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# EXPERIMENTAL AND NUMERICALFRACTURE TOUGHNESS OFHUMAN BONE INLINEAR ELASTIC ANDELASTIC-PLASTICFRACTURE MECHANICS IN VITRO

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**Abstract:** In this search, study and investigate is done on the fracture toughness in linear elastic and elastic-plastic fracture mechanics LEFM and EPFM for each cadaveric bovine cortical bone and human cortical bone. Fresh and frozen human cadaveric cut as a compact tension CT specimen from the tibia for five males are prepared from the forensic medicine department ages (25, 31, 39, 45 and 51) years and (18) months for bovine cortical bone are examined, where no known skeletal pathologies. The crack length is measured without removed the specimen from the grips by using ZBL F101 technique. The experimental results are compared with numerical analysis by ABAQUS program. Roughness of fracture surface for each bovine and human specimen is examined by scanning electron microscope SEM. The appropriate method for cutting the bone has been studied. The results showed that the fracture toughness of bovine $K_C$ is greater than by 111% of human cortical bone and vice in the strain energy release rate $G_C$ for human is greater than by 124% of bovine cortical bone. So, the fracture toughness in elastic-plastic fracture mechanics showed that the $J_C$ for bovine is 108% greater than human cortical bone,but gets the opposite in crack tip opening displacement toughness $\delta_C$ where is larger in human approximately 106% as compared with bovine cortical bone. The numerical results are showed agree with experimental results. From this work, the elastic- plastic fracture toughness ($\delta_C$and $G_C$) for human cortical bone is larger than the bovine cortical bone that due to prevent the catastrophic failure when exposed to loads. The fracture surface of bovine cortical bone specimens is rougher than the fracture surface of human bone specimens.The appropriate method for cutting the bone by using the hand saw.

**Keywords**: *Fracture toughness in vitro of human bone; linear elastic of human bone, elastic-plastic of human bone in vitro, toughness of human bone in vitro*

## دراسة متانة العظم خارج الجسم في الحالة اللدنة والمرنة لميكانيك الكسر عمليا وعدديا

**الخلاصة:**هذا العمل تضمن دراسة متانة العظام لكل من العظام البشرية والبقرية في الحالة المرنة اللدنة والمرنة الخطية في علم ميكانيك الكسر. جميع عينات العظام كانت لجثث أشخاص حديثي الوفاة ومجمدة حيث ان العظام البشرية لاشخاص اعمارهم (51,45,39,31,25) سنة جهزت من الطب العدلي وبالنسبة للعظام البقرية كان معدل العمر لها 18 شهر غير معروفة الامراض الهيكلية. استعملت تقنية مشاهدة انتشار الكسر وطوله مباشرة. دراسة خشونة سطح الكسر للعظمين البقري والبشري بواسطة المجهر الالكتروني الماسح.تمت مقارنة النتائج العملية مع نتائج الرنامج العددي ABAQUS تم دراسة الطريقة الافضل لقطع عينات العظام. بينت النتائج العملية متانة العظم في الحالة المرنة الخطية تركيز الاجهاد اكبر في العظم البقري بمقدار 111% منه في البشري, ويحصل العكس في حالة طاقة الانفعال المتحررة حيث تكون في العظم البشري بمقدار 124% اكبر من في العظم البقري. كذلك ميكانيكية الكسر في الحالة اللدنة المرنة فتكون متانة العظم كالطاقة المتحررة اثناء الكسر في العظم البقري بمقدار 108% اكبر منه في العظم البشري اما بالنسبة لمتانة ازاحة راس فتحة الشق فتكون في العظم البشري بمقدار 106% اكبر منه في العظم البقري. نستنتج من هذه الدراسة ان متانة العظم في حالتي متانة ازاحة

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راس فتحة الشق والطاقة المتحررة في الحالة المرنة الخطية في العظم البشري اكبر منه في العظم البقري حيث يدل ذلك على تحمل العظام للفشل المفاجئ الذي يحصل اثناء تعرضها للاحمال. كذلك تم ايجاد ان خشونة السطح لعينات العظم البقري المكسورة هي اخشن من سطح عينات العظام البشرية المكسورة.اظهرت النتائج التحليليةتطابق مع النتائج العملية.الطريقة الافضل لقطع العظام في هذه الدراسة هي بواسطة المنشار اليدوي.

## 1. Introduction

Bone is as a natural polymer, anisotropic and a specialized tissue qualified for changing its structure accordingly stresses results to which it is subjected; bone consisted of fibers, matrix and cells [1]. It's tough because having a degree of elasticity (presence of organic fibers) and calcination of its extracellular matrix. In the face of apparently freezing in a solidified state, have basic physiological functions [1]. First, simultaneously with the kidney and intestine. It subsists in two shapes: compact and cancellous ; cancellous bone consists of a branching network of trabeculae.

The bone consists of (i) cortical and cancellous bone macrostructure level; (ii) system of haversian (osteons) trabeculae or interstitial tissue at the sub millimeter scale; (iii) the lamellae comprised canaliculi and lacunae at the micron level; (v) collagen fibrils and mineral matrix at the sub-micron scale and (iv) collagen, water molecules and mineral crystals at the nanometer level [1]. Also, there are several important features in bone like, cells of bones, non-collagens proteins, spread patches and damage in the shapes of linear microcracks[1]. Despite that, (i) mainly consists of collagen (90%) and the organic matrix of bone occupies about (32%) of the volume of bone but important quantity of non-collagenous proteins, such as osteonectin and osteocalcin, (ii) the mineral phase occupies about 43% of the bone volume and consisted of primarily phosphate and calcium with small considerable amounts of carbonate and (iii) water makes up to 25% of the volume of bone and is spread during the tissue in distinct shapes on free ambulant in lacunar- canalicular - vascular space [1]. Fracture toughness of bone or bone's resistance to fracture is divided into fracture toughness in LEFM ($K_C, G_C$) and fracture toughness in EPFM ($J_C, \delta_C$).

## 2. Literature Survey

Norman and Burr (1996) studied resistance the bone to crack growth, they hypothesized that resistance of human bone to crack growth under shear loading is greater than under tensile loading. The specimens from the human's tibias of nine males aged (mean 73.3 years) and six females aged (mean 77.7 years) and found that the strain energy rate $G_{Ic}$ of shear loading is 6000 N/m but, $G_{Ic}$ of tensile loading is 400N/m. Also, they found the variation of $G_{Ic}$ with age (550-2.84*age) and (13711-128.4*age) for both tensile and shear testing respectively [2].Zioupos and Currey(1998) investigated the effect of age on the five mechanical properties (fracture toughness $K_c$, $J$ integral, flexural strength $\sigma_f$, work of fracture $W_f$ and modulus of elasticity E) of male's human femoral aged between (35-92) years.These properties decreases with agebecause the effects of diseases and deteriorating [3].

Vashishth(2004) determined the comparison R curve between bovine bone and antler through crack growth resistance. They concluded that antler cortical bone demonstrated lower initiation than bovine bone and greater slope value for antler bone. The increase in R curve back to experience plasticity during fracture. Plasticity in a quasi-brittle material comes from microcrack formation in front and the process zone [4].Nalla (2005) found the resistance curve of human cortical bone. The fracture resistance increased with crack length (i.e.rising resistance). By x-ray tomography indicated that the bridging zone extends for some 5mm or so behind the crack tip. They used compact tension specimen from human cortical bone in the testing [5]. Yan (2007) investigated elastic-plastic of fracture mechanics (EPFM) of bone in the two orientations transverse and longitudinal. They concluded that the transverse EPFM properties more than of longitudinal. Single-edge notched specimens were cut from the mid diaphysis of two bovine femurs. The fracture surface of transverse specimens is much rougher than from longitudinal specimen indicate that more energy was consumed in the transverse specimen [6].

## 3. Aims of this Research

This study aims at:

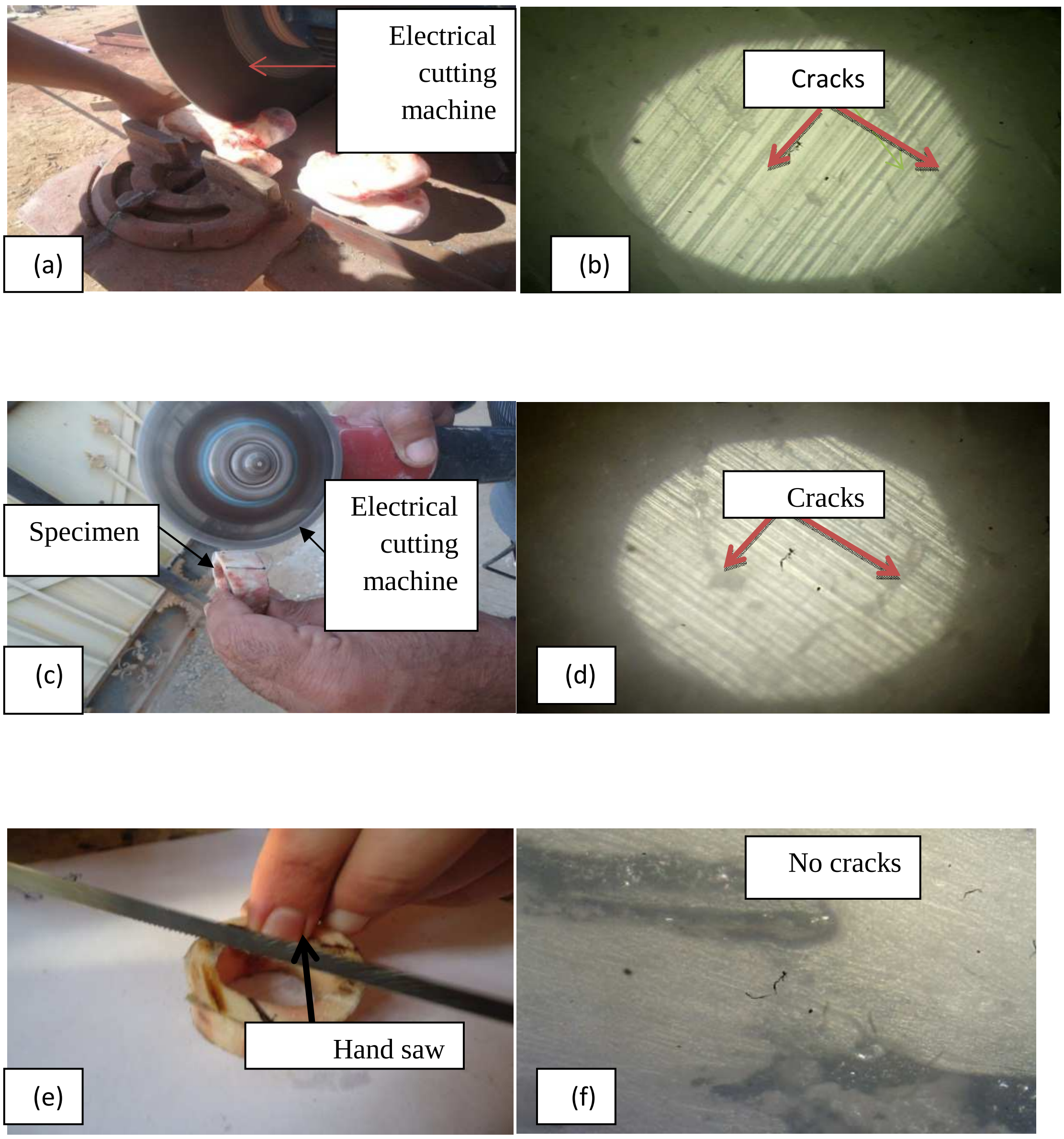
- Inspecting the appropriate method for cutting the bone.
- Studying the fracture toughness in LEFM and EPFM for each cadaveric bovine cortical bone and cadaveric human cortical bone by design and manufactured tensile fatigue rig.
- Inspecting the roughness of the fracture surface for each cadaveric human cortical bone specimens and cadaveric bovine cortical bone specimens by scanning electron microscope SEM.

## 4. Types of Procedures

### *4.1.* Experimental Procedures

For this work, the tensile fatigue equipment is design and manufactured because not available in the Iraq universities. The tensile fatigue rig consists of the frame that manufactured from cast iron with thickness 7mm and width is 98mm, throttle valves to control on the load, sensor and indicator of displacement (type SF 648J)that imported from China that used to estimate the displacement in fracture toughness test, online monitor, pneumatic(FESTO, max pressure 12bar, DNC-63-45, PPV-A, and the piston length is 40mm and diameter is 10mm), compressor ( TATA air compressor, max pressure 12 bar) , sensors (FESTO), solenoid (FESTO, max pressure 8 bar) , are designed and used to give the linear motion and the tensile load, grips, limit switch(type: WL. NJ S2)and counter(type: ZSUOB, JDM 11-6H) to calculate the number of cycles, load cell and weight indicator to estimate the applied load, limit switch and contactor to shut down the rig when the specimen is failed, grips and finally the rig is covered with alucobond and connect the indicators on it as shown in figures (3), (4) and (5).

Online monitoring technique (ZBL F101) is imported from China and used to measure the crack length without removing the specimens from the grips at the moment. This tensile fatigue rig is used to inspect the tensile fatigue and fracture toughness test for all materials. To get accuracy in the results, the appropriate method for cutting the specimens of the bone is inspected. Three methods for cutting the specimens are examined, the first method involved cut of specimens by electrical machining cutting tool with diameter 60 cm as shown in figure (1-a) where there are cracks on the cutting surface as shown in figure (1-b), the second method included cut of specimens byan electrical machining tool with a diameter 12cm as shown in figure (1-c) where there are cracks on the cutting surface as shown in figure (1-d) and the third method included cuts of the specimens by hand saw as shown in figure (1-e) where there are no cracks on the cutting surface as shown in figure (1-f).



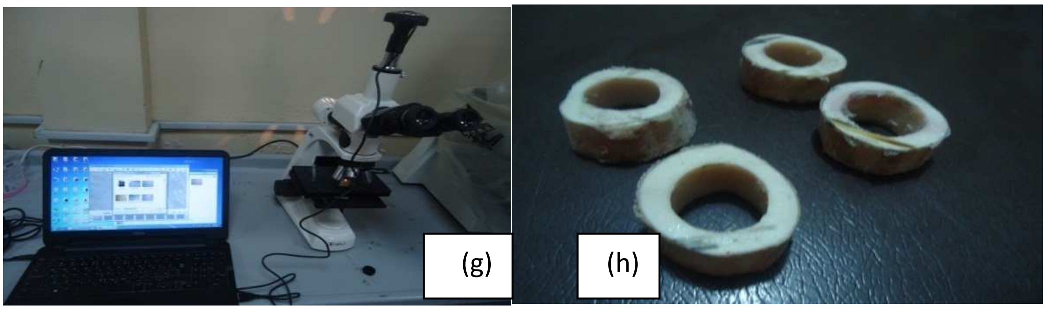



Figure (1). (a) Cutting of bone by electrical cutting machining (diameter of the disc is 60cm), (b) the microscopic inspecting of surface in figure (a), (c) cutting of bone by electrical machine (diameter of the disc is 12cm), (d) the microscopic inspecting of fracture surface in figure (b), (e) cutting the bone by hand saw, (f) the microscopic inspecting of fracture surface in figure (e), (g) The electron microscope in Almustansirya University- Materials engineering department (Type: MEIJI. Made in Japan, USB with camera, 400X) and (h) the specimens of the bone after the cutting.

All fracture surfaces of the cadaveric bovine cortical bone after the cutting by three methods is inspected by electron microscope as a figure (1-e). The appropriate method is used the hand saw because there is no crack and the heat generated from the cutting is small. Before the testing of the fracture toughness for each bovine cortical bone and human cortical bone, the specimens of bone are tested according to ASTM D 638-Type V because the bone is a natural polymer [7] in University of Technology-Materials Engineering Department (type LARYEE, 50KN, WDW-50, China) as a figure (2) illustrated.Fresh and frozen cadaveric human cortical and bovine bone was cut from mid cortical of the tibia, the cadaveric human bone is prepared from the forensic medicine department for persons ages (25, 31, 39, 45, 51) years and the age of cadaveric bovine cortical bone is 18 months.The tensile specimens were cut from the mid cortical bone in the longitudinal direction by hand saw and the gage length is prepared by milling machine as shown in figure (2). In this work, the specimens in all testsare kept in buffered phosphate saline to maintain the properties of the bone during the test for period time is two days because the test is in vitro.

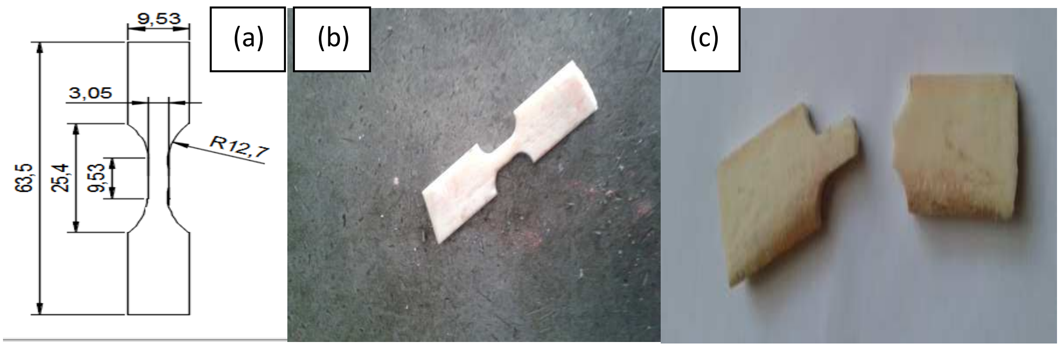



Figure (2). (a) The dimension of the specimen of tensile test for the bone according ASTM D638 [7]. Type V, all dimensions in mm, (b) and (c) The tensile test specimen of the human bone before and after the failure respectively.

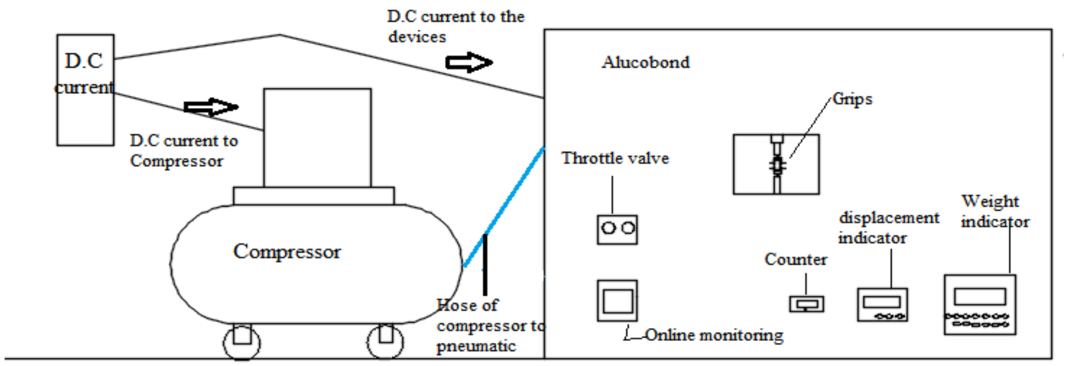



Figure (3).Schematically of the final assembly of tensile fatigue rig after the indicators is covered by alucobond plate.

For Fracture toughness testing, the specimens cut as compact tension CT specimens according ASTM E399 with the width is 14 mm [8] as shown in figure (6). The specimens were cut from mid cortical bone by hand saw in the transverse direction and the crack is prepared by milling machine in perpendicular direction on the osteon as a figure (6) illustrated. All specimens are immersed in buffered phosphate saline to maintain the properties in vitro to the end of the test. The loading rate that used in the work is 1 mm/min to prevent the failure.Where the load is applied at loading rate is 1mm/min for each crack and the displacement sensor is estimated the crack mouth opening displacement CMOD. After the specimens are failed, the load- CMOD is concluded. In order to understand the mechanical properties of bone materials, it's important to understand the mechanical properties of its component phases, and the structural relationship between them at the various levels of the hierarchical structural organization [11].

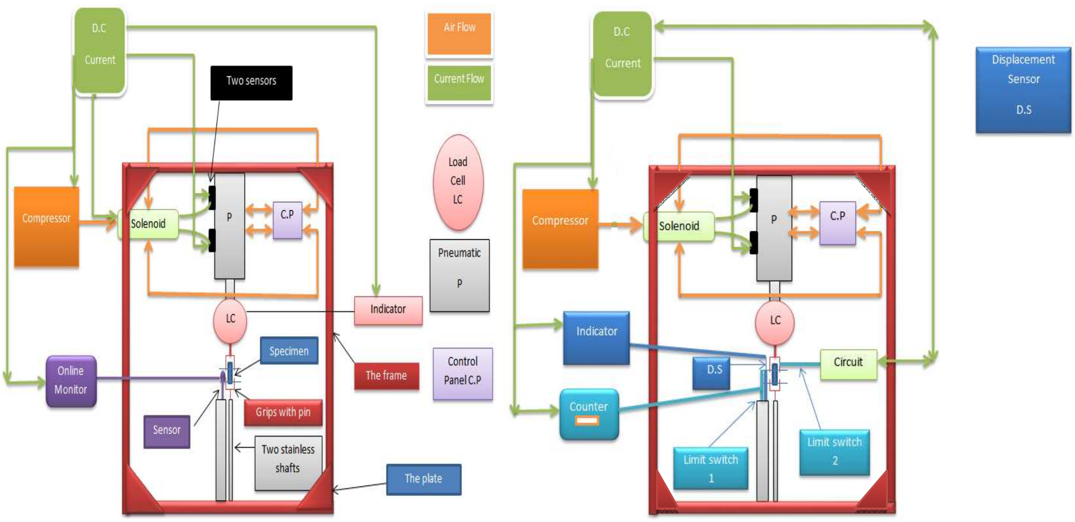



Figure (4). Schematically of tensile fatigue rig that designed and manufactured by Al-Mustansiryah University- Collage of Engineering- Mechanical Department.

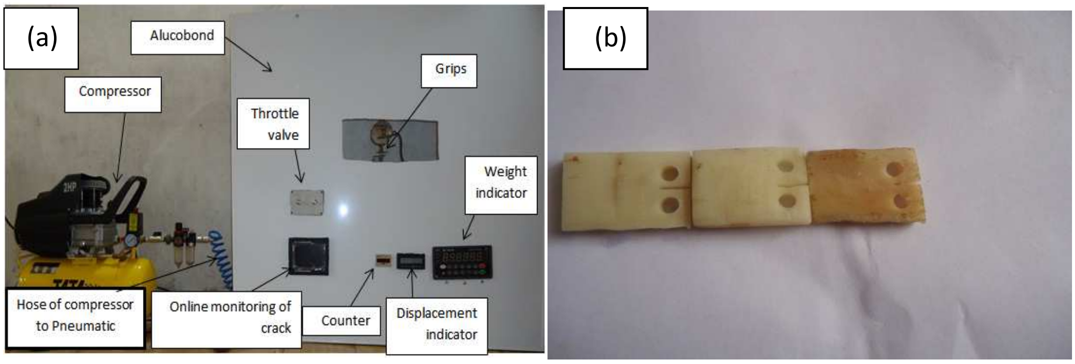



Figure (5). (a) The tensile fatigue rig and (b) The compact tension specimens of human bone that used in fracture toughness testing according ASTM E399 [8].

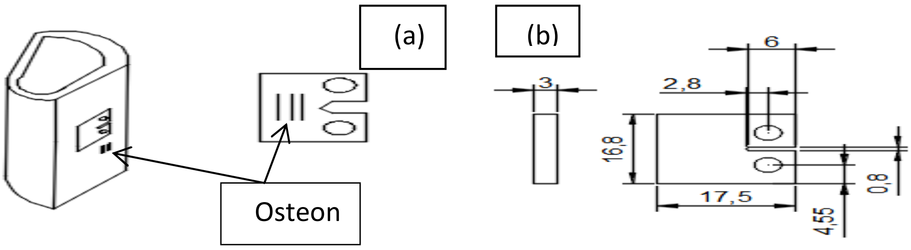



Figure (6).(a) The direction of the crack on the osteon in the bone and (b) The dimensions of the CT specimen that used in this work, where all dimensions in mm according ASTM E399 [8].

These levels and structures are; (1) the macrostructure: cancellous and cortical bone; (2) the microstructure (from 10 to 500 $\mu$m): Haversian systems, osteons,single trabeculae; (3) the sub-microstructure (1-10 $\mu$m): lamellae; (4) the nano structure (from few hundred nanometers to mm); fibrillar collagen and embedded mineral; (5) the sub nano structure (below a few hundred nanometers): molecular structure of constituent elements, like nano collagen organic proteins and mineral collagen. This hierarchically organized structure irregular, yet optimized; orientation of the components and arrangement, making the material of bone heterogeneous and anisotropic [11]. Figure (7) shows the hierarchical and mechanism of fracture for the bone [11]. Finally, the roughness of specimens of cadaveric bovine cortical bone and cadaveric human cortical bone are inspected by scanning electron micrograph SEM in Technology University- Baghdad- Iraq and the properties of SEM are (VEGA/TESCAN), SEM MAG: 1kx, SEM HV: 10 kv as shown in figure (8). From the Figure (8) is shown that the roughness of fracture surfaces for each specimen of bovine cortical bone and human cortical bone, the fracture surface of bovine cortical bone specimens is rougher than the specimens of human cortical bone because the bovine cortical bone is tougher than human cortical bone.

The differences between human cortical bone and bovine cortical bone are belonging to osteon density, water content and hierarchical.

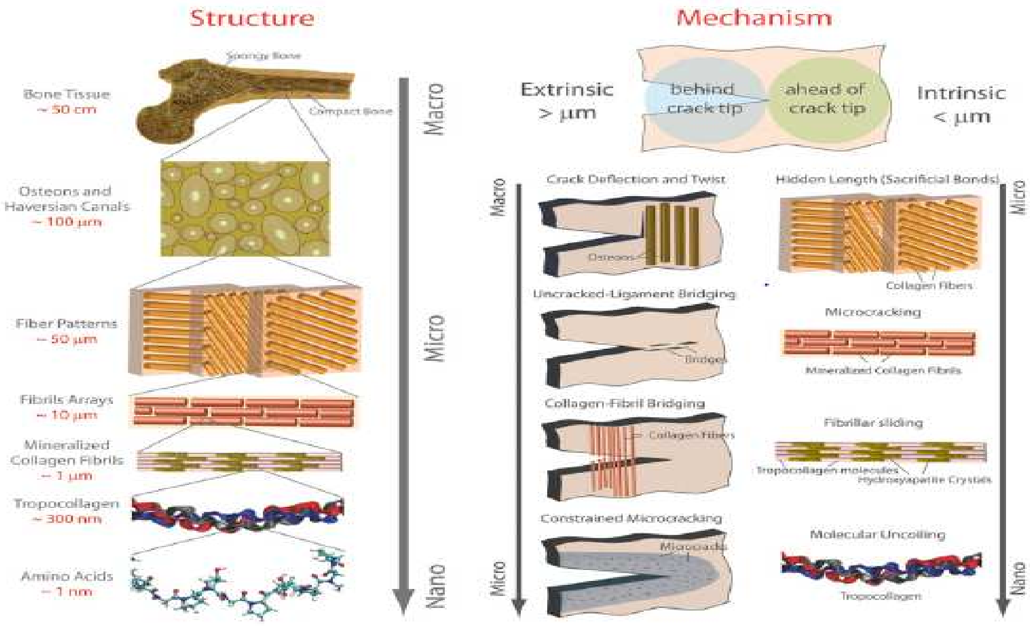



Figure (7).The mechanism of the fracture and hierarchical of the bone [11].

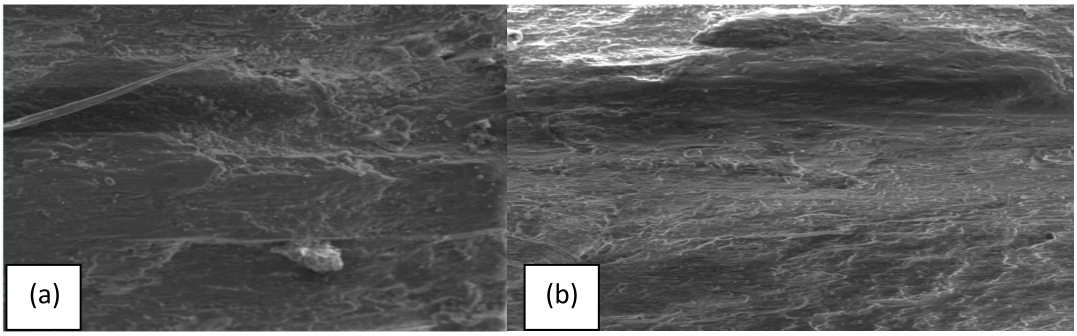



Figure (8). (a) The roughness of the fracture surface of human cortical bone specimens and (b) The roughness of bovine cortical bonespecimensby scanning electron micrograph SEM (VEGA/TESCAN), SEM MAG: 1kx, SEM HV: 10 kv.

### *4.2. Theoretical Procedures*

Fracture mechanics is the science that deals with cracks, unexpected failure of weapons, bridges, ships, trains, airplanes, bones (in the present study) and various mechanics has occurred throughout the industrialized world. It is divided into two analytical approaches LEFM and EPFM [8]. In this work, a compact tension CT specimen of bovine and human cortical bones is used and that due to mention a relationship related with CT specimens in metals or polymer because the bone as a natural polymer. The relationships of the fracture toughness in metals that used in this study are concluded from ASTM E399 [8]. Fracture toughness in fracture mechanics is divided into fracture toughness in LEFM and EPFM [9]. Fracture toughness in LEFM is represented by stress intensity factor toughness $(K_C)$ and strain energy release rate toughness $(G_C)$ but, the fracture toughness in EPFM is represented to the energy that consumed during fracture ($J_C$) and crack tip opening displacement CTOD ($\delta_C$) [9]. Stress intensity toughness can be calculated by eq. (1) and eq. (2) [8]:

$$K_i = \frac{P_{(i)}}{B\sqrt{W}} f(\frac{a_{(i)}}{W}) \qquad (1)$$

$$f\left(\frac{a_{(i)}}{W}\right) = \frac{2+\frac{a_{(i)}}{W}}{(1-\frac{a_{(i)}}{W})^{\frac{3}{2}}}\left[0.886 + 4.64\frac{a_{(i)}}{W} + 13.32(\frac{a_{(i)}}{W})^2 + 14.72(\frac{a_{(i)}}{W})^3 - 5.6(\frac{a_{(i)}}{W})^4\right] (2)$$

Where $P_i$: The load at each crack length and $B$, $w$ are the thickness and the width of the specimen respectively.
To calculate the strain energy release rate$G_I$,eq. (3)is used[8]:

$$G_I = \frac{K_I^2}{E^-} \qquad (3)$$

But,it was a great success as a fracture characterizing parameter for the behavior of materials is nonlinear. Through idealizing nonlinear elastic as elastic-plastic deformation, Rice established the basis for expanding the methodology well beyond the veracity limits of LEFM [5]. The $J$ integral has a unit energy/area. When the behavior of the material is linearelasticand the fracture toughness in EPFM that divided intothe energy that consumed through the fracture can be calculated by eq. (4) and eq. (5) [9]:

$$J = J_{el} + J_{pl} \qquad (4)$$

$$J = \frac{K_{(i)}^2}{E^-} + \frac{\eta_{(i)} A_{pl(i)}}{B_N b_{(i)}} \qquad (5)$$

And, it is the grade of blunting of crack that an increase in proportion to the material's toughness. Wells performed an approximate analysis that related crack tip opening displacement (CTOD) to the $K_I$ in the small scale yielding limit and CTOD toughness can be estimated by eq. (6) and eq. (7). CTOD is the distance between the mouth of the crack extension, where its calculatedin two scales yielding, elastic and plastic zone [9]. To calculate CTOD, $J$ integral and the area under load- CMOD is calculated as follows:

$$\delta = \delta_{el} + \delta_{pl} \qquad (6)$$

$$\delta_{(i)} = \frac{J_{(i)}}{m\sigma_{ys}} + \frac{[r_p(W-a_{(i)})]V_{pl(i)}}{[r_p(W-a_{(i)})+a_{(i)}+z]} (7)$$

### *4.3. Numerical Procedures*

A dimensionally scalable finite element model FEM of CT specimen for each human cortical bone and bovine cortical bone is developed. An elliptical fit was applied to parameterize each of outer contours. In the FEM, the architecture of interest is divided into separate shapes called elements. The most common element types one dimensional, like beams, two dimensional, like a plane strain or plane stress elements and three dimensional, like tetrahedrons or bricks. The elements are associated at node points where the continuum of the displacement fields is imposed [9].The parametric coordinates, which are also called local coordinates, differ from -1 to +1 during the element area; the upper right hand corner is at (+1,+1) in the local system while the node at the lower left hand corner has parametric coordinates (-1,-1). Note that the parametric coordinate system is not necessarily perpendicular. In this work, ABAQUS program is used fortheanalysis of the fracture toughness foreach bovine and human cortical bone and to compare with the experimental results. Finite element mesh was created within that volume.

A parametric FEM was developed in three steps: (1) semi- automatic extraction of bone properties data and outer surface geometry, (2) determination of the inner boundary of cortical bone, and (3) generation of quadratic finite element mesh. The typical crack analysis uses quadrilateral elements for two dimensional specimens, for example, the compact tension specimen (plane stress) that used in this study and brick element for three dimensional specimen [9].An FEM representing the original anatomy of the CT specimen of bone tibia was constructed using the methods just described. The nodal contains 1220 elements and 1310 nodes as shown in figure (9-b). Stress analyses were performed on all FEM. For meshing the specimen by ABAQUS, the mesh, seed edges and by number are applied as a figure (9) illustrated. Material properties of the bone were assumed to be isotropic and linear elastic; were based on similar data reported in this work. The Young modulus was (11.5) GPa for bovine cortical bone and (7.5) GPa for human cortical bone. The Poisson's ratio for the bovine cortical bone was 0.26 and for human cortical bone was (0.25) is calculated experimentally according ASTM D638 [7].

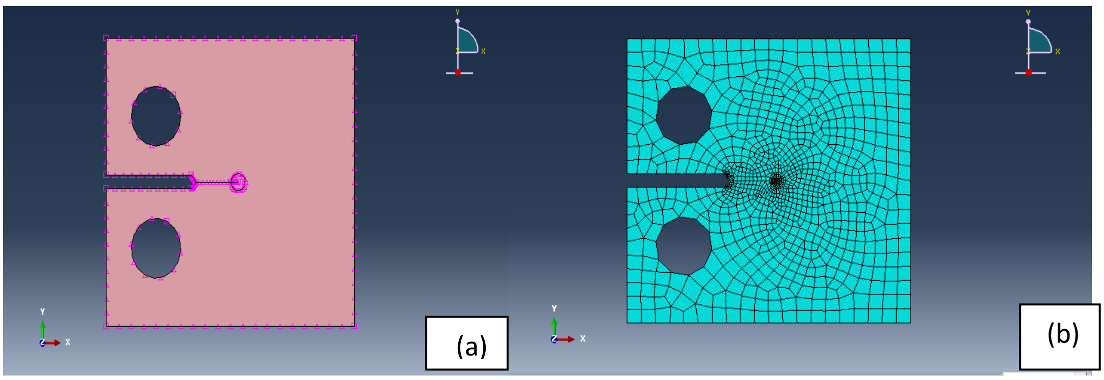



Figure (9).(a) The nodes in the specimen by ABAQUS program and (b) meshing of the specimen.

A single distributed vertical force from experimental load- CMOD in this work. An ABAQUS program is appropriate analysis is used to analyze the fracture toughness of bone because is giving the properties in EPFM and LEFM such as ($K_{C,} G_C$ $and$ $J_C$). Figure (10) shows the Von- Mises stresses in ABAQUS program about the crack in the CT specimen of the bone.

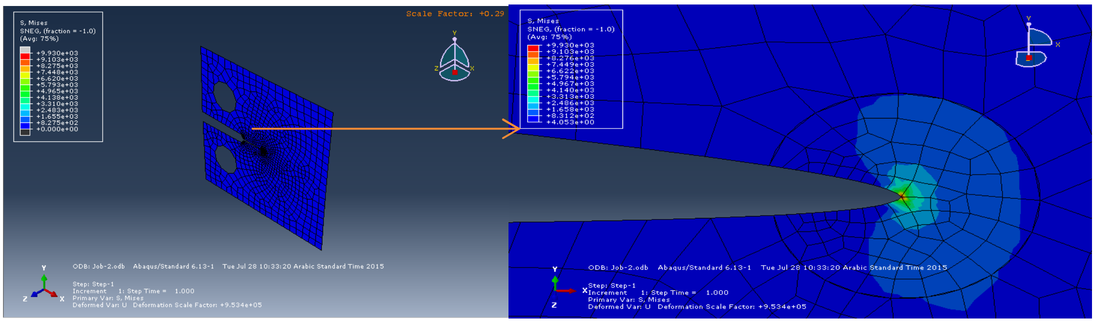


Figure (10).Von-Mises stress distribution about the crack of the compact tensionspecimen for bone by ABAQUS program.

## 5. Experimental, Numerical Results and Discussion

Because of the unstable behavior of the stress- strain and load- CMOD curve, the results in figure (11)and (12) show the bovine cortical bone is tougher than of the human cortical bone because the osteon density, mineral and water content of bovine is more than human cortical bone [1]. The behavior of the bone in tensile test is a brittle material as shown in figure (11).$K$-$R$ Curve is the relation between stress intensity factor and crack extension or root square of crack extension as a figure (13) illustrated. To evaluate the $K_C$ toughness by applying the equations(1) and (2).From figure (13) presents the stress intensity factor fracture toughness for the bovine and human tibia cortical bone and compared the results of the $K$-R curve in this study and the previous studies for bovine cortical bone and human cortical bone. The mechanical properties $(E, \sigma_y, \sigma_{ULT})$ in a tensile test for human cortical bone are (7.5 GPa, 67 MPa, 73 MPa) and for bovine cortical bone are (11.5 GPa, 94 MPa, 110 MPa) respectively.

The cortical bone showed a linearly rising resistance curve is a distinguishing of materials that experiment plasticity through the fracture. Plasticity in a quasi-brittle materials such as bone, produced from the formation of microcracks in behind (a zone defined as process region wake or wake) the tip of the crack propagation and a front (a region defined as a process zone).Microcracks produced in the frontal process region supply easy path for crack extension and expatiate crack tip stresses. Besides, the microcracks created in the shield the crack tip, wake and redeployment the stresses at the crack tip. Various studies on bovine and human cortical bone exhibit that microcracks are always current in bovine and human cortical bone [2].

Vashishth (2004) found increasing R-curve behavior for transverse growth of crack in bovine and antler bone, with average ($K_o = 4$ MPa m$^{0.5}$) and the slope of the rising R-curve is ($K = 0.8082 + 3.6829, r^2 = 0.9735$) [4].He used compact tension (CT) specimen and tested under load (0.05mm/min) in all studies. It was also noted that the cortical bone illustrated increasing R-curve behavior linearly, with mean crack initiation toughness, ($K_o = 2.169$ MPa m$^{0.5}$) for human cortical bone and ($K_o = 2.42$ MPa m$^{0.5}$) for bovine cortical bone bone. Also, it can be seen monotonically rising the $R$-curve values such as (slope $K = 3.914\Delta a - 0.6788, r^2 = 0.9707$) for experimental bovine cortical bone in the present study, ($K = 3.4804\Delta a - 0.5355, r^2 = 0.9614$ ) for experimental human cortical bone. The experimental results are approximately agreed with the numerical analysis results were ($K = 3.9022\Delta a - 0.7093,\ r^2 = 0.9666$) for the numerical analysis of bovine cortical bone and ($K = 3.4742\Delta a - 0.56635,\ r^2 = 0.9672$) for the numerical study of human cortical bone.These toughness data are partially larger than the results of Nalla (2005) where ($K_o = 3$ MPa $m^{0.5}$) and the slope of the curve rising is ($K = 3.1619\Delta a - 1.4789, r^2 = 0.9991$). They used the compact tension (CT) specimen of longitudinal direction for human bone (mean age 37.71 years) where the critical load approximately is 30 N [5].From the figure (14), the relation between $G_c$ and crack extension increases linearly for both human and bovine bone with a slope of R-curve ($G_c = 4.4331\Delta a - 3.6124, r^2 = 0.9433$) and ($G_c = 3.4405\Delta a - 2.7327, r^2 = 0.931$) for human cortical bone and bovine cortical bone respectively. The experimental results nearly agreed with the numerical analysis where the slopes of R-curve are ( $G_C = 4.5059\Delta a - 3.7168, r^2 = 0.9523$) and ( $G_c = 3.4573\Delta a - 2.7808, r^2 = 0.9314$) for each human and bovine cortical bone respectively.

Also, it may be noticed that the strain energy release rate is about (1.15-1.33) times higher for the human bone as compared to the bovine cortical bone. These results between crack length (3.8-6.8 mm) in the specimen represented the fracture toughness for bovine and human cortical bone. In unstable crack growth, the $G_C$ rising with crack growth. As a simple illustration for some specimens configuration the relations between $G_C$and $\Delta a$ are like that $G_C$ is corresponding to$a$. Thus, as $a$ increases, $G_C$ rises and stay over the critical value of $G_C$ propagation of the crack is unstable. Arithmetic differences occur between unstable (initiation) crack growth tests and stable (propagation) [2]. The factors effect on strain energy release rate are porosity, pore size, osteons density and age [3].

Fracture toughness rises with the diminishing pore size in the tibia and femur. Crack initiation fracture toughness diminishes with the rising osteonal area in the tibia and femur[2]. Aging negatively affects the $\sigma_{ult}$and$\sigma_y$ of of bone as it looks in uniaxial tests in quasi static loading. In aging bone there was fragility in the elastic properties of the material. This diminished the properties of elastically calculated, ($K_C, G_C$and $J$) [3].). $J$-integral is a factor that can be used to determine both the energies wasted in the plastic and elastic deformations of affected object [9].

J.Yan et al (2007) found the average of $J_{pl}$ for femur of bovine bone in the transverse direction for single-edge notched beam (SENB) specimen is (5.3KPa.m) was described to be 4.1 times the mean of $J_{el}$ magnitude (1.3KPa.m) [5]. In this work, the mean of $J_{pl}$ value (6.635KPa.m) was found to be 2 times the mean of $J_{el}$ value (3.203KPa.m) for compact tension (CT) specimen from the tibia of bovine cortical bone. In contrast, for tibia of human bone the average of $J_{pl}$ value (5.133KPa.m) was shown to be 1.3 times the average of $J_{el}$ value (3.98 KPa.m) for CT specimen from the tibia of human. The total $J_C$ of bovine cortical bone (9.22 KPa.m) was 108% larger than that of human cortical bone (8.573 KPa.m) as shown in figure (15).

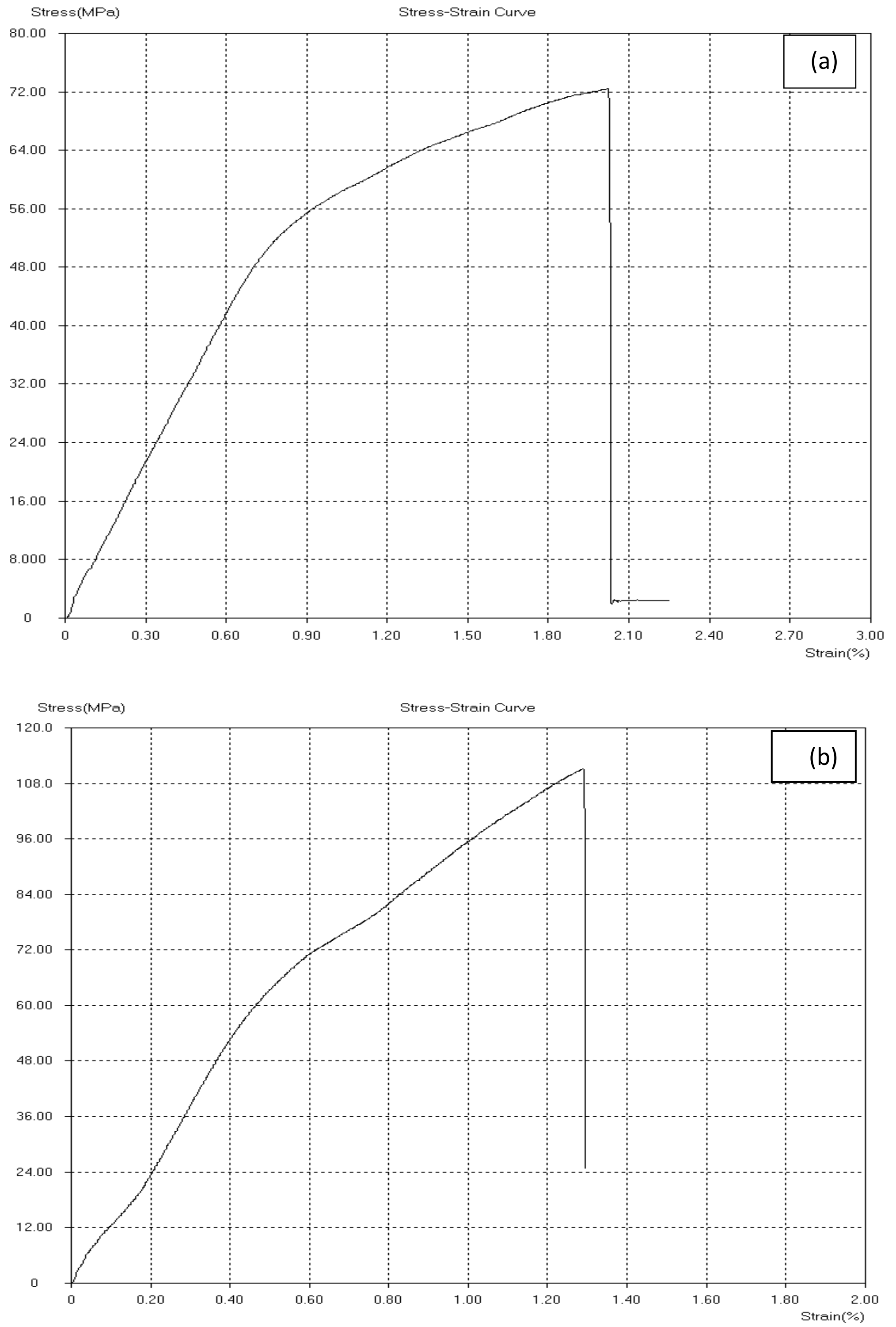



Figure (11). (a) Average stress- strain curve in tensile test of human cortical bone, mean age is 39 years in the longitudinal direction and (b) averagestress-strain curve of bovine cortical bone, the average age is 18 months in the longitudinal direction.

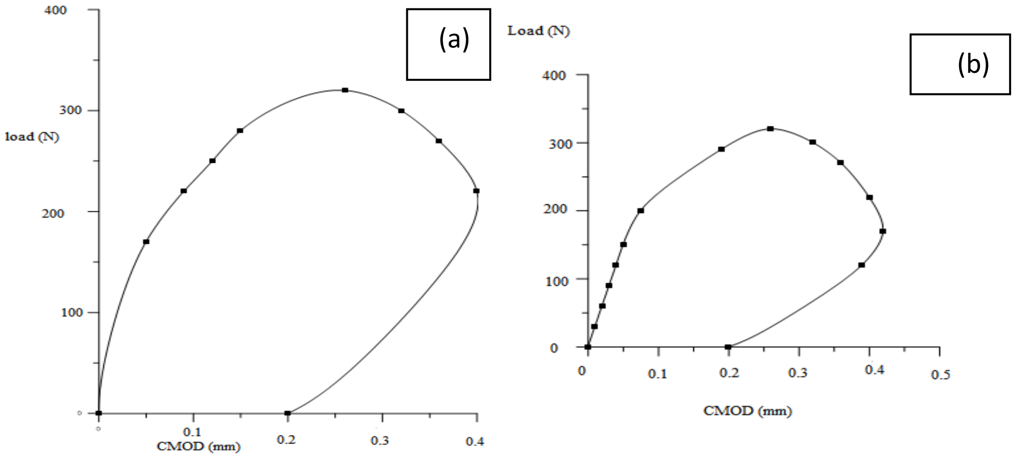



Figure (12). Typical load-CMOD (a) For CT specimens of bovine cortical bone average age 18 monthsin the transverse direction and (b) for human tibia cortical bone for compact tension CT specimen (mean age 39 years) in the transverse direction.

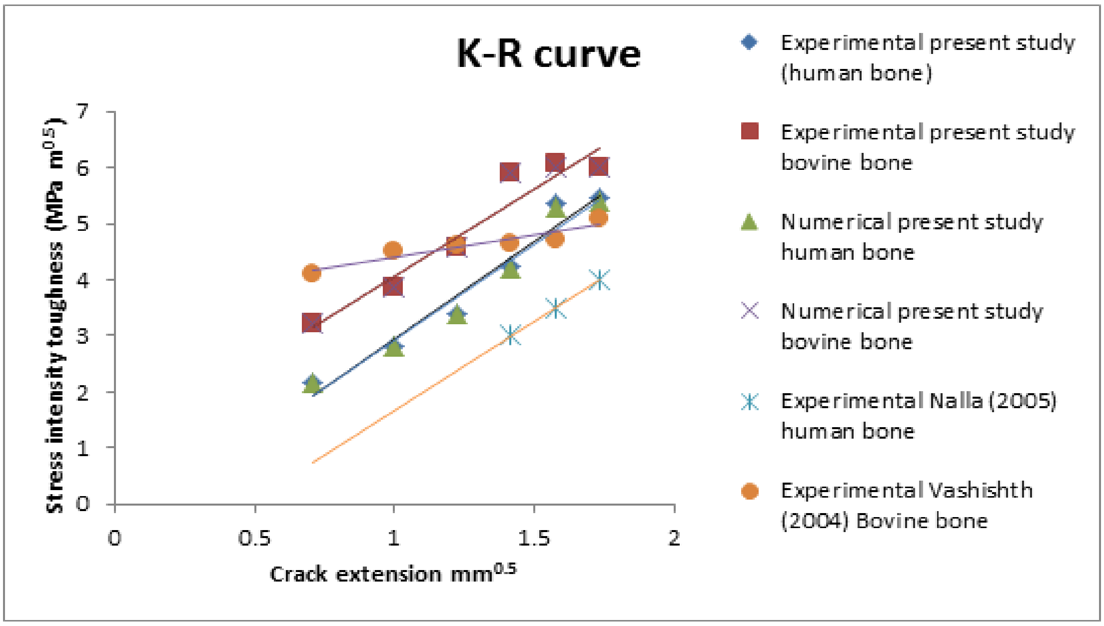



Figure (13).$K$-$R$curve of human and bovine cortical bone for present study (experimental and numerical) and previous studies.

From eq. (4) and (5), the experimental results show that bovine cortical bone and human cortical bone have a less smaller of $J_{el}$ than $J_{pl}$, which mean that the bones have a greater possibility to prohibit calamitous failure even if a major crack begins to develop (as noted when the slopes of the load-CMOD changes and the specimens don't fail instantly).The assistance mechanisms for this could be (1) bone has a large amount of organics, (2) bone has a complicated hierarchical assembly, (3) bone consists of water that can affect the properties of collagen. Many investigators studied crack growth resistance $(K - \Delta a)$ approach that's based on LEFM. The crack growth resistance

$(J - \Delta a)$ that based on EPFM on the compact tension (CT) specimen in transverse orientation is studied. Figure (16) shows the $J$ toughness for human cortical bone and bovine cortical bone, where the $J_C$ increases as logarithmic function for each experimental and numerical analysis.

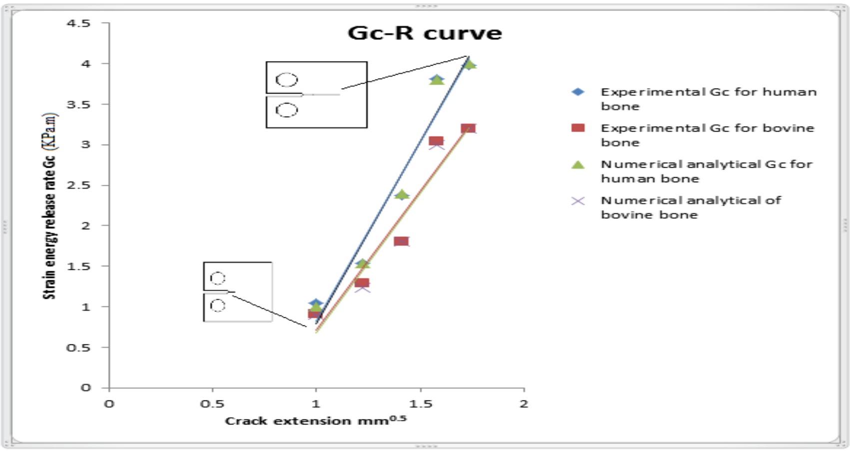



Figure (14).$G_c - R$curvefor human cortical bone and bovine cortical bone for two analyses, experimental and numerical.

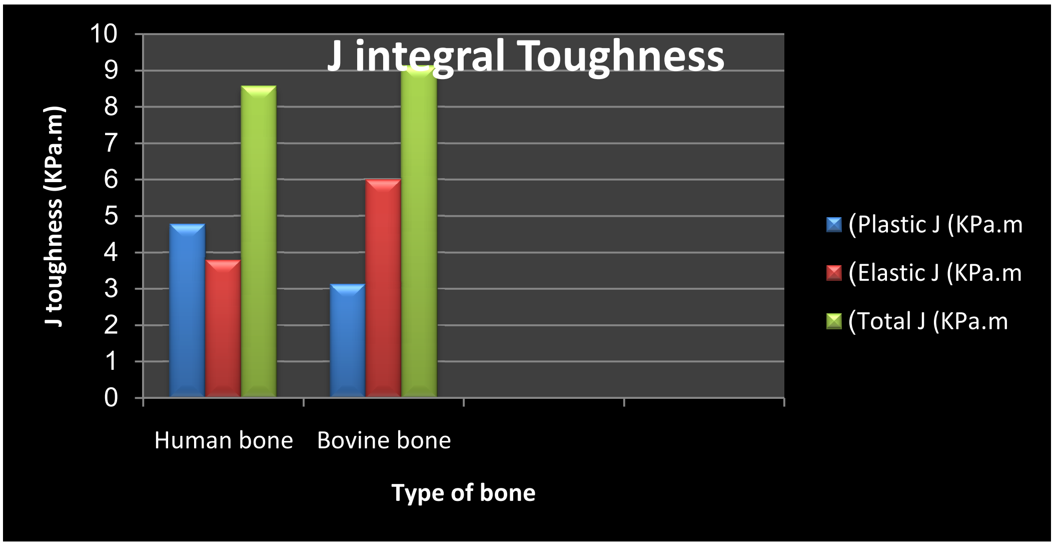



Figure (15).The comparison between elastic and plastic of $J$ integral for human cortical bone and bovine cortical bone.

The $J_C$ of human cortical bone and bovine cortical bone increases as the slope $(J = 13.128 ln \sqrt{\Delta a} + 1.0106,\ r^2 = 0.96)$ and $(J = 12.053\ \ln\sqrt{\Delta a} + 0.9856, r^2 = 0.9502)$ respectively.These results agreed with numerical analysis such as, the slope of $J$ - $R$ curve $(J = 13.128 \ln\sqrt{\Delta a} + 0.9906, r^2 = 0.9619)$ and $(J = 12.397 \ln\sqrt{\Delta a} + 0.8989, r^2 = 0.9516)$ for bovine and human cortical bone respectively. It is obvious from the load-CMOD curve, where that is there considerable non-linearity previous sensitivity cracking in both human cortical bone and bovine cortical bone.

These differences between $J$ integral for human cortical bone and bovine cortical bone have led to the differences of mechanical properties in tensile test and Young modulus is (1.53) times of bovine as compared human cortical bone.This non-linearity may be lead to various most stringent mechanisms like, microcracking, viscoelasticity and plasticity [10]. The existence of water in bone material may also have a contribution to this non-linearity of the toughness curve [10]. Mechanistically, like, aging-related decadence in (i) the growth toughness from the effective of decreasing the crack bridging (the essential microscopic toughening mechanism in the direction) led to the larger osteon density in older bone and (ii) the initiation toughness to be marked at least in part, to rise cross clinging of the collagen, which suppresses plasticity in bone (from a mechanism like, fibrillar sliding) [5].

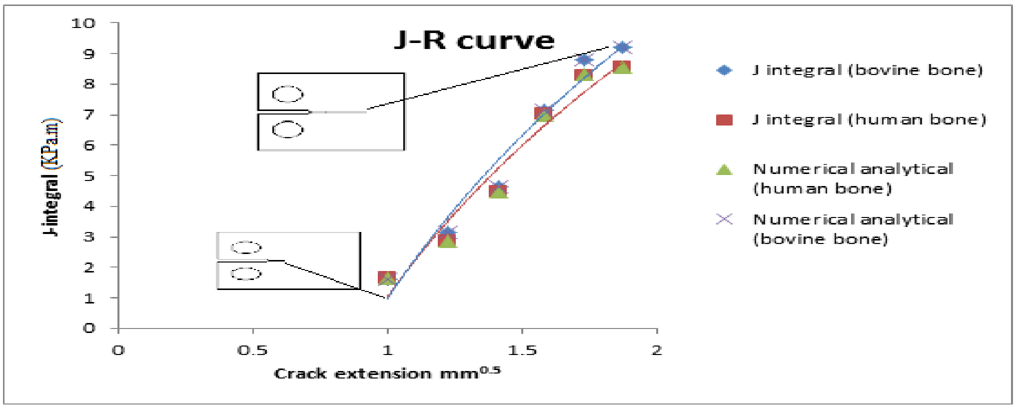



Figure (16). The $J$- R curve in EPFM for human cortical bone and bovine cortical bone

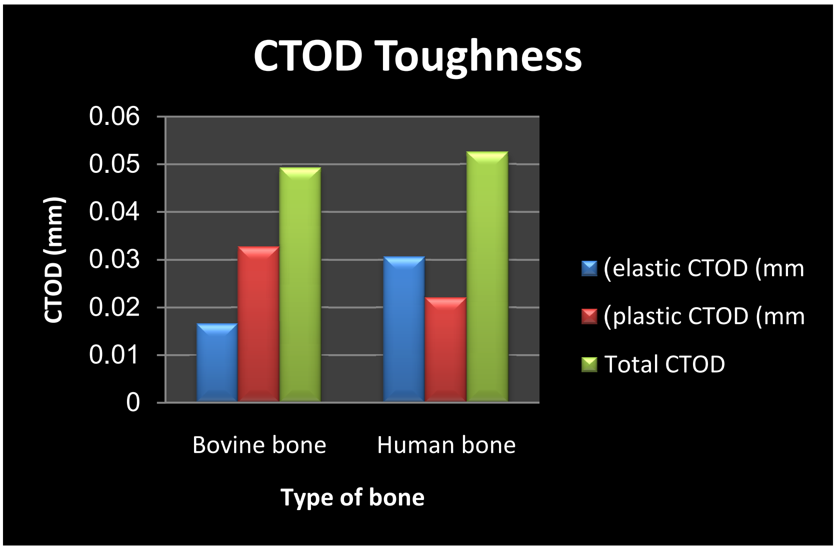



Figure (17).The comparison between elastic and plastic crack tip opening displacement CTOD for each bovine cortical bone and human cortical bone.

The relationship between potency of crack bridges and osteonal density are generated during the formation (cement-line) microcracks ahead of growing crack tip, their average size being a function of the spacing of the osteons [5]. It be noticed that the $\delta_C$ is about 1.1 times higher for the bovine cortical bone as compared to the human cortical bone. From eq. (6) and (7), the elastic CTOD fracture toughness $\delta_{el}$ is about 1.3 times of the $\delta_{pl}$ for human bone and $\delta_{pl}$ is about 2 times of the $\delta_{el}$ for bovine cortical bone as shown in figure (18). When predominantly strength and fracture toughness have an opposite a relationship [3].Figure (18) shows crack growth resistance in EPFM that represented the relation between crack tip opening displacement toughness CTOD $\delta$ and crack extension. CTOD rises linearly with $\Delta a$ for each bovine and human cortical bone as ( $\delta = 0.0239\sqrt{\Delta a} + 0.0122, r^2 = 0.9798$) and ( $\delta = 0.0221\sqrt{\Delta a} + 0.0107, r^2 = 0.9591$) for human and bovine cortical bone respectively. These differences belong to the mechanical properties of bone in tensile test and non-linearity of the load- CMOD curve.

The rising resistance to fracture in the bovine and human bone is assumed to be led to different factors like, fiber bridging, crack deflection and microcracking. The organic matrix of bones has strong bonding of the apatite crystals and may also force the crack to crack from its straight path force the same to pursue a tortuous/ zigzag path due to a considerable amount of energy assumption. The factors affected on fracture toughness are porosity, pore size and osteon density. Figure (7) shows the mechanism of fracture toughness for the bone. This mechanism is same in all fracture toughness test such as LEFM and EPFM for each bovine cortical bone and human cortical bone.

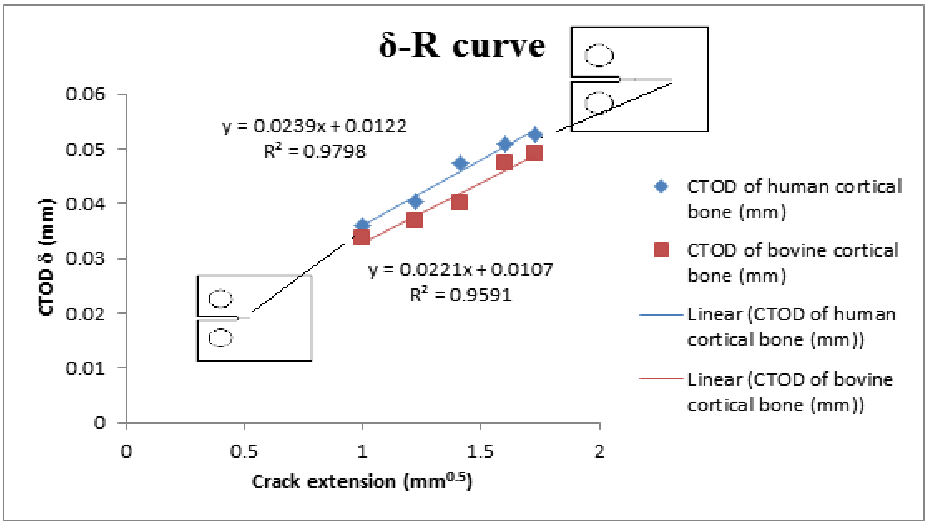



Figure (18).$\delta$-R curve that represented crack growth resistance in EPFM for each human cortical bone and bovine cortical bone.

## 6. Conclusions

According to the experimental and numerical results, several conclusions can be drawn from this work:

1. The appropriate method for cutting the specimens of the bone in all tests by using the hand saw because the generated heat on the surface is low and don't cause any crack on the fracture surface.
2. The experimental results of fracture toughness agree with the numerical results analyses of theABAQUS program for each human and bovine cortical bone.
3. The energy spent in the plastic deformation of the transverse fracture for human and bovine specimens was found to be larger than the value that consumed in elastic deformation, such as ($J$ integral and crack tip opening displacement (CTOD) $\delta$ fracture toughness) because the bones have the high amount of organics and water assisted bonding, was shown imbibe a great amount of energy in plastic deformation before fracture.
4. Fracture toughness in LEFM $(K - R), (G - R)$ curves and EPFM $(J - R), (\delta - R)$ curves in vitro has been examined in human and bovine cortical bone from the tibia of mean age for a human is 38.5 years and 18 months for the bovine cortical bone. The human cortical bone had a lower fracture toughness in LEFM and EPFM $(J - R)$ than bovine cortical bone when the crack length equaled 6.3 mm. Consistently, the bovine cortical bone had a lower fracture toughness in EPFM $(\delta - R)$ curve than human cortical bone when the crack length equaled 5.8mm. The fracture toughness of bovine $K_C$ is greater than by 111% of human cortical bone and vice in the strain energy release rate $G_C$ for human is greater than by 124% of bovine cortical bone. So, the fracture toughness in elastic- plastic fracture mechanic showed that the $J_C$ for bovine is 108% greater than human cortical bone, but gets the opposite in crack tip opening displacement toughness $\delta_C$ where is larger in human approximately 106% as compared with bovine cortical bone.
5. The fracture surface of the specimens of bovine cortical bone is rougher than the fracture surface of specimens for human cortical bonebecause the bovine cortical bone is tougher than human cortical bone.

**Abbreviation**

| | |
|---|---|
| ASTM | American society for testing materials |
| CMOD | Crack mouth opening displacement |
| CT | Compact tension |
| CTOD | Crack tip opening displacement ($\delta$) |
| EPFM | Elastic-plastic fracture mechanic |
| FEM | Finite element method |
| LEFM | Linear elastic fracture mechanic |
| SEM | Scanning electron microscopy |
| SENB | Single edge notched beam |

**The symbols**

| | |
|---|---|
| $A_i$ | Total area under the load-CMOD curve (N.mm) |
| $(A_{el})_i$ | Elastic area in the load-CMOD curve (N.mm) |
| $(A_{pl})_i$ | Plastic area in the load- CMOD curve (N.mm) |
| $B$ | Specimen thickness (mm) |

$a$ Crack length (mm)
$P_i$ The load (N)
$w$ Specimen width (mm)
$b_i$ Uncracked ligament (mm)
$E$ Elastic modulus of bone (GPa)
$\bar{E}=E$ (plane stress) and = 1/(1-$v^2$) (plane strain) (GPa)
$G_I$ Strain energy release rate (KPa.m)
$G_C$ Strain energy release toughness (KPa.m)
$K_I$ Stress intensity factor (MPa.m$^{0.5}$)
$K_C$ Stress intensity toughness (MPa.m$^{0.5}$)
$m$ Dimensionless constant where (m=2 for plane strain and m=1 for plane stress)
$r^2$ The regression
$r_p$Factor of Plastic rotation = 0.4(1+∝)
$V_{pl}$ Component of Plastic displacement from load-CMOD curve (mm)
$z$Knife edge distance is measured from load line on the (CT) specimen (mm)

$\delta_{el}$ Elastic CTOD (mm)
$\delta_{pl}$ Plastic CTOD (mm)
$J$ The energy absorbed during the fracture (Kpa.m)
$J_I$ The energy absorbed during the fracture for each crack (Kpa.m)
$J_{el}$ Elastic $J$ (Kpa.m)
$J_{pl}$ Plastic $J$ (Kpa.m)
$\sigma_{ys}$ Yield stress (Mpa)
$\sigma_{ULT}$ Ultimate stress (Mpa)
Where $\propto = 2[(\frac{a_\circ}{b_\circ})^2 + \frac{a_\circ}{b_\circ} + \frac{1}{2}]^{0.5} - 2\left(\frac{a_\circ}{b_\circ} + \frac{1}{2}\right)$

$\eta_{(i)}$=2+0.552$b_{(i)}/w$

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