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Study of Transverse and Longitudinal Crack Propagation in Human Bone Using the Finite Element Method with MATLAB

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Abstract

A finite element is a study that is capable of predicting crack initiation and simulating crack propagation of human bone. The material model is implemented in MATLAB finite element package, which allows extension to any geometry and any load configuration. The fracture mechanics parameters for transverse and longitudinal crack propagation in human bone are analyzed. A fracture toughness as well as stress and strain contour are generated and thoroughly evaluated. Discussion is given on how this knowledge needs to be extended to allow prediction of whole bone fracture from external loading to aid the design of protective systems.

Keywords: *Bone fracture, Fracture toughness, Stress intensity factor.*

1. Introduction

Bone studies have been a subject of interest in biomechanics for more than 100 years. Many authors have studied in this field starting by (Melvin, 1993) [1] Who studied the surface cracks and found that the surface crack significantly reduces absorbed energy during the fractured bone fracture, where the fractured transverse fractures in the bone marrow and fractured bone are measured. The work in this filed still continued and updated, also evaluated the fracture toughness value experimentally in transverse and longitudinal directions.

Studies of mechanical properties of bones are important for many reasons.

First, predict how you expect the bone to behave in the body.

Second, to explain the behavior of bone as a substance, resulting in an understanding of why a given bone structure gives you its properties.

Finally, to ensure a viable system in case of substituted material for bone (Moyle & Bowden,1984)[2].

This studied will be taken in the consideration previous experiment studied and finite element analysis approach will be used for comparison reason and to approve that this technique can be used in future work instead of experiment methods which finally will take us to faster improvement and development.

2. Fracture Mechanics of Bone

The aim of fracture mechanics is to describe the fracture process in the structural material by determining the relationship between the stress field at the tip of the crack and the spread of the crater. In the other meaning the resistance of the material against rapid crack propagation which known as critical stress intensity factor (Kc) or fracture toughness [1]. Stress intensity factor is depending on the load configurations and geometry of the body as shown ie Eq.1:

$$K = \sigma\sqrt{\pi * a}f(a,\alpha) \quad \ldots (1)$$

At the fracture, stress intensity factor is considered as material property and Eq.1 will be rewrite to be as shown in Eq.2:

$$K_c = \sigma\sqrt{\pi * a_f}\, f(a,\alpha) \quad \dots (2)$$

Also there is very important parameter for this characterizing is called critical strain energy release rate (Gc), which means the energy release due to crack propagation per unit of thickness. Also, it is considered as material property at the fracture and can be calculated based on Eq.3 and 4 for plane stress and plane strain respectively:

$$G_c = K^2/E \quad \text{Plane Stress} \quad \dots (3)$$

$$G_c = K^2/E(1-\nu^2) \quad \text{Plane Strain} \quad \dots (4)$$

In order to study the fracture mechanics of any material there are several types of tests have been established for this purpose. The composite material can be considered as two-phase, one-phase mineral, collagen and terrestrial content as another stage. From the other side bone is considered as viscoelastic material that means it is sensitive to the speed at which the load is applied. In general, the faster the strain rate the higher the stiffness. For these reasons bone has some properties as creep, stress relaxation and hysteresis.

Also the bone is classified as anisotropic material that means it has different mechanical properties when loaded along different axes due to structure of the bone is dissimilar in the transverse and longitudinal directions. Most fracture in bone structure occurred as a results of several loading tension, compression, bending, torsion and shear or combination between two types of them. For example, the type of fracture that occurs in tensile is the transverse fracture while in the oblique fractional compression [3].

3. Bone Fracture Experiments

There is several number of standard test for this purpose, for example Three points bend test, Four points bend test, and Crack bridging experiment.

A number of experimental studies have investigated the fracture toughness (Kc) of the human bone. As the results of these experiments the fracture toughness (Kc) of the human bone is to be in the range of 2-8 MPa $m^{1/2}$. In experimental study, the fracture toughness value (Kc) for transverse crack is about 5 MPa $m^{1/2}$ while it in longitudinal crack is about 4 MPa $m^{1/2}$ (Nalla, Kinney & Ritchie, 2003) [4].

4. Finite Element Analysis

In this study, the finite element analysis approach is used to model and simulate the behavior of the bone by using MATLAB package [5]. Two cases are considered in this study, three points bend and compact tension specimen.

a) Three Points Bend

The objective of this case is to study the longitudinal crack where the load is parallel to crack direction as shown in Figure-1, the model used by Akram et al. [6] was employed.

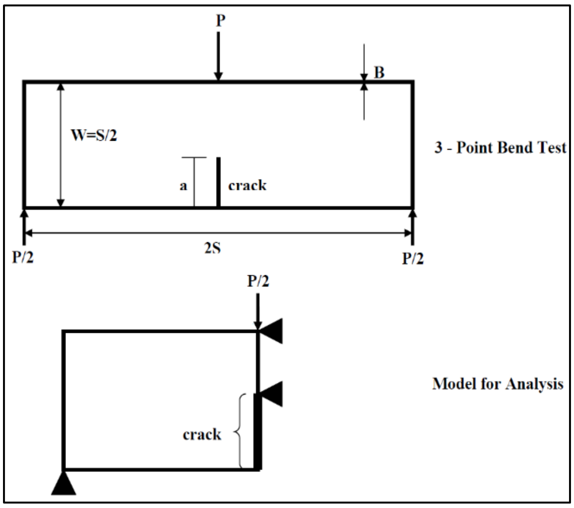

Fig. 1. Longitudinal crack case.

In this case three forces act on the structure, produce two equal moments, each being the product of one of the two peripheral force and distance to the axis of rotation.

After the material is implanted into MATLAB program and run this model for several loads as shown in Table-1 the result of fracture toughness value (Kc) is 5.98 MPa $m^{1/2}$. Figure-2 shows of one case run by MATLAB program.

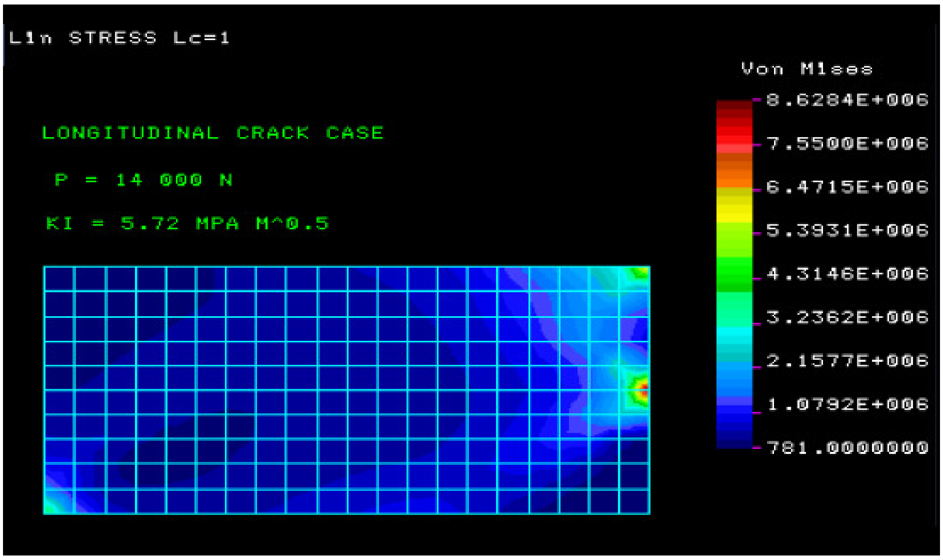

Fig. 2. Longitudinal crack case from MATLAB program.

Table 1,
List of fracture toughness value longitudinal crack.

S*	Load (P) KN	K_c MPa.m$^{0.5}$	Stress (σ) MPa
1	6	1.947	3.7
2	10	3.841	6.16
3	14	5.72	8.63
4	20	7.689	12.3
5	28	10.703	17.2
	15.6	5.98	9.598

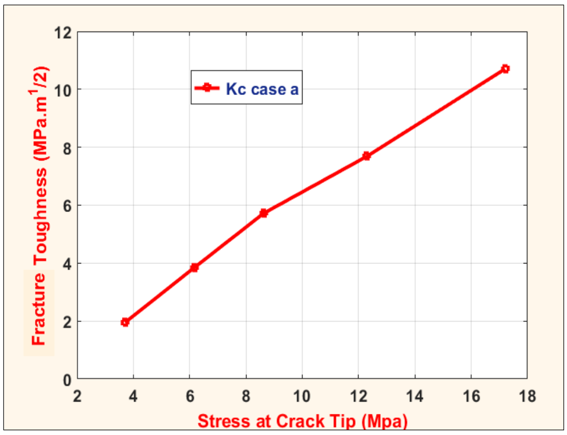

Fig. 5. Stress at crack tip versus with Kc for case (a)

b) Compact Tension

The objective of this case is to study the transverse crack where the load is perpendicular to crack direction as shown in Figure-3.

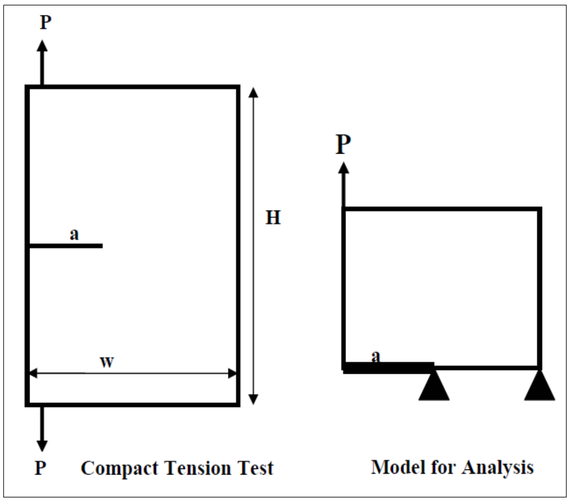

Fig. 3. Transverse crack case.

In this case two opposite forces act on the structural to open the initial crack on the structural.

Also after the material is implanted in MATLAB program and run this model for several loads as shown in Table-2, the result of fracture toughness value (Kc) is 7.15 MPa m$^{1/2}$. Figure -4 shows of one case run by MATLAB program.

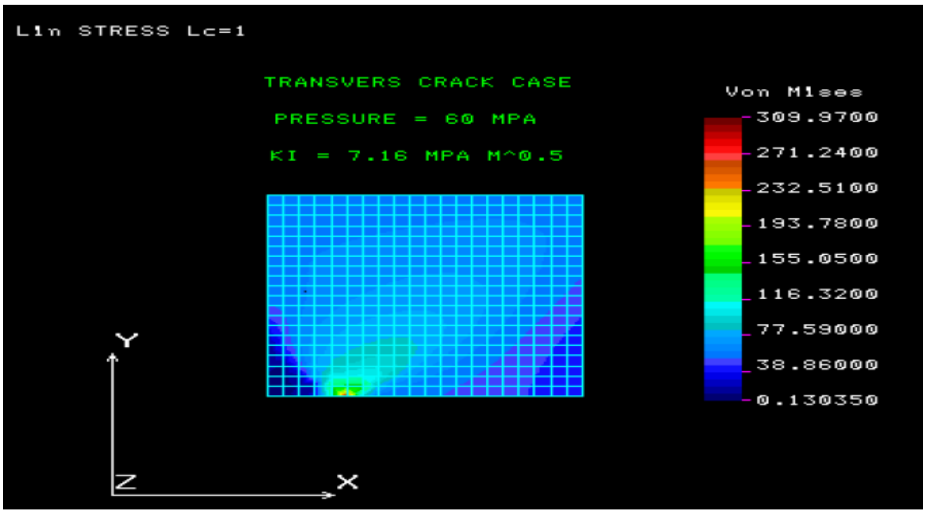

Fig. 4. Transverse crack case from MATLAB program.

Table 2,
List of fracture toughness value for transverse crack.

S*	Load (P) KN	K_c $MPa.m^{0.5}$	Stress (σ) MPa
1	40	4.77	206
2	50	5.96	258
3	60	7.16	310
4	70	8.34	362
5	80	9.54	413
	60	7.15	309.8

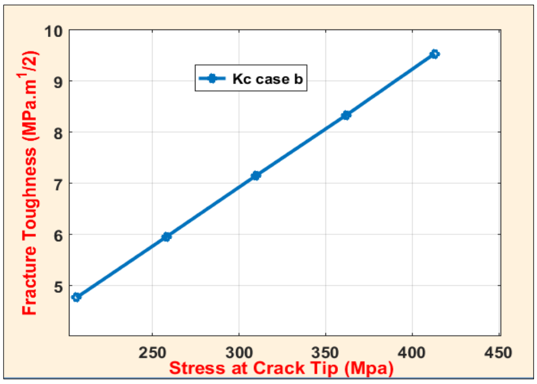

Fig. 6. Stress at crack tip versus with Kc for case (b).

Isotropic material properties were used follows: σ_{yield} = 85, $\sigma_{ultimate}$ =120, E=18000 (MPa). The weight was regarded as a boundary condition. Segment weights expressed in percentage of total body weight. Were used [3]. In comparison to peer studies such as Jaafar et al. [7], We note that the results are very close

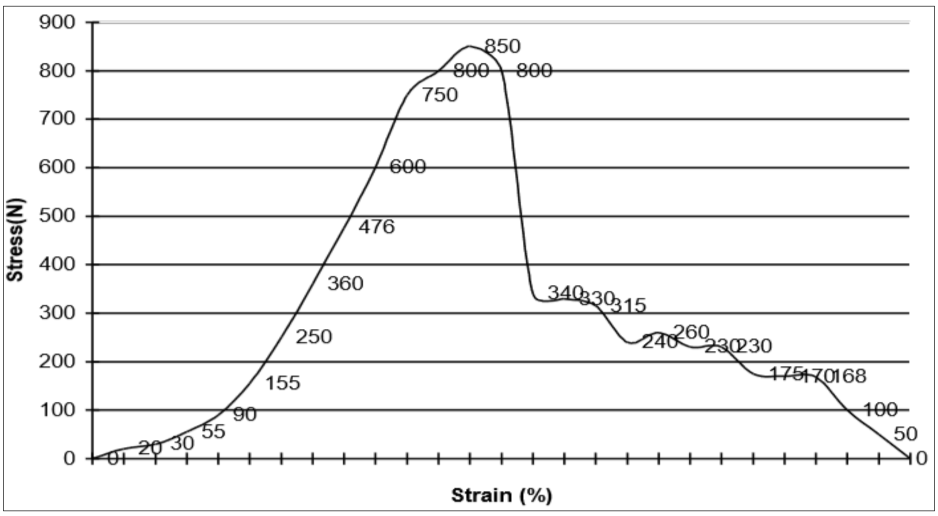

Fig. 7. Stress-Strain Curve of Human Bone.

5. Conclusion

As mentioned previously, the main objective of this study is to evaluate the by the fracture toughness by using Finite Element Analysis approach (MATLAB program). The results of this study are compared with the previous experimental results to check the possibility of using this approach in future work.

The results of Finite Element Analysis using MATLAB program found are consistent with the experimental results that give the fracture toughness of the bone to be between 2-8 $MPam^{1/2}$ and to be higher in transverse direction. The highest fracture toughness direction is when the crack path deflects at 90 degree to the plane of maximum tensile stress. Also as shown in Figure (5,6) the stress at the crack tip in Transverse crack is higher than in longitudinal crack.

Nomenclature

a	Crack Length
E	Modulus of Elasticity
KC	Stress Intensity Factor (Fracture Toughness)
P	Load

Greek Symbol

σ	Stress at any time
σ_f	Fracture Stress
υ	Poisson's Ratio
af	Crack Length at fracture

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دراسة نمو الشق الطولي والعرضي لعظم الانسان باستخدام طريقة العناصر المحدودة بوساطة الماثلاب

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الخلاصة

ان اي دراسة باستخدام طريقة العناصر المحدودة قادرة على توقع نمو الشق ومحاكاة توليد الشق ونشأته في العظم الانساني. ان النموذج المادي مطبق في رزمة من برنامج الماثلاب بوساطة طريقة العناصر المحدودة التي تسمح للامتداد الى اي شكل هندسي واي ترتيبه حمل مما يمكن عوامل ميكانيك الكسر من تحليل توليد الشق الطولي والمستعرض في العظم الانساني .ان صلابة الكسر فضلاً عن مخطط الاجهاد والانفعال يولدان ويقيمان كليا. ان المناقشة اعطت كمَاً من المعرفة الضرورية التي تمدد للسماح لتنبؤ بالكسر العظمي الكامل من التحميل الخارجي لمساعدة تصميم الانظمة الوقائية.