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Original Research

Finite Element Study on Mechanical Properties of The Normal and Transverse Fracture Bones – A Computational Simulation

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ABSTRACT

There are lots of cases of injury or trauma that can cause broken or cracked bones. Long treatment can be more dangerous when combined with some of the diseases they have. Despite this, there is still not much research on the mechanical properties of bone, especially in the elderly. To develop bone tissue engineering and the design of bionic bones, it is essential to understand the mechanical properties and microscopic failure mechanisms of bones. Proper bone function also depends on the mechanical properties of the bone. The purpose of this study is to develop the three-dimensional bone model for finite element analysis simulation and examine the mechanical behavior of two different types of bone (normal and non-displaced transverse fracture bone) through ANSYS Workbench. The 3D bone model design of normal and cracked bone was imported, analyzed, and simulated in ANSYS with varying loads applied. To get the parameter of mechanical characteristics of bones to result. Application of finite element method using ANSYS Software as a computational technique that uses continuum mechanics theories to solve biomedical engineering problems may require the accurate analysis of the mechanistic properties of human bone. There was no significant difference in elastic modulus between normal and fractured bone. The maximum Young's modulus was found at 8.225×10-7 with a minimum of 4.095×10-5. Despite this, the shear strain and stress hold a huge gap in the maximal and minimum position of both types of bone. Certainly, transverse fracture bone got the highest number of total deformations. The normal bone got 0.00023607 m for total deformation, alternatively, 0.00031965 m occurs in transverse fracture when the greatest load is performed. This clearly states, that cracked bone has a greater risk of failure and stiffness especially in elderly people. These mechanical properties findings of fractured bone are considered suitable for further development, especially in the prevention and treatment to decrease the revision of critical surgery in the future.

INTRODUCTION

Bone is a damaging material that cracks when it is loaded. It is common to find bone to have cracks that occurred naturally during life. These cracks are usually quite small and are called microcracks. No matter how small the cracks are, if a large enough load is applied, the cracks will start to grow larger (propagate). The whole science of ‘‘fracture mechanics’’ has developed to deal with such problems. Bone fractures are a verry common injury and can affect everyone at any age. There’s some type of fractures, such as transverse, oblique, greenstick, and comminuted fracture. This study will overcome with two most common fractures which are transverse and oblique (Clin, O., 2009). The deformation of vertebrae and sudden fractures of long bones, which are caused by essentially normal loading, are

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common problems in osteoporosis. In order to explain and predict unexpected bone failure in normal loading, one must understand the mechanical properties of the whole bone-which are determined by its internal and external geometry, its mechanical properties, and the way in which it repairs damage. A discussion of some potential drawbacks of each method is provided along with examples of how to measure the important mechanical properties. There is a particular emphasis placed on methods applicable to the measurement of bone toughness loss due to mechanical fatigue, medication side effects, and matrix damage (David et al., 2015).

In younger patients, comminuted fracture most often caused by road traffic accidents and sport injuries and are best treated with anatomical reduction and internal fixation. In contrast, transverse and oblique femoral fractures in elderly patients are often caused by minor trauma. The osteoporotic bone and patient's comorbidities and poor mobility make treatment more difficult (Cohen et al., 2016). That's really critical when affect to elderly people, due to they are more vulnerable and their cells and tissues don't grow as much, the wound also doesn't heal as quickly as teenagers or children. In addition, they have bones that have started to decrease in performance. There are lots of cases of injury or trauma that can cause broken or crack. Long treatment can be more dangerous when combined with some of the diseases they have. Despite this, there is still not much research on the mechanical properties of bone, especially in the elderly.

The scope of this study is to examine and see the difference on the mechanical properties of the normal and fractured human femur bone and compare the result between both bones. Due to comparison, it means the type of bone should be similar in both studies. Furthermore, each parameter was measured using the same specimen, dimension and force applied. This analysis performed using the Finite Element Method (FEM) using ANSYS software with yield strength and strain, total deformation and stiffness (Young's Modulus) the variables. Firstly, get the specimen femur bone of 69 age's man from the A. Kalaiyarasan study. From this, data cloud was obtained which can be imported in CAD software to obtain the geometric features of a femur bone. Then, the femur CAD model was developed at SolidWorks® using a 2D to 3D geometry transformation technique using previously acquired cloud data. Developing the normal bone first, then improved the design as the transverse and oblique fracture bone.

This study is conducted to study about the mechanical characteristic of normal and deformation femur human bone and compare the result to ensure and validate that any difference on the mechanical properties of normal and deformation bone or not by identify some parameters. The results data of this research may assist physicians or experts during routine health screening routines or in diagnosing, as well as deciding what type of surgery to perform when dealing with these types of fractures. No matter whether surgery is necessary or not, external or internal fixation should be used. In selecting implant materials, these mechanical properties can be considered so that they are mechanically compatible and can prevent host reactions (infections), which may require revision surgery. It can minimize or prevent revision surgery for non-displaced transverse fractures of the femur by using these data. Due to, revision surgery is very critical, especially for the elderly.

MATERIALS AND METHOD

Develop 3D Bone Model

Get the subject data from the previous study, this data cloud was obtained which can be imported in CAD software to obtain the geometric features of a femur bone. Then, the femur CAD model was developed at SolidWorks® using a 2D to 3D geometry transformation technique using previously acquired cloud data. Developing the normal bone first, then improved the design as the transverse and oblique fracture bone. Manually create the line (cracked) according the suitable fracture type and using break features and split commands to split or making the micro gap of the bone. Table 1 show the details of bone subject and Figure 2 illustrate the design of normal femur bone and the dimension show in Figure 3.

Table 1 Bone details subject (Nareliya, et al., 2011).

Bone Details (left leg)	
Gender	Male
Age	69 years old
Weight and Height	79 kg and 188 cm

Fig. 1 Normal bone model.

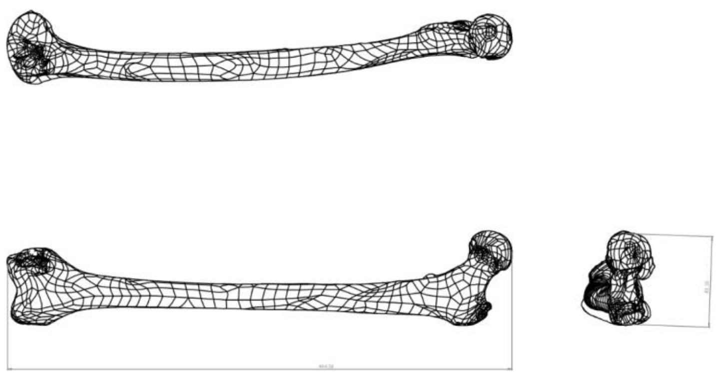

Figure 2. Dimension of the normal bone model

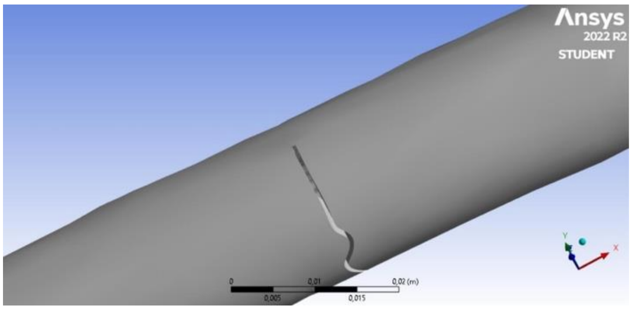

Fig. 4 Detail gap of transverse fracture femur bone model.

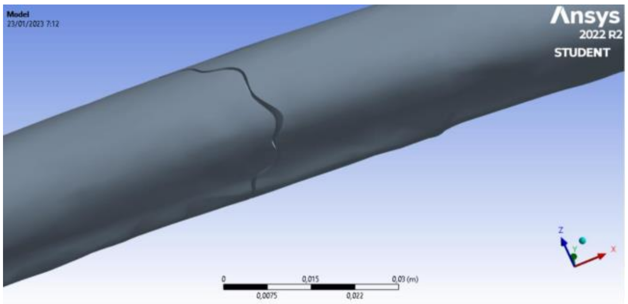

Fig 5. Detail gap of oblique fracture femur bone model.

The break features in Solidwork using split commands create the fracture of the bone model from normal femur bone type. Precisely, the micro gap between these bones not just line. Import the original normal femur bone design and adding the crack in horizontally perpendicular to the bone (opposite the direction of the bone) with add some element into that crack. Figure 4 and 5 illustrate the detail of micro gap in transverse and oblique fracture after developed from normal 3D bone model.

Finite Element Analysis

Finite Element Analysis (FEA) software or structural engineering simulation software allows to do virtually test and predict the behavior of structures subjected to static and dynamic loading conditions and solve a wide range of structural engineering problems. This study investigates the total deformation, stress distribution which included the maximum and minimum shear stress and calculated Young's Modulus of a normal and fractures (transverse and oblique) femur bone for variating the load (250, 500, 750 and 900 Pa) during normal position.

ANSYS Software

The Ansys engineering simulation and 3D design software provides scalable simulation and physics-based Multiphysics product modeling solutions. A variety of task can be performed by ANSYS, including detection of discontinuous functions, solve partial differential equations, see the concentration of selected free parameters, simulate the dynamics of partial differential equation solutions, and find a spatial distribution of partial derivative solutions for various discrete time scales.

In previous study, the strength of an artificial leg is determined by using finite element analysis, ANSYS, to calculate the stress and strain in the pelvis and femur of a patient at six months after the operation (Sebastian et al., 2016). ANSYS shows to be an exceptionally useful and powerful tool for finite element integrals. It is an excellent product for assisting with decision making on finite element optimization tasks. In this study, use the ANSYS Workbench product to analyze the mechanical properties of normal and crack bone trough the static structural feature. Since human bone is highly heterogeneous and nonlinear in nature, assigning material qualities along each direction of the bone model is challenging. A material can be assigned in one of two ways: in Mimics or in the Finite element module (Kalaiyarasan, et al., 2019). Table 2 illustrates the bone properties used in this analysis and some previous study.

Table 2 Properties of bone (Nareliya et al., 2011).

Density	2000 Kg/m^3
Young's Modulus	2.130 GPa
Poisson's Ratio	0.3

Simulation Analysis

Bone specimen already exported and meshing, the fixed support, specific pressure for the parameter and direction of force are necessary to set before the analysis started. The boundary condition given for the femur bone before simulation illustrated in this Figure 6. An eccentric and concentrate pressure of 250, 500, 750 and 900 Pa applied at the head of femur bone in axial direction like in normal standing position and fixed support is provided at lower surface.

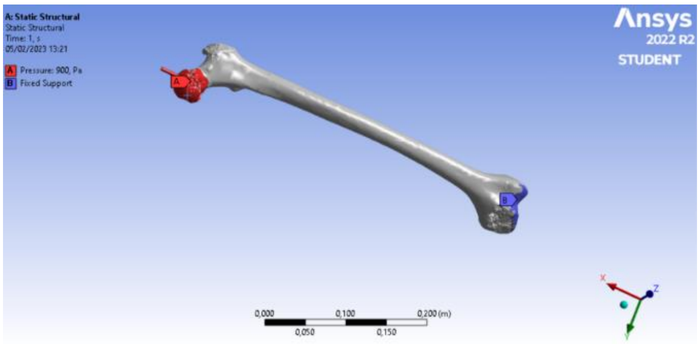

Fig 6 Boundary condition in ANSYS

Table 3. The specific pressure for every parameter used.

Parameters	Measurements (in Pa)
Yield Strength (Stress – Strain)	250, 500, 750 Pa (Nareliya et al., 2011) and 900 (Kalaiyarasan et al., 2020)
Deformation	250, 500, 750 and 900 Pa

Pressure Specification

Varying load or pressure was chosen, under different fracture loads the regions of maximum and minimum von Mises stress and strain (same as the other parameter) of various types of bone were identical (Zhao Min et al., 2014). The occurrence of transverse fractures in the elderly is often caused by minor trauma or accidents, such as pedestrian accidents. Pressures of 250 - 500 Pa are regarded as minor pressures. In Nareliya's research, the 750 Pa used to get the results was based on the accuracy of the FE model in relation to real-life conditions suitable for the subject body weight. The highest pressure for this analysis is 900 Pa since it is ten times the body weight and represents 1/3 of the strength of normal adult femurs, so it can cause the bone to be cracked (A. Kalaiyarasan et al.,2020).

RESULT AND DISCUSSION

3D Bone Model of Transverse and Oblique Fracture

The result of non-displaced transverse fracture femur bone as illustrated in Figure 7. On the other hand, a non-displaced oblique fracture is generated if the bone is broken at an angle. In other words, the break runs all the way through the bone. Therefore, from the normal femur bone model the crack added in angle with more element needed. The final result of non-displaced oblique fracture shows in Figure 8 and the details illustrated in Figure 9.

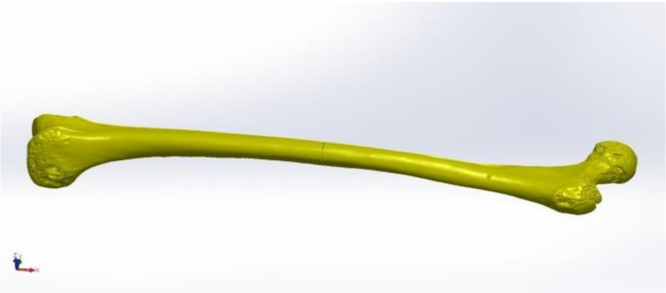

Fig 7. Non-displaced transverse fracture bone model.

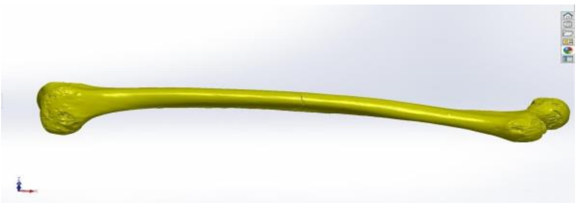

Fig. 8 Non-displaced oblique fracture bone model.

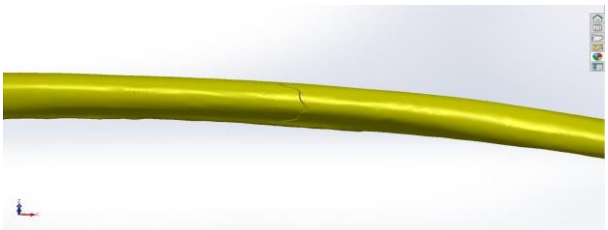

Fig. 9 Details of non-displaced oblique fracture bone model

Finite Element Analysis

Normal Femur Bone

From all the loading applied in normal femur bone, result show that increasing the load will increasing the total deformation. Meanwhile, the maximum and minimum shear strain and stress have huge the gap of number. The details number shows in Table 4 the result illustrated for eccentric load maximum. Total Deformation for the lowest load is 0.00006557 m was obtained. Otherwise, 0.00023607m. Total Deformation occur in the highest load. Results show that higher deformation occurs at the head of femur and lowest occurs at the lower end. In the Kalaiyarasan study, total deformation occurred from the lowest load up to 750 Pa with the highest pressure of 0.000046907 m to 0.00002795 m, meaning the result is acceptable in this range, based on the previous study.

Maximum shear strain and stress at 250 Pa are 0.00002268 (m/m) and 18580 Pa. Passingly, the minimum shear strain and stress are 2.654x10-9 (m/m) and 2.1743 Pa. For the highest load, the maximum shear and strain increasing slightly which have 0.000081649 (m/m) and 66889 Pa. However, the minimal shear strain and stress at this load sharply increase to 9.5545x10-9 (m/m) and 7.8273 Pa. In spite of the many differences between the numbers for each load, Young's modulus doesn't differ much when rounded up. The maximal value of Young's modulus for the normal femur bone is 8.225x10-7 and the minimum value is 0.0001506 N/m2.

In general, mostly all the parameters increase significantly from the lower load to the huge load. This actively demonstrate that, highest load or clash will increase the risk of bone deformation. Similarly for the distribution of strain and stress which increases the stiffness (Young's Modulus) of the bone femur. The purpose of this model is to evaluate whether the mechanical properties of the femur bone can vary differently under physiological conditions, as well as among individuals. According to the results, heavier weights result in greater displacements (Nareliya et al., 2011).

Non-displaced Transverse Fracture Femur Bone

Based on all the loading applied to the transverse fractured femur bone, the results show that increasing the load would increase the total deformation. Meanwhile, the maximum and minimum shear strain and stress have huge differences in each load. The details are listed in Table 5 a maximum Total Deformation of 0.000088791 m was obtained for eccentric load for the lowest load as illustrated. Alternatively, 0.00031965 m Total Deformation occurs when the load is high. Results show that higher deformation occurs at the head of the femur and less distortion at the lower end. Maximum shear strain and stress at 250 Pa are 0.00018761 (m/m) and 1.5369×105 Pa. Additionally, the minimum strain and stress at 250 Pa are 7.8117×10- 9 (m/m) and 6.3996 Pa. Under the highest load, maximum strain and stress increase slightly, with 0.000067539 (m/m) and 5.533×105 Pa. The minimal stress and strain at this load, however, dramatically increase to 2.8112×10-8 (m/m) and 23.038 Pa. Despite all the differences between the numbers for each load, Young's modulus did not vary much when rounded up. Transverse fractured femur bone has a Young's modulus of 8.225×10-7 with a minimum of 4.095×10-5.

Table 4. Mechanical properties of normal bone result.

Load (Pa)	Normal Bone						
	Total Deformation (m)	Shear Strain (m/m)	Shear Stress (Pa)	Young's Modulus (N/m^2)	Von-mises strain (m/m)	Von-mises stress (Pa)
250	$6,557\times10^{-5}$	Max $2,268\times10^{-5}$	Max 18580	$8,225\times10^{-7}$	Max $1,8367\times10^{-5}$	Max 35674
		Min $2,654\times10^{-9}$	Min 2,1743	$1,506\times10^{-4}$	Min $5,4327\times10^{-9}$	Min 3,9729
500	0,00013115	Max $4,536\times10^{-5}$	Max 37161	$8,225\times10^{-7}$	Max $3,6734\times10^{-5}$	Max 71349
		Min $5,308\times10^{-9}$	Min 4,3485	$1,506\times10^{-4}$	Min 1,0865e-8	Min 7,9458
750	0,00019673	Max $6,8041\times10^{-5}$	Max 55741	$8,225\times10^{-7}$	Max $5,5102\times10^{-5}$	Max $1,0702\times10^{5}$
		Min $7,9621\times10^{-9}$	Min 6,5228	$1,506\times10^{-4}$	Min $1,6298\times10^{-8}$	Min 11,919
900	0,00023607	Max $8,1649\times10^{-5}$	Max 66889	$8,225\times10^{-7}$	Max $6,6122\times10^{-5}$	Max $1,284\times10^{5}$
		Min $9,5545\times10^{-9}$	Min 7,8273	1.506×10^{-4}	Min $1,9558\times10^{-8}$	Min 14,302

In general, mostly all the parameters increase significantly from the lower load to the huge load. This actively demonstrate that, highest load or clash will increase the risk of bone deformation. Similarly for the distribution of strain and stress which increases the stiffness (Young's Modulus) of the bone femur. Based on the findings of this study, follow-up actions for fracture patients can be made more efficiently. Especially, for the non-displaced closed transverse fractured femur bone case. In mechanical testing, fracture load and stiffness correlated linearly, while FEA prediction showed an excellent correlation (Miura et al., 2017).

Comparison of Normal and Non-displaced Transverse Fracture Bone

Normal and fracture bone especially for transverse non-displaced has been analyzed in ANSYS Software. Here, the different between two types of bone will appear. Figure 10 illustrate fracture bone has higher number of total deformation than normal bone. This actively demonstrate that fractures bone has greater risk to deform than normal bone. Due to, fracture bone has been cracked by an accident or others condition. In general, fractured bones have lower strength than normal bones. Other than that, bones that have begun to deteriorate with age, especially those of those who have osteoporosis. Mechanical test results showed a significant linear relationship between fracture load and age (Miura et al., 2017). The higher deformation number, the greater change in shape and less likely it will return to its original form.

In shear strain, there are a huge different between the maximal and minimal condition from the cracked and normal bone. The maximum position of shear strain in Figure 11 illustrated the normal femur bone has greater shear strain in maximum than fractures bone. However, there is not a great deal of difference between the numbers in each load. Otherwise, Figure 12 show the shear strain in minimum value. The normal bone possesses the lowest number than fractures bone. Based on the maximal and minimal condition, meaning that strain fractures of bone are relatively less range tolerance than those of normal bone.

Figure 12 illustrated the shear stress in maximum position. Meanwhile, Figure 13 show the minimum position of the shear stress. In shear stress, transverse fracture femur bone has greater shear stress than normal bone in both position (maximum and minimum). However, there is similar pattern between the maximal and minimal position in each load. An increase in shear stress indicates that there is a great deal of force acting on the bone. This is because transverse bones have a lower strength than normal bones, which means they are subject to the highest force effect. Furthermore, aging can also result in decreased bone strength. A number of changes can occur in the mechanical properties of cortical bone, trabecular bone, and entire bones with the onset of aging and disease. Individuals' quality of life can be profoundly affected by changes in mechanical behavior caused by aging and/or diseases such as osteoporosis and diabetes (Morgan et al., 2018).

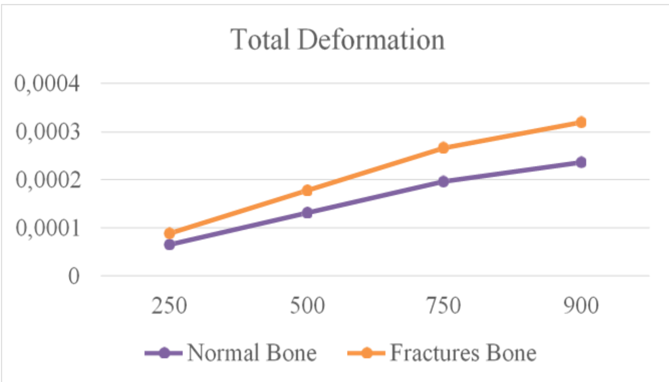

Fig. 10 Total Deformation Graph

Table 5 Mechanical properties of transverse fracture bone result

Load (Pa)	Transverse Fracture					
	Total Deformation (m)	Shear Strain (m/m)	Shear Stress (Pa)	Young's Modulus (N/m^2)	Von-mises Strain (m/m)	Von-mises Stress (Pa)
250	$8{,}8791\times10^{-5}$	Max 0,00018761	Max $1{,}5369\times10^{5}$	$8{,}225\times10^{-7}$	Max 0,00016559	Max $2{,}992\times10^{5}$
		Min $7{,}8117\times10^{-9}$	Min 6,3996	$1{,}506\times10^{-4}$	Min $6{,}0903\times10^{-9}$	Min 11,464
500	0,00017758	Max 0,00037521	Max $3{,}0739\times10^{5}$	$8{,}225\times10^{-7}$	Max 0,00033118	Max $5{,}984\times10^{5}$
		Min $1{,}5623\times10^{-8}$	Min 12,799	$4{,}095\times10^{-5}$	Min $1{,}2181\times10^{-8}$	Min 22,928
750	0,00026637	Max 0,00056282	Max $4{,}6108\times10^{5}$	$8{,}225\times10^{-7}$	Max 0,00049676	Max $8{,}977\times10^{5}$
		Min $2{,}3435\times10^{-8}$	Min 19,199	$4{,}095\times10^{-5}$	Min $1{,}8271\times10^{-8}$	Min 34,392
900	0,00031965	Max 0,00067539	Max $5{,}533\times10^{5}$	$8{,}225\times10^{-7}$	Max 0,00059612	Max $1{,}077\times10^{6}$
		Min $2{,}8122\times10^{-8}$	Min 23,038	$4{,}095\times10^{-5}$	Min $2{,}1925\times10^{-8}$	Min 41,271

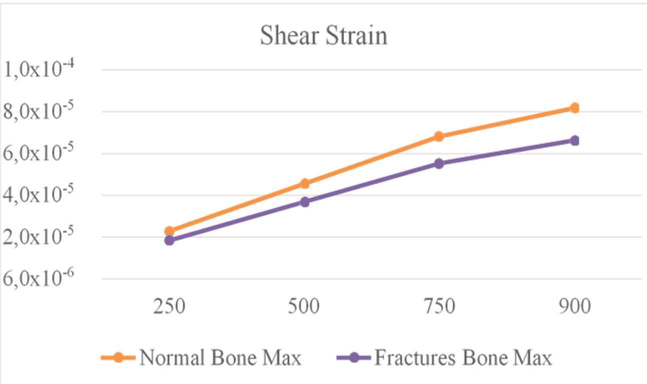

Fig. 11 Shear Strain (Max) Graph

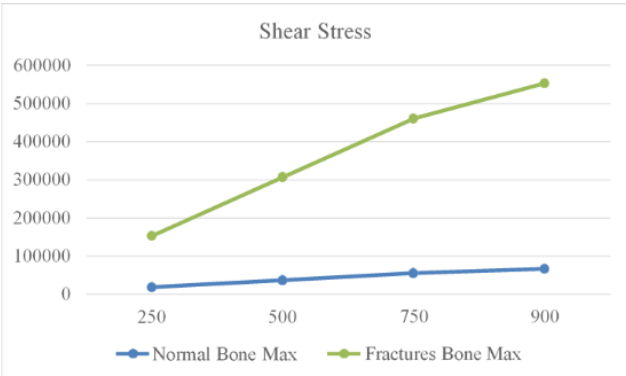

Fig. 13 Shear Stress (Max) Graph

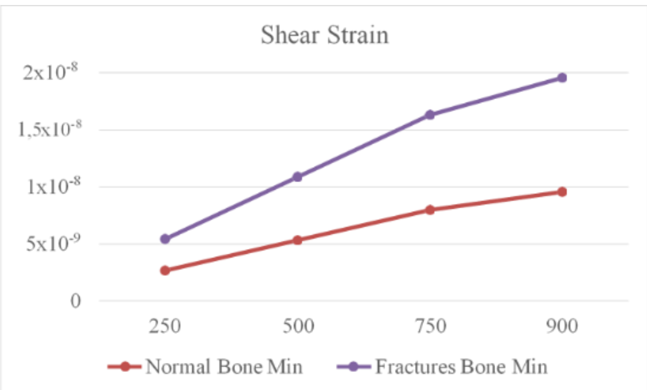

Fig. 12 Shear Starin (Min) Graph

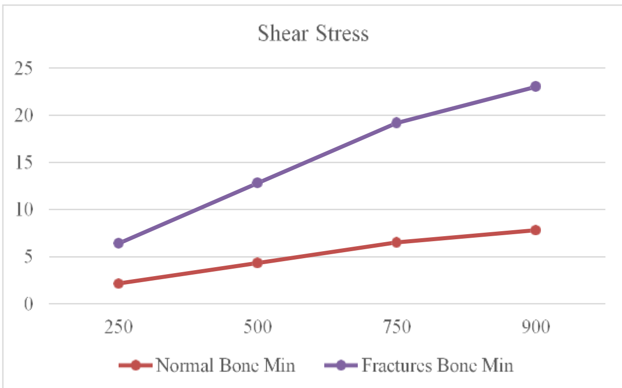

Fig 14 Shear Stress (Min) Graph

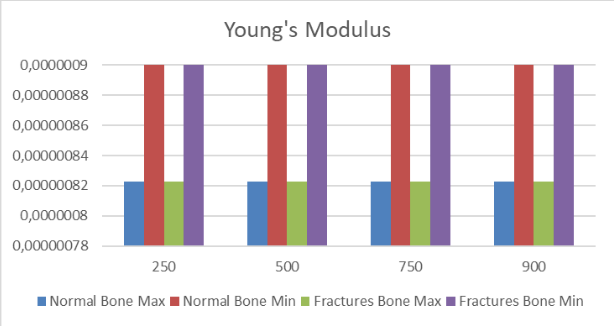

Fig. 15 Young Modulus Graph

In spite of the significant difference in numbers of shear strain and shear stress, both normal and transverse bones have the same Young's Modulus. As shown in Figure 14. A maximum for normal and cracked bone is 8.2x10-7. Alternatively, 0.9x10-7 occurs when the minimum condition. Results show that higher difference in maximal and minimal condition. As elastic modulus indicates stiffness, a material whose modulus is higher will deform less when given a force due to its high elastic modulus value. In other words, a higher modulus value means that less elastic strain occurs, or that it is stiffer. When the value of E (Elastic Modulus) becomes smaller, the material is more likely to suffer from elongation, shortening, or even breaking (D. P. Fyhrie, B. A. Christiansen., 2015).

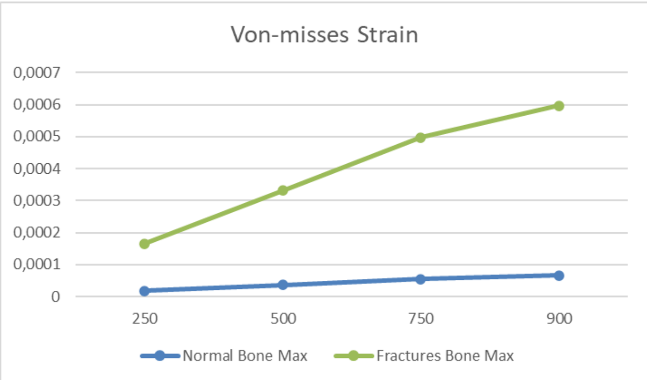

Fig. 16 Von-misses Strain (Max) Graph

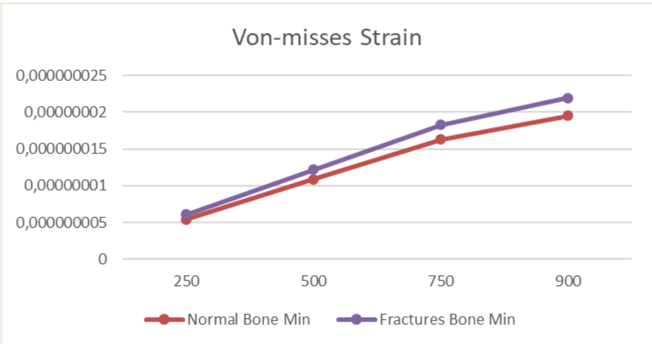

Fig. 17 Von-misses Strain (Min) Graph

Based on Figure 16 and Figure 17 which shown the von-misses strain in maximal and minimal position, its different with the shear strain graph. In von-miss strain or called as equivalent elastic strain, the fractures bone got the highest numbers than normal femur bone in all position (maximum and minimum). The difference between each load is considerable under maximum conditions. Nevertheless, there is not a great deal of difference in numbers under minimal conditions.

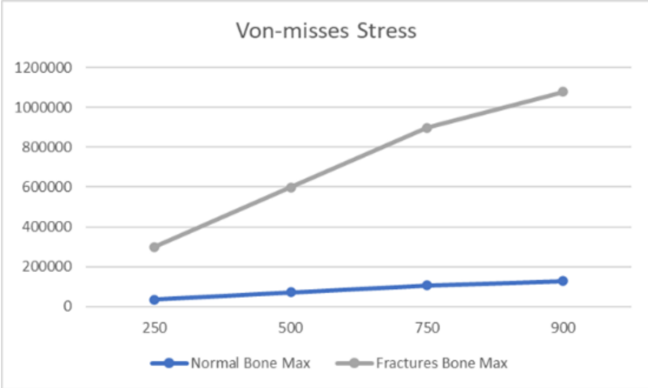

Fig. 18 Von-misses Stress (Max) Graph

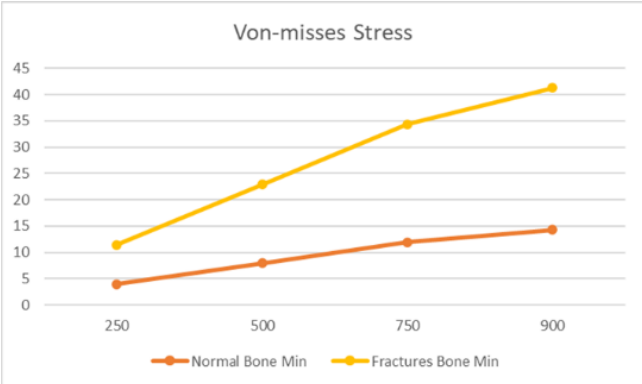

Fig. 19 Von-misses Stress (Min) Graph

The von-miss stress in maximum position illustrated by Figure 18 and the minimum position illustrated in Figure 19. This von-miss stress similar like shear stress, the normal femur bone holds the lowest points in all positions. Meaning, non- displaced transverse fracture has higher numbers than normal bone. This present that, the force applied to broken bone is greater than that which is applied to normal bone. Additionally, broken bones have a smaller surface area than normal bones. According to the study findings Zhao Min, Master et al., 2014, mechanical properties can be used as a basis for making follow-up steps more efficient for fracture patients, especially the elderly. As well as reducing the number of repeated operations caused by a failure to understand the mechanical conditions of the bones, it can prevent them from being repeated.

CONCLUSION

The Finite Element Analysis method is done on the normal and non-displaced transverse fracture femur bone. FEA analysis can be done in simulation using a software or structural engineering simulation software allows to do virtually test and predict the behavior of structures subjected to static and dynamic loading conditions and solve a wide range of structural engineering problems. The objectives of this research are to develop the 3D design of normal and fractures bone and look up for the mechanical properties of bone that have been achieved. Design for simulate and analyze the mechanical properties trough ANSYS Workbench. In order to see the difference of mechanical behavior between normal and cracked bone. There is no significant difference of elastic modulus between normal and fracture bone. In spite of, the shear strain and stress hold the huge gap in maximal and minimum position of both types bone. Certainly, transverse fracture bone got the highest number of total deformations. This clearly state, cracked bone has greater risk of failure and stiffness especially in elderly people. Details number of mechanical characteristic of fractures bone is considered suitable for further development especially in the prevention and treatment to reduce the revision of critical surgery.

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