Biomechanics

Third Stage/ Biomaterials Engineering and prosthesis Branch

Presented By

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Lecture Eight

Fluid biomechanics (blood flow)

Dr. Alaa Abed

Biomechanics of the blood vessels

The cardiovascular system consists of the heart, blood vessels, and approximately 5 liters of blood. It is responsible for transporting oxygen, nutrients, hormones, and cellular waste products throughout the body. The blood vessels are the part of the circulatory system that transports blood throughout the human body. The size of blood vessels corresponds with the a mount of blood that passes through the vessel. All blood vessels contain a hollow area called the lumen through which blood is able to flow and they are all lined with a thin layer of simple epithelium known as endothelium that keeps blood cells inside of the blood vessels and prevents clots from forming.

Fluid biomechanics (blood flow)

➢ There are three major types of blood vessels:

a) **Arteries and arterioles** - Arteries transport the blood away from the heart. They face high levels of blood pressure because they carry blood being pushed from the heart under great force. That's why walls of the arteries are thicker, more elastic, and more muscular than those of other vessels. Arterioles are thinner arteries that branch off from the ends of arteries and carry blood to capillaries. They face much lower blood pressures. Arteriole walls are much thinner than those of arteries and they can also use smooth muscles to control the blood flow and pressure.

b) **Capillaries** - Enable the actual exchange of water and chemicals between the blood and the tissues. They are the smallest and thinnest of the blood vessels in the body and also the most common. Capillaries connect to arterioles on one end and venules on the other. Capillaries carry blood very close to the cells of the tissues of the body in order to exchange gases, nutrients, and waste products.

c) **Veins and venules**- Carry blood from the capillaries back to the heart and they are subjected to very low blood pressures. This lack of pressure allows the walls of veins to be much thinner, less elastic, and less muscular than the walls of arteries. Veinsuse the force of skeletal muscle contractions to help push blood back to the heart. To facilitate the movement of blood, some veins contain valves that prevent blood from returning to the extremities. The skeletal muscles when contract, they squeeze nearby veins and push blood through valves closer to the heart.

Fluid biomechanics (blood flow)

- Blood is known to be one of the connective tissues in the human body as the blood connects every single cell, tissue, and organ in the body together. All necessary substances are transported through the vascular system. The science of blood flow and the mechanics of blood flow is known as hemodynamics. Hemodynamics is a significant element of cardiovascular mechanics and engineering as it simply clarifies the physical laws that direct the bloodstream within the blood vessels. A considerable number of dysfunctions that occur due to cardiovascular diseases and disorders such as hypertension and congestive heart failure are linked to systemic hemodynamics.
- The shear stress and wall shear stress in the bloodstream throughout the entire cardiovascular system is significantly impacted by the physics and mechanics of the blood. In particular, these values play and important role in the design and development of medical devices for cardiovascular applications. In the area of cardiovascular engineering and technology and medical devices, hemodynamics and the mechanics of blood are undisputedly vital to be well understood and considered.

Fluid biomechanics (blood flow)

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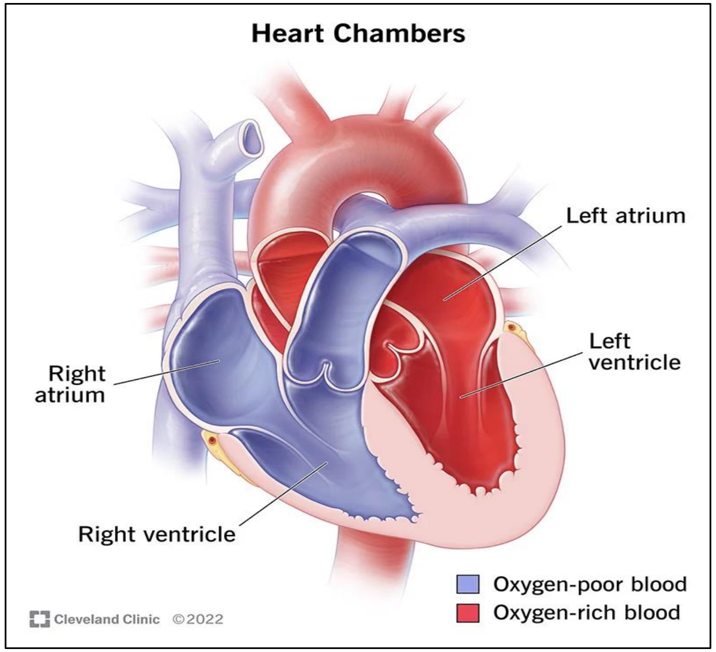
Hemodynamics and flow types

Blood circulation: Blood flow in the circulatory system is determined by the pulsing drive that is developed from the heart, the individual mechanical and flow properties of the fluid, and the structure and mechanical properties of blood vessels. These factors combined at appropriate levels ensure that the cells of the body receive adequate amounts of oxygen as well as maintain waste management.



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***Flow pulse development*:** The main function of the heart is to circulate blood throughout the human body. It is composed of four chambers: two chambers known as ventricles on the lower half of the heart and two chambers known as atria composing the upper section as shown in . Upon the propagation of bioelectricity through these different components of the heart, contraction of each chamber occurs, moving blood throughout the body in a system known as the cardiac cycle. The cardiac cycle can be easily separated into two main time events: systole and diastole. These two events refer to the action of either the heart pumping blood into the circulatory system or receiving blood from the venous system. In addition to these events, other factors of the blood such as velocity are initialized from the cardiac output of the heart.

***Systole and diastole*:** Systole is when the pressure in the circulatory system is the highest due to the force of the heart that is used to pumping blood into the aorta and pulmonary artery, whereas during diastole the blood is moved into the heart due to a pressure difference between the vena cava and the right atrium, and pressure is lowest. These periodic variations in pressure is what causes blood flow to be considered “pulsatile”. This pulsatile action is what makes blood flow unable to be effectively modeled by standard flow models unless specific assumptions are applied.

Fluid biomechanics (blood flow)

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Cardiac output: The amount of blood that flows out of the heart in 1 minute is known as the cardiac output and varies dependent on the weight of an individual. Standard values of cardiac output are within the range 4.0–8.0 L/min. Cardiac output is dependent on four main components: heart rate, contractility, preload, and afterload.

The heart rate is directly proportional to the velocity of the blood moving throughout the body because under normal circumstances the blood maintains a constant volume. As heart rate increases, the velocity increases, which affects the viscosity and turbulent effects of the flow. A similar relationship is seen with contractility as the greater the force the heart initially enacts while emptying the left ventricle, the larger the pressure will be that is pushing the blood from the heart, increasing the initial blood velocity. Preload is the degree of myocardial extension prior to shortening which maintains a direct relationship with cardiac output . Afterload is the force that the ventricle must overcome in order to push the blood into the system of blood vessels. These components combined affect the initial velocity, pressure, and forces applied on the blood flow. However, this system is only effective if the components of the heart are working properly and can differ if there are defects present in the heart.

Fluid biomechanics (blood flow)

blood flow

Blood circulation begins by the heart pumping deoxygenated red blood cells (RBCs) to the lungs which are then oxygenated and released back to the heart through the pulmonary circuit. These oxygenated RBCs are then pumped through the systemic circuit to deliver oxygen to various tissues. The RBCs become deoxygenated after releasing and depositing oxygen within the tissues and travel back to the heart through the system circuit to repeat the cycle. The flow of fluid within the circulatory system is dependent on a variety of factors but can be characterized by considering the laminar and turbulent properties of the flow. In addition to the laminar and turbulent properties of the flow, it is also important to consider the motion of the suspended particles within the heterogenous fluid allowing it to cohere to adequate blood flow needs.

Fluid biomechanics (blood flow)

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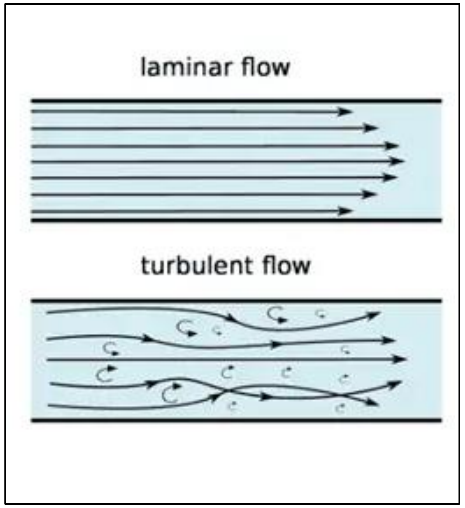
1. Laminar and turbulent blood flow: the blood flow may be laminar flow or turbulent flow depended on Reynolds number.

Reynolds number (R_e): is the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities.



$R_e = \frac{inertia\ forces}{viscous\ forces}$, $R_e = \frac{\rho * V * D}{\mu}$ (R_e is dimensionless)

Where

ρ : fluid density (Kg/m^3)

V: velocity of fluid (m/s)

D: characteristic dimension (length of fluid, hydraulic diameter….etc) (m)

μ:dynamic viscosity of the fluid ($N.s/m^2$) or kinematic viscosity of the fluid (m^2/s).

Laminar flow occurs at low Reynolds numbers where viscous forces are dominant, and its characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds number and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities. So, can express the type of flow in numbers:

- $R_e > 4000$ is considered turbulent flow.
- $R_e = 2300\text{-}4000$ transitional flow.
- $R_e < 2300$ is laminar flow.

Typical value of Reynolds number (blood flow in brain ≈ $1*10^2$, blood flow in aorta ≈ $1*10^3$)

Fluid biomechanics (blood flow)

- This logic cannot be applied to the flow of blood as blood is not a homogenous fluid and blood vessels are not perfectly cylindrical and possess viscoelastic properties. Though directly corresponding to Reynolds numbers will not accurately represent the type blood flow, it is generally considered that the possibility of turbulence will increase as the Reynolds number increases, regardless of the precise critical Reynolds number values for transition. Adhering to this logic, as seen in, the possibility for turbulent flow will increase as the velocity increases, the diameter increases, the density increases, or as the viscosity decreases. As a flow develops into turbulence unsteady vortices appear and interact with each other leading to the development of eddy currents, small currents where the flow differs from that of the general flow. Turbulence occurs naturally in locations of the circulatory system where the Reynolds numbers are comparatively elevated such as the ventricles and ascending aorta. In addition to this, turbulence can also be initiated due to branches or curves in the flow, irregularities due to surgical implants, and improper function of circulatory valves. Under diseased or abnormal conditions, other segments in the circulatory system can experience turbulent flow which can have negative effects on epithelial function.

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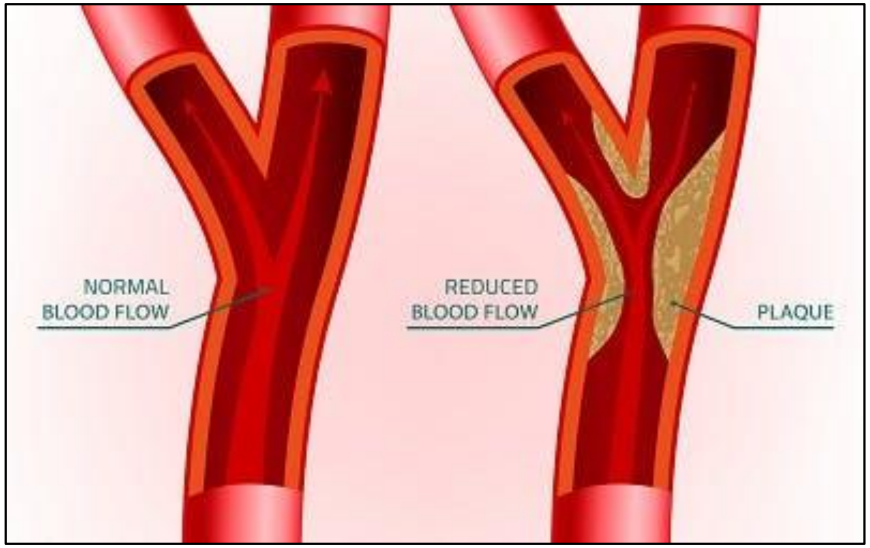
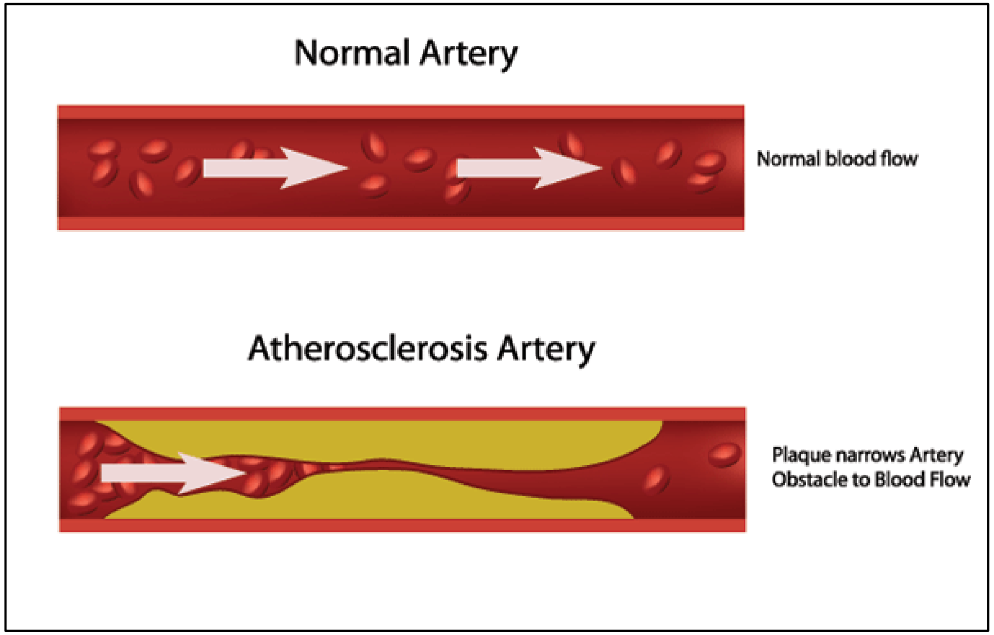
- Risk factors that increase turbulence, such as plaque build. Up or hardening of the arterial walls (atherosclerosis), serve to increase vascular resistance (sometimes).

Atherosclerosis تصلب الشرايين





For normal blood flow

- **Blood density 1060 kg/m^3**
- **Blood viscosity 0.0035 kg/m.s**

Fluid biomechanics (blood flow)

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2.Viscosity: The viscosity of the blood is due to the internal friction between the flow, incorporating the effects of the suspended particles present in the blood, inclusive of red blood cells (RBCs), white blood cells (WBCs), and platelets. As this internal friction increases, more force is required from the heart in order for it to maintain the desired cardiac output of the blood in the circulatory system. This requires a heightened contractility from the muscles of the heart which can result in the fatigue of the heart and, in major cases, heart collapse. The opposite case where there is a lack of proper internal friction in blood flow will cause a decrease in the ability of one's blood to clot, which imposes risk when blood vessels are damaged and the blood continues to flow out of the site of damage for a prolonged period of time.

The viscosity of blood is dependent on many factors such as the properties of blood plasma, the hematocrit levels, and the individual mechanical properties and influence of the suspended particles in the flow; however, this is inherently dependent on whether blood is considered as a Newtonian or non-Newtonian fluid. The true nature of blood is that it exhibits non-Newtonian properties under specific conditions; however, these conditions arise at very few locations throughout the circulatory system.

Fluid biomechanics (blood flow)

- **Newton's law of viscosity:** newton's law of viscosity states that shear stress is directly proportional to viscosity gradient. That is the shear stress between the two adjacent layers of fluids is directly proportional to the negative values of the velocity gradient between the same two adjacent fluid layers.

- Two basic type of fluids regarding their viscosity behavior Newtonian and non- Newtonian fluids .

- **Newtonian Fluid:** where stress is directly proportional to rate of strain or fluid with a constant viscosity at a fixed temperature and pressure. Newtonian fluids viscosity remains constant no matter the amount of shear applied for a constant temperature, these fluids have a linear relationship between viscosity and shear stress as shown in fig. (1). The obey the Newton's law of viscosiy which is:

  $\tau = \mu \, du/dy$

Where :

τ: shear stress exerted by the fluid.

μ: fluid viscosity.

du/dy: velocity gradient perpendicular to the direction of shear.

Fluid biomechanics (blood flow)

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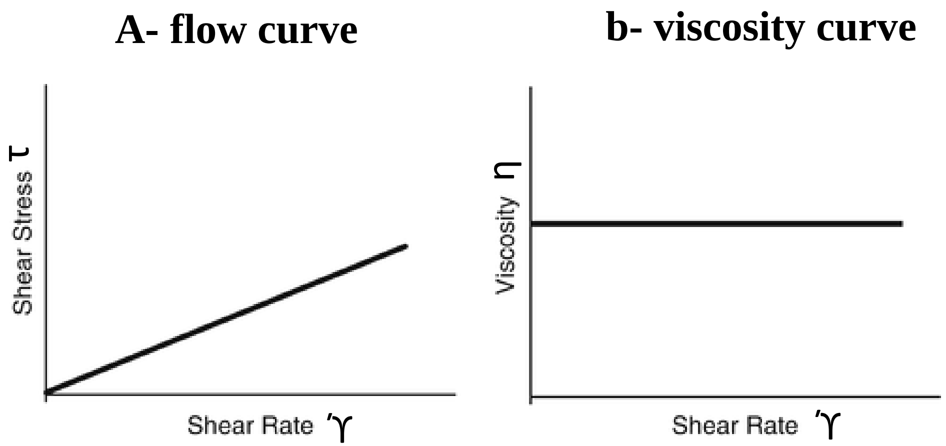

Fig. (1): flow and viscosity curves for Newtonian fluid.
Curve (A): Shows that the relationship between shear stress and shear rate is a straight line,
Curve (B): Shows that the fluid viscosity remains constant as the shear rate is varied.

- **Non-Newtonian fluid** :fluids are the opposite of newtonian fluids where shear is applied to newtonian fluids. where shear is applied to non-newtonian fluids , the viscosity of the fluid is change (Fig.2 Curve B). A non-newtonian is broadly defined as one for which the relationship between shear stress and shear strain is not a constant it means that there is non-linear relationship between shear rate and shear stress. In other word, when the shear rate is varied, the shear stress does not vary in the same proportion (or even necessary in the same direction), (Fig. 2 Curve A).

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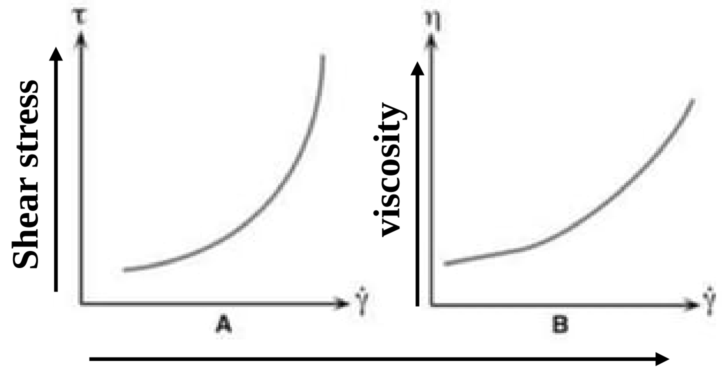
A. Flow curve **B. Viscosity curve**



Shear rate

Fig. (2): flow and viscosity curves for Non- Newtonian fluid.

Fluid biomechanics (blood flow)

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➢ <u>Newtonian and non-Newtonian conditions</u>

Blood possesses non-Newtonian properties when the shear rate is above 100 s^{-1} and follows shear-thinning effects. High shear rates occur in the capillaries and the larger arteries coming directly from the heart because the shear rate of a fluid through a vessel increases with increasing velocity and decreasing diameter. Due to the fact that the main non-Newtonian properties of blood occur in small diameter vessels, it is argued that the non-Newtonian effects that occur within the largest arteries can be ignored .
In blood vessels that possess a diameter in the more medial range or where there is decreased velocity, such as veins and arterioles, these non-Newtonian factors have minute effects on the properties of the flow, causing them to be neglected for these areas as well.
is not an accurate representation of proper blood flow as blood flow is subject to fluctuations based on the viscoelastic properties of the vessel walls, the alternating pressures from systolic and diastolic, and when present the non-Newtonian properties of the blood itself; however, it is used hereto outline the relationship between the shear rate and vessel size and diameter.
Considering the above, the non-Newtonian effects of blood are only active within a small portion of overall blood flow and acquire more importance when blood flow at those selected areas are specifically studied. When being considered as a Newtonian fluid, the viscosity of blood in addition to being impacted from the vessel size and blood velocity is also affected by the blood plasma and the concentration of suspended particles in the flow.

Fluid biomechanics (blood flow)

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- **Factors of blood as a Newtonian fluid**: The blood plasma is mainly composed of water (roughly 91% by volume) proteins, hormones, and glucose and acts as a Newtonian fluid with standard values between1.1 and 1.3 m Pas at the human body temperature of 37°C. Blood plasma accounts for approximately 55% of the volume of the blood in the body and due to the incredibly high water content in the substance, the viscosity of plasma is highly affected by the hydration levels of the individual. As a human becomes dehydrated this percentage decreases and the blood becomes more viscous. In addition to hydration levels, blood plasma viscosity is also directly affected by the amount of proteins and lipids in the blood post consumption. The higher the concentration of these elements, the more viscous the plasma will become. In addition to the direct effects on plasma, the shear in the flow is also affected by the amount of suspended particles in the flow. In heterogeneous fluids where particulates are present, these particulates alter the velocity profile of the fluid due to the increased shear at the fluid particle interface. As aside from plasma, the majority of the remaining volume of the blood is composed of RBCs, RBCs are the particles that impose this effect to the flow in the greatest magnitude. Aside from the direct viscosity of the plasma itself, plasma also affects the viscosity of the blood by the housing of certain proteins such as fibrinogen that cause aggregation in the suspended particles.
- **Factors of blood as a non-Newtonian fluid**: The percentage comparison of the volume of blood cells to the total volume of blood is known as hematocrit and is the main factor contributing to the viscosity of the blood. This is because the blood's ability to flow is highly dominated the ease of movement of RBCs. At high shear rates the deformability of RBCs is what effectively determines the viscosity of the fluid; however, at low shear rates the viscosity is controlled by the unique property of RBCs to aggregate

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Forces in Blood Flow

Blood flow, like all fluid flows, is governed by a balance of forces. Fluid forces can act either at a fluid surface or at the center of mass of the fluid. Accordingly, fluid forces may be classified as normal forces, shearing forces, or body forces. Normal forces act perpendicular to a fluid surface, and shearing forces act parallel to a fluid surface. Body forces are forces that act at the center of mass of the fluid. For blood flow, the relevant forces are pressure forces, viscous forces, and inertial forces. Pressure forces are normal forces—they act perpendicular to a fluid surface. Viscous forces, by contrast, are shearing forces—they act parallel to a fluid surface. Inertial forces are body forces - they act at the fluid's center of mass and arise when fluid accelerates. Fluid may accelerate by changing its velocity with respect to time (i.e., flow rate) or space (i.e.,flow direction).

Fluid biomechanics (blood flow)

Continuity Equation

The continuity equation is important for describing the movement of fluids as they pass from a tube of greater diameter to one of smaller diameter. It is critical to keep in mind that the fluid has to be of **constant density** as well as being incompressible. This can be related to the body in several ways, but we must be carefull. This concept is important when it comes to arteries, which divide into capillaries, and then join to form into veins. This equation is usefull for calculating the speed of the blood as it travels through the vessles. Although, vessels are elastic structures so the equation has to be applied with caution and several other factors have to be considered. This includes how elastic the vessles are, and the changing diameters of the vessles. To understand the **continuity equation** it helps to consider the **flow rate:**

F= A*V

Where :

F: flow rate

A: area

V: velocity of the fluid

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This can be important when calculating the amount of blood that the heart pumps per minute through vessels, thus determining if the person is healthy and efficient. Also this can be usefull in determining if a vessel is clogged with plaque, and might help to prevent heart diseases or myocardial infarctions. So, when fluid transfer from one part to another. Since the liquid is incompressible in the same time interval the same volume of the fluid will pass through each cross section of the pipe or in this case, vessles. The equation below means that the flow rate of both liquids are constant:

$$\mathbf{F_1=F_2}$$

Therefore:

The form of the continuity equation is given below. It means that the cross section area times the speed of fluid going through it is equal to the cross section area of another vessel of different diameter times the speed of the fluid passing through it. This means that if blood is passing through a large artery with a certain volume, it will have to speed up alot if it then goes through a capillary with a smaller diameter.

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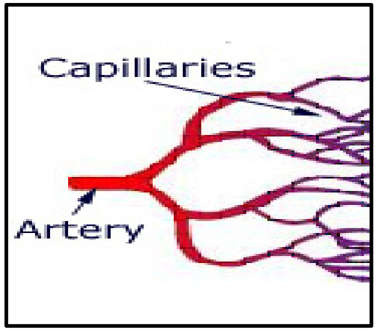
$$A_1*V_1=A_2*V_2$$

A_1: is the area of the cross section of the wider part, A_2 the cross-section area of the narrow part ; V_1 and V_2 show the velocity of the fluid passing through A_1 and A_2.

Example: in the human body, the radius of aorta is about 1.2 cm and the blood passing through has a speed of 40cm/s. A capillary however has a radius of $4*10^{-4}$ cm and blood passing has a speed of $5*10^{-2}$. approximately how many capillaries are found in our body? Assume density of blood doesn't change?



Answer: $F_1=F_2$

$(A_{aorta}*V_{aorta}=A_{capillary}*V_{capillary})$

$$(\pi r_{aorta}^2)\, V_{aorta} = M\, (\pi\, r_{capillary}^2) V_{capillary}$$

$$M= \frac{\pi r^2_{aorta} * V_{aorta}}{\pi r^2_{capillary} * V_{capillary}} = \frac{(1.2)^2*40}{(4*10{-}4)^2*5*10{-}2} = 7.2*10^9$$

Numerical Analysis of Biomechanics

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- Numerical methods in biomedical research belong to a rapidly developing field which provides a state-of-the-art tool for biomedical research and applications. Reliable predictions will lead to patient-specific simulations in the next decade to improve the diagnosis and treatment of diseases. The main focus of this method (numerical analysis) is on the interface between numerical methods and biomedical applications for the human body. It is also interesting to have quantitative analysis from the molecular up to the whole organ level.
- Finite element method (FEM) is among the methods of approximation, which is abundantly used to solve the real-life problems that cannot be solved with the analytical methods. The biological systems are complex in nature in terms of geometry, material properties, functioning, and case-to-case deviation. Thus, the standard analytical methods suffer catastrophic limitations in this area. Mainly for this reason, biomechanics is highly enriched with the integration of FEM, which opens a new window with extended capabilities against a logically acceptable margin of approximation
- Finite element modelling (FEM) is a computational technique which can be used to solve the biomedical engineering problems based on the theories of continuum mechanics .

Numerical Analysis of Biomechanics

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➢ The FEM Process:

The finite element process is generally divided into three distinct phases:

1. Preprocessing

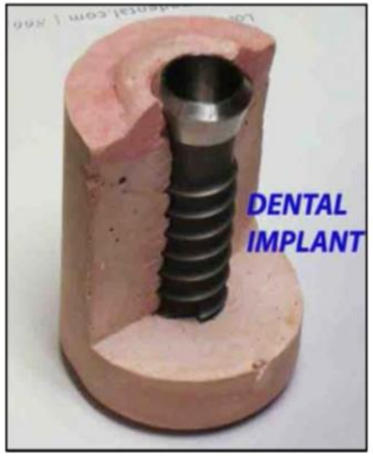
The user constructs a model of the part to be analyzed in which the geometry is divided into a number of discrete subregions, or "elements,“ connected at discrete points called "nodes“.

2. Analysis

The dataset prepared by the preprocessor is used as input to the finite element code itself, which constructs and solves a system of linear or nonlinear algebraic equations.

3. Post processing: in this step obtained final results.

<u>Case study : for example screw dental implant made from titanium with bone jaw</u>



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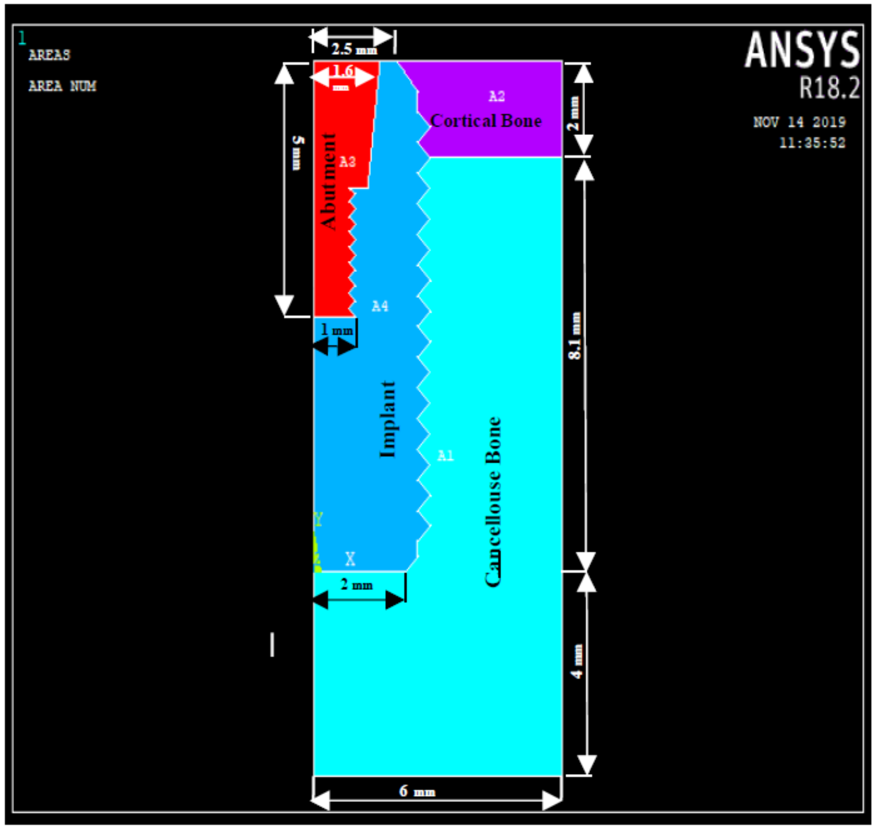
Steps of Analysis:

1. **Geometric Modeling:** The first step in FEM is a geometric modeling. In this step, by using the (ANSYS) program, implant is built according to its dimensions as shown in following Figure:



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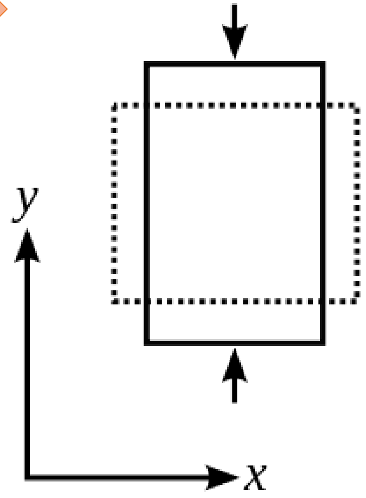
2. Element type: this option chose from ANSYS program depend on shape of case study.

3. Material Properties

Most element types require specific material properties depending on the application of these materials. This properties involve young's modulus and Poisson's ratio (Possion's ratio: the ratio of transverse strain (x direction) to the axial strain (y direction) OR: the deformation (expansion or contraction) of a material in directions perpendicular to the specific direction of loading).



For this case study this properties fro each part as shown in the following Table:

Type	Young's modulus(GPa)	Poisson's ratio
Cortical bone	14	0.30
Cancellous bone	1.37	0.31
Titanium implant	110	0.35

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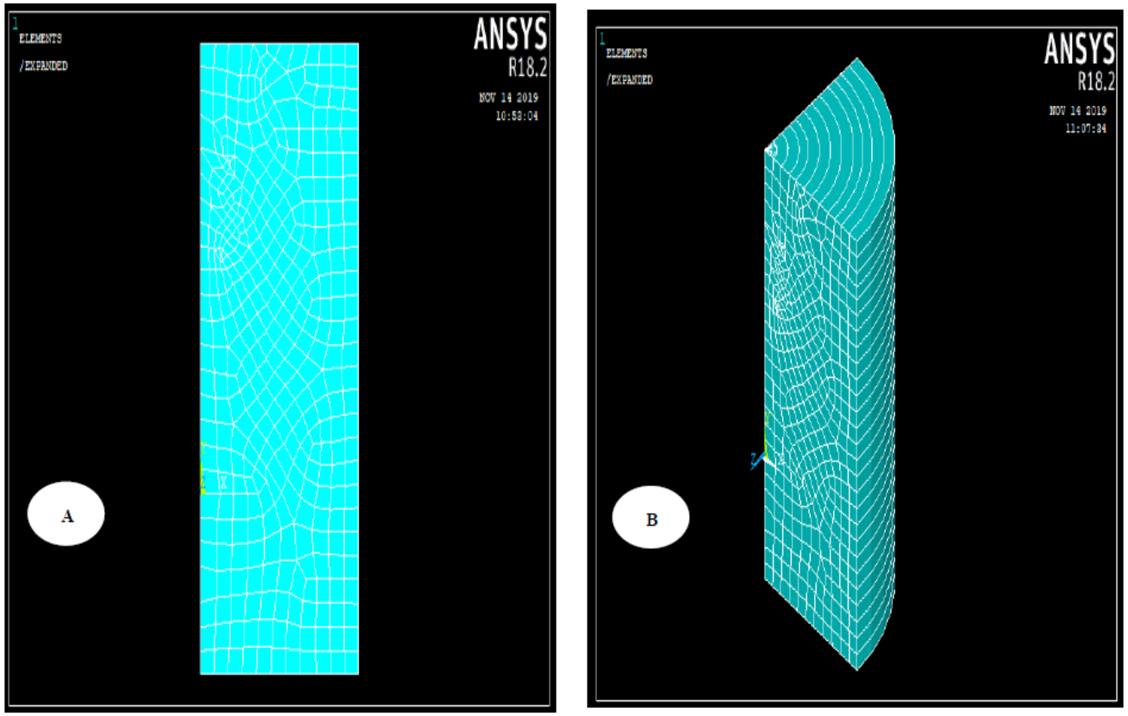
4. Meshing: Meshing involves discretization of geometric model into finite discrete elements. this option chose from ANSYS program which accor as number. The mesh density of a model is important. If mesh density is coarse, the results can contain errors. So a fine mesh density was chosen which gave results. Meshing result of implant with bone as shown n the following figure:



The Mesh of Implant Specimens A) Front View b) 3D Axisymmetric.

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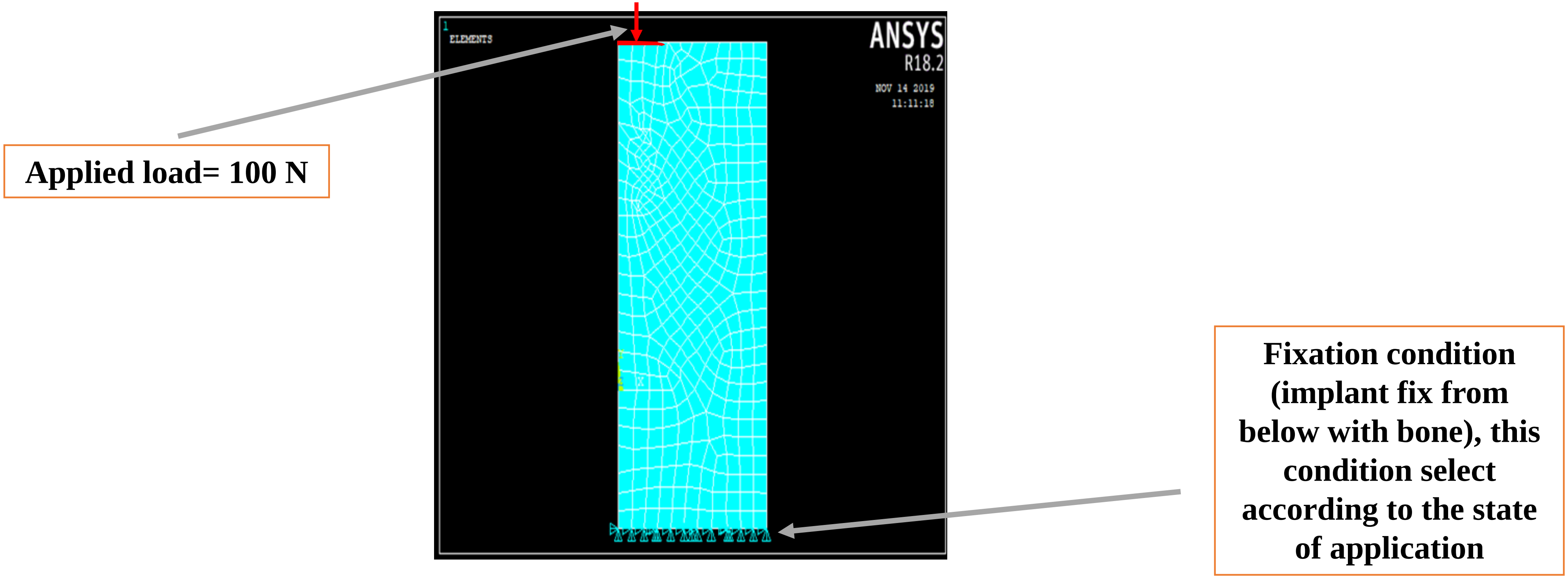
5. Load and Boundary Condition: The word of loads in ANSYS terminology includes boundary condition and externally or internally applied force functions, such as displacements, forces, a pressure, gravity in structural disciplines, as shown in following figure. In this case the load was applied as a pressure on the top of Abutment of screw with (100N)



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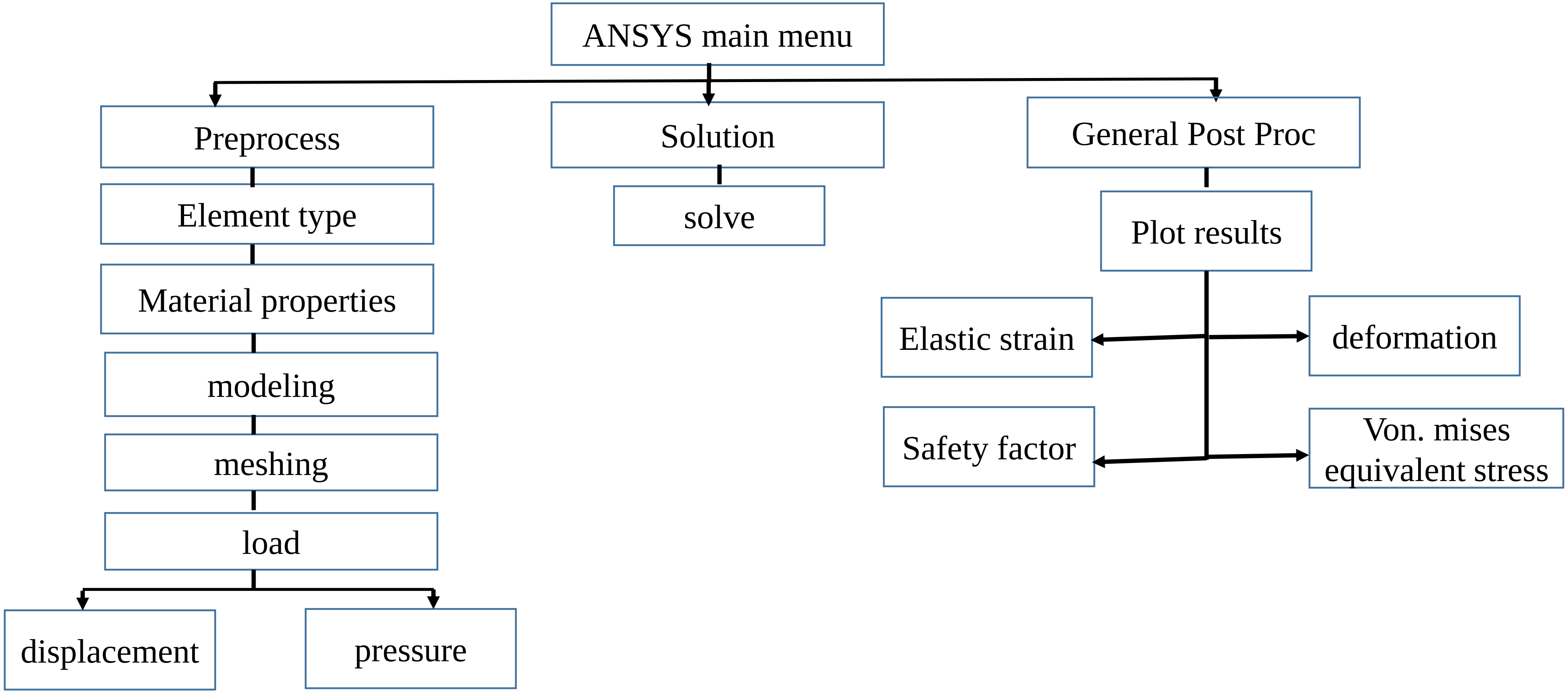
6. Analysis: The used steps to solve the finite element analysis of dental implant in bone are presented in the flowchart of analysis procedure as shown in following Figure.



Flowchart of Dental Implant Analysis by FEM.

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7. Obtained the results.

Stress

- Max. Normal Stress
- Max. Shear Stress
- Von Mises stress

-Deformation

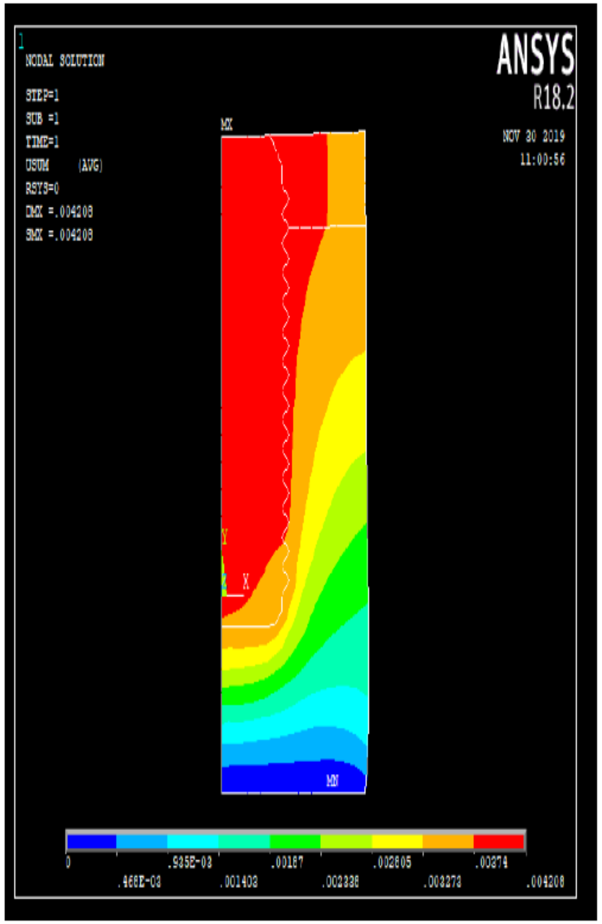
- Linear
- Angular

-Fatigue ratio

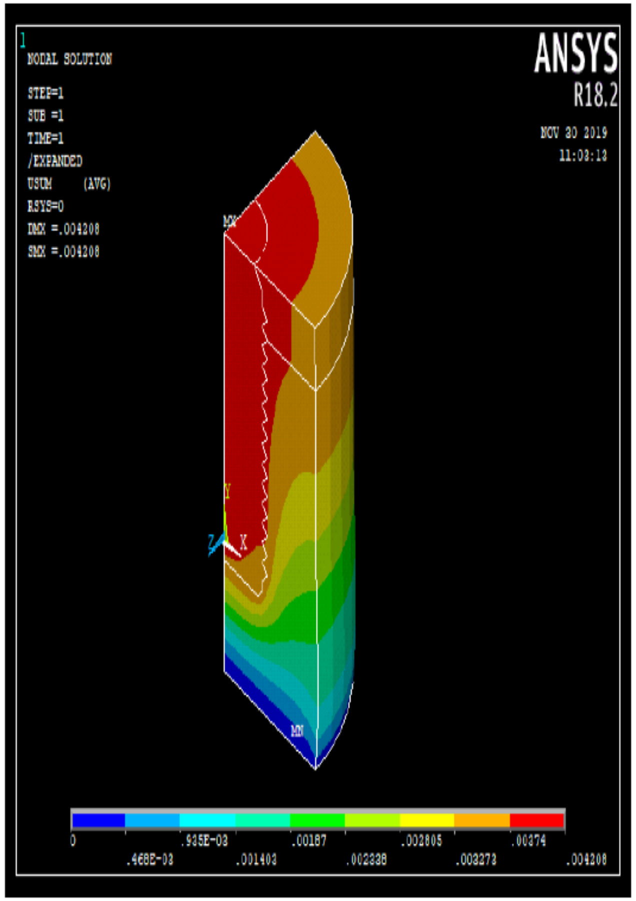
-Strain energy

-Failure index

-Safety factor



Front view



3 D axisymmetric

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In addition, the Von Mises failure theory is used to determine the equivalent elastic strain and total deformation distribution values

$$\sigma_{vm} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}}$$

Where:

σ_x = Principal normal stress in x-dircetion (MPa).

σ_y = Principal normal stress in y-direction (MPa).

σ_z = Principal normal stress in z-direction (MPa).

τ_{xy} = Shear stress in xy-plane (MPa).

τ_{yz} = Shear stress in yz-plane (MPa).

τ_{zx} = Shear stress in zx-plane (MPa).

$$n = \frac{\sigma_y\ (\sigma_u)}{\sigma_{vm}}$$

It must be $\sigma_{vm} \leq \sigma_y$ (safe).

Where:

n = Safety factor.

σ_y = Yield stress.

σ_u = Ultimate tensile stress.

σ_{eq} = Equivalent stress.

The End of Lecture