastic limit, and is defined by the stress level and the corresponding value of elastic strain.

Rate of deformation is proportional to applied stress. Proportionality factor is called viscosity.



Plastic body deformation



- During tensile straining and constant rate of deformation ϵ

$$d\epsilon / dt = k$$

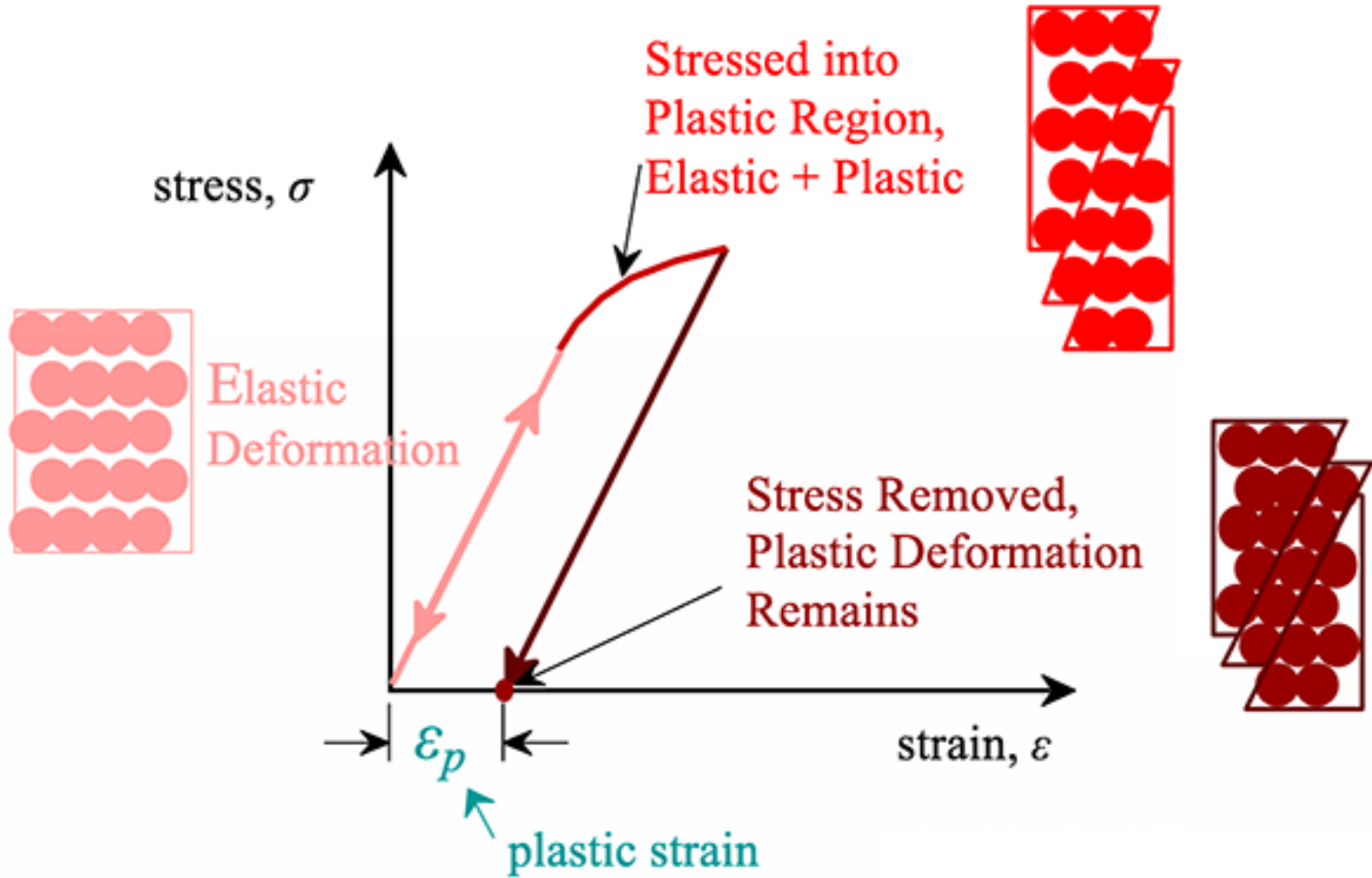
is dependence between stress and strain constant (curve 1).

$$d\sigma / dt = k$$

- During tensile straining and constant rate of loading is dependence between stress and strain of ideal plastic body concave (curve 2).

$$\sigma = \sqrt{2 * k * \epsilon * \eta}$$

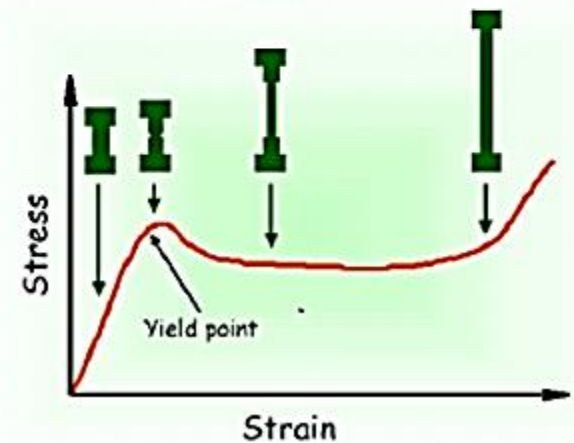
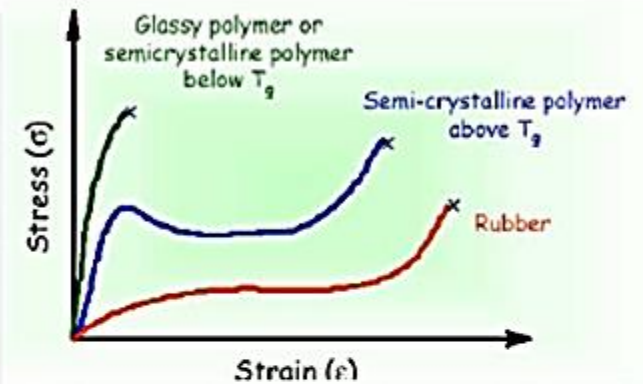
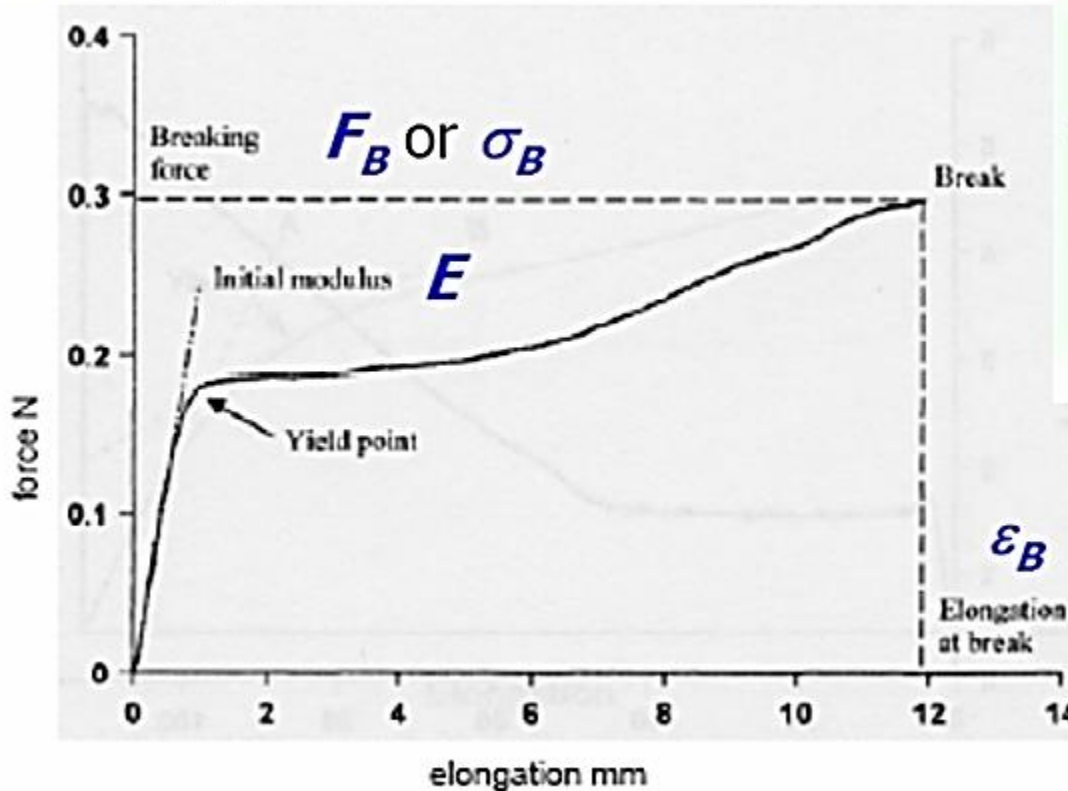






Tensile characteristics of fibers

■ Analysis of stress- strain curves



- **Strength** is defined as load (at break) F_r [N/tex] or stress at break σ_p [GPa].
- **Extensibility** is deformation to break ε_p [%].
- **Relative strength** $F_r = P/T$ [N/tex]. Standard fibers have relative strength in units of $[\text{cN} \cdot \text{dtex}^{-1}] = [\text{g} \cdot \text{tex}^{-1}]$
- **Break length** l_T - length [m], at which will fiber break due to its own mass.

$$F_p = l_T * \rho * S \quad \sigma_p = l_T * \rho \quad l_T = \frac{\sigma}{\rho} = 1000 * F_r$$

F_p load at break

Deformation work $W[\text{J}]$ $W = \int_0^{\varepsilon_1} F * dl = V_o * U_D$

Deformation energy U_D $U_D = \int_0^{\varepsilon_1} \sigma * d\varepsilon$



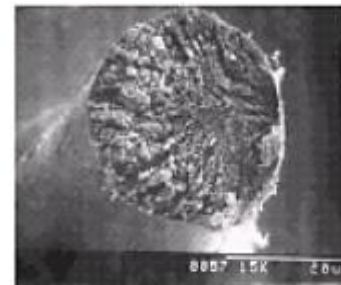
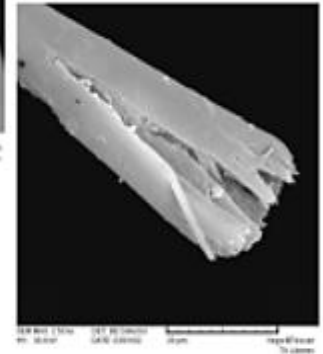
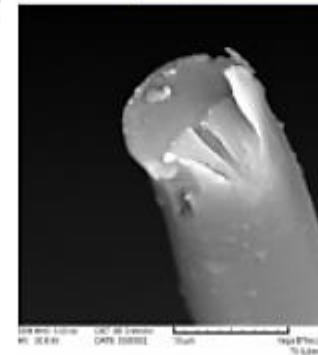
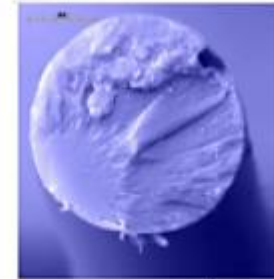


Fiber	strength [cN·dtex⁻¹]	Break elongation [%]	Wet strength [%] of dry	Wet break elongation [%]
wool	1–2	20–40	80–90	25–50
cotton	2.7–4.3	3–10	100–110	3.6–12
viscose	2 – 3	15–30	44–72	20–40
acetate	1.3	20–45	60–70	30–50
PA 6	3.7–5.2	25–40	85–90	20–50
PA 6.6	3.7–5.4	25–40	85–90	20–50
PES	4.1–4.5	19–23	100	19–23
PP	2.7–6.3	25–75	100	25–75
PAN	2.0–2.9	20–28	80–90	26–34
Kevlar	19	4	100	4





- Fibers in glassy state and glass or ceramic fibers exhibit typical brittle fracture
- Majority of synthetics fibers produced by melt spinning exhibit ductile fracture
- High strength fibers as aromatic polyamides and PBO exhibit axial splitting.
- Fibers spun from solvents and micro porous fibers (containing network of micro voids) is typical granular fracture





1. At sufficiently low temperatures $T < 0,8 T_g$ fibers are breaking by brittle fracture in the places of local defects. The shape of stress strain curve (dependence of stress on deformation) is **linear** with modulus E . Strength at brittle fracture is expressed by empiric relation

$$\sigma_P = 30 * \sqrt[3]{E^2}$$

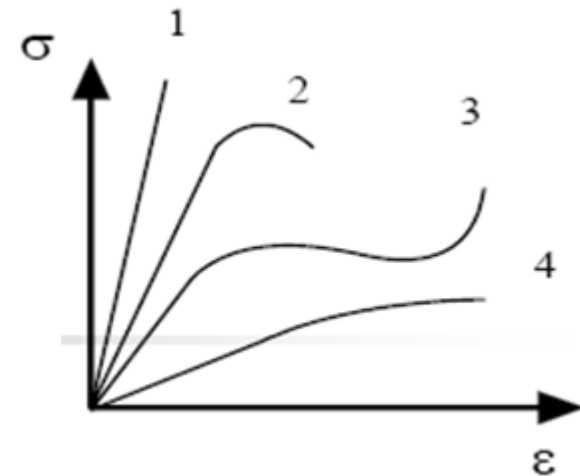
Fiber are in the glassy state when polymeric segments are vibrating around mean positions.

2. At temperature $T = 0,8 * T_g$ the plastic deformation start and stress strain curve exhibits **concave bend**. During fiber failure the cracks appear. Fibers are in transition state where the diffusion type movements of polymeric segments arise (small scale movement).





Temperature dependence - II



3. At glass transition temperature T_g the marked plastic deformations are arising or appearance of neck drawing. Stress strain curve has typical **sigmoid shape** and **yield region**. This temperature corresponds to state when segmental mobility of polymeric chains are creating local free volumes enabling e.g. diffusion of penetrants through fiber body.
4. At temperatures sufficiently above T_g the quasi viscous flow appears and failure is typical for plastic materials. Fiber is in the rubbery state (entropic deformation) or in the state of elastic flow.

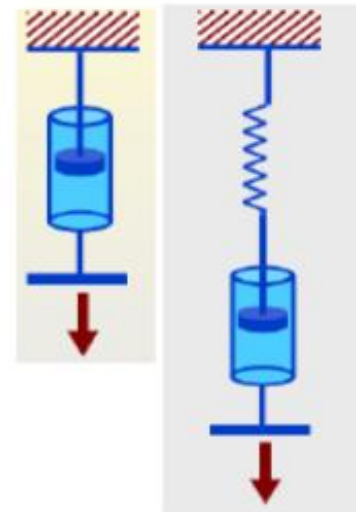
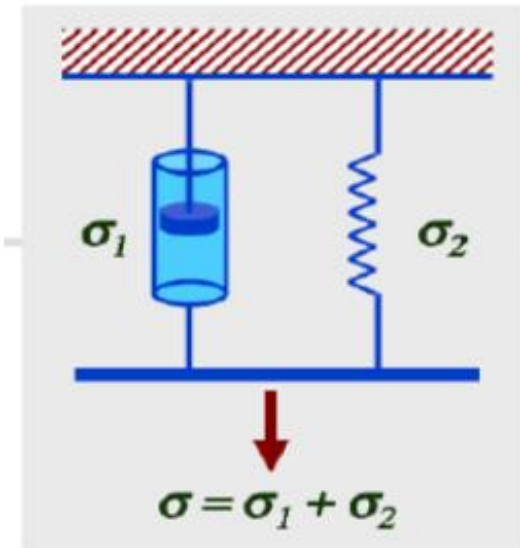




Viscoelastic deformation

Plastic deformation is usually accompanied by some elastic strain. The phenomenon of elastic strain and plastic deformation in a material are called *visco elasticity* and *visco plasticity*, respectively.

The magnitude of plastic strain, when it does appear, is likely to be much greater than that of the elastic strain for a given stress increment.



Viscoelastic body deformation

- Partially reversible and time dependent.
- Deformation is modeled as combination of elastic and plastic terms.

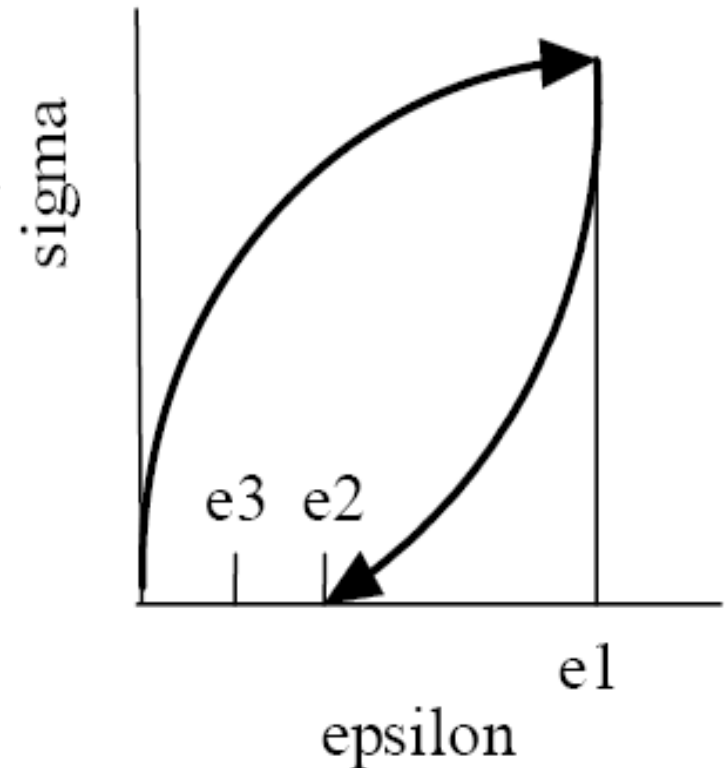
Typical stress strain curve during loading and unloading is dependent on time.

e_1 is total deformation,

e_3 is plastic deformation

$(e_1 - e_2)$ is elastic deformation

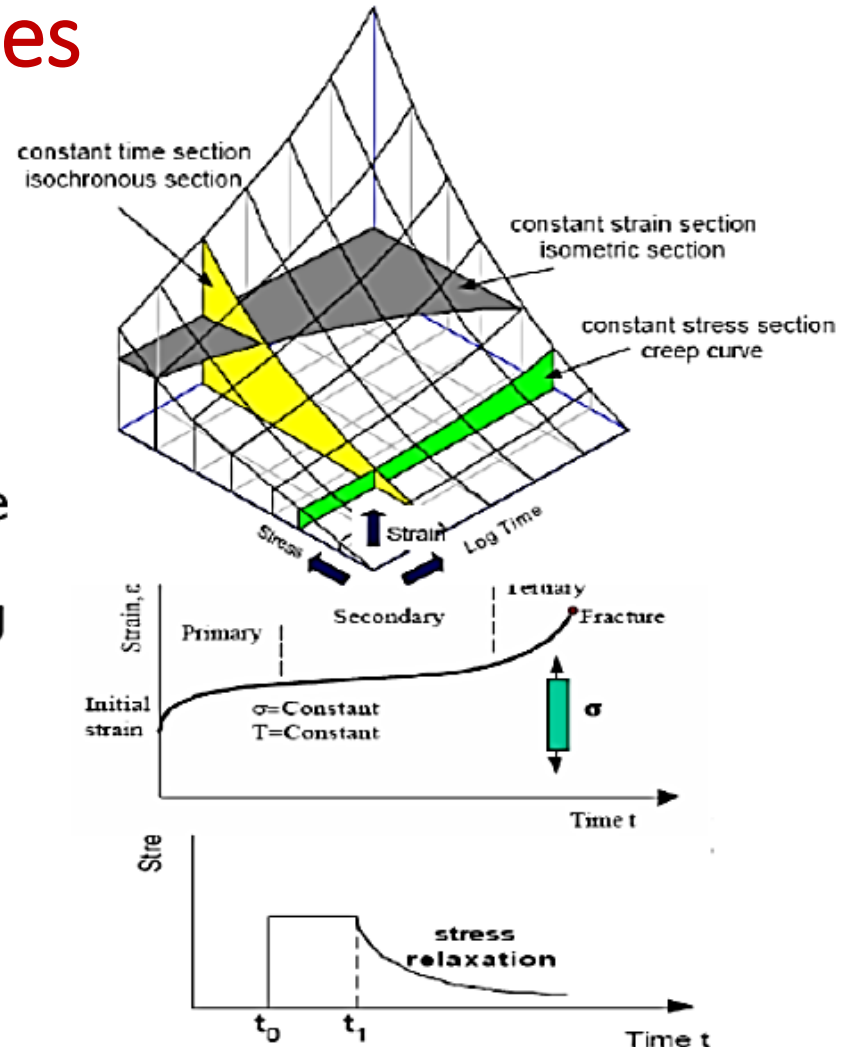
$(e_2 - e_3)$ is viscoelastic deformation





Viscoelastic properties

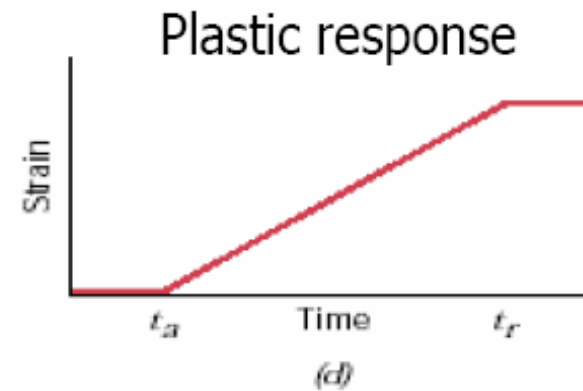
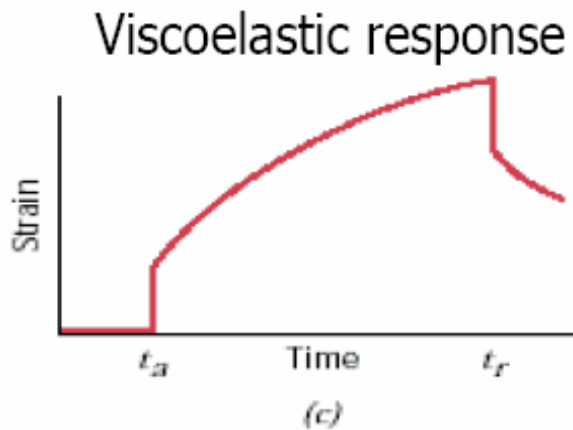
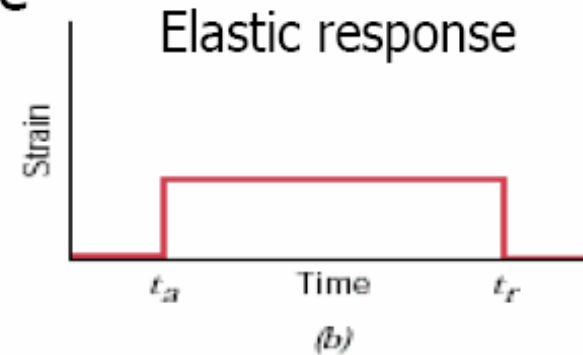
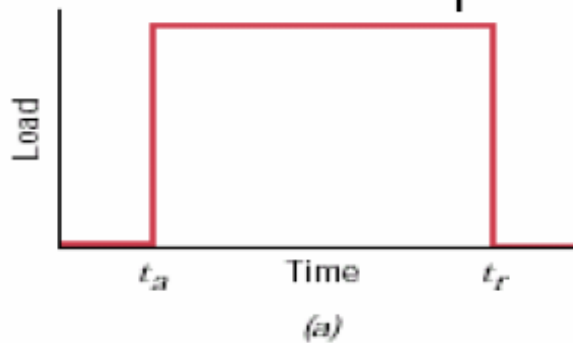
Polymer fibers exhibit time dependent behavior. The stress and strain induced by load are function of time. The stress-strain-time response can be determined by loading of fibers at a constant stress (**creep**) or a constant strain (**stress relaxation** or isometric). It is possible to construct isochronous curve as stress strain dependence at constant time.





Time dependent response

Load – time dependence

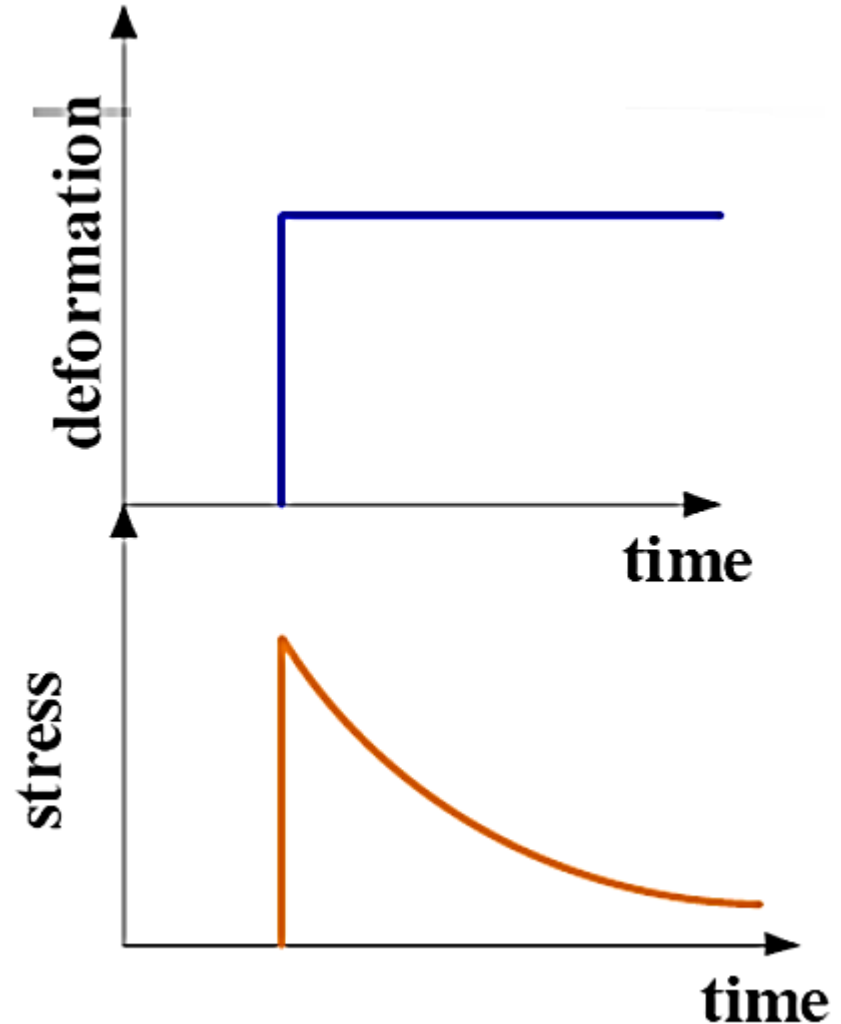




Stress relaxation

Dependence of stress
on time at constant
deformation

$$e = e_0$$
$$\frac{de}{dt} = 0$$



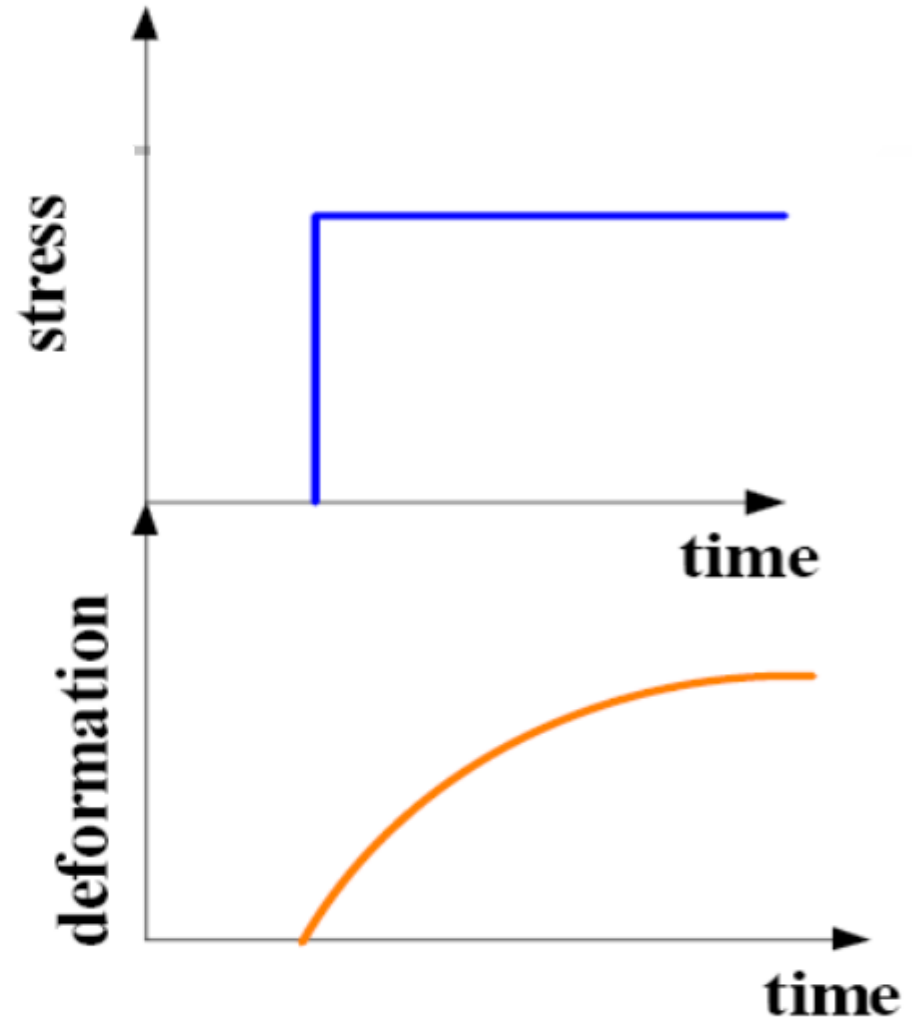


Creep

Dependence of
deformation on time
at constant stress
(load)

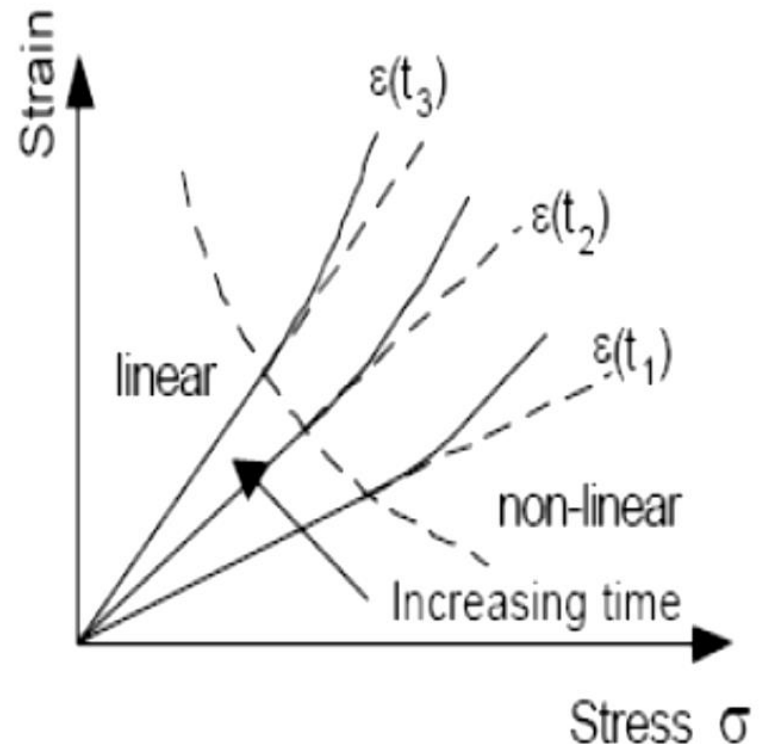
$$\sigma = \sigma_0$$

$$\frac{d\sigma}{dt} = 0$$





- **Linear viscoelasticity** – behavior is independent on the stress level and time and obey linear relation between stress and strain .
- **Nonlinear viscoelasticity** – behavior will not obey linear relation between stress and strain
- Transition from linear to nonlinear viscoelasticity appears at low stresses. Corresponding strain is often around 0.5 %





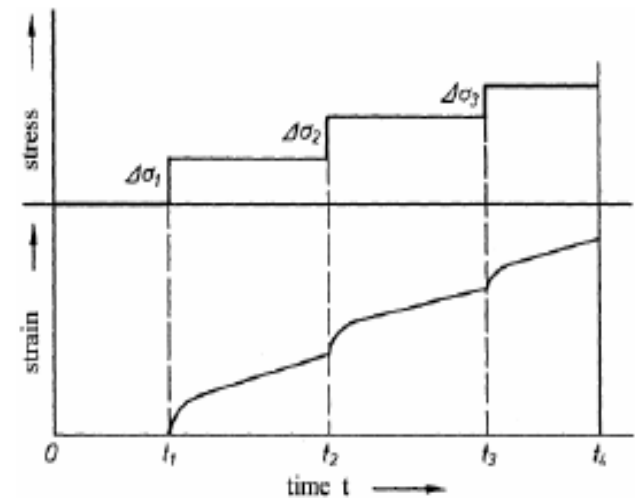
For ideal case of linear viscoelasticity is relation between stress, deformation and time described by linear differential equation of n -th order with constant coefficient (combination of springs and pistons).

$$a_0 * \sigma + a_1 * \frac{d\sigma}{dt} + \dots + a_n * \frac{d^n \sigma}{dt^n} = b_0 * \varepsilon + b_1 * \frac{d\varepsilon}{dt} + \dots + b_m * \frac{d^m \varepsilon}{dt^m}$$

where a_i and b_i are coefficients containing moduli E and viscosities η

Boltzmann superposition

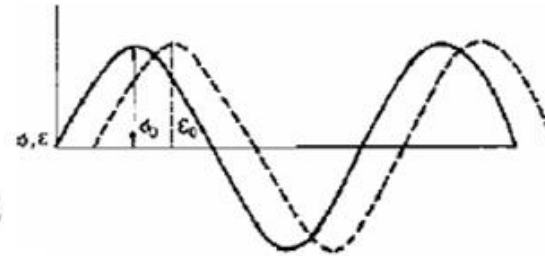
$$\begin{aligned} \sigma_1(t) &\Rightarrow \varepsilon_1(t) \\ \sigma_2(t) &\Rightarrow \varepsilon_2(t) \end{aligned} \quad \longrightarrow \quad \sigma_1(t) + \sigma_1(t) \Rightarrow \varepsilon_1(t) + \varepsilon_1(t)$$





Dynamic analysis

$$0 \leq \delta \leq \pi / 2$$



Let the response of material to sinusoidal tensile deformation having frequency ω is investigated. Cyclic straining (dependence on time t) is defined as

$$\varepsilon = \varepsilon^0 \sin(\omega t) \quad d\varepsilon / dt = \omega \varepsilon^0 \cos(\omega t)$$

Hookean solid (no phase shift) $\sigma(t) = E * \varepsilon(t)$

$$\sigma(t) = E * \varepsilon_0 * \sin(\omega * t) = \sigma_0 * \sin(\omega * t)$$

Newtonian liquid (phase shift 90°) $\sigma(t) = \eta * d\varepsilon(t) / dt$

$$\sigma(t) = \eta * \omega * \varepsilon_0 * \cos(\omega * t) = \eta * \omega * \varepsilon_0 * \sin(\omega * t + \pi / 2)$$

$$\sigma(t) = \sigma_0 * \sin(\omega * t + \pi / 2)$$

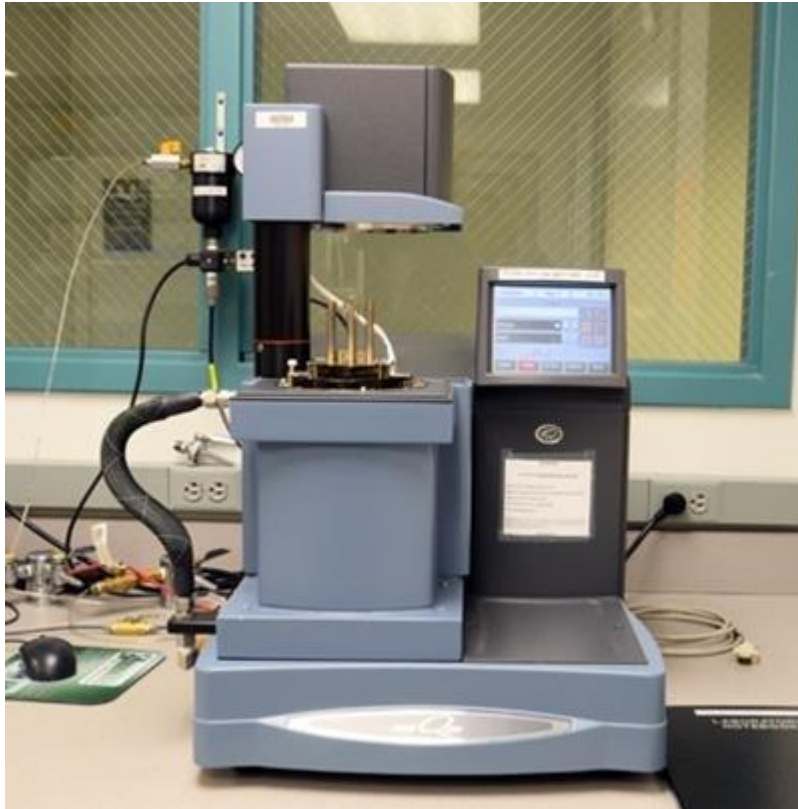
Viscoelastic body (phase shift δ) $\varepsilon(t) = \sigma^0 (D' \sin(\omega t) + D'' \cos(\omega t))$

$$\sigma(t) = \sigma_0 * \sin(\omega * t + \delta) \quad \sigma(t) = \varepsilon^0 (E' \sin(\omega t) + E'' \cos(\omega t))$$

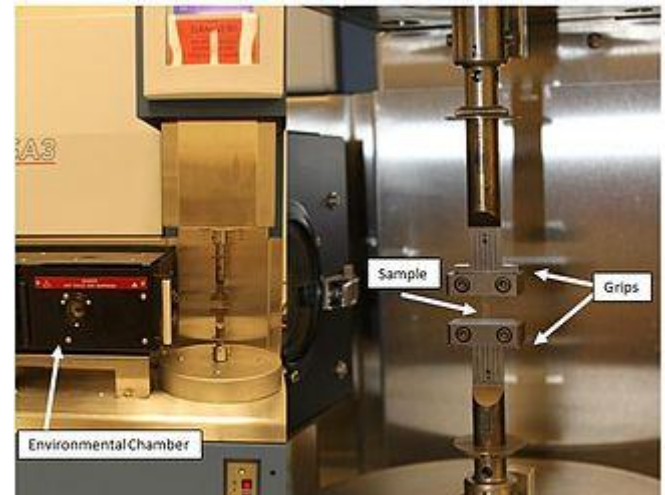




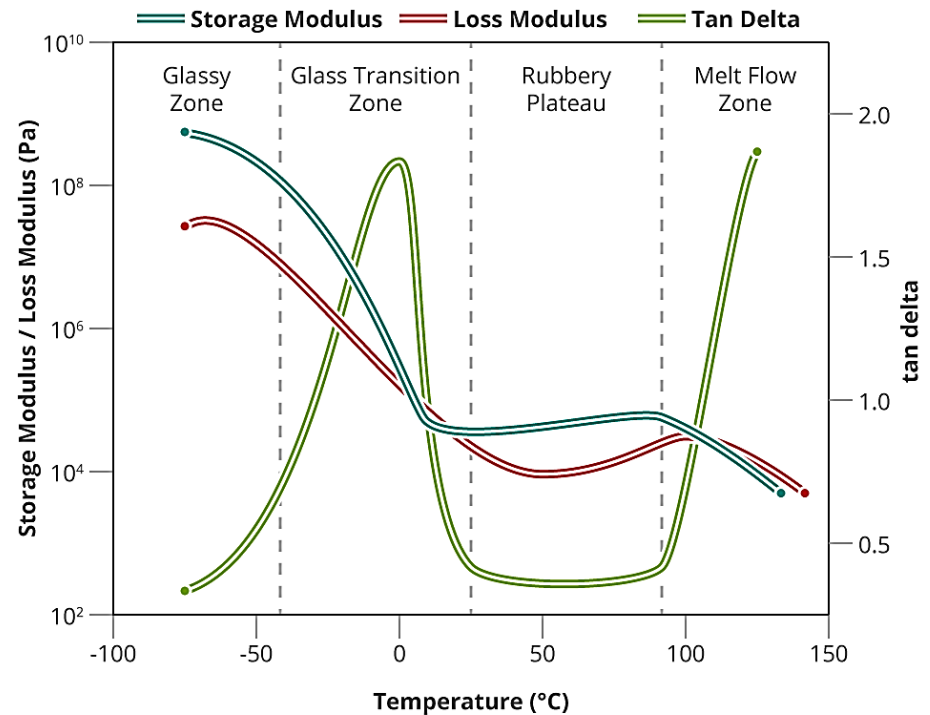
Dynamic mechanical analysis (DMA)



DMA also works in TMA mode.



DMA Thermal Scan

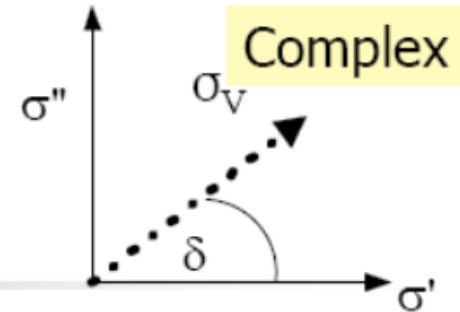




Dynamic moduli - I

Elastic
 $\sigma' = \sigma_V * \cos \delta$

Plastic
 $\sigma'' = \sigma_V * \sin \delta$



The time-dependent properties of materials are characterized by storage E' and loss moduli E'' , and the storage and loss compliances D' and D''

$$E' = \sigma' / \varepsilon^0 = (\sigma^0 / \varepsilon^0) \cos(\delta) \quad D' = (\varepsilon^0 / \sigma^0) \cos(\delta)$$

$$E'' = \sigma'' / \varepsilon^0 = (\sigma^0 / \varepsilon^0) \sin(\delta) \quad D'' = (\varepsilon^0 / \sigma^0) \sin(\delta)$$

For anisotropic materials are these quantities dependent on the direction. It is suitable to introduce complex modulus E^* and complex compliance D^* . The simple relations are valid

$$E^* = \sigma_V / \varepsilon^0 = E' + iE'' \quad D^* = D' + iD''$$





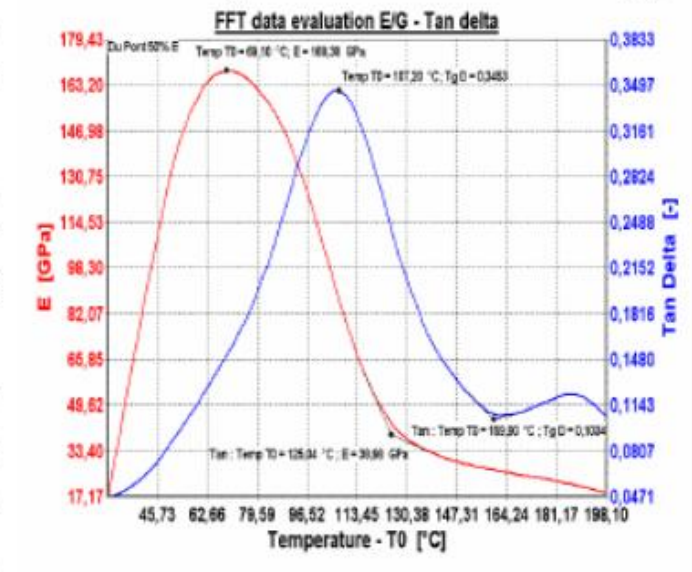
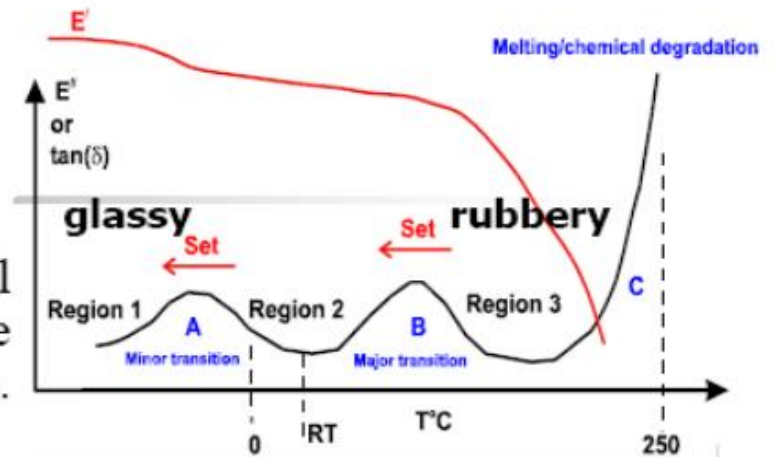
Dynamic moduli interpretation

The **storage modulus** is equivalent to real part and **loss modulus** to the imaginary part of complex modulus. The same is valid for compliances.

The **elastic part** (storage modulus E') is proportional to the energy fully recovered per cycle of deformation

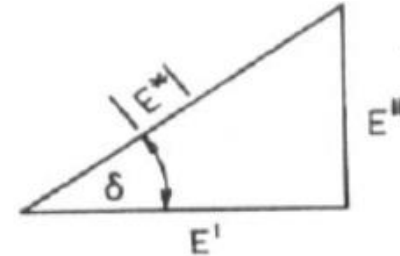
The **imaginary component**, E'' is proportional to the net energy dissipated per cycle in the form of heat.

The **dynamic storage modulus** E' is the component which is in-phase with the applied strain and E'' is the component, which is 90° out-of-phase.





Loss tangent



Tangent of phase angle $\text{tg } \delta$ (loss tangent, damping factor) is defined as

$$\text{tg } \delta = E'' / E' \quad \text{tg } \delta = D'' / D'$$

For solids, which are purely elastic, $\text{tg } \delta$ equals zero. Low damping materials such as metals and quartz conform fairly closely to the this ideal, while polymers have values of δ of the order of several degrees. From the expression of the complex modulus in complex plane the following relations are derived

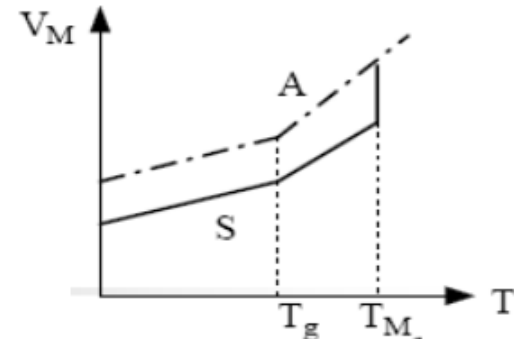
$$E = |E^*| = \sqrt{E'^2 + E''^2} \quad E' = |E^*| \cos \delta \quad E'' = |E^*| \sin \delta = \eta^* \omega$$

Measure of dissipated energy is loss factor $\text{tg } \delta = \eta^* \omega / E'$
where η^* is viscosity of fibrous structure and ω is frequency of cyclic loading.





Glass transition temperature - I

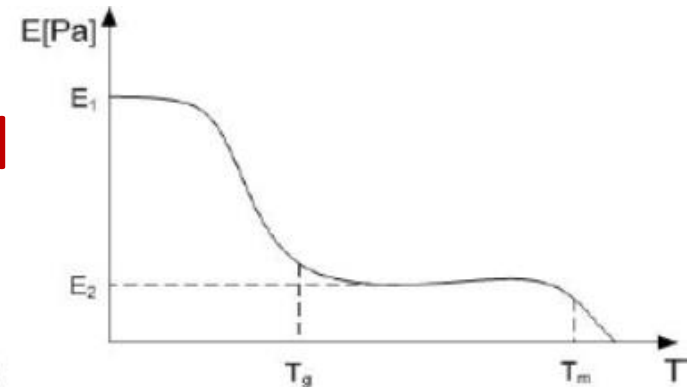


- The amorphous polymers under increasing temperatures obey transition from glass to rubbery state.
- This transition appears in some temperature interval called glass transition region.
- Mean temperature of this glass transition region defines glass transition temperature T_g . At this temperature the total volume is increased more markedly. The melting point T_M is here not unique.
- The semicrystalline polymers, which contain the amorphous and crystalline parts are both T_g and T_M defined from changes of total volume changes.
- Above T_g , the polymer becomes rubbery and capable of elastic or plastic deformation without fracture.





Glass transition temperature - II



- In polymers, T_g is often expressed as the temperature at which the Gibbs free energy is such that the activation energy for the cooperative movement of 50 or so elements of the polymer is exceeded. This allows molecular chains to slide past each other when a force is applied.
- With thermoplastics polymers, the stiffness of the material will drop due to this effect.
- T_g can be significantly decreased by addition of plasticizers into the polymer matrix. Smaller molecules of plasticizer embed themselves between the polymer chains, increasing the spacing and free volume, and allowing them to move past one another even at lower temperatures. For partially hydrophilic polymers is plasticizer water as well.





Melting temperature

fiber	T_g [°C]	T_M [°C]
polyethylene	-80	145
polypropylene	-18	170
PA 6.6	82	256
PA 6	65	220
PES	67 amorfni	256
PVC	80	190

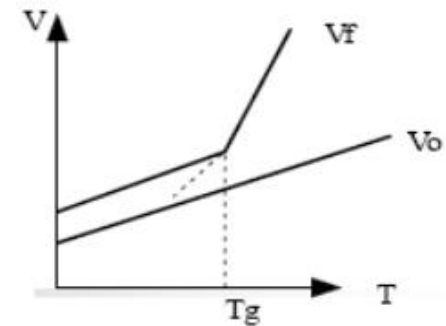
- Temperatures of sudden changes of physical properties (phase or thermal transitions) are closely connected with fiber macromolecular chains segmental mobility.
- The phase transitions of I. and II. order are most interesting .
- First order phase transition is characterized by change of state (gas, liquid, solid). Change from solid to liquid is called melting and corresponding temperature is melting temperature T_M .

The **melting point** of a crystalline solid is the temperature at which it changes state from solid to liquid. Amorphous polymers have not this phase change temperature clearly defined





Free volume



- Total volume of amorphous polymers V_M is composed from chains volume V_o and free volume V_f
- Below glass transition temperature T_g the macromolecular segments are vibrating around specific equilibrium positions. The volumes V_o and V_f are increasing by the same rate.
- At T_g the energy supplied to segments is sufficient to overcome energetic barrier of internal rotation around covalent bonds. These rotations are called segmental mobility.
- Above T_g the segmental mobility causes markedly faster increasing of V_f .





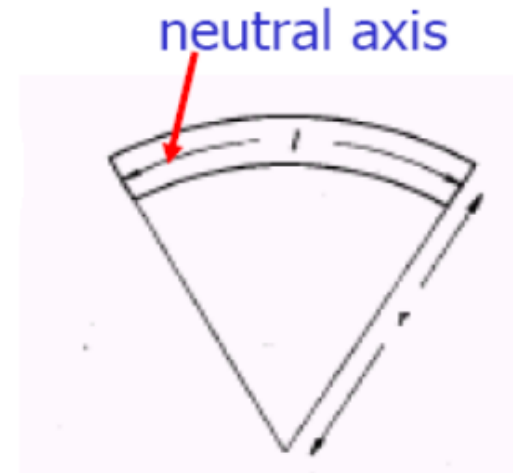
Bending stiffness

Bending stiffness — governs the handling, comfort, and conformability of a fabric.

The most important factors affecting bending stiffness are: **shape of the fiber** S , **tensile modulus** E , **fineness** T and **density** ρ of fiber .

Generally, the higher the fineness or the modulus or the lower density, the higher the bending stiffness.

For example, polyester has a higher modulus than nylon, and it is stiffer material. Polypropylene, with a lower density than nylon, should have a higher stiffness, assuming all other factors are equal.



Flexural rigidity FR [N mm²] force to bend fiber about neutral axis to unit curvature ($r = 1$)

$$FR = \frac{10^{-3} * S * E * T^2}{4\pi * \rho}$$

Circular fiber $S=1$

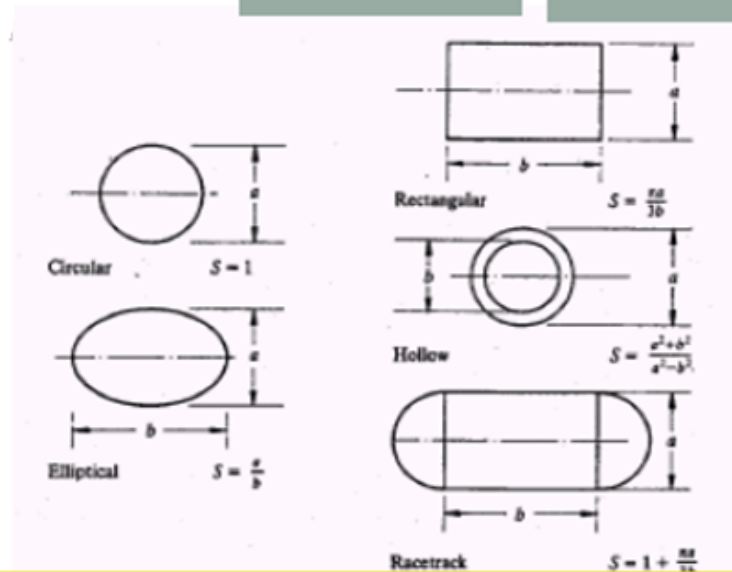
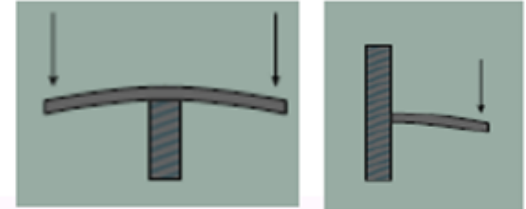




Bending stiffness - II

Monofilament materials are much stiffer than multifilament.

With all other factors constant, the bending stiffness of a monofilament of fineness T will be roughly n times greater than a multifilament with n filaments of fineness T/n each. The use of multifilament yarns and/or finer fibers in the yarn produces a more flexible structures.



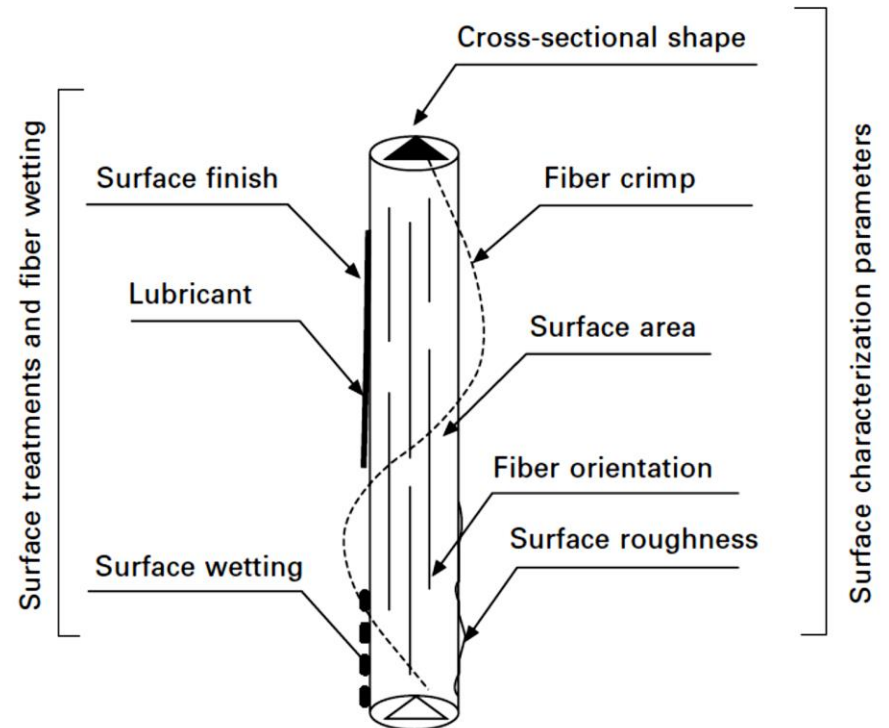
S is related to the radius of gyration (k) of fiber cross section (cross section area A) about axis of bend

$$S = 4 * \pi * k^2 / A$$



Surface characteristics

- Revolutionary developments have been made through utilization of the friction phenomenon for *creating special adhesion effects and through modification of surface texture for achieving special thermal and moisture and transfer characteristics.*
- The parameters that could be changed during the spinning process:
 - **Surface area, fiber cross section (Scanning electron microscope), crimp, fiber orientation and surface roughness (Scanning electron microscope, confocal microscope, etc.).**
- Altering fiber surface at the nanolevel without influencing key physical characteristics.

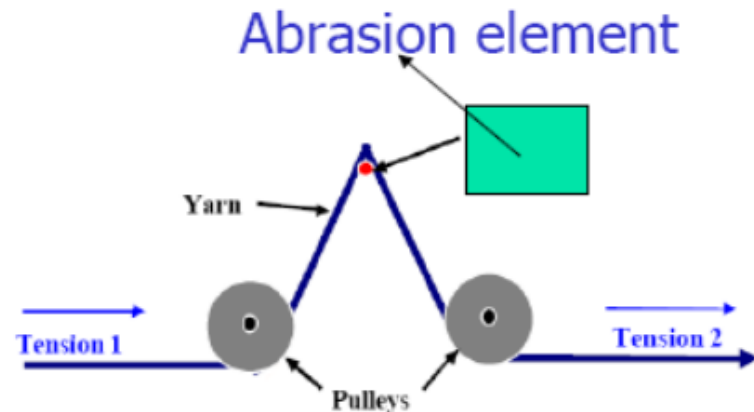


Surface characterization parameters and surface treatments of synthetic fibers.



Abrasion resistance

Whenever fibers rub against themselves or other structures, abrasion resistance assumes an important role. A high value is usually desirable



The abrasion resistance of a fibers is influenced by several factors:

- The fineness of the fiber (the lower the fineness, the lower the resistance).
- The orientation of molecules in the fibers (the higher the orientation, usually the lower the resistance).
- The surface coefficient of friction (the higher the friction, the lower the resistance).

