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## Experimental and Theoretical Fatigue Crack Propagation in Vitro of the Bovine and Human Cortical Bone in Linear Elastic and Elastic-Plastic Fracture Mechanics

**Abstract-** This study involved studying fatigue crack propagation in elastic-plastic and linear elastic fracture mechanics LEFM fracture mechanics EPFM for each bovine and cadaveric human cortical bone. The results of the fatigue crack propagation showed that the fatigue crack propagation in elastic-plastic fracture mechanics is better than fatigue crack propagation in linear elastic fracture mechanics for comparison of the bone at small frequencies. Therefore, fatigue crack growth rate in cadaveric human bone is larger than bovine cortical bone. In addition, the cutting of the bone by hand saw is the better method than any an electric cutting machine.

**Keywords-** Crack propagation in vitro of bone; Crack propagation of bovine and human bone, Experimental fatigue of human bone in vitro, Theoretical crack propagation of bone.

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### 1. Introduction

Bone is as a natural polymer [1], a specialized tissue and anisotropic qualified for changing its structure accordingly stresses results to which it's subjected; bone consisted of matrix, fibers and cells [1]. It is tough because having calcination of its extracellular matrix and a degree of elasticity (presence of organic fibers). In face of apparently freezing in solidified state, has basic physiological functions [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 ( $J_C, \delta_C$ ). Norman and Burr hypothesized resistance the bone to crack growth, they studied that resistance of human bone to crack growth under tensile loading is smaller than shear loading [2]. The specimens from the human tibias of six females aged (mean 77.7 years) and nine males aged (mean 73.3 years) and found that,  $G_{Ic}$  of tensile loading is 400N/, and the strain energy rate  $G_{Ic}$  of Shear loading is 6000 N/m. In addition, they found the variation of  $G_{Ic}$  with age ( $13711-128.4*age$ ) and ( $550-2.84*age$ ) for both shear and tensile testing respectively [2]. Zioupos and Currey investigated the effect of age on the five mechanical properties ( $J$  integral, fracture toughness  $K_c$ , flexural strength  $\sigma_f$ , modulus of elasticity  $E$  and work of fracture  $W_f$ ) of male human femoral aged between (35-92) years [3]. These properties decreases with age because effects of deteriorating and diseases [3]. Vashishth determined the comparison R curve between antler and bovine bone through crack growth resistance.

They concluded that crack initiation for bovine bone higher than antler cortical bone demonstrated and smaller slope value for antler bone. The increasing in R curve belong to experience plasticity during fracture. Plasticity in a quasi-brittle material causes by microcrack formation in the process zone and the front [4]. Nalla found the R curve for human cortical bone. The resistance of the fracture increased with crack length (i.e. rising resistance) [5]. By X-ray tomography pointing to the bridging zone expands for some 5mm or so back the crack tip. Yan et al. inspected (EPFM) of bone in the two orientations longitudinal and transverse. They estimated that the longitudinal EPFM properties less than of transverse [6]. Single-edge notched specime was cut from the mid diaphysis of two bovine cortical bone [6]. The fracture surface of longitudinal specimens is less tougher than from transverse specimen indicate that less energy was consumed in the longitudinal specimens [6]. Ozan et al. studied microcracks growth during cyclic loading ( $R=1$  and the stress from 50-80MPa) femoral of human cortical bone ages range (37-40) years and investigated that the cortical bone tissue has an essential resistance to fracture by arresting and deceleration of microcrack growth [7]. Microcracks propagated and arrested in generally less than 10,000 cycles and microcracks growing rate was observed to be range  $5*10^{-5} - 5*10^{-7}$  mm/cycle [7]. Zioupos et al. suggested effective frequency on fatigue life for bovine and human bone at different frequencies (0.5, 5Hz). Strain increased and time to failures is

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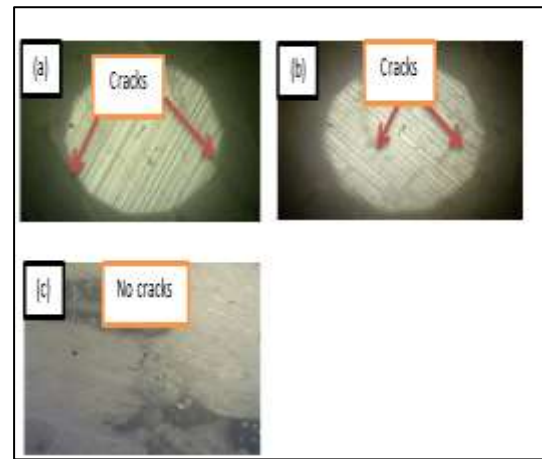
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decreased at two frequencies at same magnitudes, but cycles to failure of 0.5Hz is less than 5Hz in the same time [8]. Taylor and Lee studied stress-life and the fatigue crack growth rate of bone and found the crack density increases with increases numbers of cycles [9]. Several metallic materials, bone exhibit almost the same fatigue behavior in compression and tension. They determined a relationship of stress range with crack density [9]. Nalla studied the R-curve for human cortical bone. Resistance of fracture increased with crack length [10]. In  $(da/dt > 10^{-9})$  and higher driving force, the crack growth fastly, but  $(da/dt < 10^{-9})$  the crack growth is slowly. In cortical bone, deflection essentially over the weaker cement line that keeping crack tip sharp and cracks tend for propagation around the osteons [10]. In this work, the tensile test and fatigue crack propagation test for each human and bovine cortical bone are studied and investigated.

## 2. Experimental Procedures

Before the inspecting of the bone, the appropriate method for cutting the bone in this section is inspected. The specimens of the bone are saved at  $-20^{\circ}\text{C}$  in buffered phosphate saline to maintain the mechanical properties of bone. The buffered phosphate tables are immersed in distilled water for five minutes to dissolve in the distilled water and freezes at  $-20^{\circ}\text{C}$ . Three methods for cutting the specimens of bone were examined, the first method involved cut of specimens by electrical machining cutting tool with diameter 60 cm, the second method included cut of specimens by an electrical machining tool with a diameter 12 cm and the third method included cuts of the specimens by hand saw. After cutting specimens from the bone, the bone must be cleaned with waterproof abrasive paper. By a microscope, the specimens examined to inspect the cracks that result from cutting. The electrical machining disc with diameter 12 cm has a small cracks and low heating that generated on the specimens. The hand saw cutting don't generate cracks and the heat is very low on the specimens. Figure (1) shows the microscopis inspecting for three methods are used to cut the bone in this work. Hence, the handsaw cutting is the best cutting for cutting the bone that used in this study. Before the inspecting of fracture toughness and fatigue crack propagation, the tensile test for the bone must be studied.

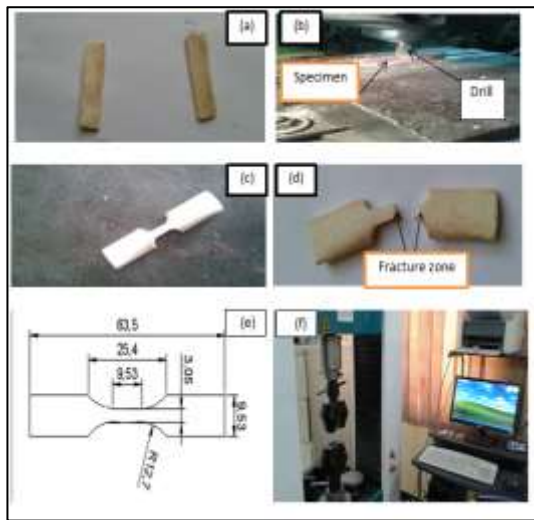


**Figure 1: (a), (b) and (c), The microscopic inspecting of surface by electrical cutting machine (diameter of the disc is 60cm), by the electrical machine (diameter of the disc is 12cm) and by hand saw respectively**

### I. Tensile Test of Bone in Vitro

Bones are affected by several factors like sex, age and mineral content. In this work, five specimens for each cadaveric human cortical bone and bovine cortical bone were taken according ASTM D638 [11] because the bone as a natural polymer. The specimens are inspected in plastic tensile rig in University of Technology- Materials Engineering (LARYEE, 50KN, WDW-50, China) as shown in Figure (2-f). Bone specimens were cut in a (rectangular) by hand saw, as shown in Figure (2-a) and the gage length region cut by the milling machine as shown in the Figure (2-b). After the inspection, the specimen fails in the weakest region at gage length region as shown in Figure (2-d) because bone behavior as a brittle material. The tensile testing rig of plastic is connected with a personal computer to give two important curves, like (stress-strain) and (load-extension) curves. To get mechanical properties of bone from the stress-strain curve as ASTM D638 [11], a line (0.2% offset yield strength) is drawn and from the intersection of the line with the curve,  $(\sigma_y, \epsilon)$  is calculated and by dividing yield stress on the strain to get elastic modulus E. For calculation Poisson's ratio by using the equation (1) [1]:

$$\nu = \frac{\epsilon_t}{\epsilon_l} \quad (1)$$



**Figure 2: Dumbbell specimen for tensile testing (a) rectangular specimens of bones, (b) milling machining for making the gage length, (c) the specimen of bone for tensile testing, (d) the specimen after the failure, (e) the dimensions of the dumbbell specimen in millimeters according ASTM D 638 and (f) Tensile test machine**

## II. Fatigue Crack Propagation Testing of Bone in Vitro

This work is aimed to study fatigue crack propagation in EPFM and LFM for each bovine and cadaveric human cortical bone by designed and manufactured of tensile fatigue rig. For this work, the tensile fatigue rig is manufactured and design because not available in the Iraq universities. The tensile fatigue rig as shown in Figure 3 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, DNC-63-45, max pressure 12bar, PPV-A, and the piston length is 40mm and diameter is 10mm), compressor (TA TA 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 is designed and manufactured from cast iron according ASTM E 647 [12], 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. Online monitoring technique (ZBL F101) is imported from China and used to measure the crack length without removing the specimens from the grips now. This tensile fatigue rig is used to inspect the tensile fatigue and fracture toughness test for all materials. To get accuracy in the results, an

appropriate method for cutting the specimens of the bone was inspected. Fresh and frozen human and bovine bone was cut from mid cortical of the tibia, the human cadaveric bone is prepared from the forensic medicine department for persons ages (25, 31, 39, 45, 51) years and the age of bovine 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 tests are kept in buffered phosphate saline to maintain the properties of the bone during the test for two days. Before the testing of the fatigue crack propagation for each cadaveric human and bovine cortical bone, the specimens of bone are tested according to ASTM D 638- Type V because the bone is a natural polymer [11] in University of Technology- Materials Engineering Department (type LARYEE, WDW-50, China) as shown in Figure (2-f). For fatigue crack propagation testing, the specimens cut as compact tension CT specimens according ASTM E647 with the width is 14 mm [12] as shown in Figure 4. The specimens were cut from the mid diaphysis of cortical bone by hand saw in the transverse direction and the notch is prepared by milling machine in perpendicular direction on the osteon as shown in Figure 4. 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. To calculate fatigue crack propagation for each cadaveric human and bovine cortical bone, the (load- crack length) is inspected by tensile fatigue rig as shown in Figure 3-a and 3-b according ASTM E647 [12]. Ten specimens for five men, where ages are (25, 31, 39, 45 and 51) years are used for fatigue crack propagation test. Where the load is applied at a displacement rate is 1mm/min for each crack and the weight indicator is calculating the load for each crack as shown in Figure 5. In contrast, the counter calculates the number of cycles for each frequency. In this work, two frequencies are used, 1Hz and 2 Hz. To understand the mechanical properties for bone components, it is 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]. These structures and levels are; (1) the macrostructure: cortical bone and cancellous; (2) the microstructure (from 10 to 500  $\mu\text{m}$ ): Haversian systems, single trabeculae, osteons; (3) the sub-microstructure (1-10  $\mu\text{m}$ ): lamellae; (4) the nano structure (from few

hundred nanometers to mm); embedded mineral and fibrillar collagen; (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 3: (a) The tensile fatigue rig, (b) the devices about the specimen and (c) The compact tension specimens of human and bovine cortical bone that used in fracture toughness testing

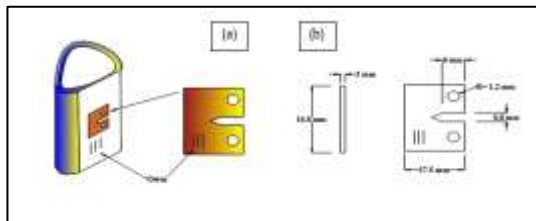


Figure 4: (a) The direction of the crack on the osteon in the bone and (b) The dimensions of the CT specimen that used in this work, where all dimensions in mm

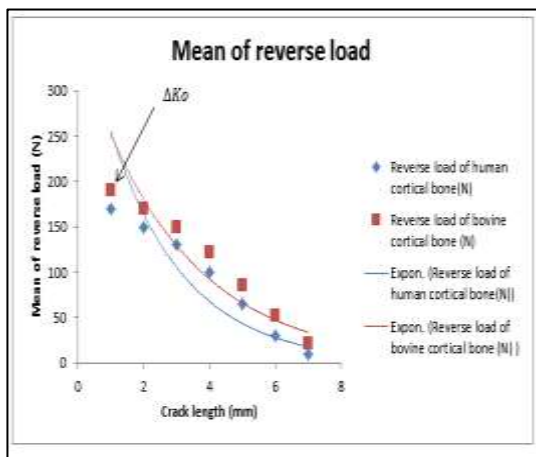


Figure 5: Experimental mean of reverse load- crack length for each bovine and human cortical bone, according to ASTM E647

### 3. Theoretical Procedure

In 1960, Paris [7] demonstrated that fracture mechanics is a useful tool for singularity crack growth by fatigue. This section enhanced practical applications of the fracture mechanics and the fundamental concepts approximation to fatigue crack propagation. The relationship between  $(\frac{da}{dN}$  and  $\Delta K$ ) of bones approximately linear [8]. Fatigue crack propagation is the relationship between crack growth rate  $da/dN$  and stress intensity range  $\Delta K$  in LEFM. In addition, the relationship between crack growth rate  $da/dN$  and  $J$  integral range  $\Delta J$  is fatigue crack propagation in EPFM. The linear region in log-log plot of  $\Delta K$  and  $\frac{da}{dN}$ ,  $\frac{da}{dN}$  and  $\Delta J$  and  $\frac{da}{dN}$  and  $\Delta \delta$  curve be qualified by a power rule:

$$\frac{da}{dN} = f_1(\Delta K, R) \tag{2}$$

$$\frac{da}{dN} = C \Delta K^m \tag{3}$$

And

$$\frac{da}{dN} = f_2(\Delta J, R) \tag{4}$$

$$\frac{da}{dN} = \bar{C} \Delta J^{\bar{m}} \tag{5}$$

Where  $C$ ,  $m$ , Paris exponents and  $\bar{C}$ ,  $\bar{m}$  are constants of the power equation that are found experimentally,  $(R = \frac{K_{min}}{K_{max}})$  and  $\Delta K = K_{max} - K_{min}$  [12,13].

$$\frac{da}{dN} = \frac{a_{i-1} - a_i}{N_{i-1} - N_i} \tag{6}$$

$$\Delta K = \Delta K_o e^{(C^*(a-a_o))} \tag{7}$$

$$\Delta J = \Delta K^2 / E' \tag{8}$$

Where  $(C^*)$  is the  $K$ -tendency and  $(\Delta K_o)$  the initial  $\Delta K$  at the start of the test and  $C^* = +0.08 \text{ mm}^{-1}$  in the test [12,13].

**Note:**  $\Delta J \neq J_{max} - J_{min}$  [4].

Klensil and Lukas [4] modified equation (10) to account for the threshold:

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}^m) \tag{9}$$

Where  $\Delta K_{th}$  is the threshold stress intensity factor. Some of the references, calculated threshold when  $\frac{da}{dN} \approx 10^{-10} \text{ m/cycle}$ .

In this study, a relationship in EPFM of fatigue crack propagation is investigated. This relation relates CTOD range  $\Delta \delta$  with the fatigue crack growth  $(\frac{da}{dN})$ .

$$\frac{da}{dN} = f(\Delta \delta, R) \tag{10}$$

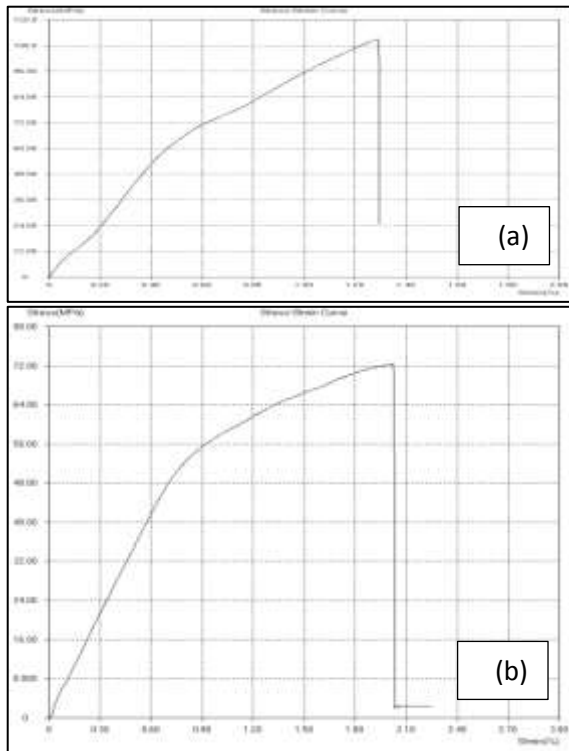
$$\frac{da}{dN} = \bar{C}(\Delta\sigma)^{\bar{m}} \quad (11)$$

Where  $\bar{m}$  and  $\bar{C}$  are exponents of the power equation.

#### 4. Results and Discussion

##### I. Tensile Test Results

Figure 6, (a) and (b) shows the results of the tensile test of bovine and cadaveric human cortical bone in longitudinal direction found with the help of uniaxial tensile equipment.



**Figure 6: Typical  $\sigma - \varepsilon$  curve of cadaveric human tibia cortical bone for dumbbell specimen (mean age 38.5 years) in longitudinal direction on the osteon**

Similarity, the yield strength of the cadaveric human cortical bone is about (0.7) times of the bovine cortical bone and ultimate strength for cadaveric human cortical bone is about (0.6) times of bovine bone. Differences between the mechanical properties in a tensile test for each human and bovine cortical bone are belong to various factors [1]. These factors are included water content, mineral and architecture of human cortical bone is less than bovine cortical bone [1]. Besides, there are a number of factors effect on the mechanical properties of bone like, osteon density, microcracks, where these factors increase, the cortical bone becomes tougher. For the human bone, the aging decreased the mechanical properties of bone for human ages above 40 years. Mechanical property for the bone has stated to be more affected by the collagen fiber direction. Because the osteons arrangement is a subsidiarity system different direction, geometry

of an osteon and size so based on which cross section has been studied. For this orderly, the mechanical properties of tensile test for bone though the morphology (density and the number of the osteons) are important to identify the properties of bone. Bovine cortical bone is about (1.4) times is tougher than Human tibial plexiform, it should predictable lower absolute toughness [7].

##### III. Fatigue Crack Propagation Results

Nalla et al. founded by using two different methods, a transition from mostly time-dependent cracking at larger  $\Delta K$  to a real fatigue (cyclic-dependent) at smaller  $\Delta K$  values at growth rates of crack approximately  $5 * 10^{-7}$  m/cycle [10]. The first method involved tests where cycling was periodically holding, stopped the specimen at sustained load for a defined period of time before cycling again [10]. The results exhibited that at  $K_I$  factors, the crack annotated during the endured loading intervals showing that cyclic loading was required to distribute the crack. Conversely, the results exhibited that larger  $K_I$  factors, the crack continued to distribute under endured load; a time dependent mechanism. Therefore, a particular mechanism of under critical crack growth under static loading has been investigated. In addition, the bone showed a system of subcritical propagation of crack that's time-dependent is not surprise [10]. In early time results on subcritical cracking lower endured quasi-static loading using tibia and bovine femur specimens showed larger driving forces ( $K$  and  $G$ ) were imposed to developed crack at above velocities higher the range ( $10^{-2} - 1$ ) mm/sec by Bonfield et al. [10]. Nalla et al. (2005), whose focused on slow crack growth in humeri of human, get similar results above a high range of growth rates ( $10^{-6} - 10^{-1}$ ) mm/sec; higher  $K_I$  values were again required to develop growth of cracks at higher rates. Therefore, the behavior is analogous to that demonstrated by many materials engineering, like ceramic and metals, therefore, can exhibit it time-dependent crack growth minimal sustained crack growth [10].

The second method used to make a singularity between time and cyclic dependent growth included the methodological studied by Evan and Fuller [10], where the cyclic of fatigue crack growth are predictable just from load- endured cracking results higher than the full range of  $K_{max}$  values [10]. These authors confirmed that the fatigue crack propagation comparable to that seen in mutual engineering materials with increasing ( $\Delta K$ ) with ( $da/dN$ ) rising according to the power law equation (2).

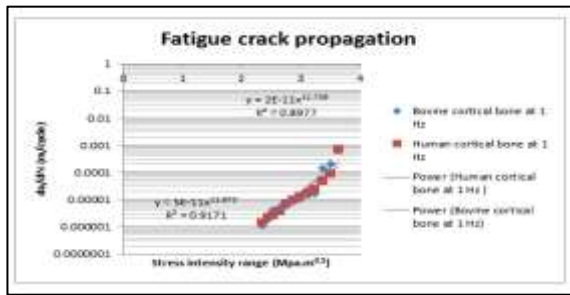


Figure 7: Fatigue crack propagation for bovine and human cortical bone at frequency 1 Hz

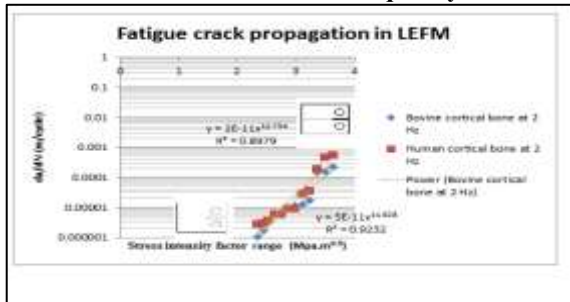


Figure 8: Fatigue crack propagation for human and bovine cortical bone at frequency 2 Hz

In this study, the crack propagates in cadaveric human and bovine cortical bone is appears in this power equation ( $\frac{da}{dN} = 2 * 10^{-11} \Delta K^{12.759}, r^2 = 0.8977$ ) and ( $\frac{da}{dN} = 5 * 10^{-11} \Delta K^{11.673}, r^2=0.9171$ ) respectively at frequency 1 Hz as shown in Figure 8. These equations show that the Paris exponent  $m$  of human is less than bovine cortical bone belong to the fatigue crack propagation in bovine cortical bone is growing lower than human cortical bone. Where  $m$  values in human and bovine cortical bone are 4.0105 and 4.38 respectively. Fatigue crack propagation of bovine cortical bone is smaller than the human cortical bone because the mineral content, hierarchical and water content of human are less than bovine cortical bone. Bone of young human is cortical tissue has an intrinsic resistance to fracture by the slowdown of microcrack growth [7]. The fatigue crack growth rate of all microcrack decreased with rising crack length dependent proportionate with theoretical prognosis and initial identity [8]. Figure 8 shows the crack propagates in human and bovine cortical bone according the equations ( $\frac{da}{dN} = 5 * 10^{-11} \Delta K^{11.628}, r^2 = 0.9232$ ) and ( $\frac{da}{dN} = 2 * 10^{-11} \Delta K^{12.734}, r^2 = 0.8979$ ) at frequency 2 Hz respectively. These relations are power functions shows the fatigue crack propagation of cortical bone decreased with frequency decreased. From Figures (8) and (9), when the frequency

decreases, the fatigue crack propagation is increasing because the number of cycles increased for same crack length. Frequency differently with the cycles to failure as a relationship of frequency, the specimen it fell on the same line as a function of time to failure [6]. The fatigue strength of human and bovine cortical bone is shown to increase with stress frequency [6]. Finally, transverse toughening is another factor, which must be considered when theorized the fatigue behavior of cortical bone. The differences between fatigue crack propagation for each bovine and cadaveric human cortical bone belong to the mineral content, microstructure and porosity. Stable crack extension, slow can occur under conditions of constant applied stress and has been noticed in many other materials; where it is commonly characterized either to the environmental factors (e.g. Viscoelasticity, time dependent, stress corrosion cracking and deformation behavior) [6]. For the bone, the critical size is predictable to be related to the improvement zone of bridging in the wake of the crack, (i.e, resistance to cracking and as bridges improves) are reinforced until a steady state bridging zone is accomplished [7]. The rising in crack growth resistance belong to extend the crack has led to the improvement of crack bridging [7]. The total rising in crack growth resistance has been situated with crack bridging [7]. Formation of bridges in the crack wake may diminished the  $\Delta K$  and sustained ratio of the load, experienced of the crack tip, affected the crack growth rates [7]. This behavior belongs to the effective of the crack size on the fatigue crack propagation; the resistance of crack propagation rises as the bridging zone extends. Microstructural barriers as cement line may be reliable for the formation of crack bridges as cracks insufficiently prepared after the deflecting about secondary osteons along the cement lines. Many researchers studied fatigue crack propagation that represented ( $\frac{da}{dN} - \Delta K$ ) approach that based on LEFM. In this work, the fatigue crack propagation ( $\frac{da}{dN} - \Delta J$ ) that based on EPFM is investigated and studied. For finding the above relationship, the equations (3) and (4) are applied. In the ( $\frac{da}{dN} - \Delta J$ ) curve, the Y-coordinate is the fatigue crack growth rate ( $\frac{da}{dN}$ ) and abscissa is  $J$  integral range. From Figure (10), the  $J$  integral range of bovine cortical bone (0.4802-1.1521 KPa.m) is less than as compared with  $J$  integral for cadaveric human cortical bone (0.57-1.5 KPa.m). The differences between  $J$  integral for

each bovine and human cortical bone are belong to  $J_{el}$  or fracture toughness ( $J_C$ ). Fracture toughness ( $J_C$ ) is mainly based on elastic modulus  $E$ , where  $J_C$  of bovine bone is less than as compared with human bone as shown in Figure (10) and (11) for both the effect of frequency. The relationships at a frequency 1 Hz are  $(\frac{da}{dN} = 2 * 10^{-5} \Delta J^{5.8677}, r^2 = 0.9182)$  and  $(\frac{da}{dN} = 8 * 10^{-5} \Delta J^{6.1622}, r^2 = 0.8906)$  for human and bovine cortical bone, respectively as shown in Figure (10). Symmetrical with the results, the propagation of cracks for the bone gained from bovine cortical bone is (1.6) is more tough from the human bone in the elastic modulus from tensile test. Also, the relationships at frequency 2 Hz are  $(\frac{da}{dN} = 7 * 10^{-5} \Delta J^{5.8139}, r^2 = 0.9232)$ ,  $(\frac{da}{dN} = 3 * 10^{-6} \Delta J^{12.899}, r^2 = 0.8168)$  for bovine and human cortical bone as shown in Figure (11). The fatigue crack propagation in EPFM ( $\frac{da}{dN}, \Delta J$ ) affected by several factors, like frequency and type of bone as shown in the above Figures. Fatigue crack propagation of bovine is slower than human cortical bone in EPFM because of mineral, osteonal density and water content.

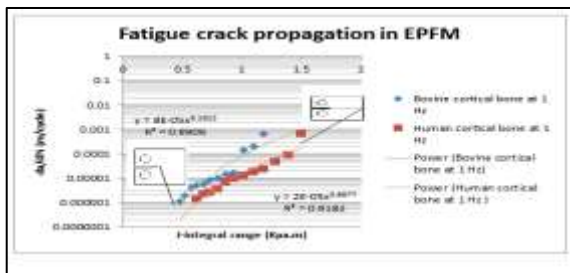


Figure 9: Fatigue crack propagation ( $\frac{da}{dN} - \Delta J$ ) in EPFM of human and bovine cortical bone.

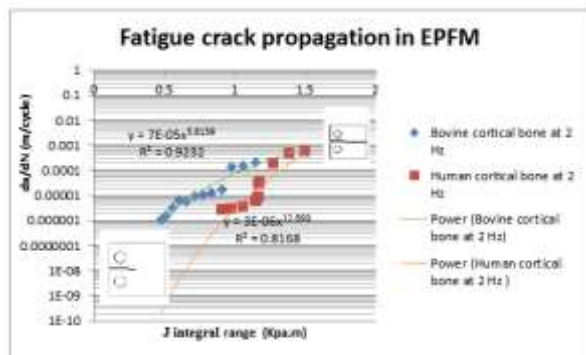


Figure (10). Fatigue crack propagation in EPFM ( $\frac{da}{dN} - \Delta J$ ) for each human and bovine cortical bone at frequency 2 Hz.

The fatigue crack propagation in EPFM is better than LEFM when the frequency is low because the variability and clarity results are concluded. This is extremely unexpected because bone is composed of collagen fibrils reinforced with Nano crystalline of apatite mineral. In bones, the collagen is regulated lamellae and a more complicated hierarchical structure, where collagen direction that constitutes a simple scaffold is perpendicular to the dentinal tubules [6]. A few studies are showed the fatigue crack propagation between ( $\frac{da}{dN} - \Delta \delta$ ). The following law has been derived from fracture mechanics that depend on (EPFM). The relationships of fatigue crack propagation for human and bovine cortical bone are  $(\frac{da}{dN} = 3 * 10^6 \Delta \delta^{6.1895}, r^2 = 0.9225)$  and  $(\frac{da}{dN} = 4 * 10^8 \Delta \delta^{6.3961}, r^2 = 0.8985)$  at frequency 1 Hz respectively as shown in Figure (12) respectively. In addition, the relationships of fatigue crack propagation of bovine and human cortical bone are  $(\frac{da}{dN} = 2 * 10^7 \Delta \delta^{5.8282}, r^2 = 0.9724)$  and  $(\frac{da}{dN} = 10^8 \Delta \delta^{6.9229}, r^2 = 0.9232)$  at frequency 2 Hz respectively as shown in Figure 12. The differences between fatigue crack propagation for each human and bovine cortical bone are due to the mechanical properties of tensile test such as, yield stress  $\sigma_y$  and young modulus  $E$ .

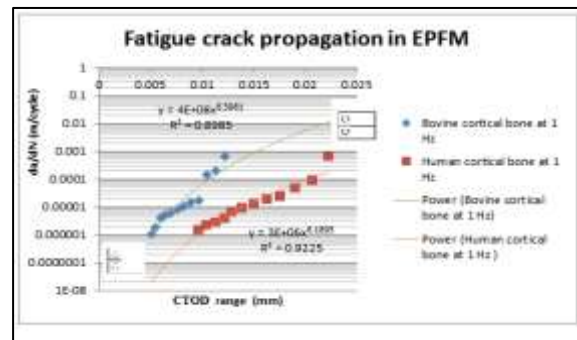
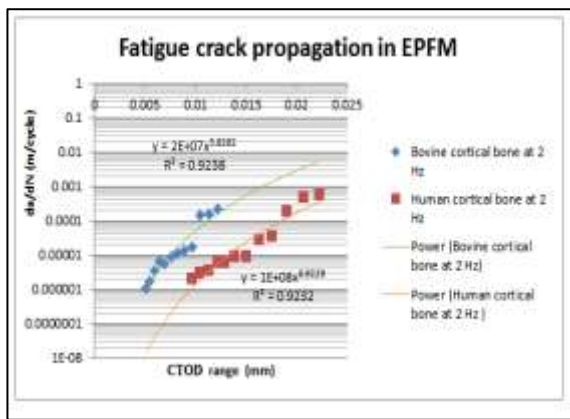


Figure 11: Fatigue crack propagation in EPFM ( $\frac{da}{dN} - \Delta \delta$ ) for each bovine and human cortical bone at frequency 1 Hz.



**Figure 12: Fatigue crack propagation in EPFM ( $\frac{da}{dN} - \Delta\delta$ ) for each human and bovine cortical bone at frequency 2 Hz.**

Increasing in CTOD for bovine cortical bone at two frequencies is belonging to multiply the two properties ( $\sigma_y * E$ ) is less than the human cortical bone. As has been notified newly for human and bovine cortical bone results reaffirm the concept that crack bridging is a main toughening mechanism as shown in Figure 12 [9]. Comparing the behavior of fracture in cortical bone, it is predictable that the increasing crack growth resistance with crack extension is belonging to crack bridging development [7]. From the preceding studies that the contribution mechanism of the bone is concluded that (i) a complicated hierarchical assembly (ii) a significant amount of organic and (iii) water that affect the properties of collagen. Which the hierarchical structure of bone, which is created from organic and inorganic components, has been evidenced to extend from nano scale [7]. There are some of toughening factors, such as microcracking, crack deflection and fiber bridging have been noticed in the fatigue crack propagation of cortical bone. These factors could influence slow, deflect or stop the propagation of the crack. In addition, crack bridging can reduce the net stress intensity factor at the tip of the crack, but rise the toughness of the composite materials [9]. Nyman et al. also expressed that the cortical bone be brittle and less toughness after the water was removed in a vacuum when the temperature is above the elevation [9]. The collagen hydration is important factor and playing an important mechanism in the mechanical properties of cortical bone. Bella et al. advised effect of collagen peptide model on molecules of absorbed water from a highly ordered network. This effect of the network lead to the more stabilization of the triple-helix of tropocollagen through formation extra water arranged hydrogen bonds between all residual back bone peptide groups [10]. Bone is complicated hierarchical and

has a high amount of water and organic that belong to absorb a great quantity of energy and prevent the calamitous failure. The differences of fatigue crack propagation results between two frequencies in ( $\frac{da}{dN} - \Delta J$  and  $\frac{da}{dN} - \Delta\delta$ ) are better than ( $\frac{da}{dN} - \Delta K$ ) because a clear difference in the relationship of fatigue crack propagation in EPFM and LEFM.

## 5. Conclusion

Several conclusions can be drawn from this work:

1. Experiments have been carried out with a tensile fatigue equipment and a rig to apply equivalent GRF on the bone, equipment specially designed for the tensile fatigue test. This design allowed to the immediate tests in simplified manner and an easy belong to the employment of the mechanism of the changing of the grips.
2. The suitable method for cutting the specimens of the bone in all tests by using the hand saw because don't cause any crack on the surface and the generated heat on the surface is low.
3. The average elastic modulus and yield strength for human cortical bone are (7.5 GPa and 67 MPa) respectively, for average age (38.2 years) from the forensic medicine department and for bovine cortical bone (11.5 GPa and 94 MPa) respectively, for average age (18 months).
4. Fatigue crack propagation in LEFM ( $\frac{da}{dN} - \Delta K$ ) and EPFM ( $\frac{da}{dN} - \Delta J$ ), ( $\frac{da}{dN} - \Delta\delta$ ) have been inspected for each bovine cortical bone (mean age 18 months) and human cortical bone (mean age 38.2 years) at two frequencies 1 and 2 Hz. Human cortical bone was more fatigue crack growth rate than the fatigue crack growth rate of bovine cortical bone in LEFM and EPFM for both frequencies.
5. The fatigue crack propagation in EPFM is best from fatigue crack propagation in LEFM for comparing the results between human and bovine cortical bone at small frequencies because the differences are clearly at two frequencies 1 and 2 Hz.
6. The number of cycles to the failure of the bovine cortical bone and human cortical bone has been found when the bone is subjected to the reverse load ( $R = -1$ ), the number of cycles to the failure ( $N_f$ ) are (5630 and 5780 cycles) for human cortical bone at frequencies 1 and 2 Hz respectively, but the number of cycles to the failure of human cortical bone is (5410 and 5562 cycles) at frequencies 1 and 2 Hz respectively because the human cortical bone is less tougher than the bovine cortical bone.



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## Subscripts

LEFM	Linear elastic fracture mechanic
EPFM	Elastic- plastic fracture mechanic
CT	Compact tension

## Abbreviations

$B$	Specimen thickness (mm)
$a$	Crack length (mm)
$da/dN$	Fatigue crack growth rate (m/cycle)
$\Delta K$	Stress intensity range ( $\text{MPa}\cdot\text{m}^{0.5}$ )
$\Delta J$	J integral range ( $\text{KPa}\cdot\text{m}$ )
$\Delta\delta$	Crack tip opening displacement range (mm)

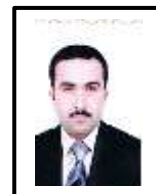
$w$	Specimen width (mm)
$b_i$	Uncracked ligament (mm)
$E$	Elastic modulus of bone (MPa)
$\bar{E}$	$=E$ (plane stress) and $=1/(1-\nu^2)$ (plane strain) (MPa)
$G_I$	Strain energy release rate ( $\text{KPa}\cdot\text{m}$ )
$G_C$	Strain energy release toughness ( $\text{KPa}\cdot\text{m}$ )
$K_I$	Stress intensity factor ( $\text{MPa}\cdot\text{m}^{0.5}$ )
$K_C$	Stress intensity toughness ( $\text{MPa}\cdot\text{m}^{0.5}$ )
$r^2$	The regression
$N$	number of cycles to failure (cycles)
<b>Greek Symbols</b>	
$J$	The energy absorbed during the fracture ( $\text{KPa}\cdot\text{m}$ )
$J_I$	The energy absorbed during the fracture for each crack ( $\text{KPa}\cdot\text{m}$ )
$\sigma_{ys}$	Yield stress (MPa)
$\sigma_{ULT}$	Ultimate stress (MPa)

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