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Modelling and Fracture Analysis of Femur Bone using Extended Finite Element Method (XFEM) and Applications in Aerospace

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Abstract:- Modelling the femur bone and study of fracture analysis is important to understand orthogonal properties of the bone and is the way to find the compact results in order to initiate the new researches for dealing with the complex structures at both macro and micro level in this field. The main focus of this study is bone's orthogonal properties and effect on bone's mechanical properties at specific loading conditions. The fracture will be dealt through initiating crack on the body of femur under XFEM Crack Growth using Abaqus, modelling was done through MIMICS and stress and deformation analysis was carried out. This research includes stress strain analysis and also shows the biomechanical properties of bone and its composition along with applications of biomechanics in aerospace industry . The mechanical analysis shows equivalent elastic strain about 1.5 × 10^{-3} to 1.7 × 10^{-3}. Dimensions were taken in millimetres.

Keywords:- *Femur bone; XFEM; fracture analysis, crack growth, biomechanical properties.*

I. INTRODUCTION

Bio mechanics is the field where we study biological systems; be it mammals, plants or living organisms of any level, combined with physical laws of mechanics, study their structure and mechanical aspects under different static and dynamic conditions. As we can see that human body experiences different forces and stresses when performing different tasks or when confronted with accidental injuries and almost every field is interconnected so bio mechanic engineers study human body for different fractures/ injuries[1].

Femur bone is the largest and strongest bone in human body and so is one of major concerns and field of study for bio mechanic engineers to observe various mechanical phenomenon (stress analysis, strains variations etc.[2]. Femur bone is divided into mainly three parts: 1) Upper extremity of femur containing head, neck and two trochanters 2) Shaft 3) Lower extremity. Its body is almost cylindrical in form. Lower extremity is somewhat cuboid in form and larger than upper extremity (Figure 1).

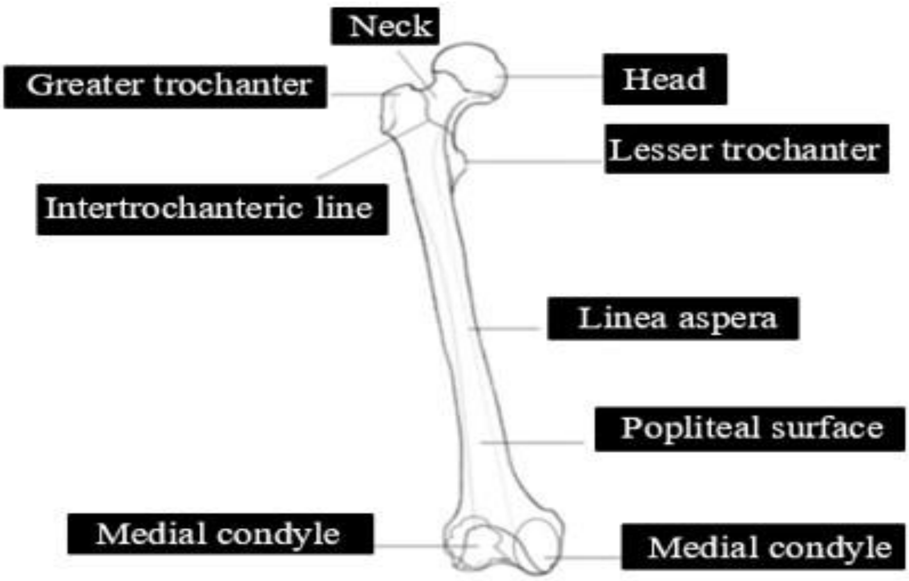

Fig. 1: Parts of Femur Bone

Femur structure mainly consists of two layers: 1) An outer dense layer also called cortical or compact bone which prevents bending. 2) Inner portion which is spongy in nature and mainly resists compression[3]. The major part of bone is called diaphysis which is also shaft of the bone. The both ends of the bone, surrounding diaphysis ae called epiphysis. The upper end which is connected to hip joint is called proximal epiphysis. The lower end, connected to knee joint is called distal epiphysis. The layer separating epiphysis and diaphysis is called epiphyseal line. The outer connective tissue around cortical bone is called periosteum except the joints sections and the inner portion is called endosteum. Bone marrow is stored in the central part of bone, along shaft of bone and is called medullar cavity. At last, the whole bone is covered with cartilage.

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Since femur bone is one of main study areas for bio mechanic engineers, fracture analysis is one of important mechanical aspect of study. Fracture is simply the separation or fragmentation of a body into two or more pieces in response to imposed stresses that may be static or varying with time and also at temperatures that are low relative to the melting temperature of the material. Stresses applied in the material resulting in fracture may be compressive, tensile, shear or torsional. Femur bone has mainly six types of fracture: 1) Femoral head fracture 2) Femoral neck fracture 3) Intertrochanteric fracture 4) Sub-trochanteric fracture 5) Femoral shaft fracture 6) Distal femur fracture[4]. There are many causes of fracture/ failure occurrence in engineering machines e.g. stress concentrations, stress variations and also due to dislocation of joints.

There are many numerical/ analytical techniques to study various mechanical aspects like displacements, stress variations etc. and also to study biomechanical systems on 3D computational models of physical bodies. However, FEM (Finite Element Method) is one of most commonly used and widely accepted technique for biomechanical analysis of any body organ of different species of animals having complex geometries e.g. human bone structure. It is also used to study structural analysis, heat transfer and fluid flow etc. on mathematical and engineering models. FEM is based on computer based programming. We have a special branch of FEM to study complex structural geometries and their biomechanical analysis, which is XFEM (Extended Finite Element Method). XFEM is a sub branch of FEM which is specially developed to treat discontinuities in biomechanical structure. Specifically talking about bone structure of mammals, it has many small discontinuities and complexities in its structure that are at most times difficult to cater them into a 3D model[2]. Moreover, these complexities in bone structure, despite being minute in appearance can have big effects on biomechanical analysis of the bone and cause variations in stress due to their response to different loading conditions. For this sole reason, XFEM technique is a very good choice for the biomechanical analysis of bone structure and as in our case on Femur bone.

Femur bone shows non-linear behaviour which means their properties do not remain same at all positions[5]. Properties of Femur bone show variations at different locations under different loading conditions[6]. Due to this reason, the choice of applying loads is taken to be those points where fracture probability is considerably high.

Hip fractures is one of the main concerning problems of bone failure in human body. According to[7] low impact falls cause hip fractures and the mechanical analysis of proximal femoral part may predict hip behaviour during a fall. In another study[8] femoral fracture analysis has been carried out in tensed, relaxed and slap condition. In this work fracture analysis of femur bone has been carried out through XFEM technique under different fall configurations. The fracture has been studied defining fracture onset on proximal femur and mechanical analysis has been carried out. Femur has been modelled through CT images and then mechanical analysis has been carried out.

II. METHODS

The dimensions of femur bone vary from person to person based on differences in age group, gender, person's health etc. A study has shown a rough estimate of dimensions of different parts of femur bone[9].

Many researchers have used different methods to model femur bone. A study[10] has used Digital Image Correlation (DIC) for bone modelling and strain measurements on its surface. Another study[11] has used CT images of bone to model the femur bone through its voxels Hounsfield Units (HU). In this study we have collected CT images of femur bone through extensive literature review (DICOM files) and imported into software "Mimics Medical"[12].

Some steps have been performed to create 3D model of femur bone using these CT images[13] (Figure 2).

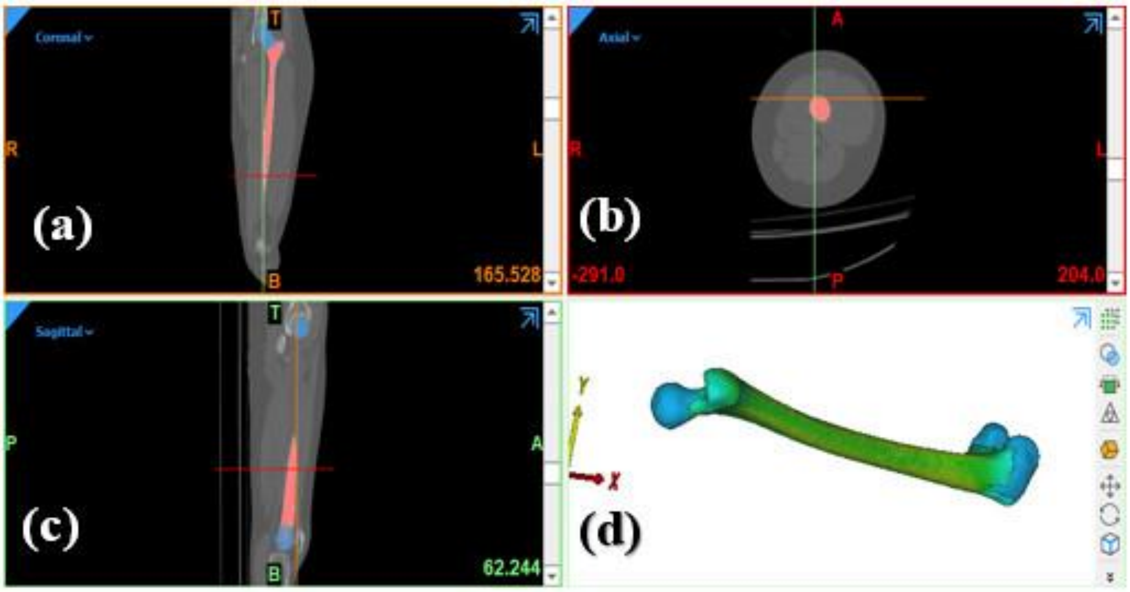

Fig. 2: (a) CT image in Coronal view (b) Axial view (c) Sagittal view (d) 3D bone model

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By selecting the respective views of bone, extra surfaces, volumes and edges have been removed by using icon "New Mask". In this we define upper and lower threshold ranges have been defined, the segment was divided, floating pixels from the region have been removed and a rough model was created[14].

The non-linear elements and errors are further removed by using 3- matic medical and a refined 3D model of femur bone is created.

The femur model shown above has the dimensions approx. equal to average human femur bone. It is about 440 mm in length and approx. 26.4 mm in diameter. Wrap option that is in fix design menu, it will do a couple of things; it can close any hole on the surface of your part; it also smooths it out and it can also be used to remove any of the internal shells in your model so it's going to make a smoother bone. A smallest detail of 7.5 mm has been selected which indicated the smallest element of size to make the smooth bone.

After smooth 3D model was made, meshing was also done in 3-matic medical. At first, surface mesh was performed on the bone model to generate a fine mesh for good analysis. Since we have 3D model of femur bone and for 3D bodies volume meshing is most commonly used so now we apply volume mesh and tetrahedral elements were used.

Uniform mesh is generated on 3D femur (Figure 3). The model was composed of 26,293 nodes with altogether 52574 elements having element size of 0.7 mm.

3D volumetric model was reloaded in MIMICS for material assigning. Material was assigned in MIMICS according to the gray value based method from the CT Scan images of femur bone based on HU[7]. Different material properties were assigned to bone using built in formulas in MIMICS using Hounsfield units from CT images.

$$\rho\left(g/cm^3\right) = 0.0000464HU + 1 \quad (1)$$

The bone materials are dependent on effective density[15]. Since mechanical properties of bone are dependent on its density and as it follows that density varies with human factors (age, sex) so their mechanical properties also vary[8]. From literature, the relationship between apparent density and Young's modulus[16] is shown in Eq (1), (2) and (3).

$$E(MPa) = 0.04\rho^{2.01} \quad (2)$$

$$\nu = 0.3 \quad (3)$$

Where E is Young's Modulus and v is Poisson's Ratio (Table 1).

Table 1: Material Assignment in MIMICS

Density ρ (g/cm^3)	Young's Modulus E (MPa)	Poisson's Ratio ν
50	10.399	0.3
14368	86.766	0.3
328.527	457.47	0.3
513.386	1122.16	0.3
698.245	2082.17	0.3
883.105	3338.45	0.3
1067.96	4891.69	0.3
1252.82	6742.46	0.3
1437.68	8891.24	0.3
1622.54	11338.4	0.3
1807.4	14084.4	0.3

The 3D model prepared in MIMICS is reloaded in Abaqus/Standard for fracture analysis. Fracture analysis has been dealt in Abaqus by initially defining a crack as fracture onset on the surface of proximal femur (Figure 3).

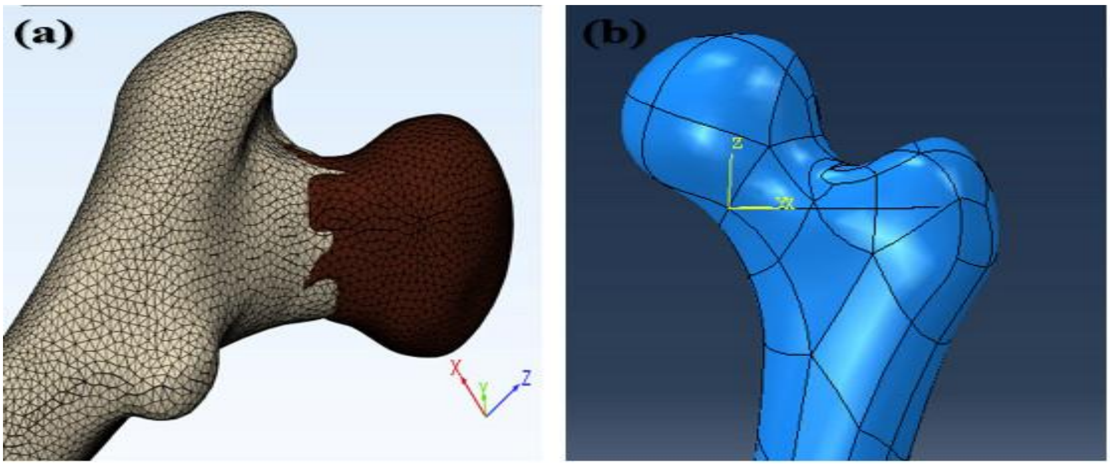

Fig. 3: (a) Uniform mesh of 3D femur bone model (b) Fracture onset prediction

The properties related to fracture criteria were obtained from[17] that must be input in our FE model for XFEM crack growth. Critical energy values like fracture toughness K dependent on bone density has been described in Eq (4), (5) and (6).

$$K\left(Nm^{-1.5}\right) = 0.7413.10^{6}.\rho^{1.49} \quad (4)$$

$$G(Jm^{-2}) = \frac{K^{2}\left(1-v^{2}\right)}{E}. \quad (5)$$

$$G_{IIC}/G_{IC} = G_{IIIC}/G_{IC} = 0.33 \quad (6)$$

The crack propagation was selected based on XFEM capability in Abaqus and the failure criteria was selected on the basis of mixed mode behaviour of Benzeggagh-Kenane expression[18]. The XFEM capability has the advantage that it allows crack propagation regardless of mesh geometry. The analysis has then been carried out in different configurations relating to hip fractures. The boundary conditions have been applied such that the distal part of the femur has been constrained as a fixed support and concentrated loadings have been applied such that the analysis is carried out in 1) Stance configuration 2) Trochanter fall configuration 3) Sideways fall configuration (Figure 4).

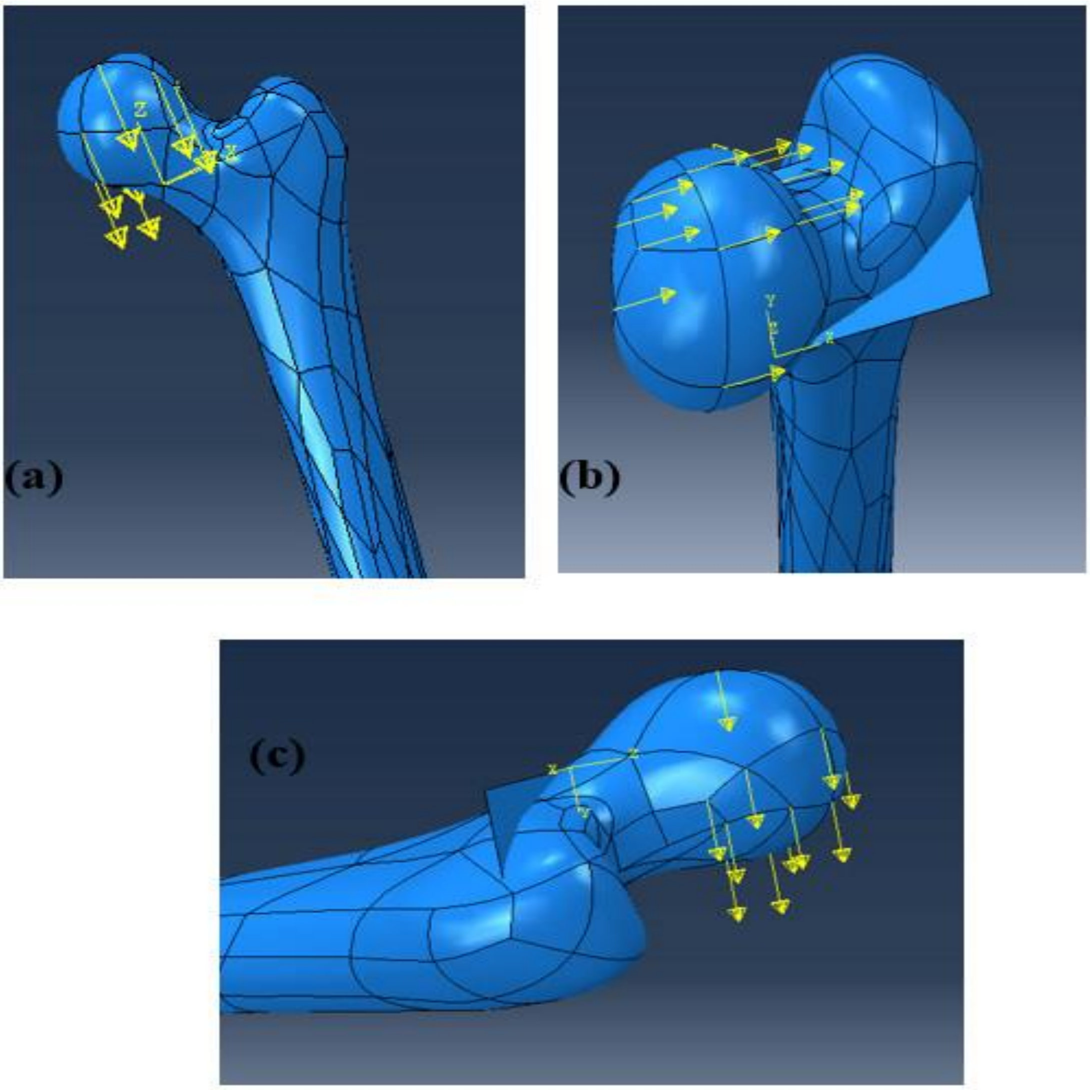

Fig. 4: Loading applied in (a) Stance configuration (b) Trochanter configuration (c) Sideways fall

A concentrated loading of 750 N was applied under the configurations to analyse the deformations in the femur and stress and strain variations in the elastic range.

III. RESULTS

Loading was applied in the configurations related to hip fractures listed above to study femoral deformations, stress and strain variations occurring and the fracture path that is being followed by the crack under XFEM crack growth. The rotation is applied to femur internally along its axis on some certain nodes. The results have been shown in the form of Equivalent Von-Mises stress, equivalent elastic strain, total deformation and fracture path followed under XFEM crack growth function of Abaqus/Standard. The results have been summarized (Table 2).

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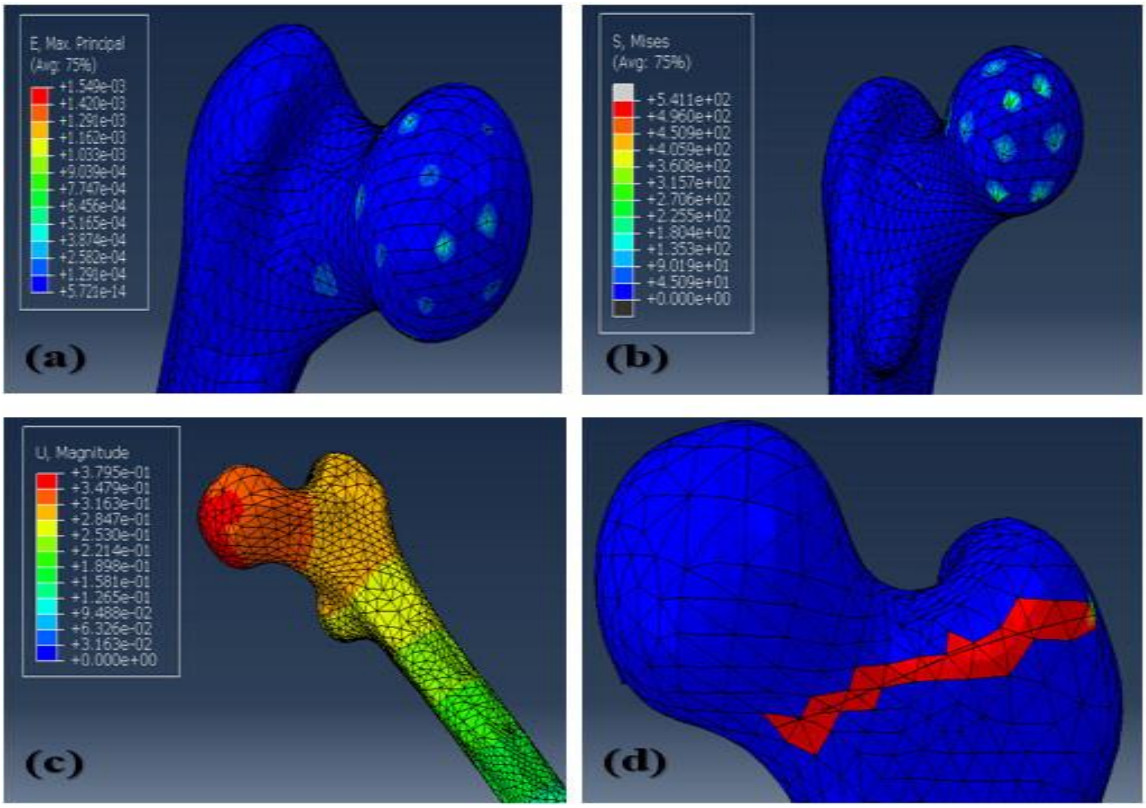

Fig. 5: (a) Equivalent Elastic strain (b) Equivalent Von-Mises Stress (c) Total deformation (d) Fracture path under stance configuration

The values of equivalent elastic strain, Von-Mises Stress and total deformation under stance configuration are 1.549×10^{-3} mm/mm (maximum), 5.411×10^{2} Pa (maximum) and 8.19×10^{-1} mm (maximum) respectively (Figure 12). As it can be observed that the maximum stresses and strains have been experienced by proximal femoral area and from the deformation results it can be seen that the maximum deformation is occurred on the proximal femur and has started decreasing along femoral shaft towards distal femur. The XFEM fracture path can be seen that under stance loading it is somewhat bent downwards.

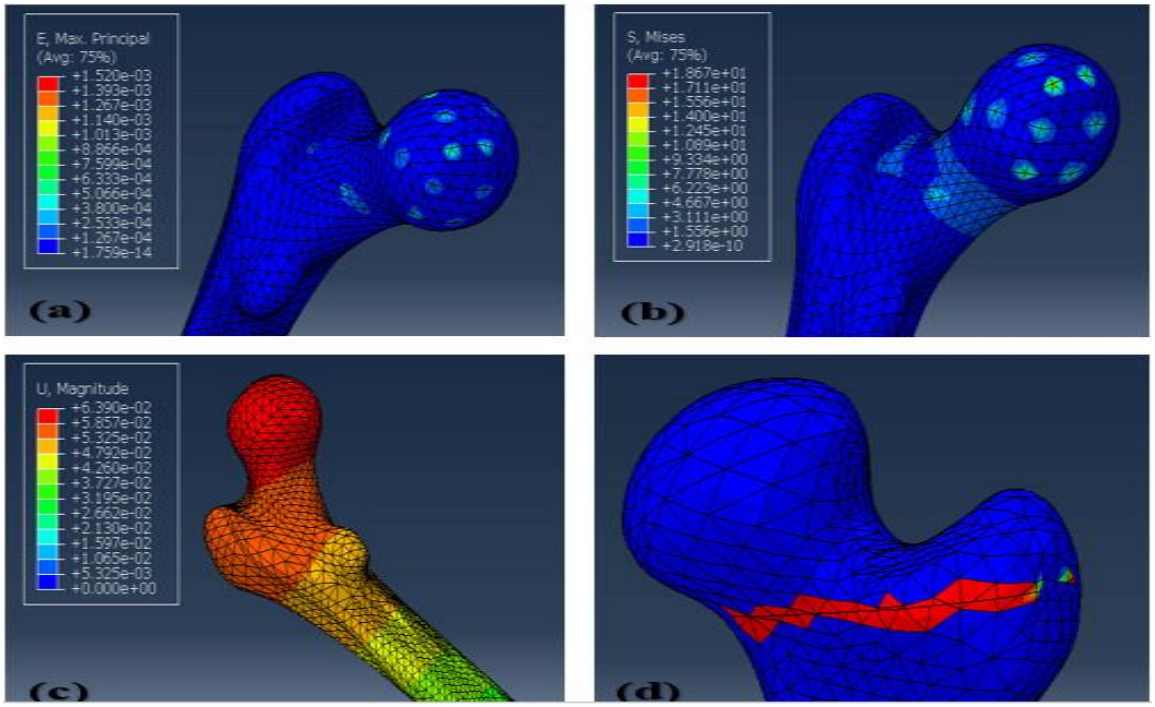

Fig. 6: (a) Equivalent Elastic strain (b) Equivalent Von-Mises Stress (c) Total deformation (d) Fracture path under trochanter fall configuration

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The values of equivalent elastic strain, Von-Mises Stress and total deformation under trochanter fall configuration are 1.52×10^{-3} mm/mm (maximum), 1.86×10^{-1} Pa (maximum) and 6.39×10^{-2} mm (maximum) respectively (Figure 13). It can be seen that stresses and strains have been mostly experienced by femoral head and neck region and from deformations results and it can be seen that maximum deformation has been experienced by proximal femoral region and been decreasing along femoral shaft towards distal femur. The XFEM fracture path can be observed such that under trochanter fall configuration femoral head is bent a little to the side.

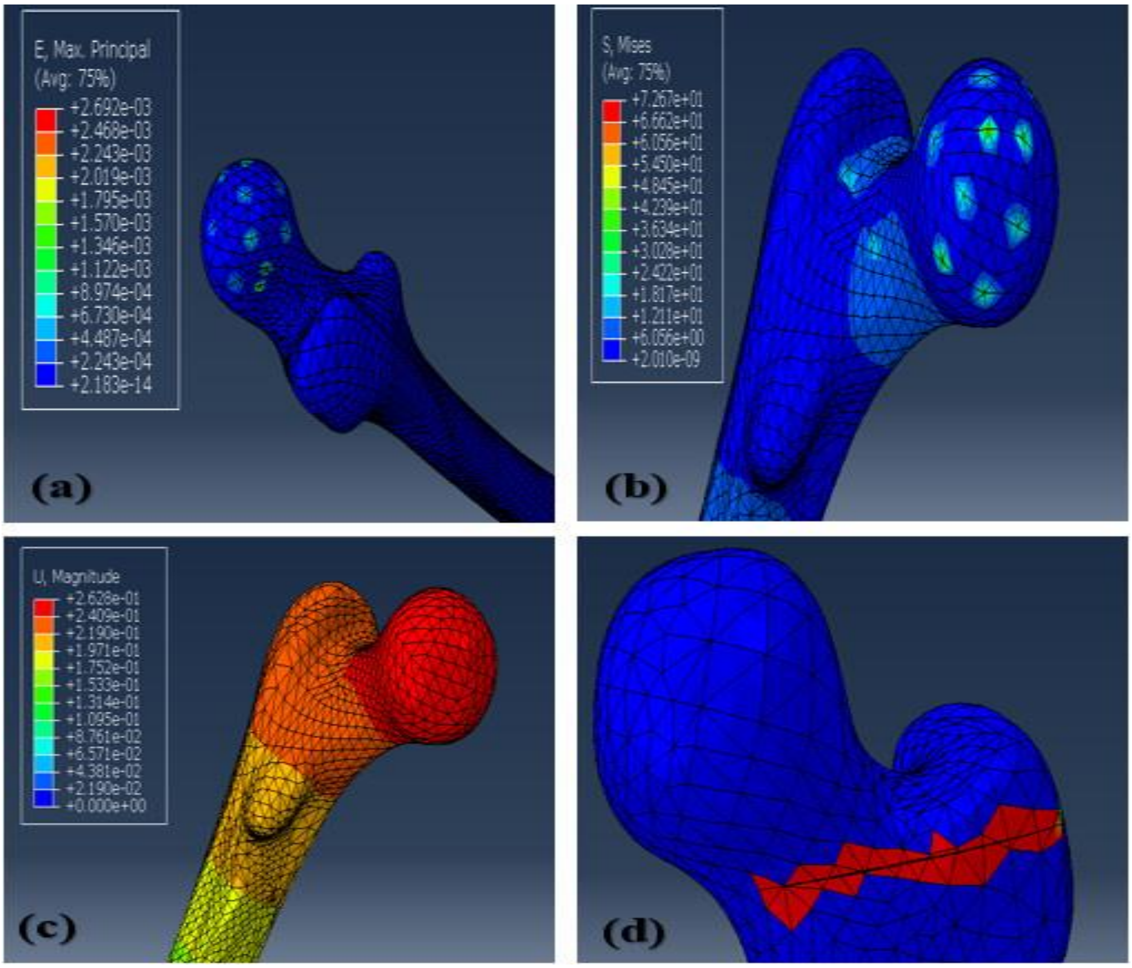

Fig. 7:(a) Equivalent Elastic strain (b) Equivalent Von-Mises Stress (c) Total deformation (d) Fracture path under sideways fall configuration

The values of equivalent elastic strain, Von-Mises Stress and total deformation under sideways fall configuration are 2.692×10^{-3} mm/mm (maximum), 7.267×10^{1} Pa (maximum), 2.628×10^{-1} mm (maximum) respectively (Figure 14). The stresses and strains mostly experienced by proximal femoral region as loadings are applied to femoral head. Moreover, deformations are highest at the femoral head and femoral neck and continued to decrease along femoral shaft towards distal femur. The XFEM fracture path has propagated such that some fracture is being observed. Results have been summarized in (Table 2).

Table 2: Results of mechanical analysis of femur in different fall configurations

Configuration	Equivalent Elastic Strain (mm/mm)	Von-Mises Stress (MPa)	Total deformation (mm)
Stance	1.549×10^{-3}	5.41×10^{-4}	8.19×10^{-1}
Trochanter fall	1.52×10^{-3}	1.86×10^{-5}	6.39×10^{-2}
Sideways fall	2.69×10^{-3}	7.26×10^{-5}	2.63×10^{-1}

For the strain analysis, the data is compared with the work done by[17]. From their analysis, they have performed FE strain analysis of femur bone at various loadings (250 N, 500 N and 750 N) under stance configuration. In their research the maximum value of equivalent elastic strain was obtained as 1.77×10^{-3} and the results have been calculated in this research for the comparison of our values and 12.4% error has been calculated. Our numerical model analysis was correlated with their FE model calculations for all three loadings ($R^2 = 0.93$, $R^2 = 0.937$ and $R^2 = 0.95$) with a slope of regression line of 2.5, 2.6 and 2.3 for values of strains with time (Figure 15).

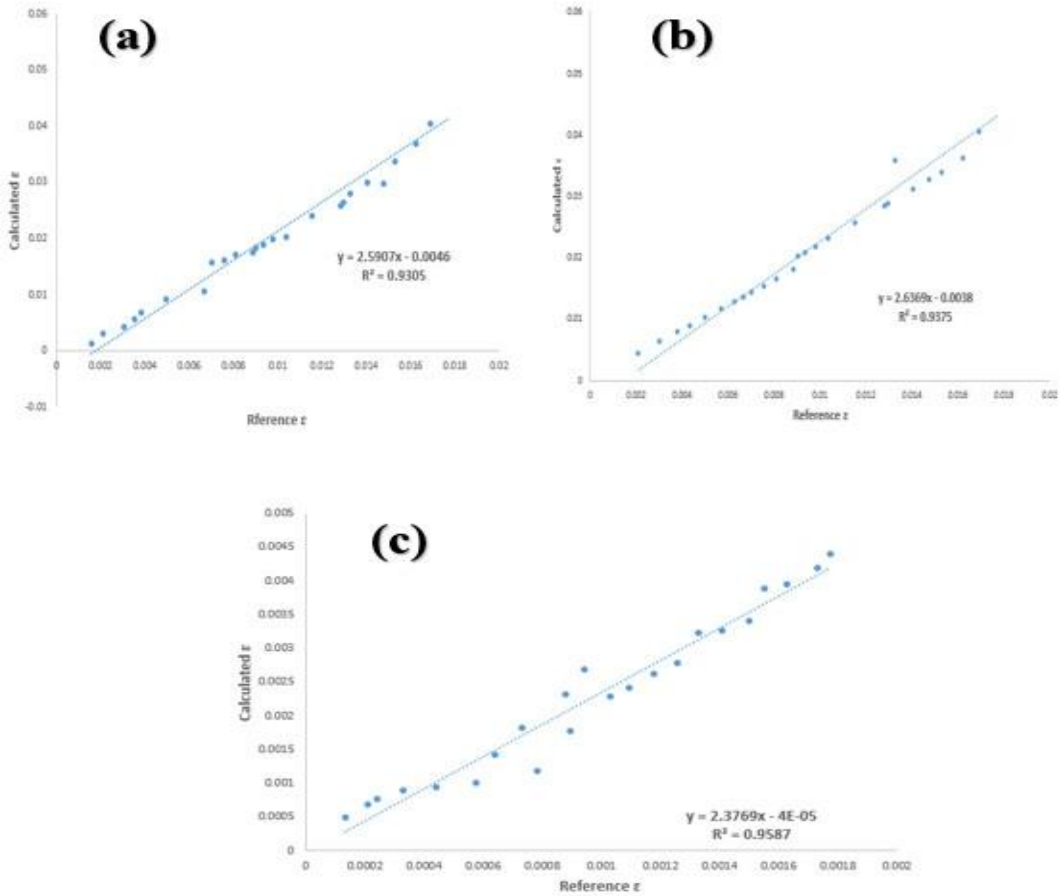

Fig. 8: Comparison between the numerical model and reference strain values under stance loading of (a) 250 N (b) 500 N and (c) 750 N. The blue line represents regression line.

Several factors may lead to differences in measured and expected values. There may be a difference in position of load application on certain nodes of femur FE model. Secondly the boundary conditions imposed on the numerical model may impose some error due to difference in selection of nodes and elements. Also there may be some difference in material properties assigned to the femur bone.

This study[17] has obtained a correlation of their numerical model analysis with their experimental work (R^2 = 0.99) of the strain values with a slope of regression line of 0.81. Another study[19] got a slope close to 1.0 in their research work. Another research [20] shows the same work with a slope of 0.8 and another study[21] predicted their numerical strains with an error of 15%.

IV. BIO MECHANICS IN AEROSPACE

There are various applications of biomechanics in aerospace industry as discussed below:

As the name suggests, “micro” means very little and hence, microgravity means very little gravity. Microgravity is very essential for bio mechanic engineers as astronauts and scientists travel to space for space missions and they spend months and years in space outside Earth’s atmosphere. Out in space the only gravity is Sun’s gravity which is very little. It is a point of concern for astronaut’s health as a person’s bones become very weak in absence of gravity. The reason is that bone’s major strength is due to bone density in it. In outer space, due to very little gravity, bone’s density continuously decreases and we want to keep our astronauts healthy so bio mechanic engineers monitor bone density and bone strength of astronauts so we want to send those astronauts whose bone density is sufficient22.

Moon and mars are going to be next main research areas of astronauts where gravity is less as compared to Earth (16% and 38%) respectively. These conditions are called hypo gravity. When an astronaut goes for inter-planetary mission and when he lands on surface of the moon, bone density continuously decreases by walking on the surface. Some treatments have been proposed regarding this. A study published in research article shows us that experiments are being carries out to make the Moon a natural habitat for astronauts on the mission. If this experiments are proven successful, then astronauts can easily explore space and they will be breaking the record of Apollo 17of about 75 hours. Some hop exercises are being suggested for the astronauts to do on the surface of the moon which can prevent bone loss during their stay in space. But the effects of long stay on the moon is unknown and it is not sure that for how long these exercises can prevent excessive bone loss and keep the astronauts healthy23. like Elon Musk, CEO of Space-X has been planning missions to send people on Mars and colonialize it. So we have carried analysis of our bone to know the fracture and deformation duration and density loss.

Hyper gravity is basically greater gravity forces e.g. high g's (3g or 5g) etc. experienced by fighter pilots when they dash or dive. According to a study published in "Scientific Reports", a person experiencing high g loads will affect its muscles and bones such that under such high loads muscles and bones will be in a form of workout and your bones strength and muscles volume and strength may gradually increase with time24. Of course, the results will have limitations of age factor. So based on these conditions, we can study that how much high g loads bone can withstand.

The bone fracture risk has also an application in aviation accidents i.e. when a crash occurs, the impact of bone in different configurations may cause fracture. An example of this is shown in a case study of a crash of Boeing 737-400 aircraft on M1 motorway at Kegworth, England25 which concluded that the primary factor for femoral fracture was bending load in impact in aircraft accident and this bending can be applied in sideways fall and trochanter fall configurations which we have done in our analysis.

V. DISCUSSION

The main objective of this work is to present a method for the modelling of femur bone and perform its fracture analysis through XFEM involving material assignment to the bone followed by the validation with some published research work.

The modelling of femur bone was done through collection of CT images and 3D model was prepared in Materialise Medical along with material assignment and meshing was performed in 3-Matic. Our FE model analysis predicted the strain values with time under XFEM fracture technique. The crack was initiated as notched specimen on the surface of proximal femoral region.

Our fracture analysis of femur bone using XFEM provided good results of strain analysis under stance configuration and provided strong correlation with results of another research as validation performed above.

It is to be noted that the results may deviate and there might be changes in the FE analysis due to change in mechanical properties (Young's Modulus and critical energy). The significance of proper characterization and material assignment to the bone can be realized by differences found in results of fracture analysis when compared to other values from literature.

Our study has a limitation that only one FE model of femur bone has been used for analysis while to get accurate results and to get an idea of mechanical properties of femur with changing factors, various testing models have to be used. Another limitation our research has that experimental testing has not been used for the analysis where physical models of human bones may give a good prediction about their mechanical properties at different configurations.

This study only covers initial stages of crack propagation while fracture modelling of whole bone and to cover final stages of crack propagation is a difficult task and may include local defects in the model. The further advancement in this field can be to include fracture analysis of femur bone at micro level which studies the changes in femoral structure at micro level (tissues, nerves) and their behaviour to different configurations and loading conditions. Also the studies of material assignment to femoral structure at tissue level can be studied.

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