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Behaviour of Human Femur Bone Under Bending and Impact Loads

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Abstract: Femoral fractures are among the most common major injuries that an orthopedic surgeon will be required to treat. During fracture treatment of femur bone the biomaterials are used for fracture healing. Evaluation of femur fractures using clinical data is confounded by multiple patient and fracture specific factors making it difficult to draw meaningful conclusions, despite the inclusion of large number of patient data. Therefore the biomechanical testing of the femur bone plays a vital role in the evaluation the femoral fractures. The main mechanical characteristics which will influence on the fracture damage of the femur are impact resistance, fracture toughness and bending strength. The experimental investigation is carried out to evaluate these damage characterizing parameters in femur. In order to evaluate the influence of the loading type on the pre cracked femur, the notched femur bone has been tested under impact and bending loads. Also the effect of these loads on the femur with implant has been determined. The results have shown the femur strength is extremely variable with respect to the different regions. Each damage characterizing parameter has shown maximum dependency on the matrix of the femur and its hardness. The macroscopic observations of the fractured specimens have shown that, the chipping of the bone, longitudinal cracks and the multiple cracks in femur are most dangerous.

Keywords: Femur Bone, Bending Failure, Impact Failure, Damage Characterization

1. Introduction

In humans it is the largest most voluminous, solid inflexible and strongest bone.It can support up to 30 times the weight of an adult and is responsible for bearing the largest percentage of body weight during normal bearing weight. The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter [1-4]. The femur is the most proximal (closest to the body) bone of the leg in vertebrates capable of walking or jumping and most of the upper weight of the body is supported by femur bone. If the femur bones get fractured then the person who suffering from this unable to do many of the physical activity and this will results in the total collapse of the human body [5-6].

The incidence of osteoporotic fractures is increasing and has become one of the major health problems in developedcountries. Physical exercise has been found to be effective in the prevention of osteoporosis. There is a significant relationship between physical activity data and proximal femur bone mineral density [7].

The ultimate bone strength of the distal femur was measured radially, by indentation testing. In comparison with the tibia femoral bone strength showed generally higher values, and the decline of bone strength with depth plateaued at higher bone hardness values. Bone specimens were tested in multi axial stress and including pure shear, in a special test device. Shear strength was proportional to apparent density to the exponent 1.65 in approximate agreement with theoretical and experimental studies on the shear strengths of porous foams. The influence of the pure shear tests on the rightness of the data obtained by other type of the tests. Shear properties have been often measured on the torsion. Shear stresses may play an important role in the pathologenesis of the stress fracture in the human bone. Cortical bone is weaker in shear and subjected to fatigue under cyclic shear loads [12-16].

The body or shaft fracture occurs due to accidental loads. In most of the cases shaft fracture is due to bending. Bone tissue modulus of marine cortical bone is estimated by three-point bending tests [17-18].

The impact energy absorption of human femoral cortical bone decreases by a factor of about three between the ages of three and ninety. This decrease is partially caused by an increased mineralization of the bone and plastic deformation. It may be remembered that porosity and other variables were measured, in each femur, for those specimen that absorbed the greatest and least energy. Such a selection of specimen, though not random, increases likelihood of discovering effects of these variables on energy absorption [19-20].

Nowadays many varieties of implants can be used for the human body fractures. Metallic biomaterials have their main applications in load-bearing systems such as hip and knee prostheses and for the fixation of internal and external bone fractures. Prosthetic devices are implanted in the human body to replace the affected joint in order to eliminate pain and restore its normal function. After implantation, the implant functions just as a normal hip joint and as normal knee joint. If the femur is subjected to any type of loading like bending, impact, compressive or accidental loads, the type in which the femoral bone gets fractured is unpredictable. The metallic implants are often involved in the open reduction and internal fixation of fractures. Open reduction and internal fixation is commonly used in cases of trauma when the bone cannot be healed using external methods such as casting. The locking compression plate combines the conventional screw hole, which uses non locking screws, with a locking screw hole. Biocortical screws offer a higher résistance to torque because of their increased working length.Study of the interaction of metallic joint with bone material necessitates the mechanical properties as the grain orientation is not straight along the length of bone they are seen diverging according to the shape of bone. The small square or rectangular cross sectional sample gave good results [21-23].

The experimental study aims at determining mechanical behavior of human femur bone.This study attempts at providing mechanical properties of femur, through mechanical tests comprised of impact testing and bending test. The specimens were extracted from number of dead human (male) femur. Series of experimental data stated here include yield strength, modulus of elasticity and bending and impact strength of proximal and distal femur against metallic implants, which can reflect the complex material behavior of femur bone. Musculoskeletal loading influences the stresses and strains within the human femur. It is essential for implant design and simulations of bone modeling processes to identify locally high or low strain values, which may lead to bone, desorption and thereby affect the clinical outcome. Significant forces are present in the long bones, but their magnitudes have so far only been estimated from mathematical models. Knowledge of the forces acting on the human femur is of significant importance to health care professionals. Determination of these forces during walking and other daily living activities allows the subsequent calculation of the stresses induced in the femur and therefore the localization of the areas of frequent appearance of femur fractures. Furthermore, these forces are of great interest in the cases of total hip prostheses as well as in femoral neck and shaft fractures. In all these cases mechanical failures have been observed and therefore, a more sophisticated design of the surgical procedures and implants used to repair such cases necessitates knowledge of the forces responsible for the failures.

2. Materials and Experimentation

The specimens were extracted from number of dead human male femur (dead) of mid age of 20 to 30.The average adult male femur is 48 centimeters (18.9 in) in length and 2.34 cm (0.92 in) in diameter are been used.The mechanical properties of human long (dead) bone of middle aged cadaveric femur around various crack size and intensity of crack under different experiments such as bending and impact at various loading levels. The fig 1 shows the human femur bone used in the present study.

HUMAN FEMUR BONE

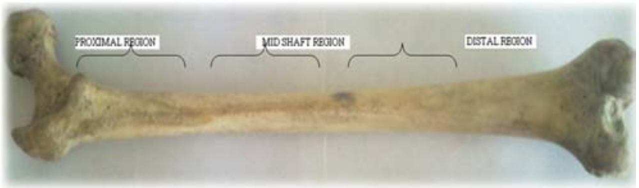


Fig. 1. *Human femur.*

Bone differs from other types of connective tissue in that the organic matrix is calcified so that bone contains about 70% bone salt in the form of minute crystals of calcium hydroxyapatite. The rest is 20% organic matrix and 10% water. The organic matrix has the same composition as tendon or ligament that is 90% collagen and 10% ground substance. The composition of femur bone used is as given in table 1.

Table 1. *Composition of the human femur (mg).*

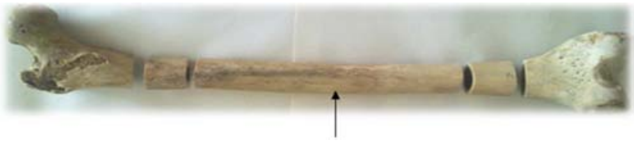
Dry matter	904
Organic matter	840
Crude protein	144
Crude fat	25
Crude fibre	150
Ash	64
Calcium	11.7
Phosphorus	5.9
Sodium	2.6
Chloride	5.8
Potassium	8.5
Magnesium	1.6
Iron	0.149
Copper	0.005
Manganese	0.044
Zinc	0.155

2.1. Specimen Preparation

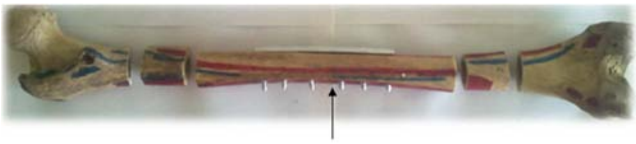
The femur bone is the longest bone in the human structure and carries much load. During functioning it undergoes a variety of varying loads which may leads for the failure of the femurs. The different parts of the femur have different strength and a prawn to different varieties of loads. Because of this reason the specimens from different regions have been taken to evaluate its strength under bending and impact loads.

Three bending specimens of size 186 mm lengths were obtained from mid regional 3 dead male femoral shafts. Since the mid shaft region is highly influenced by bending loads and impact loads the specimens for which have been taken from the same regions as shown in fig. 2. The specimen prepared without any implant for bending test is shown in fig 2.a. The specimen implanted with dynamic compression plate (DCP) with six screws, of SS316L shows the portions of shaft taken for testing the bone under bending load with implant and in fig 2.c the specimen with a co-axial crack is prepared for impact loading.

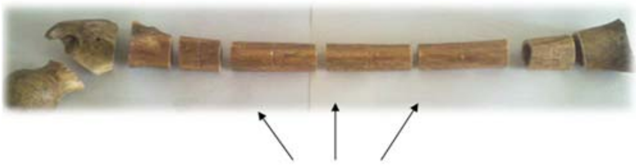
HUMAN FEMUR BONE



a) bending without implant test specimen



b) implantedbending specimen



c) impact test specimens

Fig. 2. *Portion of the shaft region taken for bending and impact loading.*

2.2. Impact Test

The impact test specimens of the proximal, distal and middle regions were tested in a low velocity pendulum impact testing machine. The impact setup is as shown in the fig 3. The experimentation was conducted on both notched and unnotched specimens.

NotchedUn-notched

Fig. 3. *a) Impact test specimen b) Testing on Impact testing machine.*

A pendulum type ‘Charpy Impact testing machine’ was used for impact testing. The experiment is carried out to describe the intensity of impact loading and to determine the relative impact resistance of bone material. In case 1 the specimen is arranged with the notch on either side way from the striking edge of the pendulum and in line with the pendulum. Release the pendulum to rapture the specimen and energy to rapture is observed.

2.3. Bending Test

The flexural modulus of elasticity of the cortical bone specimens was determined by performing three point bending test to failure. Bone stiffness as measured in three point bending tests depends on bone structure (that is shape and internal architecture) and bone tissue level material properties.Since the femur is a longest bone, it is highly sensitive to bending loads, that too in the mid shaft region. Due to this reason the specimens prepared out of mid shaft region were loaded in the UTM, in a controlled loading conditions. The bending tests were carried out for both normal and a bone with implant. The experimental setup is as shown in fig. 4.

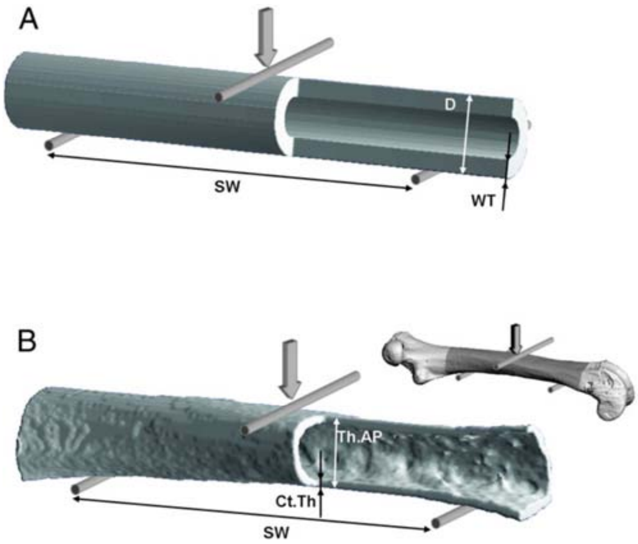


Fig. 4. *a) Bending test specimens b) Test on UTM.*

A Universal Testing Machine (UTM) was used for bending test. Bending test was performed in a custom designed 3-point bending test. The lower supports were spaced 130mm and the upper indenter was centered between the lower supports. Bending load was applied in anterior direction which increased the native ante-curvature of the diaphysis. In case 1, the specimen implanted with dynamic compression plate (Dynamic Compression Plate) with six screws, of SS316L. In case 2, the specimen is without any implant and in case 3, the specimen with a co-axial crack.

3. Results and Discussion

In mechanical testing of human femur is limited by the highly variable material properties of bone. This study presents a long bone model designed to match the mechanical properties like hardness bending strength, fracture toughness and impact strength of femur.

3.1. Hardness of the Different Femoral Regions

Bone is a complex highly organized and specialized connective tissue. Bones are made up of a mixture of hard materials that gives them the strength. Bone contains lot of calcium. Bone differs from other type connective tissues in matrix, which is highly calcified. Due to this bone contains about 70% bone salt in the form of minute crystals of calcium hydroxypatite. The rest is 20% organic matrix and 10% water. The dispersion of these minute crystals is not uniform throughout the femur. In a femur the three major regions of highly load bearing capacities are cortex, tensile fiber and compression fiber is shown in fig 4. The Rockwell ‘C’ test has been conducted on three major regions (like proximal, mid shaft and distal regions), of the femur. The results of which have been tabulated in the table 2.

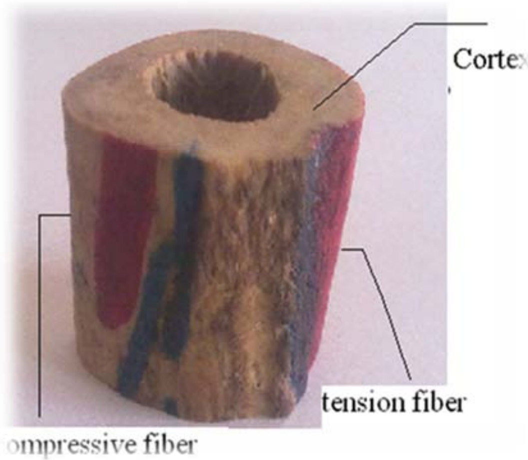


Fig. 5. *Different regions of hardness test specimens.*

The maximum hardness is obtained in the distal end at the tension fiber in femur shaft (that is 45.30 RHN No.) and at compressive fiber (that is 32.5 RHN). The minimum Hardness obtained in proximal end at cortex region (that is 21.56 RHN).

It can be observed from the table 2 that hardness of the femoral shaft is more at distal region in tension fiber i.e 45.30 RHN and minimum at cortex that is. 21.56 RHN and the hardness of the femoral shaft increases from proximal to distal region.

Table 2. *Hardness of femur in different reagions.*

Femoral Regions	RHN		
	Cortex	Tension Fiber	Compressive Fiber
Proximal	21.56	24.5	22.16
Mid Shaft	23.00	32.25	27.66
Distal	24.91	45.30	32.50

The maximum hardness is obtained at the distal region of the femur and minimum hardness is obtained at the proximal region of the femur. In the longitudinal direction of the femur the hardness seems to be increasing from proximal, this is because of the maximum dispersion of the calcium and the hard growth of the bone in these regions. The hueso compact region has lees hardness compared to the other two regions because of the layered composition and nature of the femur.

3.2. Behavior of Femur UnderImpact Loads

Large varieties of impact loads will come on different regions of the femur. In the present analysis the hardness has shown drastic variation in three different regions of the femur. Due to this reason the impact tests have been carried out on those regions. All the full scale specimens have been subjected to a low velocity impact in a pendulum type impact testing machine with the load 147.15N. The energy absorbed by the bone before fracture has been recorded and the impact energy is calculated. The results of which have been tabulated in table 3.

Table 3. *Result table for impact test.*

Femoral Shaft Regions	Impact Energy Absorbed in N-mm		Impact Strength in N/mm	
	Without Notch	With Notch	Without Notch	With Notch
Proximal Regional	8134	2058	20.713	6.400
Mid-Shaft Regional	7448	1960	18.966	6.102
Distal Regional	6860	1764	17.460	5.490

The results obtained by this are summarized as in case 1, impact strength of proximal region IE_{max}= 20.714 N/mm, mid-shaft region IE_{max}=18.966 N/mm, distal region IE_{max}=17.46 N/mm and IE_{max}=6.40N/mm, 6.102 N/mm and 5.49 N/mm respectively. Impact test related graphs are drawn based on the experimental results. From the table it can be seen that the impact energy is found be maximum in proximal region where the hardness is very less and it found to be less in distal region where the hardness is very high. Similar behavior is observed in cracked specimens also. The experimental results have been graphically shown in fig 6 and fig 7.

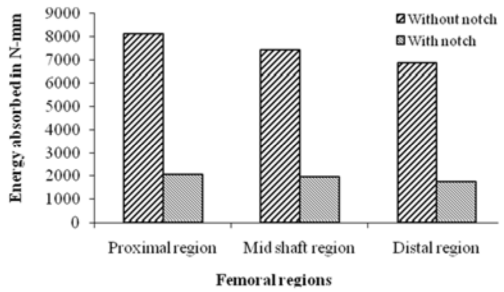


Fig. 6. *Impact energy absorbed in different regions of femur.*

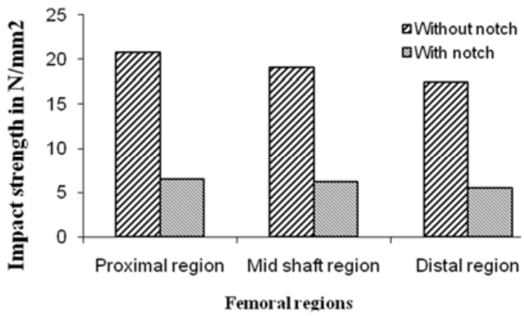


Fig. 7. *Impact strength of femur.*

The figures clearly reveal that the impact strength is very high in proximal region because of the maximum absorbed energy. Since the hardness is found to be less in proximal region a maximum amount of energy has been absorbed by the specimens before failure. The crack has been propagated in a plane strain direction as shown in fig. 8. The growth of the crack seems to be slow as compared to the distal region. Furthermore no longitudinal cracks have been observed in proximal region as shown in fig 9a. In case of the distal region because of the high hardness growth of the crack is fast and also the multiple longitudinal cracks can be seen as shown in the fig 9b. Because of this reason the distal region has less impact energy.

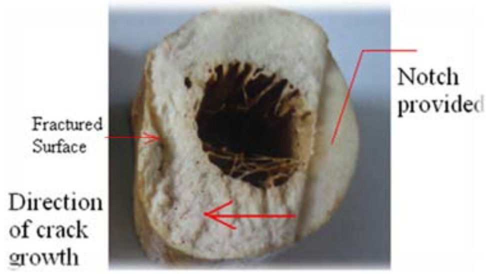


Fig. 8. *With crack specimen subjected to impact load.*

Fig. 9. *a) Proximal regional and b) Distal regional (with crack) specimen subjected to impact load.*

Fig. 10. Proximal and Distal regional (without crack) specimen subjected to impact load.

The untracked specimens have been failed with multiple fractured as shown in fig. 10. In this case also the proximal region has found to be strong under impact loads. The experimental analysis under impact loads has shown that the distal region is highly prawn to the impact loads. Also are impact on a pre cracked (distal region) femur will lead to the multiple fractures which may not be healed precisely and also very difficult for implantation. And it is observed that the impact energy absorbed as well as impact strength of the femoral shaft decreases from proximal to distal region.

3.3. Effect of Bending Load on the Behavior of Femoral Shaft Fracture

The past literature has revealed that, among all regions of the femurs the shaft is highly sensitive to bending loads. Also it is found that maximum fractures will occur in the femoral shaft. The plate implantation is the most common procedure adapted for fracture healing. Because of this reason in this experimental analysis the femoral shaft has been tested under bending loads. Three point bending test was carried out on human femur of 186 mm length and average of 30 mm diameter. The testing has been carried out on three different types of specimens namely,

- Without implant with crack depth of 0.5 mm.
- With implant with crack depth of 0.5 mm.
- With a co-axial crack with crack depth of 0.65 mm.

The raw data of load – displacement were obtained by testing. When the bending deformation becomes high enough so that the stress in the specimens exceeds the tensile strength, a set of crack developed and suddenly the specimen get fractured. The raw data obtained from the UTM. The bending strength, the modulus and fracture toughness have been evaluated is shown in the table 4.

Table 4. *Bending test resuts.*

BENDING TEST				
Specimen Type	**Deflection in mm**	**Maximum bending stress in N/mm^2**	**Young's modulus in Gpa**	**Fracture Toughness in Mpa-mm$^{1/2}$**
Without Implant	2.52	113.23	129.54	141.91
With Implant	0.83	72.05	250.28	90.30
With Crack	1.72	22.30	37.38	31.86

The load-deflection data obtained from the UTM has been graphically represented in the fig. 11. This plot has been plotted to study the effect of load and the growth of crack in the femoral shaft. The summary of the results for the structural bending property of the femur is obtained in case1 as, Maximum bending stress (σ_{max}) 113.23 N/mm^2, Modulus of Elasticity (E) 129.54 GPa and Fracture toughness (K) 141.91Mpa-mm$^{1/2}$ compared with case2 and case 3 are, case 2; σ_{max}= 72.05 N/mm^2, E= 250.28 Gpa, K=90.30 Mpa-mm$^{1/2}$ and in case 3, σ_{max}= 22.30 N/mm^2, E=37.38 Gpa and K=31.86 Mpa-mm$^{1/2}$. Depend on obtained experimental results the load/deflection and mechanical property graph are plotted below.

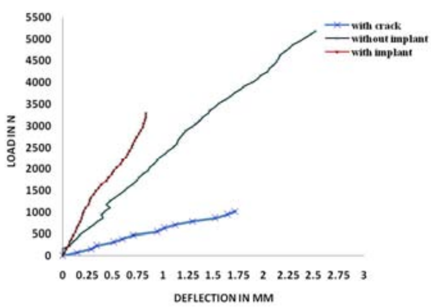


Fig. 11. Load /deflection graph of femur.

The fig. 11 shows the bending load carrying capacity of femur at maximum deflection in different cases. From the fig 11 it can be seen that the maximum load carrying capacity of femur without implant is 5179.68 N with maximum diflection of 2.52 mm. Maximum load 3296.16 N (diflection 0.83 mm) and 1020.24 N (diflection 1.72 mm) in with implant and with crack cases respectively.

From figure, it can be observed that the specimen with longitudinal crack has shown a very less load bearing capacity. From this it can inferred that femoral shaft with the longitudinal crack is highly prawn to bending loads and the longitudinal crack has proved to be the most dangerous type of crack. The trend of the curve for with and without implant is almost same, except that the load carrying capacity is higher in the implanted bones. But the deflection permitted by the bone with implant is far less than that of the bone without implant. Due to this reason it can be stated that, reloading of the femoral shaft under bending loads is most dangerous.

From these values of load displacement and the trends of the curves obtained the maximum bending stress, young's modulus and fracture toughness have been evaluated and are shown in the fig. 12.

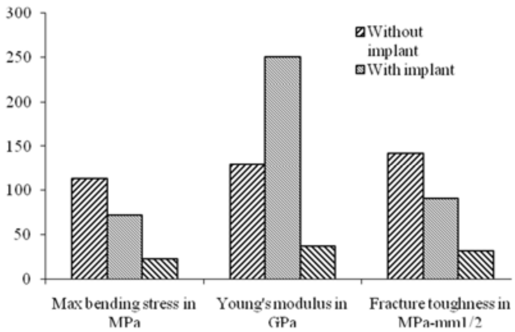


Fig. 12. Bending properties, a) without implant b) with implant c) with crack.

The bending stress is found to be very large in the specimen without implant. This is mainly because of the maximized load bearing capacity and the maximum permitted deflection. The behavior of the fractured specimen under bending loads is as shown in the fig. 13.a. The maximized bending stress and the fracture toughness have been obtained mainly because of the less hardness and the slow growth of the crack. The nature of the crack initiation, propagation and the final fracture can be seen in the fig. 13 a, b and c respectively.

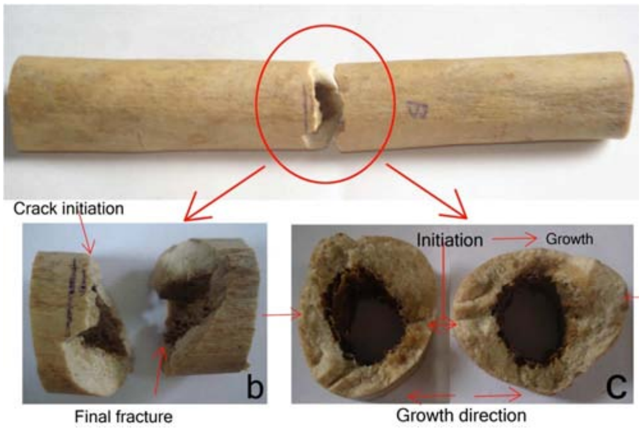


Fig. 13. Without implant bending test specimen after test.

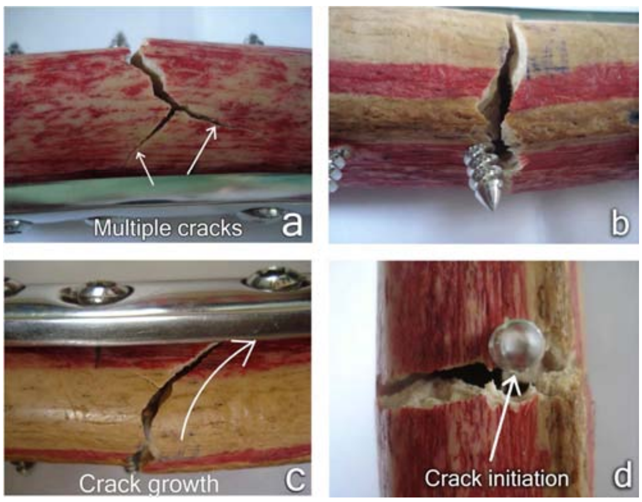


Fig. 14. With implant bending test specimen after test.

Fig. 15. With crack bending test specimen after test.

The specimen with plate implanted after failure has been shown in fig. 14 a, b c and d. It can be observed from the figure that the bending load at a minimum level has initiated a crack in a region where there is maximum stress concentration. The maximized stress concentration is present in the vicinity of the drilled holes in which the screws are present in the fig. 14 b and c. It can be observed in the fig 14a that a multiple cracks have been originated in the implanted bone. Due to this reason the fracture toughness is found to be very less.

In case of longitudinal cracked specimen the growth rate is very high and the bone will fail with a minimum load, the crack growth is found to be unstable. This leads for the sudden failure of bone in two halves. Such types of failures are most critical and almost much difficult to get healed, a typical fracture in a bone with such type of crack is shown in fig. 15.

4. Conclusions

From the experimental analysis carried out on human male femoral bone of age 20-30. The following conclusions were drawn.

- During normal activities, the femur is sensitive to different types of loads and different regions of femur process different mechanical properties. These mechanical properties like hardness, impact and bending characteristics vary from region to region because of its composition.
- The hardness of the femur shaft increases from proximal to distal region. Hardness is maximum at distal region and is found to be minimum at proximal region.
- Because of the variable hardness impact strength is more at proximal region and less at distal region. The impact loads on a pre-cracked bone, leads to the initiation and propagation of cracks these cracks may

not be multiple healed preciously and also difficult for implantation.

- The maximum bending stress and the fracture toughness is obtained more in non-implanted bone and less in pre-cracked bone. But in case of implanted bone, the young's modulus obtained is more because of maximum load bearing capacity with minimum deflection.
- From the experiments, it can be stated that different regions of femur bone are prawn to different loads and the reloading of femoral shaft with an implant is most dangerous because it leads to the formation of multiple cracks which cannot healed properly.
- The reloading of the femoral bone with an implant is most dangerous and the initiation and propagation of crack and the bone failure is unpredictable.

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