MECHANICAL PROPERTIES OF DENTAL MATERIALS

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INTRODUCTION

- In the oral environment, restorations are subjected to heavy masticatiory forces. These forces act on teeth and/ or material producing different reactions that lead to deformation, which can ultimately compromise their durability over time.
- It is important to introduce some concepts that are extremely relevant to understand the performance presented by such materials under specific test conditions.

DEFINITION

- Mechanical properties are subset of physical properties that are based on the laws of mechanics that is the physical science that deals with energy and forces and their effects on the bodies.
- These properties are expressed most often in units of stress and strain.

STRESS

- When an external force is applied to acts a body, an internal force, equal in magnitude and opposite in direction to the applied force is set up in the body.
- This internal resistance to the external force is called "*STRESS*"
- Denoted by "S" or "σ"
- Designated as force per unit area ($\sigma = N/m^2$)
- Commonly stress is reported in terms of mega Pascals. Where, Pascal = $1\ N / m^2$.

TYPES OF STRESS

- Depending on the type of force applied, following stresses are produced

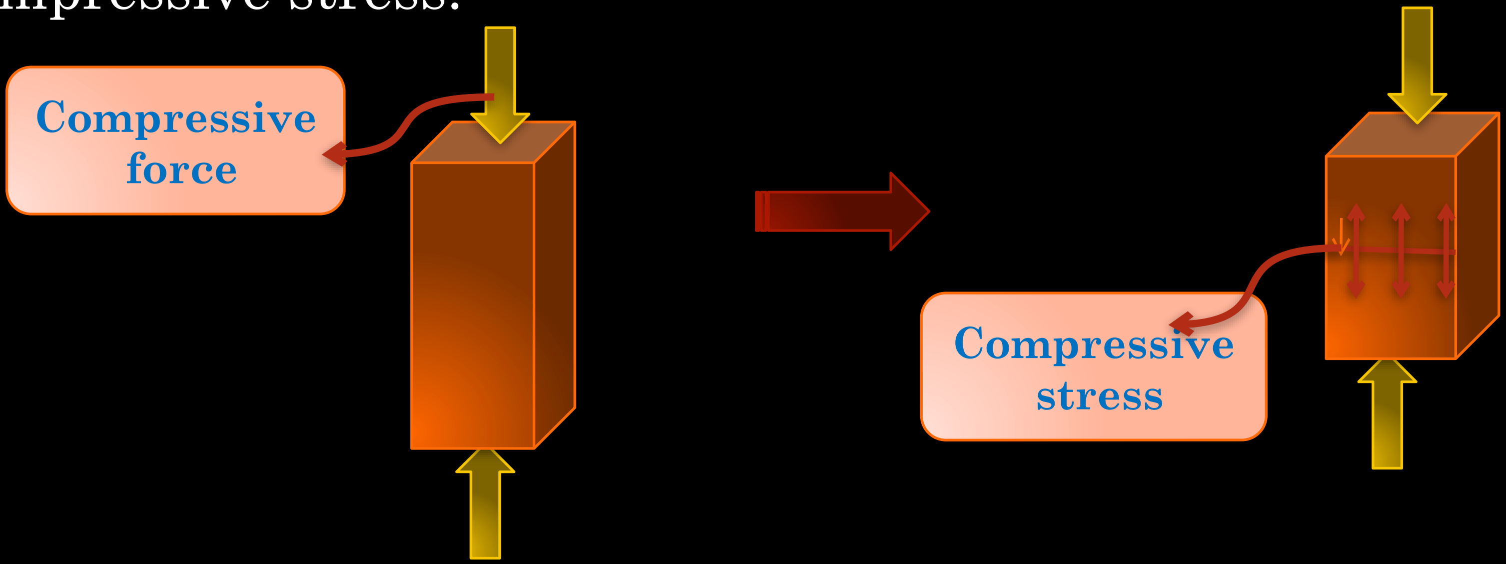
A. Axial (Tensile and Compressive)

B. Shear (sliding)

C. Flexural

COMPRESSIVE STRESS

- When a body is subjected to compressive forces (two axial sets of force are applied to a sample directed towards each other in a straight line, in order to approximate the molecular structure of the material, an internal resistance developed in the body to oppose this force is called compressive stress.



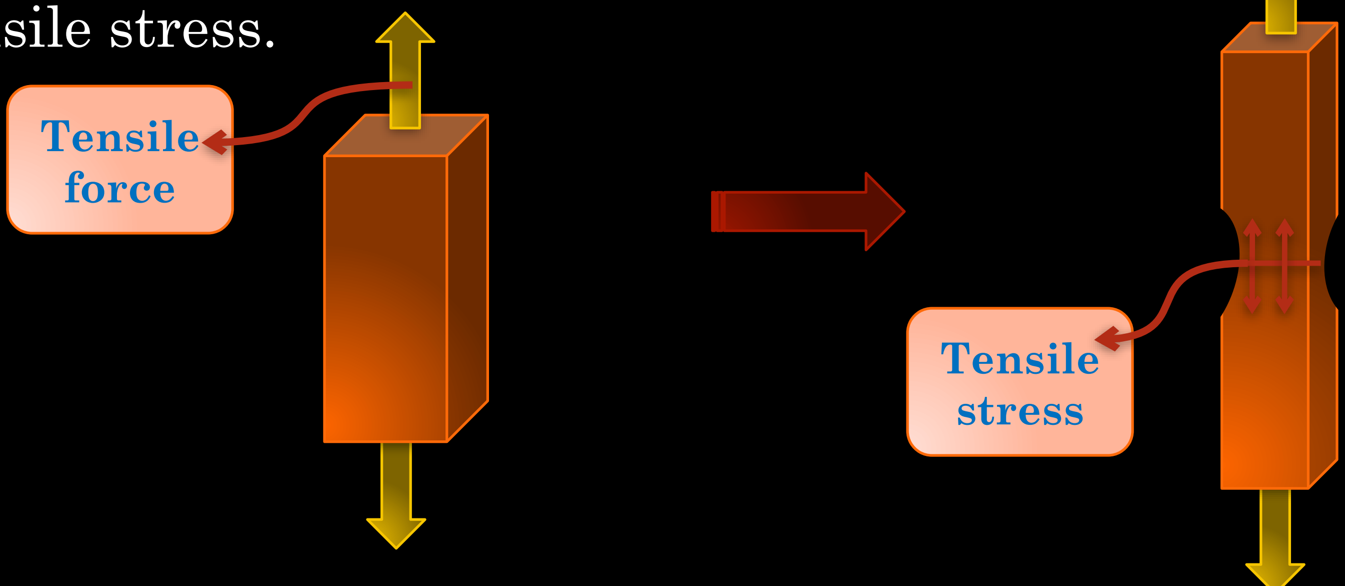
- DEFINITION OF COMPRESSIVE STRESS:
- Ratio of compressive force to cross-sectional area perpendicular to the axis of applied force OR It is the force per unit area produced in the body in response to an externally applied force, which tends to compress (shorten) the material.
- It is accompanied by compressive strain.

- Since most of masticatory forces are compressive in nature, it is important to investigate materials under this condition.

Tooth	Average masticatory force (N)
Second molar	800
First molar	390
Bicuspids	288
Cupids	208
Incisors	155

TENSILE STRESS

- When a body is subjected to tensile force (two sets of forces directed away from each other in a straight line) which tries to stretch or elongate the body, a resistance is developed in the body which is equal in magnitude and opposite in direction to the applied force.
- This internal resistance of the body to tensile force is called tensile stress.

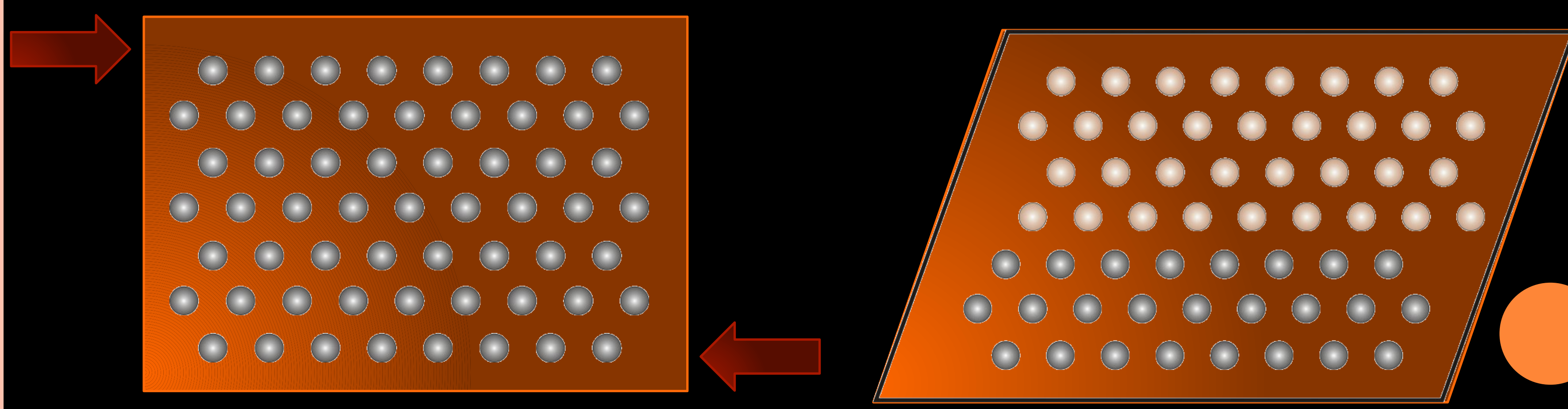


DEFINITION OF TENSILE STRESS

- It is the force per unit area produced in the body in response to an externally applied force, which tends to stretch(elongate) the material.
- It is accompanied by tensile strain.

SHEAR STRESS

- Shear is a result of two sets of forces directed parallel to each other , but not along the same straight line.
- Shear stress is the force per unit area produced in the body in response to an externally applied force, which tends to slide one portion of a body over another.

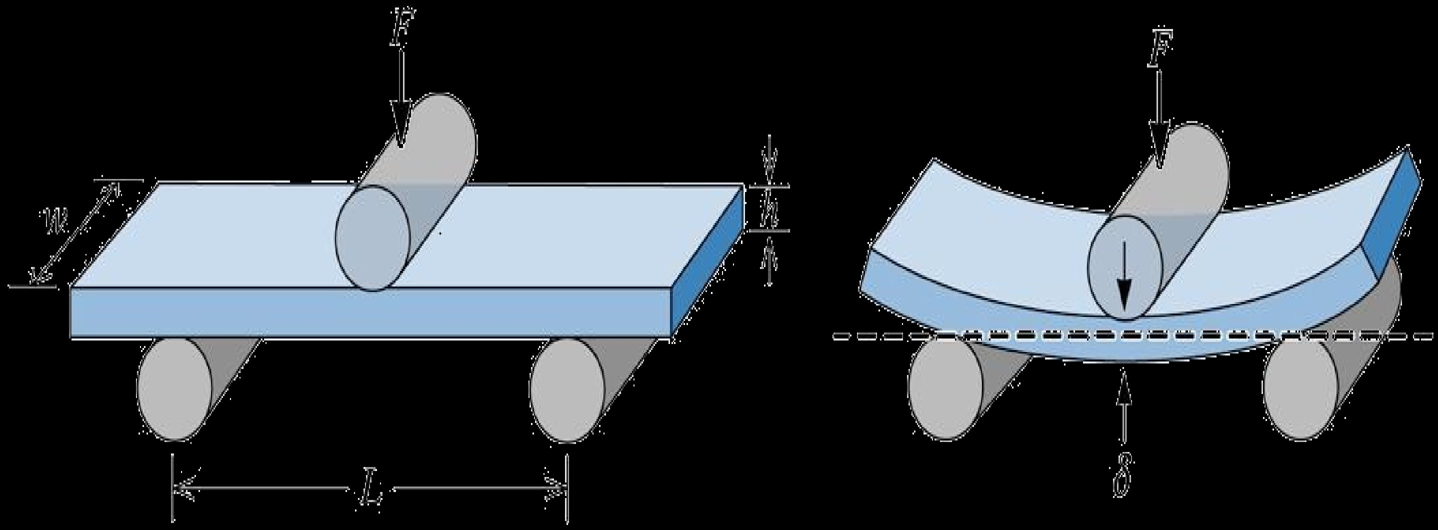


COMPLEX STRESSES

- Tensile and compressive stresses along with shear, are the three simple examples of stress which form the basis of all other more complex stress patterns.

FLEXURAL STRESS:

- Also called as bending stress.
- Produced by bending forces over the dental appliance.



STRAIN

- The application of an external force to a body results in a change in dimension of that body. The magnitude of which depends on the applied force and the properties of the material.
- The numerical value of strain is given by the expression

  Strain = Change in length/Original length.$=\Delta L/L$
- Strain is dimensionless quantity because a unit length is divided by unit length.

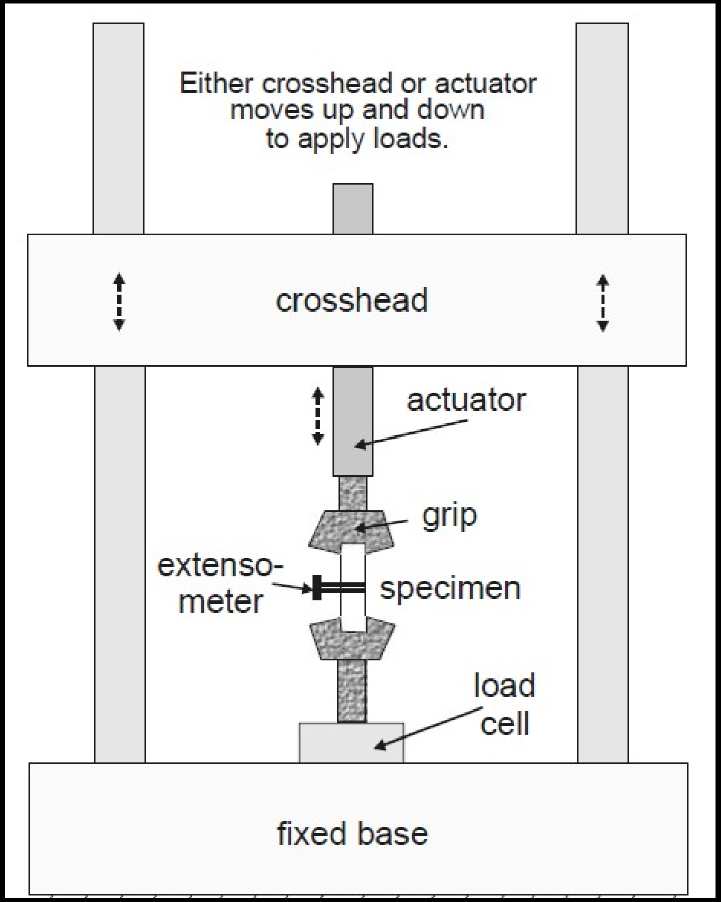
- The stain may be recoverable, that is the material will return to its original length after removal of the applied force (elastic strain), or the material may remain deformed, in which case the strain is non-recoverable(plastic strain).
- A third possibility is that the strain may be partially recoverable(visco elasticity).

STRESS-STRAIN RELATIONSHIP

- Each type of stress is capable of producing a corresponding deformation in the body.
- Therefore, stress and strain are not independent and unrelated properties, but they are closely related and may be seen as cause and effect.
- The relationship of stress and strain is often used to characterize the mechanical properties of materials.

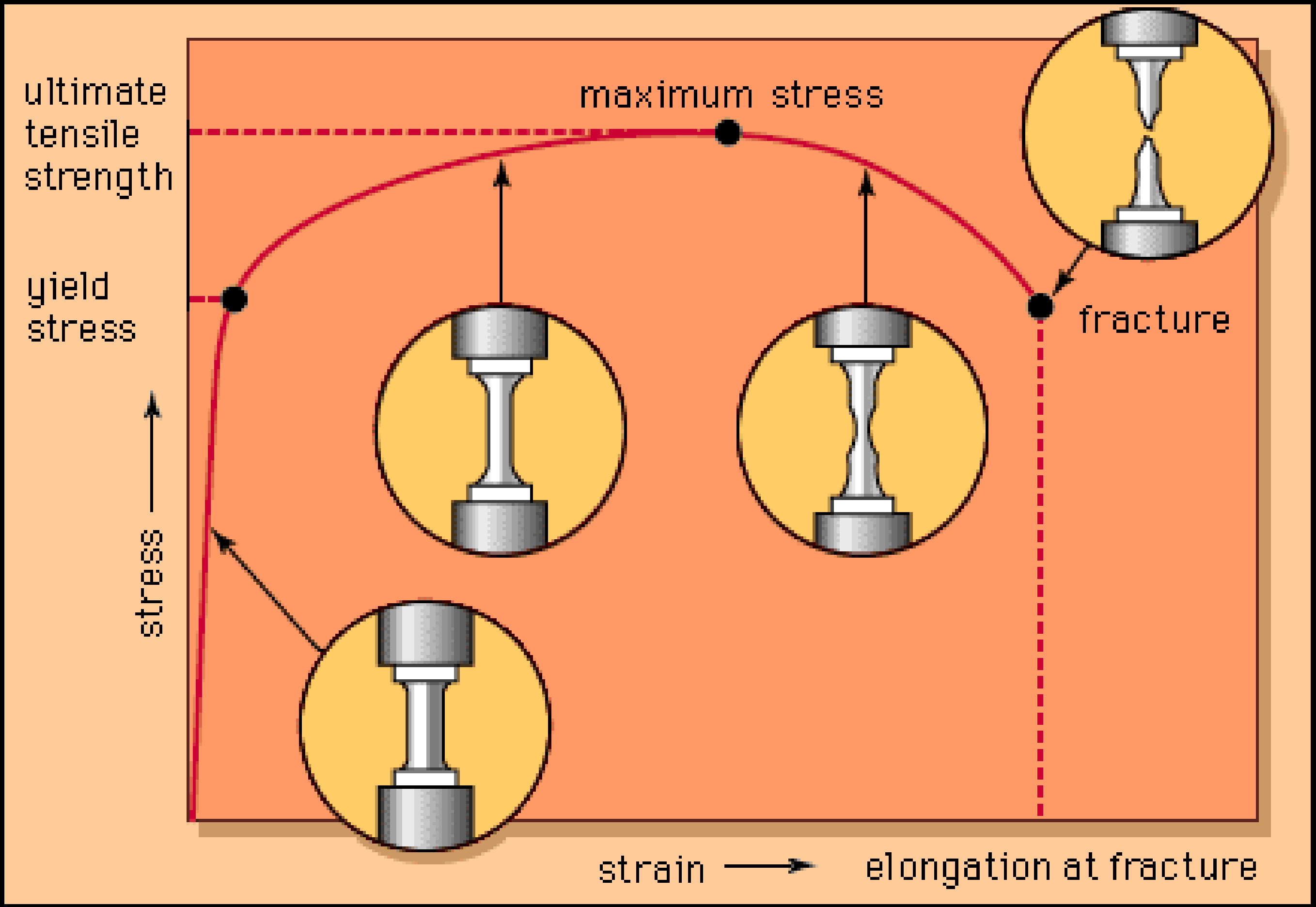
- Stress- strain data are generally obtained using a mechanical testing machine, which enables strain to be measured as a function of stress and recorded automatically in the form of a graph called stress strain curve.

Parts of universal testing machine



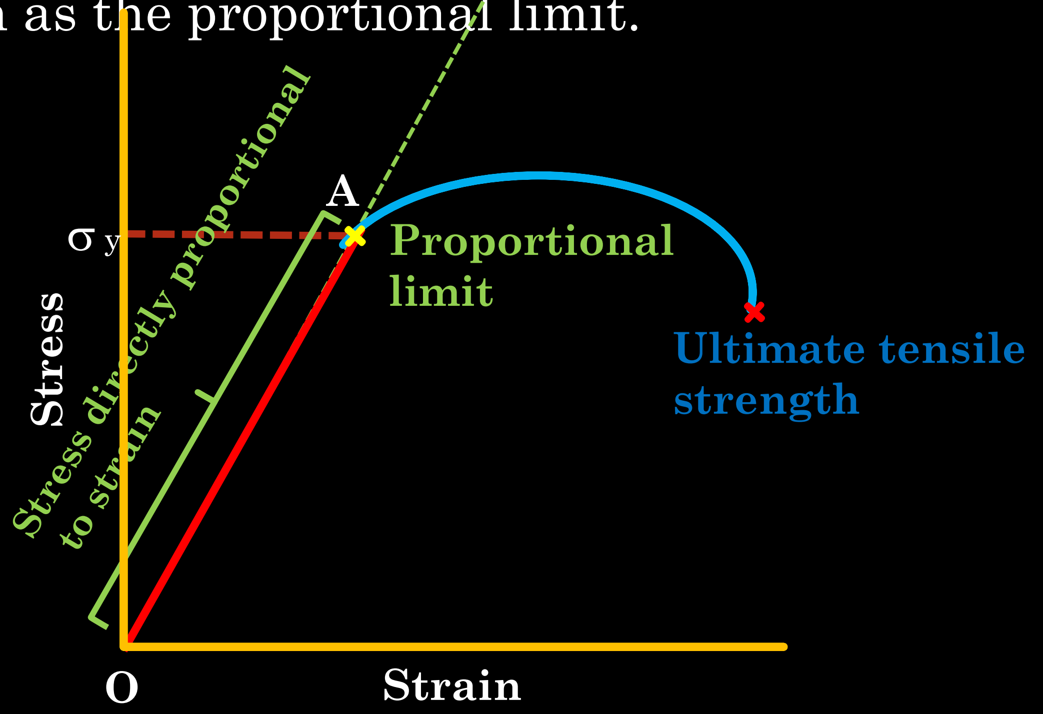
Click on it to watch a video related to tensile test and stress strain graph

- Stress strain curve for a hypothetical material subjected to increased tensile stress until failure is shown in the figure.



PROPORTIONAL LIMIT

- As the stress is increased, the strain is increased. In the initial portion of the curve, from O to A, the strain is linearly proportional to the stress. When a stress that is higher than the value registered at A is achieved, the strain changes are no longer linearly proportional to the stress changes. Hence the value of the stress at A is known as the proportional limit.



- Proportional limit is defined as the greatest stress that a material will sustain without deviation from the linear proportionality of stress to strain

ELASTIC LIMIT

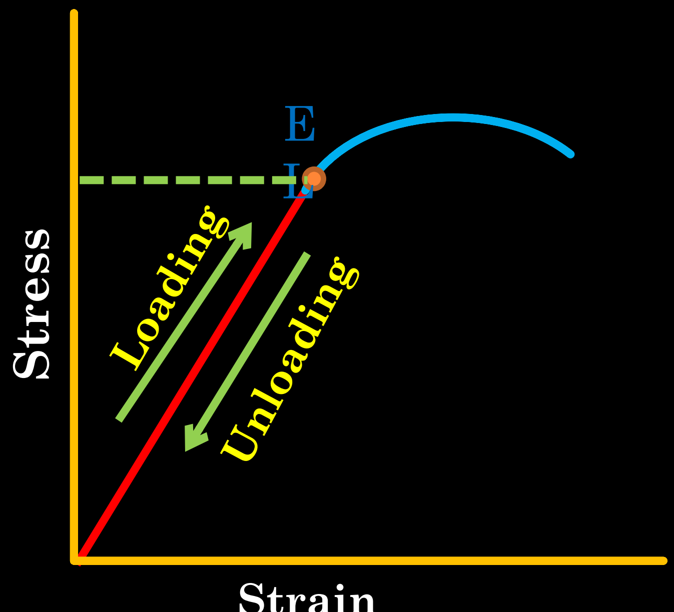
- Defined as the maximum stress that a material can withstand without permanent deformation.
- Above elastic limit, a material undergoes irreversible plastic deformation and below the elastic limit, it shows reversible elastic deformation.

NOTE

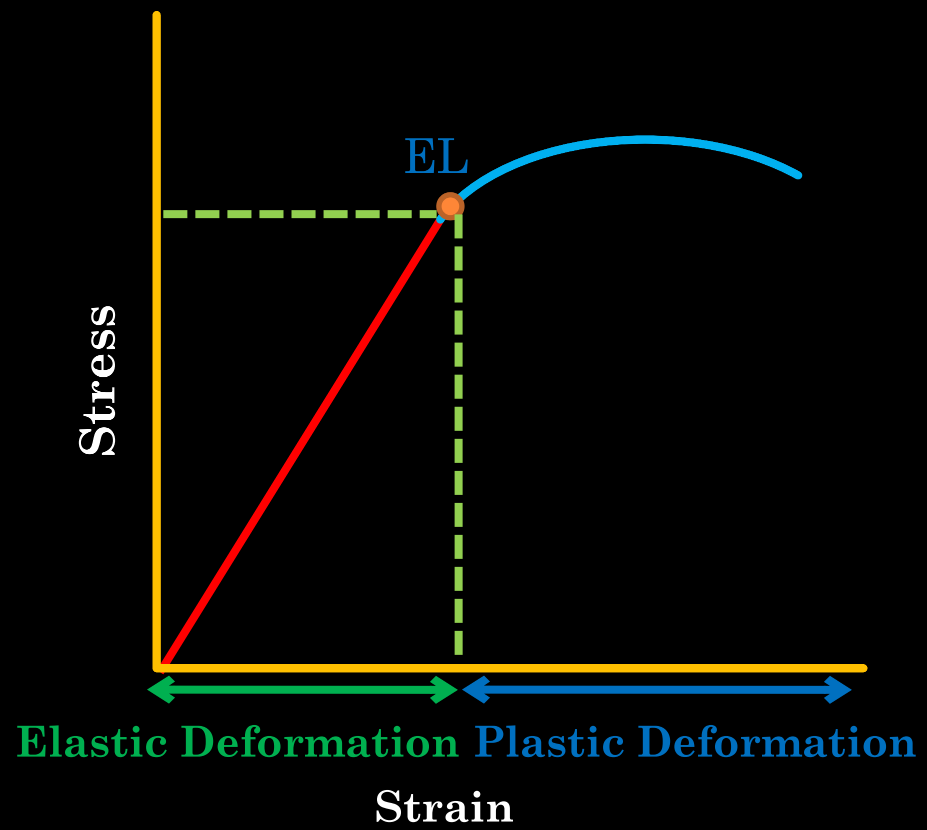
Elastic deformation → Bonds stretched→ No permanent damage

Plastic deformation → Bonds broken→ Permanent damage

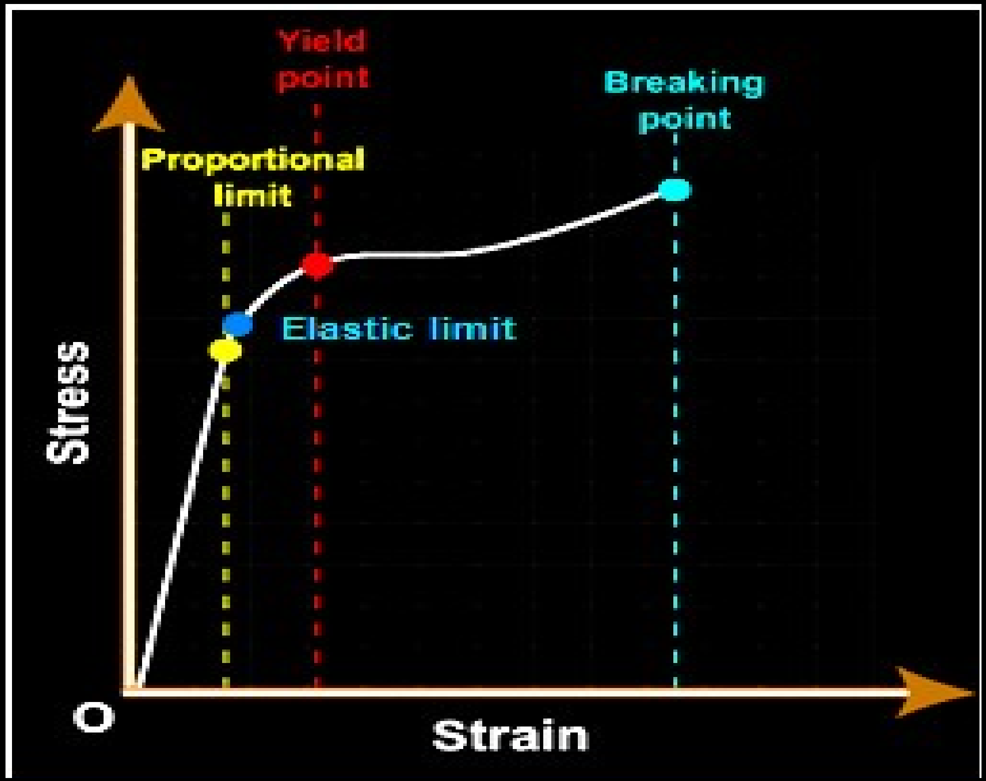
- Below elastic limit, no permanent deformation occurs in a structure. When the stress is removed, the structure will return to its original dimensions and the material is considered to be showing elastic nature.
- The region of stress-strain curve before the elastic limit is called the elastic region.



- The application of stress greater than elastic limit results in permanent or irreversible strain in the specimen and the region of the stress strain curve beyond the elastic limit is called the plastic region.

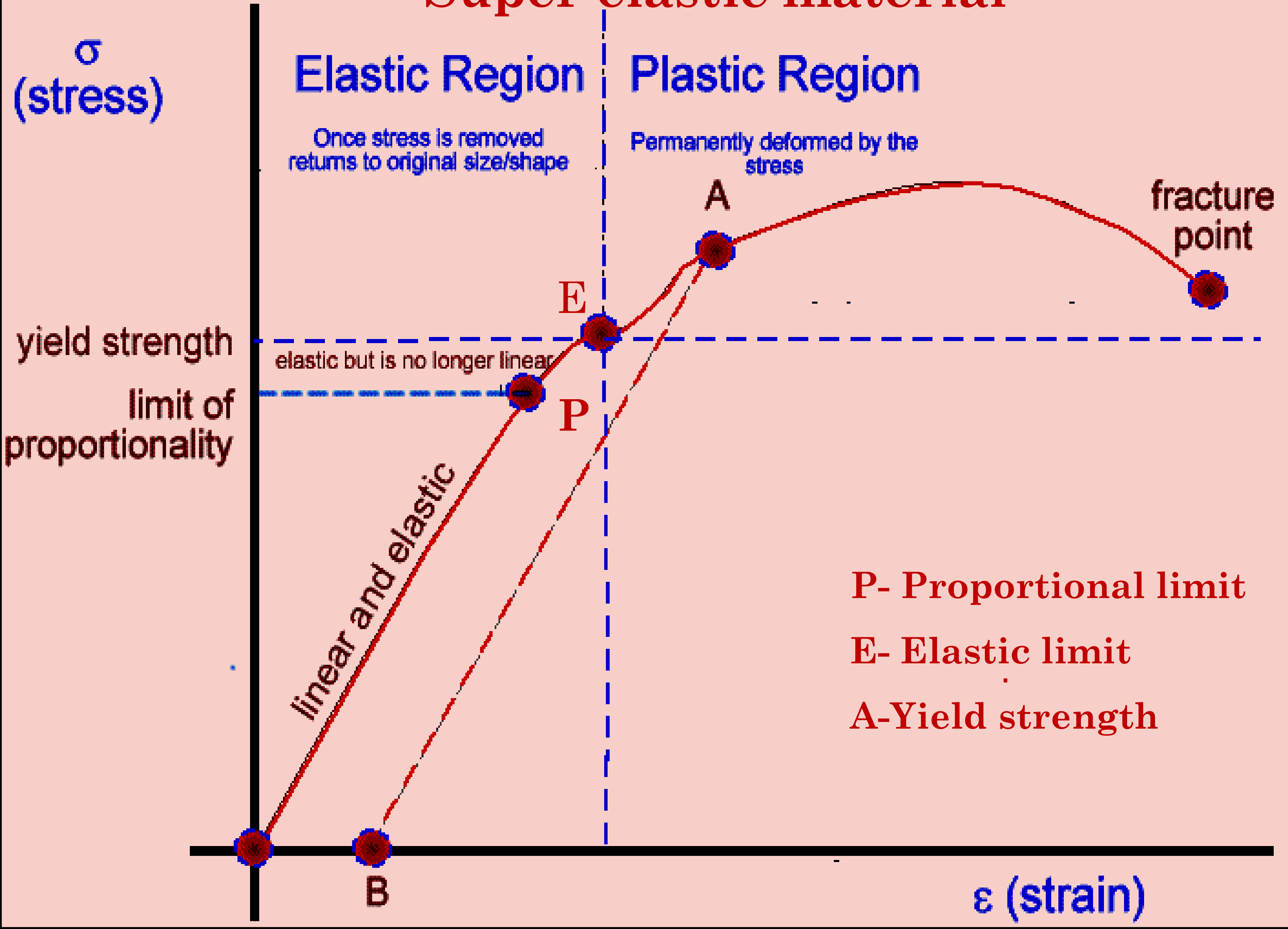


- For linearly elastic materials which obey Hooke's law(stress directly proportional to strain) the elastic limit and proportional limit represent the same stress within the structure and the terms are often used interchangeably in referring to the stress involved.



- Super elastic materials are exception to this.
- These materials exhibit nonlinear elastic behavior, and their relationship between stress and strain in the elastic region does not follow a straight line, but removal of the load results in a return to zero strain.

Super elastic material



P- Proportional limit

E- Elastic limit

A-Yield strength

- **NOTE :**
- Fundamental difference in the concept of proportional and elastic limit is one deals with proportionality of strain to stress in the structure, whereas the other describes elastic behavior of the material.

MECHANICAL PROPERTIES BASED ON ELASTIC DEFORMATION

- There are several important mechanical properties measuring reversible deformation and include

1) Elastic modulus (young's modulus or modulus of elasticity or Hooke's law)
2) Dynamic young's modulus
3) Flexibility
4) Resilience
5) Poisson's ratio

YOUNG'S MODULUS / ELASTIC MODULUS / MODULUS OF ELASTICITY

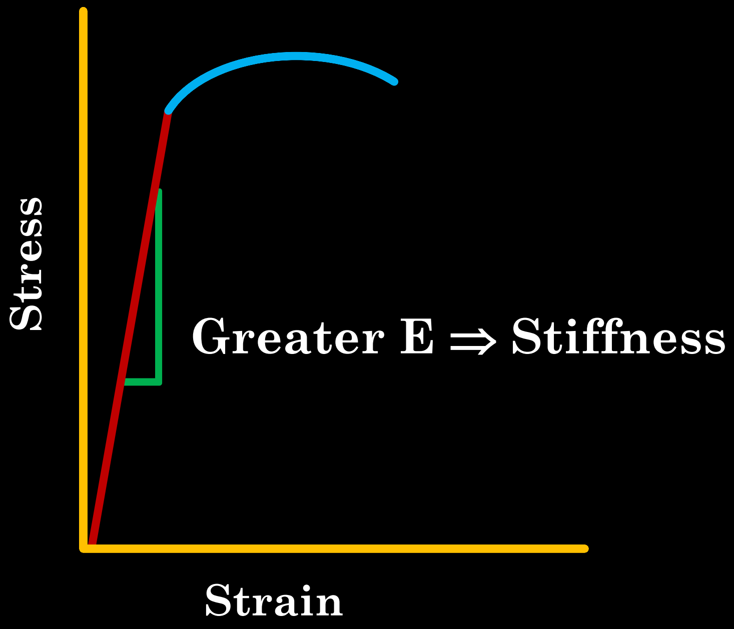
- When a material deforms elastically, strain for a given stress is always the same and the two are related by Hooke´s Law (stress is directly proportional to strain):
- $\sigma \alpha \in$
- $\sigma = E \in$

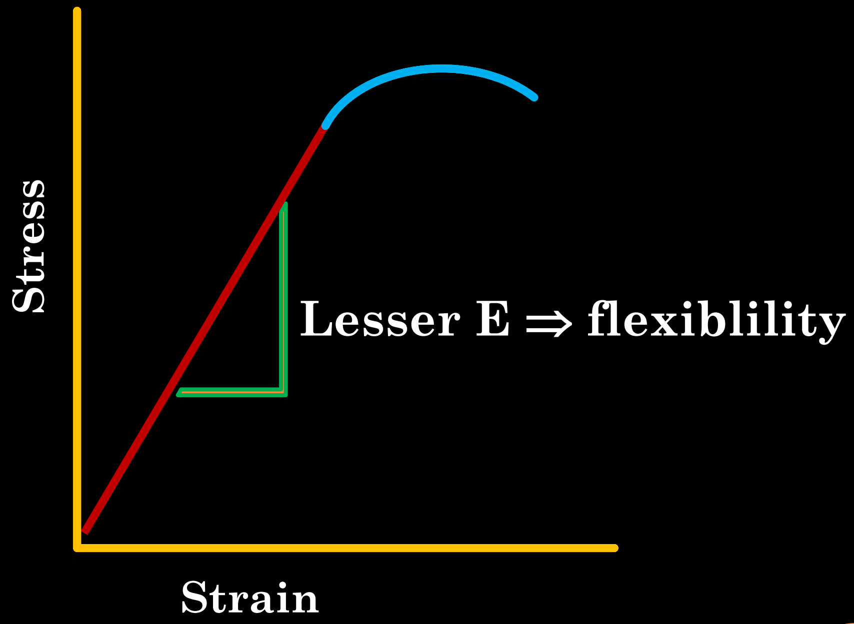
$\therefore E = \sigma/\varepsilon$

- where,
- σ is stress [MPa]
- E modulus of elasticity /constant of proportionality [MPa]
- ε strain [unitless or %]

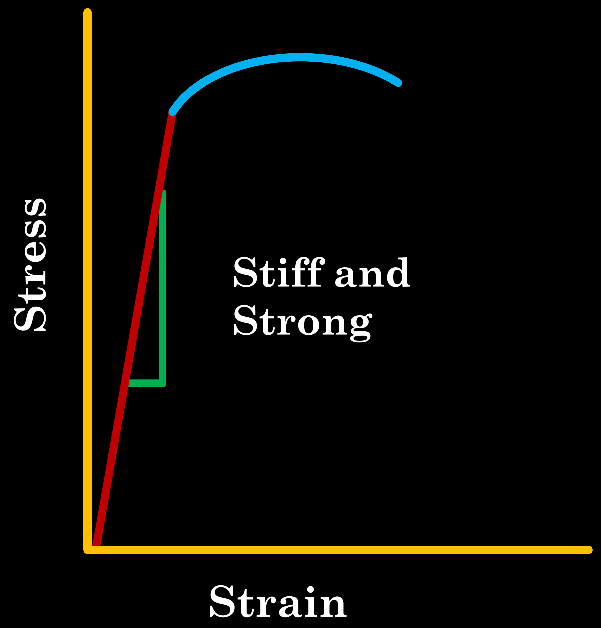
- From the Hooke's law the modulus of elasticity is defined as the ratio of the stress to the strain in the linear or elastic portion of stress strain curve.
- E is measured by the slope of stress strain graph.
- It desribes relative stiffnes or rigidity of a material.

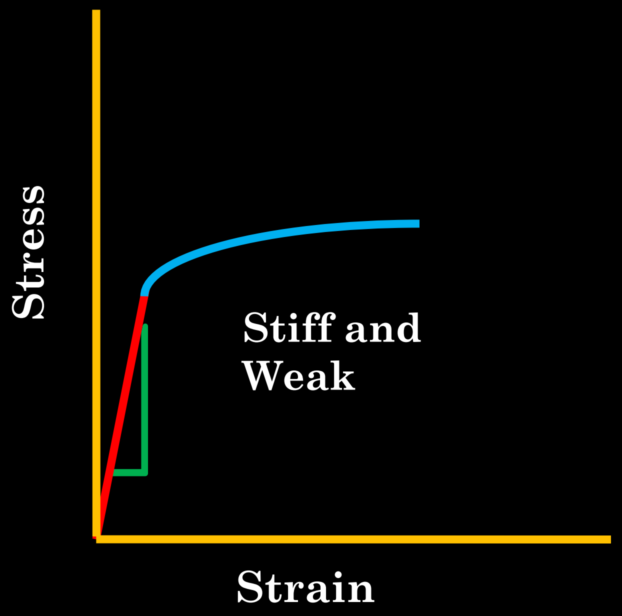
- Therefore, it follows that lesser the strain for a given stress, greater will be the stiffness and higher the Young's modulus (E) and viceversa.





- Elastic modulus of a material is a constant and is unaffected by the amount of stress induced in a material.
- Thus it is not a measure of strength. Material with a high elastic modulus can have either high or low strength values.





- **APPLICATIONS**
- The metal frame of a metal-ceramic bridge should have a high stiffness. If the metal flexes, the porcelain veneer on it might crack or separate. Such a material would possess a comparative high modulus of elasticity.
- A polyether material have greater stiffness than all other elastomeric impression materials. Thus a greater force is needed to remove a impression tray from undercuts in mouth.

- **NOTE:**
- The modulus of elasticity is an inherent property of the material and cannot be altered appreciably by heat treatment, work hardening, or any other kind of conditioning.
- This property is called structure insensitivity.

ELASTIC MODULUS OF MATERIALS

Materials	Elastic modulus (GPa)
Enamel	84
Dentin	17
Gold (type IV)alloy	90-95
Amalgam	28-59
Co-Cr partial denture alloy	218-224
PMMA	2.4
Silicone elastomer for maxillofacial prosthesis	0.002-0.003
Feldspathic porcelain	69-70

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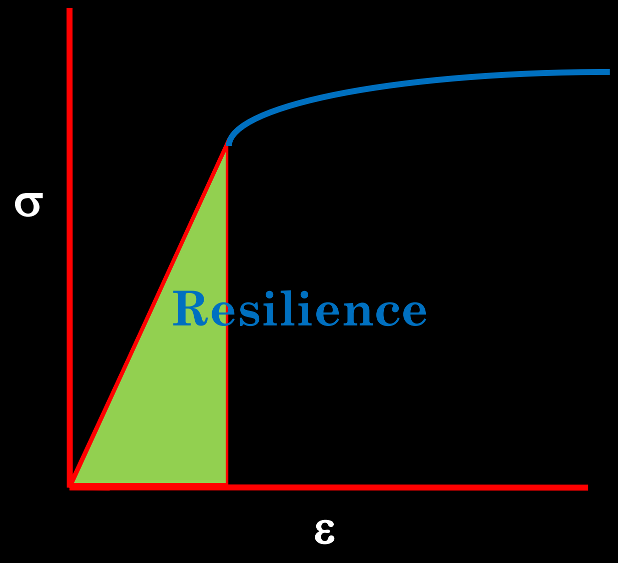
DYNAMIC YOUNG'S MODULUS

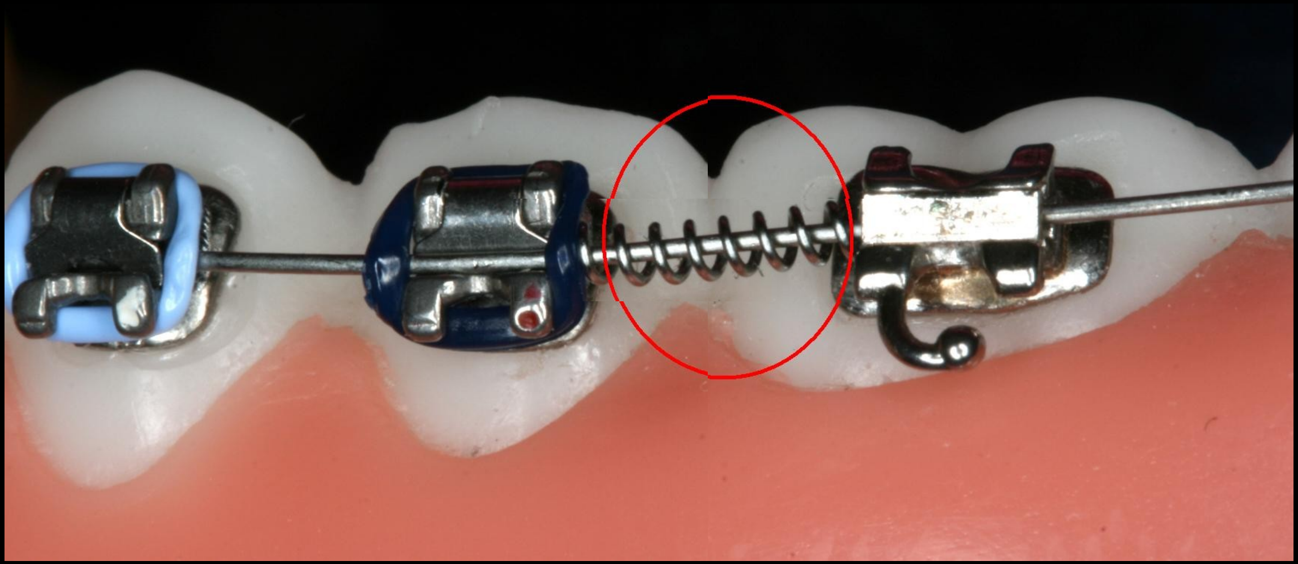
- Can be measured by dynamic method.
- Ultrasonic longitudinal and transverse wave transducers and appropriate receivers are used.
- The velocity of sound wave and density of material are used to calculate elastic modulus.

RESILIENCE

- It indicates the amount of energy necessary to deform a material to proportional limit. OR it is amount of energy absorbed by a structure, when it is stressed to proportional limit.
- Resilience is measured by the area under the elastic portion of stress strain curve.



- Resilience has particular importance in the evaluation of orthodontic wires . It determines the magnitude of the force that can be applied to the tooth and how far the tooth can move before the spring is no longer effective.

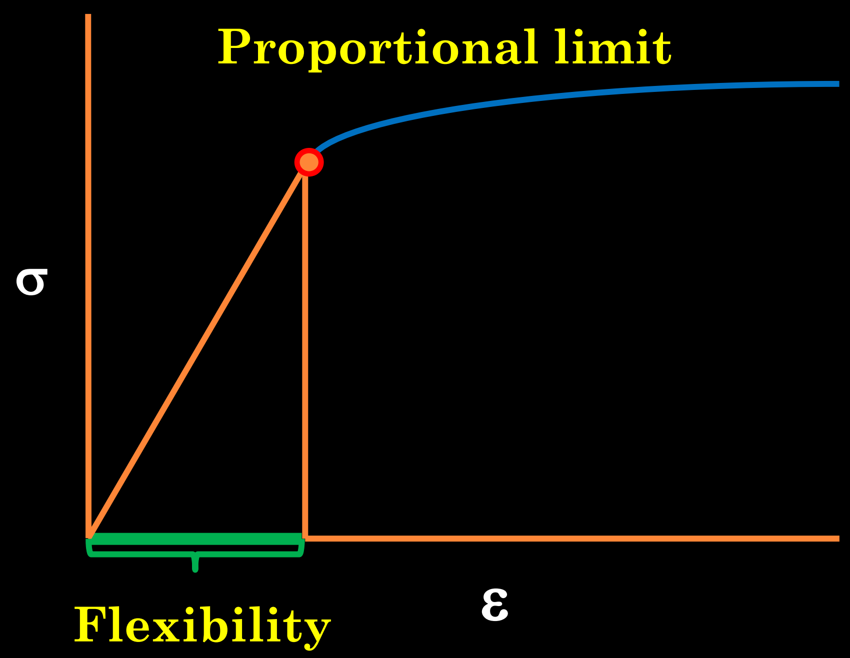


- Elastomeric soft liners absorb considerable amounts of energy without being permanently distorted when stressed and the energy stored is released when the material springs back to its original shape after removal of the applied stress. Therefore, these materials act as cushion between the hard denture base and soft tissues to reduce masticatory forces transmitted by prosthesis to the underlying tissues.

- If large proximal strains are developed during compressive loading, a proximal inlay might absorb the energy and cause excessive movement of the adjacent tooth when the absorbed energy is released.
- Hence the restorative material should exhibit a moderately high elastic modulus and relatively low resilience.

FLEXIBILITY

- It is the maximum elastic (recoverable) strain that occurs when a material is stressed to proportional limit.
- Therefore, it follows that greater the strain for a given stress in a material, greater will be it's flexibility.



APPLICATIONS:

- Restorative materials should withstand high stresses and show minimum distortion or should have minimum flexibility.
- Impression materials should have large flexibility or elastic deformation to withdraw through severe undercuts without permanent deformation.
- Maxillofacial materials and soft denture reliners should have high flexibility.

MECHANICAL PROPERTIES BASED ON PLASTIC DEFORMATION

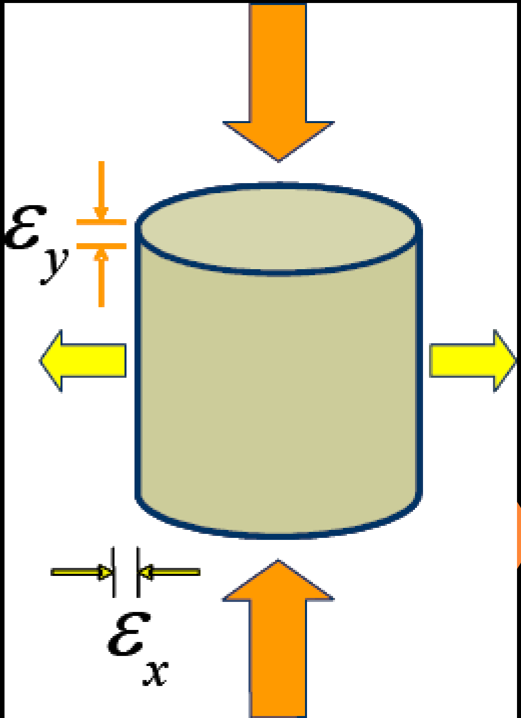
- There are several important mechanical properties measuring irreversible deformation and include

1) Yield strength
2) Toughness
3) Ductility and malleability
4) Fracture toughness
5) Ultimate tensile strength
6) Fracture strength

POISSON'S RATIO

- When a tensile force is applied along one axis to produce elongation, compressive strain is produced at right angles, proportionately.
- Within elastic range the ratio of lateral to the axial strain is called Poisson's ratio.

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}}$$

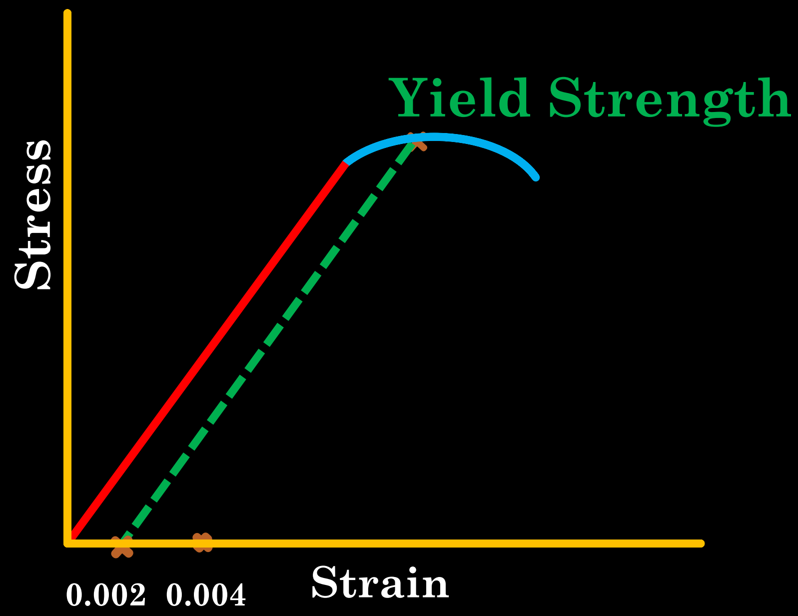


- Dental materials have Poisson's ratio value in range of 0.3 to 0.5.

YIELD STRENGTH (PROOF STRESS)

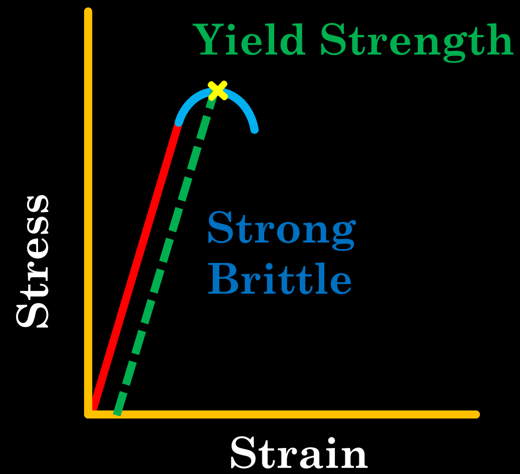
- Irregularities along the straight line region of the stress versus-strain plot may represent minor deviations from Hooke's law and cause some uncertainty in determining the precise point at which the selected line deviates from linearity(proportional limit).
- Thus a different property, yield strength, is used in cases where the proportional limit cannot be determined with sufficient accuracy.

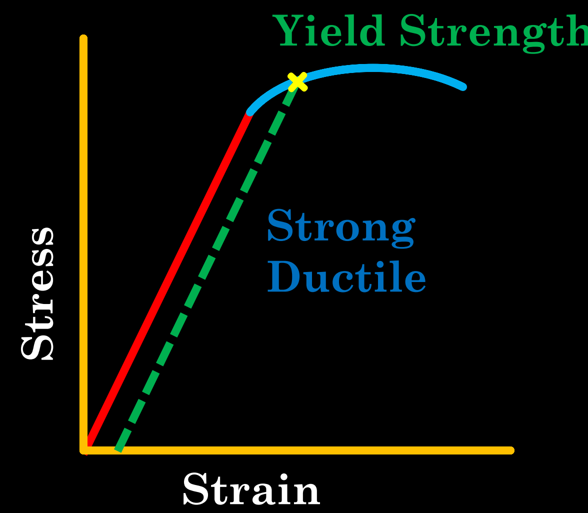
- ***Yield strength*** is the stress required to produce a small-specified amount of plastic deformation.
- To determine the **YS** for a material at 0.2% offset, a line is drawn parallel to the straight line region, starting at a value of 0.002, or 0.2% of the plastic strain, along the strain axis and is extended until it intersects the stress-strain curve.
- The stress corresponding to this point is the yield strength.

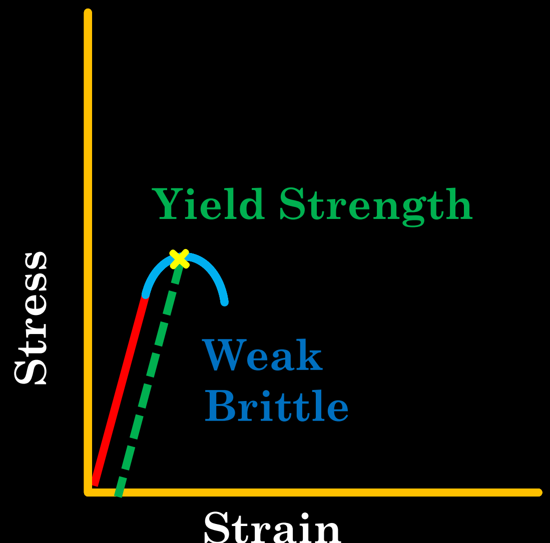


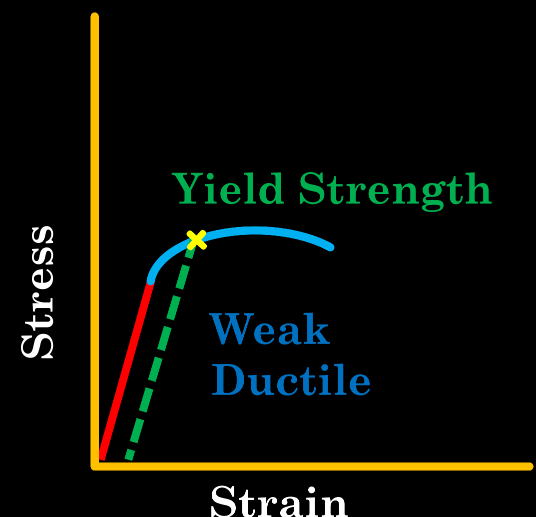
- Yield strength indicates a functional failure of a material.
- Although the term strength implies that the material has fractured, it is actually intact but has sustained a specific amount of plastic strain (deformation)
- A restoration exhibiting a permanent deformation will be no more serving the purpose in spite of the fact that it didn’t fracture.
- Yield stress is more important than the ultimate stress, because yield stress represents the clinical failure.

- Yield strength determines whether the material is strong or weak.









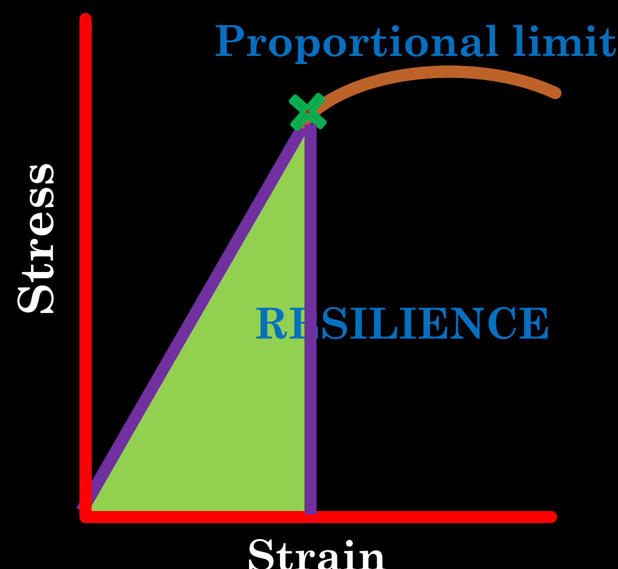
TOUGHNESS

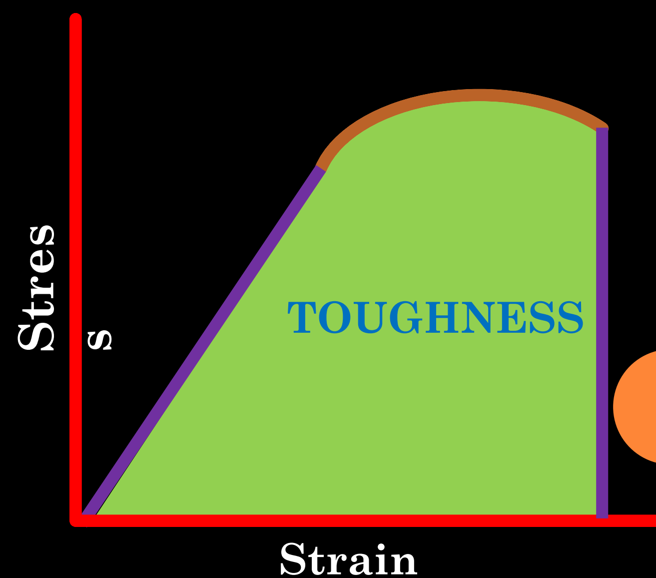
DEFINITION:

- It is the amount of elastic and plastic deformation energy required to fracture a material.
- Toughness is indicated as the area under the elastic and plastic portions of a stress strain curve/total area under stress strain curve

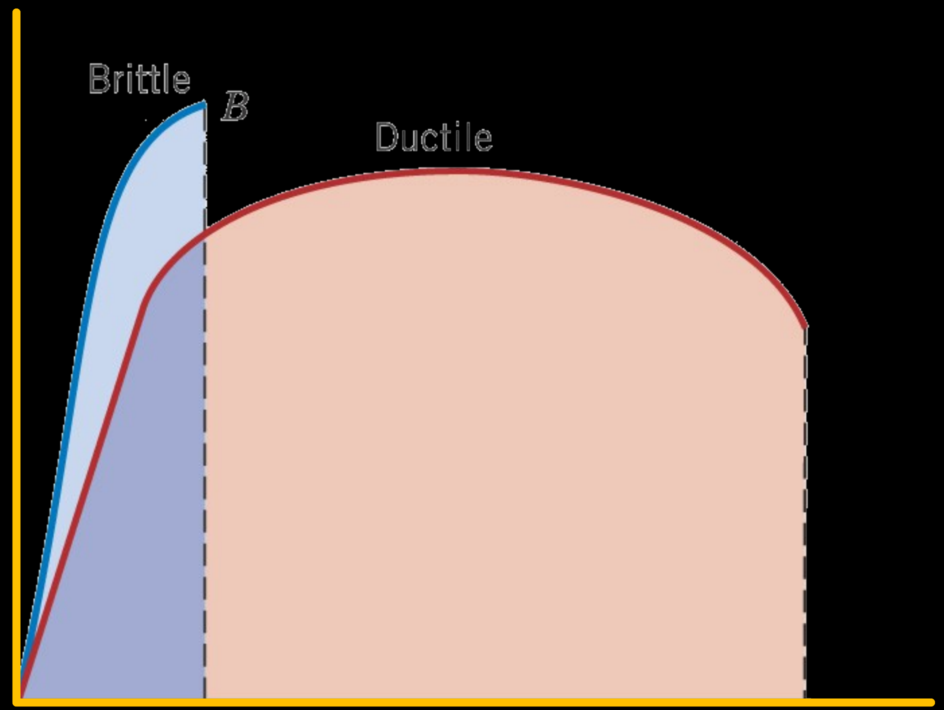
Difference between resilience and toughness

- Toughness is the total amount of energy a material can absorb up to the point of fracture.
- Whereas resilience represents the energy required to stress a material to it's proportional limit OR The maximum amount of energy a material can absorb without undergoing permanent deformation.

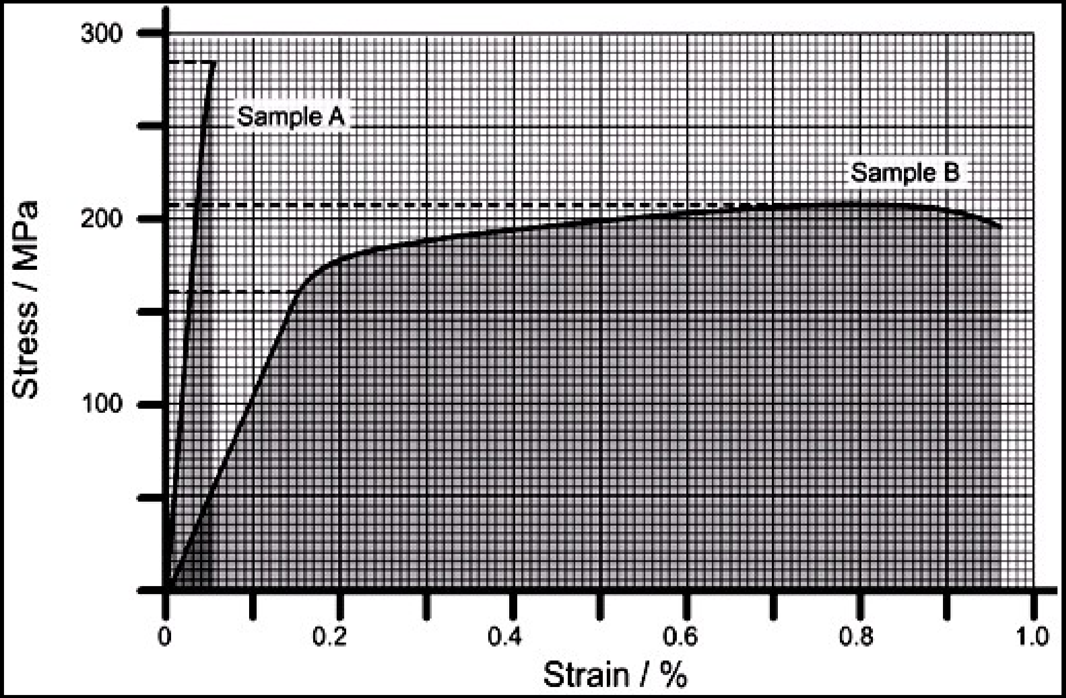




- A material capable of absorbing large amount of energy is termed a tough material.The opposite of toughness is brittleness.
- Toughness of the ductile materials is higher than toughness of brittle materials.



- Toughness is not as easy to calculate as resilience, and the integration is done numerically.
- If a sample is being tested with an automated rig attached to data logging equipment then the toughness can be reported at the end of the run.
- In case of a complex curve however there is little choice but to count the squares under the curve.

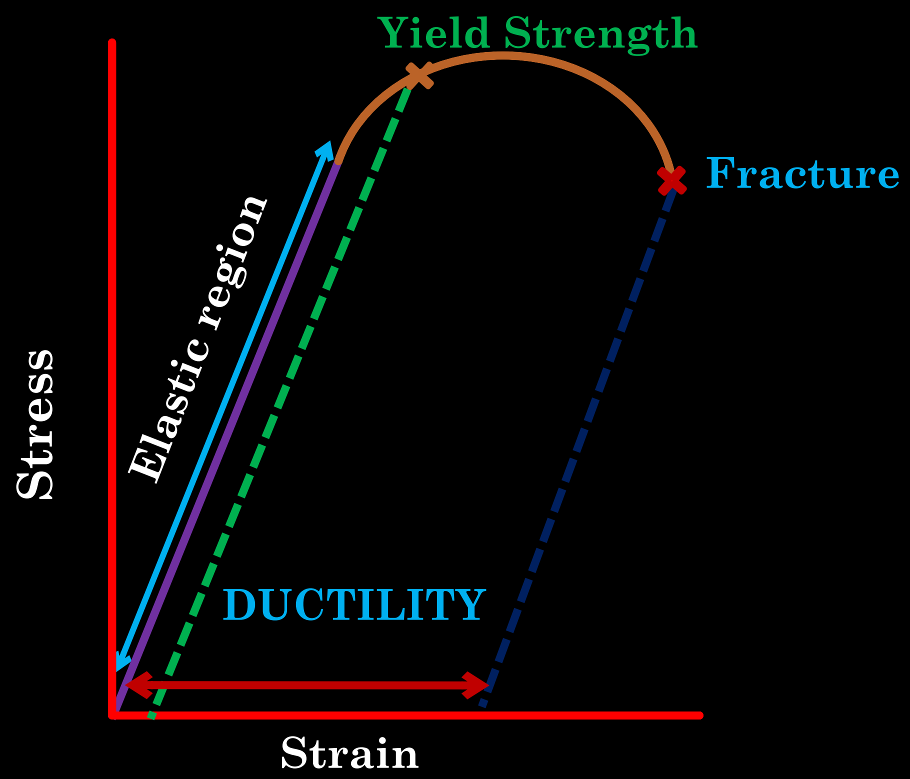


- Each large square is 50 MPa x 0.1% (0.001) = 50,000 J m^{-3}. Each small square is 1/100th of this (500 J m^{-3}).
- Sample A: large squares = 0, small squares = 195 => 97.5 kJ m^{-3}.
- Sample B: large squares = 26, small squares = 816 => 1.71 MJ m^{-3}.

DUCTILITY

- DEFINITION
- Relative ability of a material to deform physically under a tensile stress before it fractures.
- Ductility represents the ability of a material to sustain large permanent deformation under tensile load before it fractures. For example, a metal that can be drawn readily into a long, thin wire is considered to be ductile.
- A material that undergoes very little plastic deformation is brittle.

- Ductility(elongation) can measured with an extensometer while the material is being tested or calculated from the stress strain curve by drawing a line from the point of fracture, that is parallel to the elastic region of the stress- strain curve.Where this line meets the strain axis is the measure of the ductility of the material, and is frequently presented in terms of percentage elongation.



- Percent elongation gives an indication of the workability of an alloy and is calculated as follows

% elongation=(Increase in length/Original length)X100

Alloys	Percentage elongation
Ni-Cr	2.4
Co-Cr	1.5
Co-Ni-Cr	8-10

- Ductility is otherwise measured by 3 common methods

  a) Percent elongation after fracture:

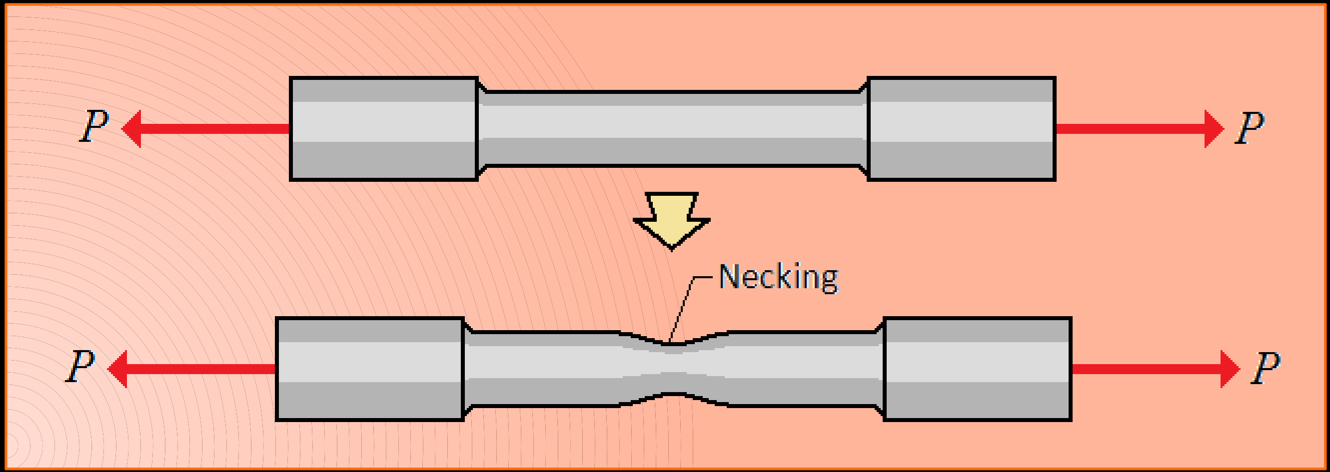
- The simplest and most commonly used method is to compare the increase in length of a wire or rod after fracture in tension to its length before fracture.

- Two marks are placed on the wire as the gauge length (for dental, materials, the standard gauge length is usually 51mm) the wire or rod is then pulled a part under a tensile load.

- The fractured ends are fitted together, and the gauge length is again measured, the ratio of the increase in length after fracture to the original gauge length is called the present elongation and represents ductility.

b) The reduction in area of tensile test specimens:

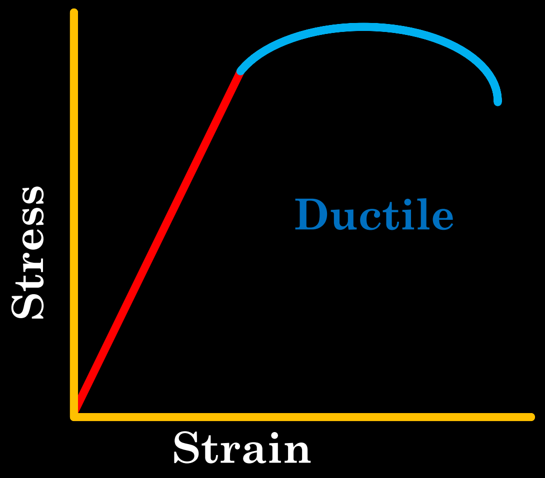
The necking or cone-shaped constriction that occurs at the fractured end of a ductile wire after rupture under tensile load, the percentage of decrease in cross-sectional area of the fractured end in comparison to the original area of the wire or rod is referred to as the reduction in area.

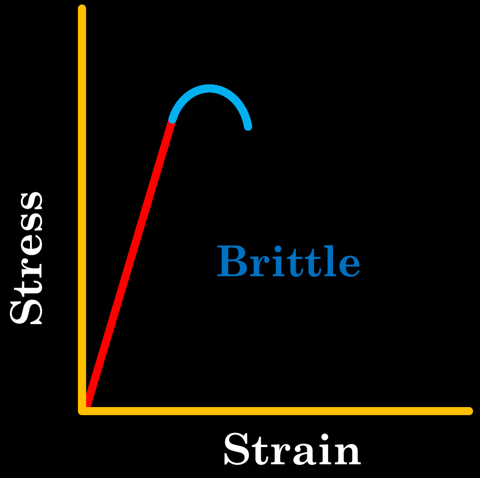


c) The cold bend test:

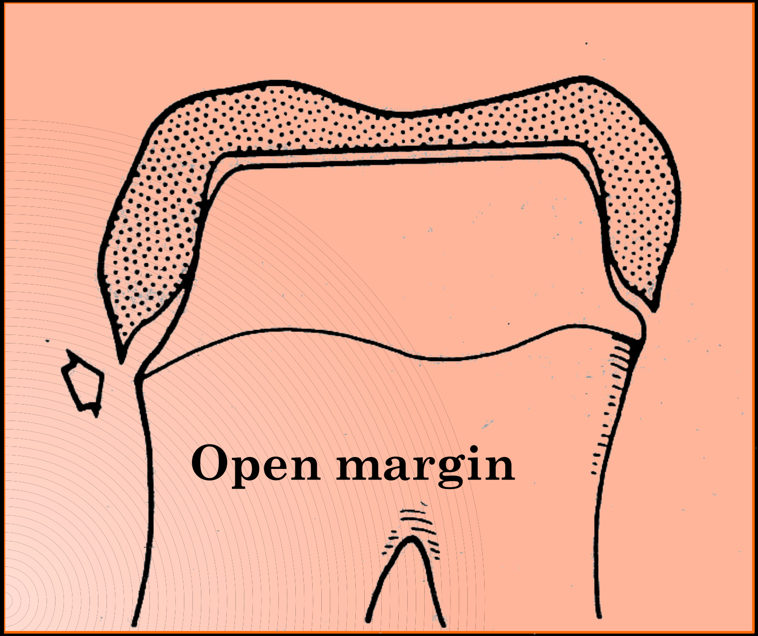
- The material is clamped in a vise and bent around a mandrel of specified radius, the number of bends to fracture is counted, with the grater the number, the greater is the ductility of the material.

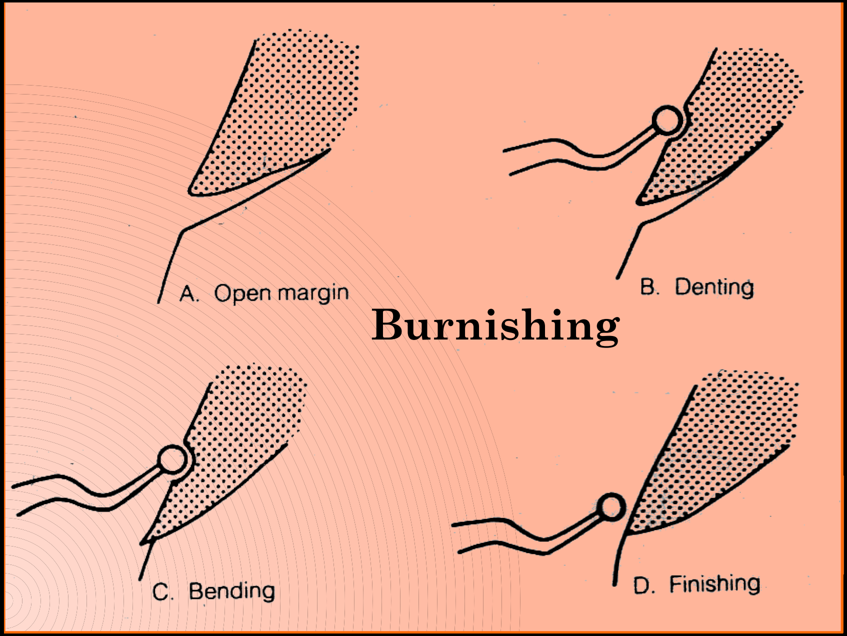
- Materials that experience a large amount of permanent deformation are said to be ductile.
- Materials that undergo little or no plastic behavior are said to be brittle. A brittle material fractures at or near its proportional limit.





- Importance of ductility in dentistry:
- Clasps can be adjusted, orthodontics appliances can be prepared, crowns or inlays can be burnished if they are prepared from alloys of high values of percentage elongation.





MALLEABILITY

- **DEFINITION**
- The ability of a material to sustain considerable permanent deformation without rupture under compression, as in hammering or rolling into a sheet, is termed malleability.
- Gold is most ductile and malleable and silver stands the second.
- Platinum is third most ductile and copper is third most malleable.

Ductility of metals in decreasing order	Malleability metals in decreasing order
Gold	Gold
Silver	Silver
Platinum	Aluminum
Iron	Copper
Nickel	Tin
Copper	Platinum
Aluminum	Lead
Zinc	Zinc
Tin	iron

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FRACTURE TOUGHNESS

DEFINITION:

- Fracture toughness is the resistance of a brittle material to catastrophic propagation of flaws under an applied stress.
- Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw.

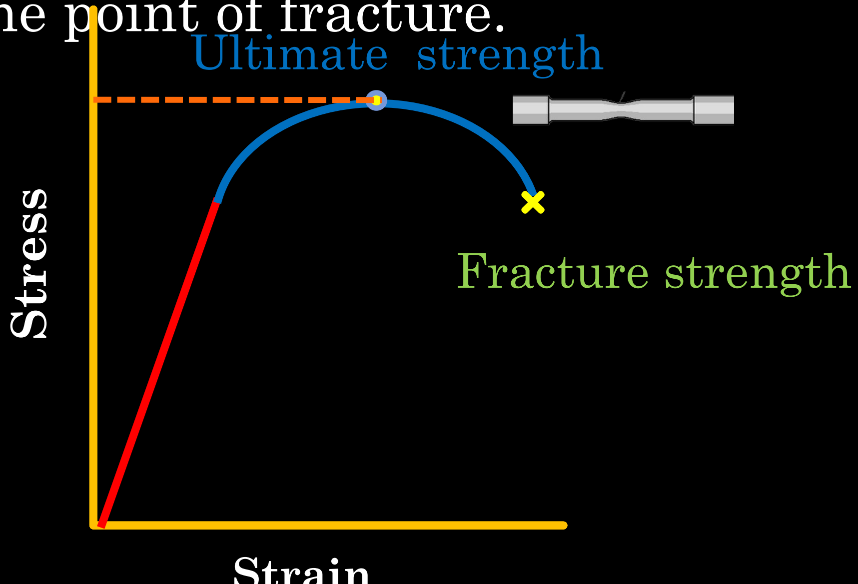
- Flaws or cracks may arise naturally in a material or nucleate after time in service.
- In either case, any defect generally weakens a material, and as a result, sudden fractures can arise at stresses below the yield stress.
- Sudden catastrophic fractures typically occur in brittle maerials that do not have ability to plastically deform and redistribute stresses.

- It is imperative to realize that ceramics, in contrast to metals, are brittle materials and are known to undergo catastrophic failure due to inherent flaws.
- For them strength is more of a “conditional” than an inherent material property.
- Therefore, strength data alone cannot be directly extrapolated to predict structural performance.
- Resistance to fracture in ceramics is determined by fracture toughness.

ULTIMATE STRENGTH

DEFINITION:

- It can be defined as the maximum stress a material can withstand before failure in compression, tension , shear or flexure loading. It is the highest point on stress strain curve and corresponds to necking in ductile materials.
- It is often different from the fracture strength which is the stress at the point of fracture.



- An alloy that has been stressed to near ultimate strength will be permanently deformed, so a restoration receiving that amount of stress during function would be useless.
- The yield strength is often of greater importance than ultimate tensile strength because it is a estimate of when a material will start to deform permanently.

TENSILE STRENGTH

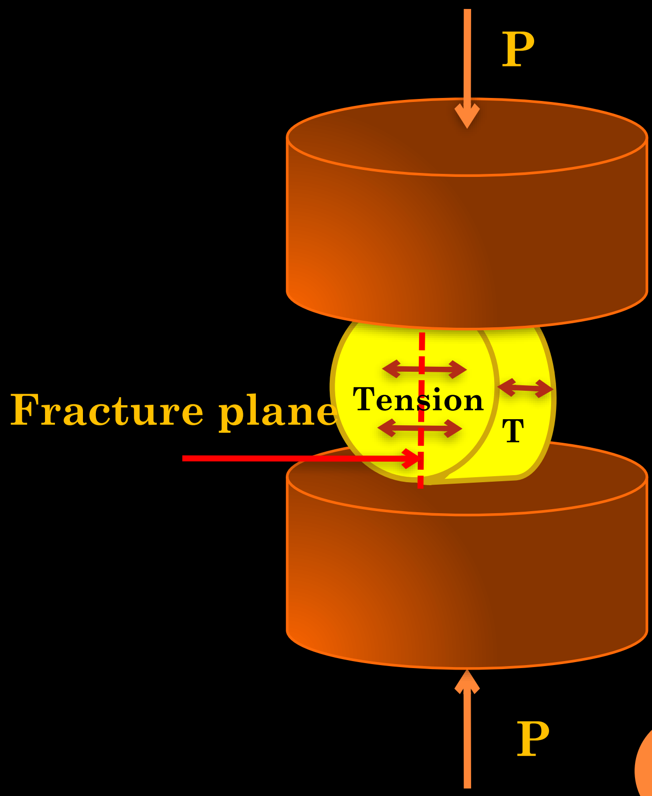
- For ductile materials, the tensile strength can be measured directly using tensiometer or dumbbell shaped cylindrical specimen, is clamped rigidly at the ends and pulled apart to fracture.
- Brittle materials may fracture at clamping points due to stress concentrations.

MATERIALS	TENSILE STRENGTH
Dental porcelain	50-100 MPa
Amalgam	27-55 MPa
Resin- Based composite	30-90MPa
Alumina ceramic	120MPa

DIAMETRAL TENSILE STRENGTH

- This test is especially useful for brittle materials like cements and ceramics.
- The small size of some dental restorations has made the preparation of large dumbbell shaped tensile specimens impractical and also clamping stress during testing of small tensile specimens of plastics and ceramics frequently cause premature fracture.
- As a result, the tensile properties of these materials are usually estimated by the diametral tensile test.

- This test involves diametric compression of a disc with a thickness one-half its diameter between two plates until fracture occurs. The compressive force introduces tensile stresses normal to the diameter under load, and failure is tensile in character.
- The tensile strength is calculated as $\sigma = 2P / \pi DT$
- Where,
- $P \Rightarrow$ load
- $D \Rightarrow$ Diameter of the disc
- $T \Rightarrow$ Thickness of the disc



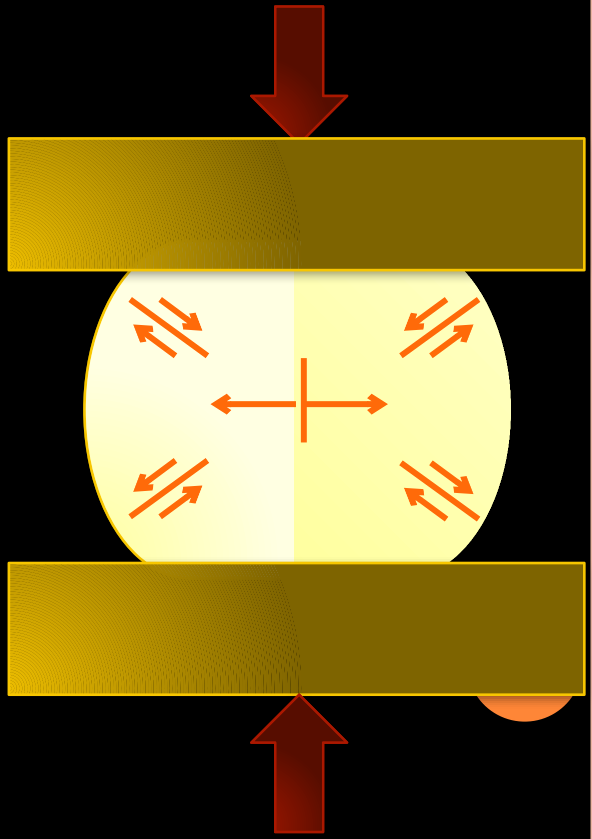
COMPRESSIVE STRENGTH

- It is the ability of a material to withstand axial forces.
- The sample of the material to be tested is constructed in the shape of a cylinder of known dimensions, usually 6x4 mm in diameter. It is then conditioned for up to 24hrs at mouth temperature and often in water to simulate intraoral conditions after placement.
- The cylinder is placed between the platens of a load testing machine and the upper paten is driven down at a constant speed until the specimen fractures.

- The ultimate load applied over the surface area is then calculated. To reduce the variation that may occur during specimen preparation, a number of specimens are produced and tested.
- The mean of the values at fracture

  are used to determine the

  compressive strength of the material.



DRAWBACKS OF THE COMPRESSIVE TEST

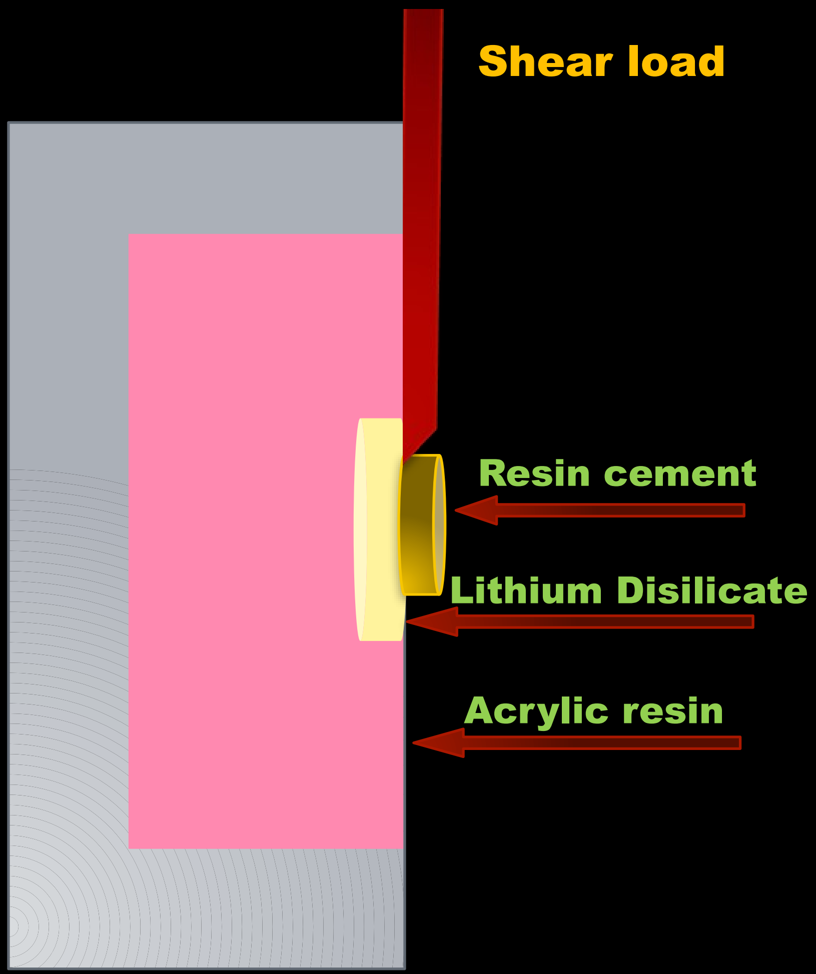
1. The test for compressive strength is not a good discriminator between different material types. The manner in which the test is carried out is obviously not representative of what occurs in the mouth. When masticatory load is applied to the restoration, the tooth tissue surrounding the restoration will act as a support and help withstand the occlusal forces encountered.

2. As the sample is constrained by friction at points of contact with the platens of the tester, there is an increase in the cross sectional area, with the material taking up a barrel shape.

This gives rise to complex stress pattern in a material that cannot be analyzed easily, which makes the interpretation of compression test very difficult.

Material	Compressive strength (MPa)
Enamel	384
Dentin	297
Amalgam	189
Feldspathic porcelain	149
Resin composite	225
Conventional GIC	180-200
Resin modified GIC	170-200

SHEAR STRENGTH

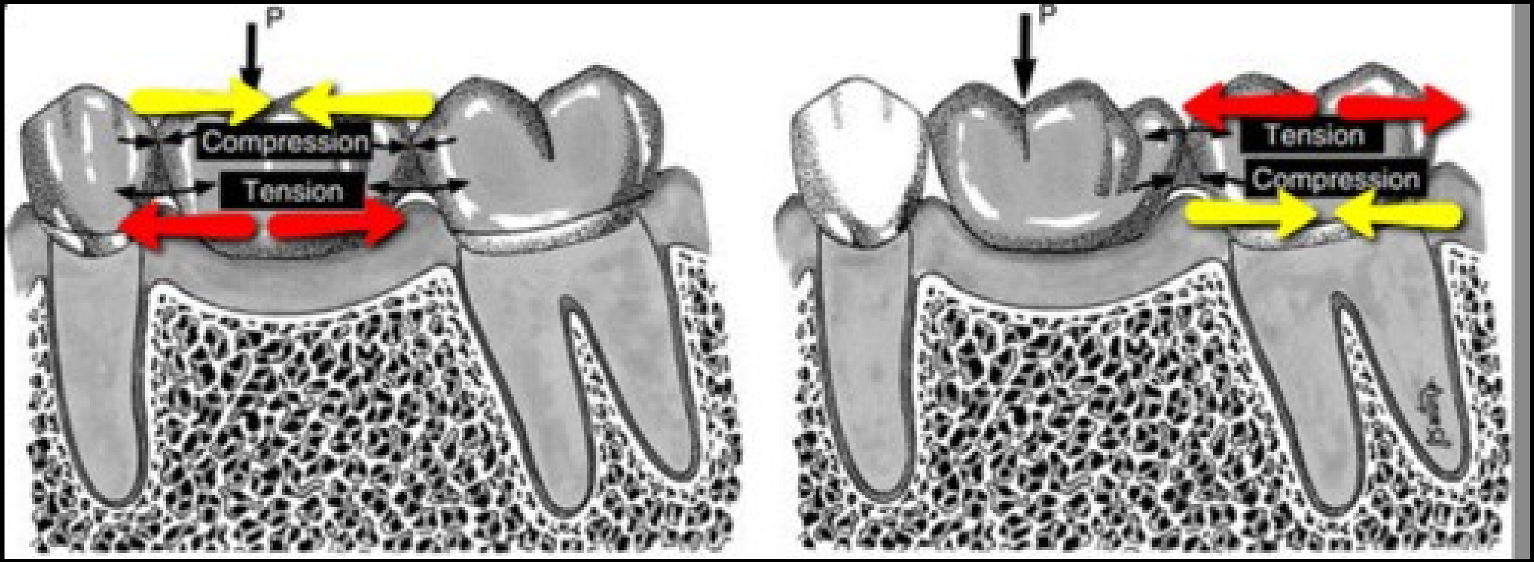


- It is the maximum shearing stress at shear failure. push-out or punch test method, (i.e. applying an axial load to push out a sample through the other side is used in this test.

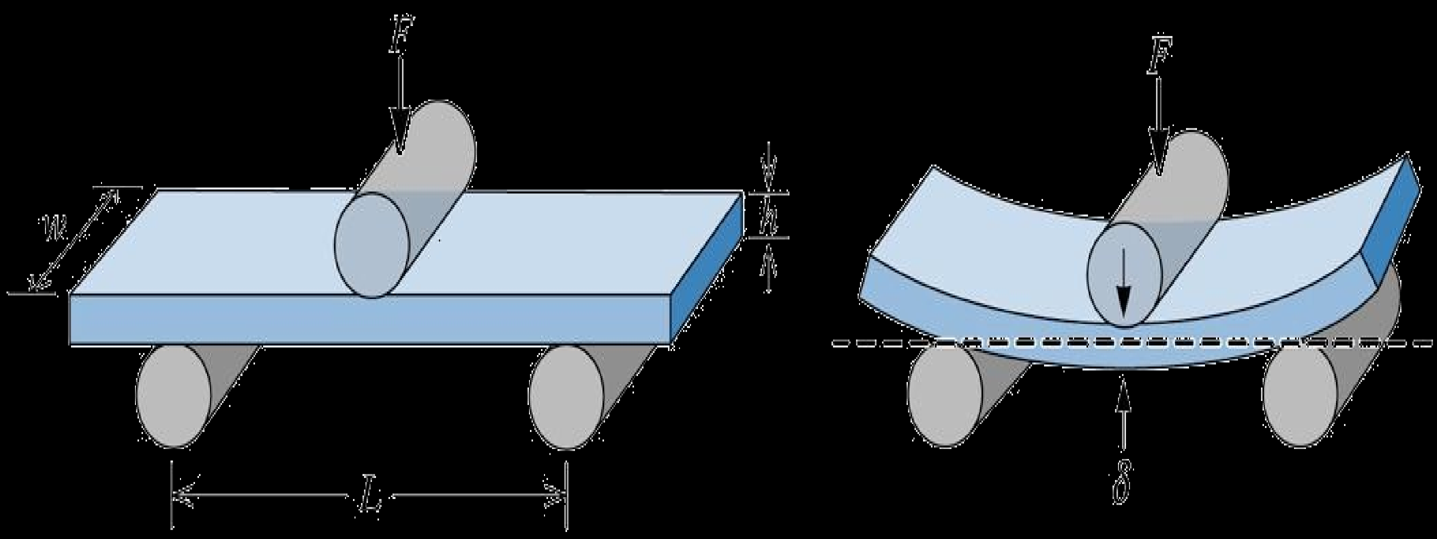
FLEXURAL STRENGTH/ TRANSVERSE BENDING (3- POINT BENDING)/ (MODULUS OF RUPTURE):

- The flexural strength of a material is its ability to bend before it breaks.
- Flexural stress is produced by bending forces and may generate all three types of stress in a structure.

- It can occur in fixed partial dentures or cantilever structures.
- Lower portion of the beam is in **tension**, upper portion is in **compression and** sides reveal **shear** stresses.



- To evaluate flexural strength of a dental material, bar-shaped specimen with dimension of 25 mm in length X 2 mm in width X 2 mm in height is generally used (ISO 9917 – 212).
- Specimens are placed on two supports and a load is applied at the center.



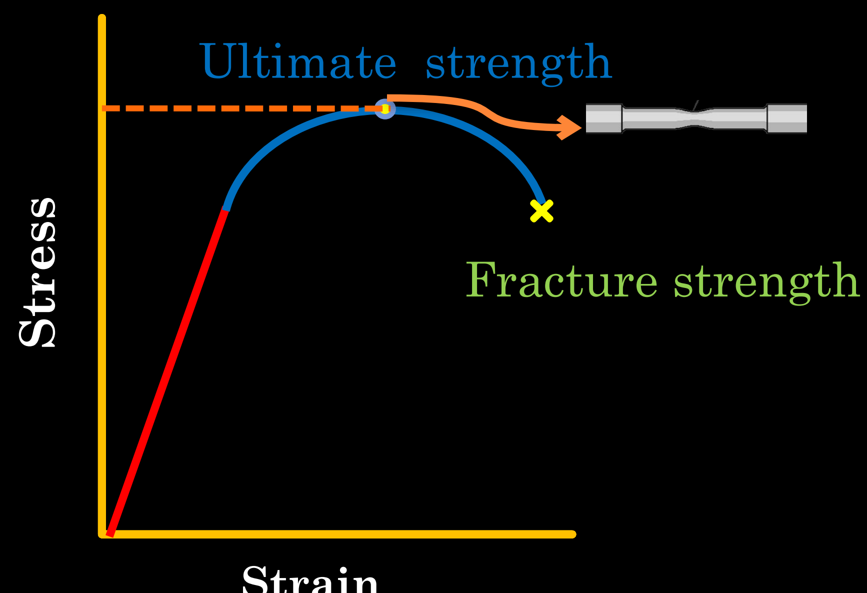
- The load at yield is the sample specimen's flexural strength that is calculated by the following formula: $3Pl/2bd^2$

where,

- P= the ultimate load at fracture,
- l= the distance of the supports,
- b= the width of the specimen,
- d= the thickness of the specimen.
- This test is also known as three-point bending test

FRACTURE STRENGTH

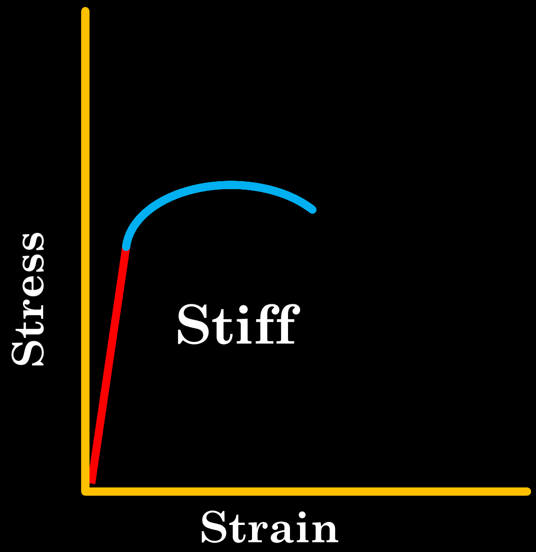
- It is the stress at which a material fractures.
- IMPORTANT NOTE:
- Ductile materials under tensile load, do not fracture at the point at which maximum stress occurs but fracture at a lower stress value.

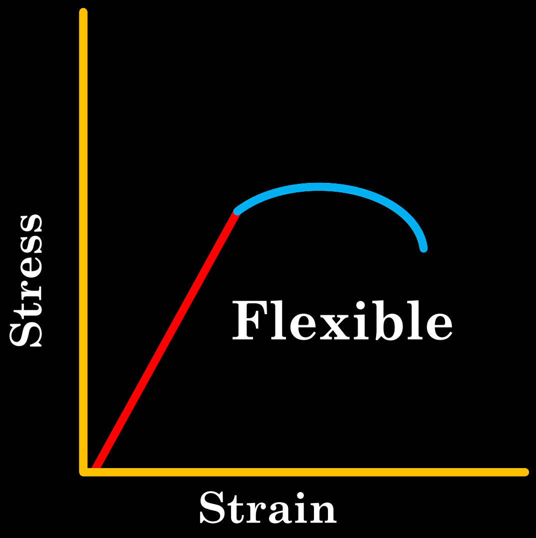


- Reason: After the maximum tensile force is applied, the specimen begin to elongate excessively, resulting in necking or a reduction of cross-sectional area.
- In engineering stress strain graph, stress is calculated from force and original cross sectional area and the actual reduction in cross sectional area is not accounted.
- Accordingly, the stress at the end of the curve is less than at some intermediate point on the curve.
- Therefore, in materials that exhibit necking, the ultimate and fracture strengths are different.
- For brittle material like ceramic, they are same points.

REVISION FOR PREDICTION OF PROPERTIES FROM STRESS STRAIN CURVE

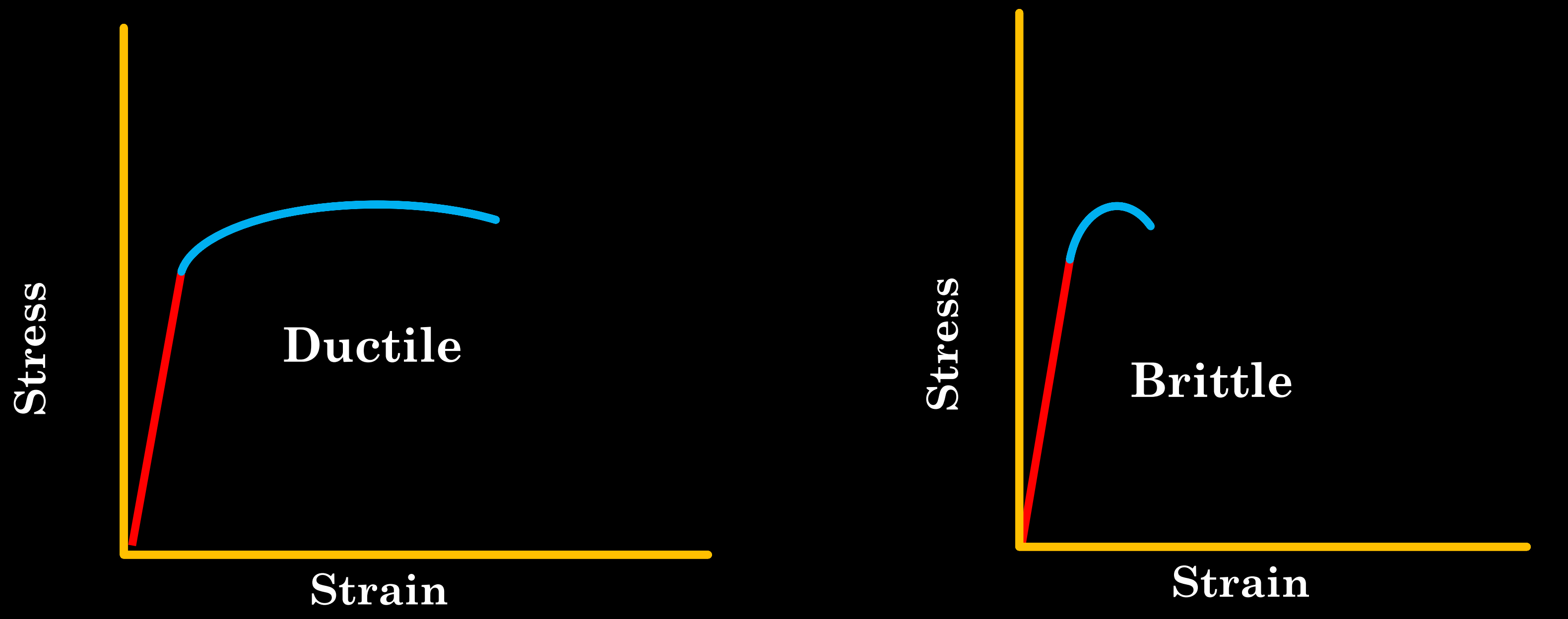
- Depending on the inclination of the curve in elastic region.





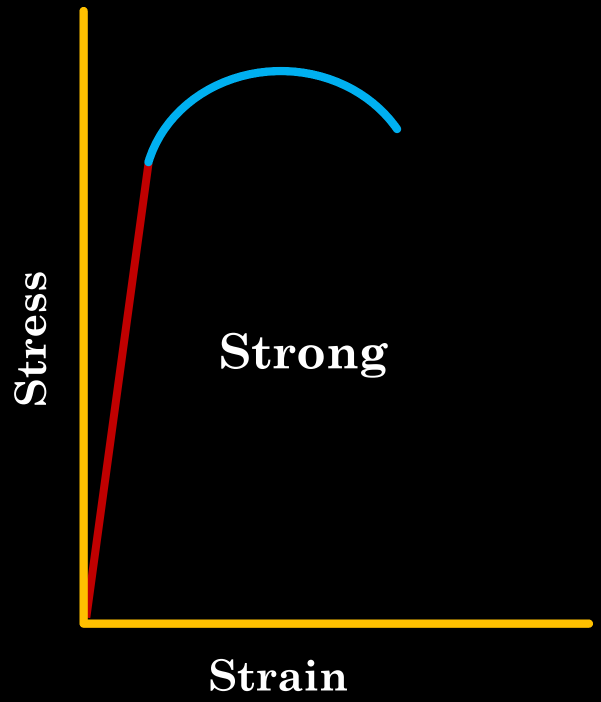
Predicting property - Elastic modulus

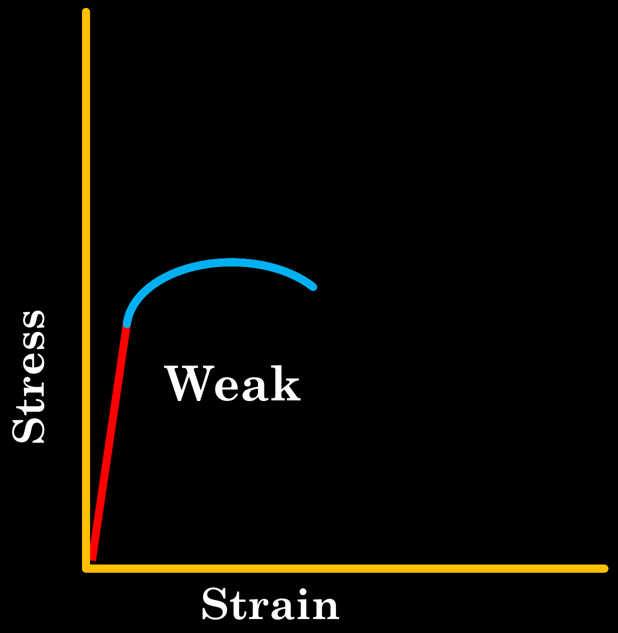
- Depending on the amount of plastic deformation



Predicting property – Plastic strain

- Depending on the height of curve.



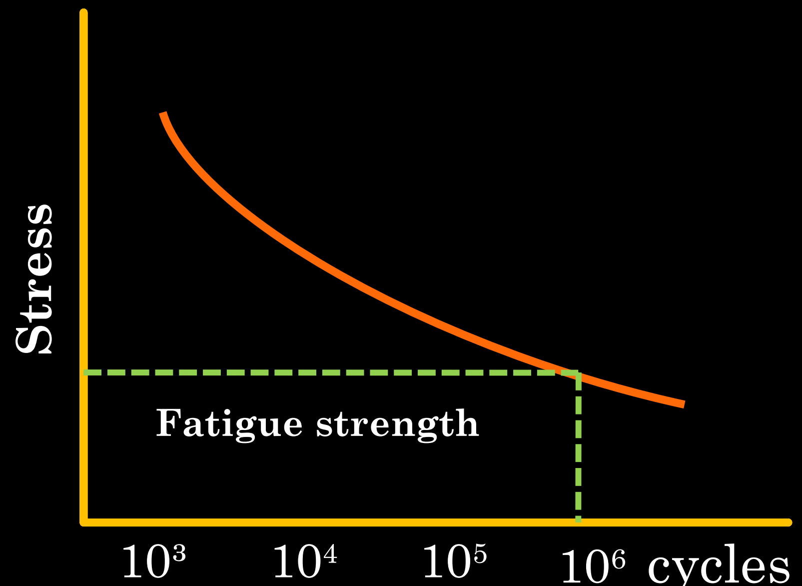


Predicting property – Yield strength

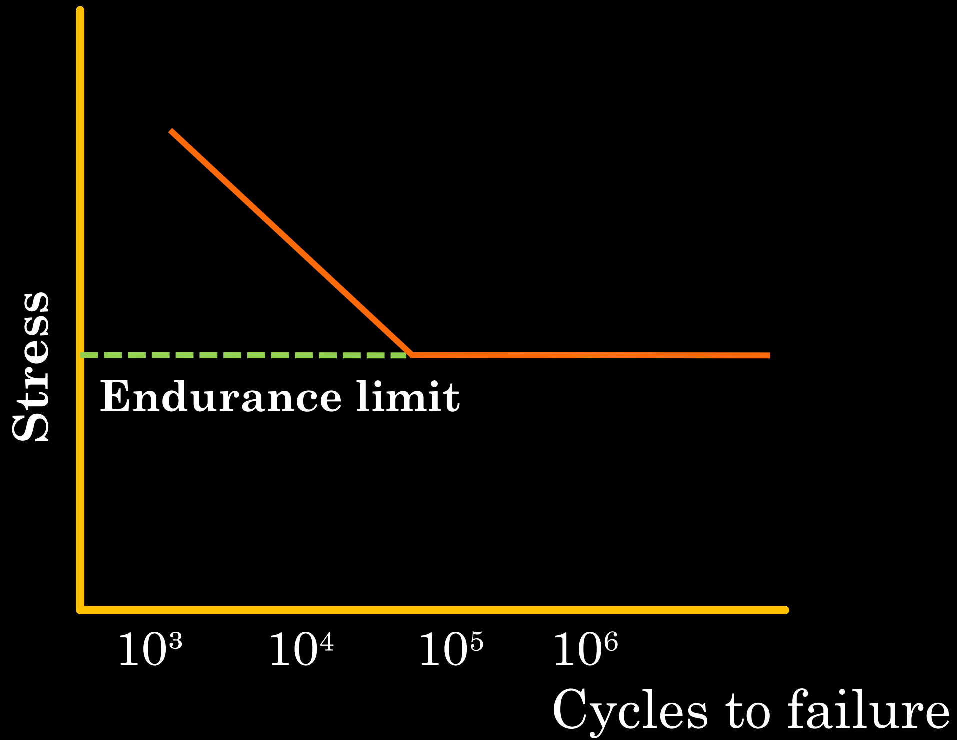
FATIGUE STRENGTH

- Stress values well below the ultimate tensile strength can produce premature fracture of a dental prosthesis or material because microscopic flows grow slowly over many cycles of stress. This phenomenon is called fatigue failure
- Fatigue strength is the stress at which a material fails under repeated loading.
- Fatigue tests are performed by subjecting a specimen to alternating stress applications below the yield strength until fracture occurs.

- Failure under repeated or cyclic loading is dependent on magnitude of load and the number of loading repetitions.
- The S-N curve shows that when stress is sufficiently high, the specimen will fracture at a relatively low number of cycles. As the stress is reduced, the number of cycles required to cause failure increases.



- For some materials, a stress at which the specimen can be loaded an infinite number of times without failing is eventually approached. This stress is called endurance limit.



IMPORTANCE OF FATIGUE STRENGTH

- Stress applications during mastication may approach 3,00,000 flexures per year, whereas the greater stress generated by removing and inserting clasp retained RPD from the mouth amounts to less than 1500 per year.
- Restorations should be designed so the clinical cyclic stresses are below the fatigue limit.

REFERENCES

- Phillips 11th edition.
- Craig 12th edition.
- Anderson's applied dental materials 6th edition.
- Introduction to dental materials. By Richard Van Noort 6th edition.
- A clinical guide to applied dental materials.

THANK YOU