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FINITE ELEMENT ANALYSIS OF MODE I AND MODE II MICROMECHANICS OF MID - DIAPHYSEAL FEMUR TRANSVERSE FRACTURE BASED ON CORTICAL BONE HOMOGENEITY

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ABSTRACT

The mechanic of diaphyseal fracture in human cortical femur bone depends on the bone fracture resistance. At microscale, composition and nanomechanical properties of diaphysis femur at all cortices may contributes to the fragility of fracture. This paper present a finite homogeneity model of two-dimensional micromechanical diaphysis cortical femur bone subjected to Mode I loading condition. The fracture parameter e.g. stress intensity factor (SIF) and strain energy release rate are evaluated based on linear elastic fracture mechanics (LEFM) theory. The finite element (FE) modeling were simulated for four anatomical positions in cortical bone which are posterior, anterior, medial and lateral at different variability of bone properties, associated to transverse crack which is isotropy linked to its microstructure. The results indicate a good agreement to the analytical formulation for brittle fracture. However, by using displacement extrapolation method, all cortices resulted with same value of SIF but not for strain energy release rate.

Keywords: diaphyseal fracture, homogeneity, SIFs, SERR, finite element method.

INTRODUCTION

Diaphyseal fracture in human long bone (e.g. femur and ulna) may result from suddenly fall, impact or trauma due to sport collision or accident. The failure of bone may cause from accumulation of micro cracks, and will affect the micro structure features. Biomechanical study demonstrates that the behavior of whole bone structure is depending to cortical bone. Due to complex microarchitecture of cortical bone, it has significant effect in mechanical and fractured properties [1]. Experimentally, transverse, longitudinal and oblique cracking mechanism in regards to osteon alignment would force different elastic damage parameters [2]. Strain energy release rate approach was adopted to replace the fracture pattern. Moreover, Li [3] studied the causes of bone failure in different crack direction, transverse, radial and longitudinal direction of crack in four cortices, posterior, anterior, medial and lateral by implementing the experimental and numerical data using J integral parameter. Computationally, several studies have been conducted to investigate the effect of cortical bone microstructure on fracture mechanism [4]-[5]. However, in modeling, the problem of geometric representation was encountered with mesh densities and elements that computationally not viable for full model of femur bone fracture especially 3D simulation (Feerick and McGarry, 2012 [6]). Based on [7], detail upscaling in bone macroscale modelling would be computationally unfeasible. In present work, the longitudinal and transverse diaphyseal femur fracture of cortical bone was simulated using continuum mechanics and brittle fracture for linear elastic model. Fracture parameters were determined by developed macro sub-routine using displacement extrapolation method (DEM) provided in ANSYS APDL software. For simplification, cortical bone homogeneity condition is assumed in the simulation.

MATERIAL AND METHOD

The first simulations used to construct the middle diaphysis finite body of single edge crack cortical bone for four cortices; anterior, posterior, medial and lateral position, subjected to uniaxial loading as depicted in Figure 1. The dimension and boundary conditions were based on [8]. A micro-structural model of secondary osteon with transverse crack is modelled by considering homogenous properties which neglect any constituents in the model. The micro-structure is modelled with dimensions of height, H = 1 mm x width, W = 1 mm [9].

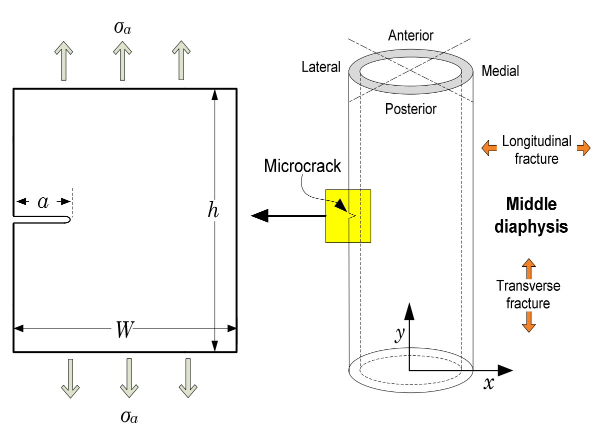

Figure-1. Middle diaphysis loading and boundary condition.

Table-1 summarizes the properties used in this numerical simulation. The material properties of these

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micro-structural and homogenous properties which regard to bone axis, longitudinal and transverse crack is obtained from experimental data, [10].

Table-1. Young's modulus and Poisson ratio for transverse fracture of four cortices.

Cortices	E_T (GPa)	Poisson ratio, v
Posterior	10.20	0.167
Anterior	13.20	0.167
Medial	14.67	0.167
Lateral	11.18	0.167

In meshing scheme arrangement, the global mesh is optimized and set to 0.02 mm while 0.01 near the crack tip, as shown in Figure-2(a). For high accuracy, 8-node quadrilateral element is employed for all the global and local elements. Singularity element surround the crack tip is based on Barsoum singularity element, set to local mesh. Figure-2(b) shows the schematic Barsoum singularity element used in the stress intensity factor (SIF) formulation for Mode I and Mode II fracture. Therefore, SIFs for Mode I and Mode II are evaluated using displacement extrapolation method (DEM) which defined by Equation. (1) and Equation. (2).

$$K_{IFE}(K_{IA}, K_{IP}, K_{IM}, K_{IL}) = \frac{E}{3(1+\upsilon)(1+\kappa)}\sqrt{\frac{2\pi}{l_y}}\left[4(v_2 - v_4) - \frac{(v_3 - v_5)}{2}\right] \quad (1)$$

$$K_{IIFE}(K_{IIA}, K_{IIP}, K_{IIM}, K_{IIL}) = \frac{E}{3(1+\upsilon)(1+\kappa)}\sqrt{\frac{2\pi}{l_x}}\left[4(u_2 - u_4) - \frac{(u_3 - u_5)}{2}\right] \quad (2)$$

where, $E(E_A, E_P, E_M, E_L)$ is Young Modulus for posterior, anterior, medial and lateral cortices for longitudinal and transverse fracture. $\kappa = 3 - 4v$ for plain stress and $\kappa = \frac{3-4v}{1-v}$ for plain strain, $l(l_y, l_x)$ is length of element, v and u are displacements in a local Cartesian coordinate system and υ is Poisson's ratio.

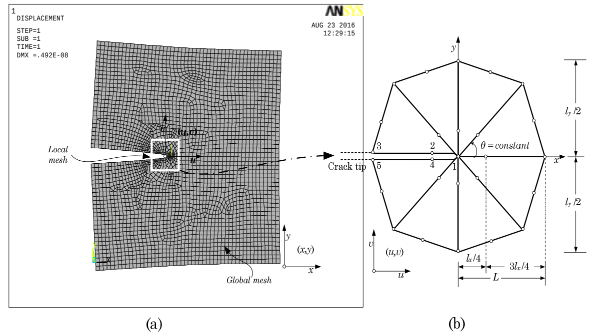

Figure-2. (a)Local and global meshing scheme and (b) crack tip singularity element.

Based on the LEFM assumption of bone fragility, the brittle transverse and longitudinally isotropic homogenous materials, Equation. (3) can be expressed as

$$K_{IFE} = Y_{FE}\sigma_{yy}\sqrt{\pi a}(a/W) \quad (3)$$

For model verification, standard brittle fracture of single edge crack analytical formulations by Tada (1973), Gross and Brown (1966) and Brown and Srawley (1964, 1966) were used for further validation. Each normalized SIFs expression are as follows:

$$Y_T = \frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)\left[0.752 + 2.02(a/W) + \frac{0.37\left(1-\sin\left(\frac{\pi a}{2W}\right)\right)^3}{(1-a/W)^{3/2}}\right] \quad (4)$$

$$Y_{GB} = 0.265(1-a/W)^4 + \frac{0.857 + 0.265(a/W)}{(1-a/W)^{3/2}} \quad (5)$$

$$Y_{GB} = 1.122 - 0.231(a/W) + 10.550(a/W)^2 - 21.710(a/W)^3 + 30.382(a/W)^4 \quad (6)$$

The strain energy release rate (SERR) for transverse cracking in all four cortices (posterior, anterior, medial and lateral) are calculated according to Equation. (7)

$$G_{T(A,P,M,L)} = \left(\frac{K_{IFE}^2}{E_T'}\right)\left[\frac{K_{IFE}^2}{E_{IT}'(E_{IA}', E_{IP}', E_{IM}', E_{IL}')} + \frac{K_{IFE}^2}{E_{IIT}'(E_{IIA}', E_{IIP}', E_{IIM}', E_{IIL}')}\right] \quad (7)$$

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where effective modulus transverse is assumed as $E'_T = E'_{IT} = E'_{IIT}$, respectively.

RESULTS AND DISCUSSIONS

Figure-3 shows the Mode I and Mode II SIFs for posterior, anterior, medial and lateral cortices. It can be seen that all cortices resulted with equal value of SIFs. This is due to the exception of material properties parameter (Young's modulus) in the determination of SIFs using DEM approach. The method is solely based on five displacement points at the crack surface in bone fracture as shown in Figure-2(b). Another fracture parameter, by using Equation. (7), transverse strain energy release rate G_T values for each cortex are different due to different Young's modulus as plotted in Figure-3. A posterior cortex is identified with the highest G_T due to lowest Young's modulus value and more G_T is increased as the a/W increased. In this case, parameter is proved to be more accurate in describing the transverse fracture. It means the consideration of plastic zone size surround the crack tip would be considered for better accuracy.

Table-2. SIFs for mode I and mode II for four cortices in transverse crack.

Crack width ratio, a/W	**Mode I SIF, K_I (N/mm)**				
	Posterior, K_{I_P}	**Anterior, K_{I_A}**	**Medial, K_{I_M}**	**Lateral, K_{I_L}**	$K_{II_{FE}}$
0.100	7.2962	7.2962	7.2962	7.2962	2.45E-04
0.125	8.511	8.511	8.511	8.5110	7.95E-05
0.175	11.09	11.09	11.09	11.0900	2.80E-04
0.225	13.966	13.966	13.966	13.9600	2.83E-04
0.275	17.215	17.215	17.215	17.2150	3.41E-04
0.325	20.916	20.916	20.916	20.9160	1.18E-06
0.375	25.188	25.188	25.188	25.1880	2.10E-04
0.425	30.228	30.228	30.228	30.2280	3.41E-04

Table-3. Comparison G_T for mode I for four cortices in transverse crack.

Crack width ratio a/W	**Strain energy release rate (G)**			
	Present	**Empirical formula**		
	$G_{I_{FE}}$	$G_{I_{Tada}}$	$G_{I_{GB}}$	$G_{I_{BS}}$
0.075	3.54606	3.2869	3.52213	3.3598
0.100	5.08934	4.6123	4.92969	4.6902
0.125	6.92516	6.1333	6.51607	6.1923
0.175	11.7579	9.9547	10.4201	9.9128
0.225	18.6472	15.1929	15.7252	15.0203
0.275	28.3323	22.4802	23.1538	22.2384
0.325	41.824	32.8362	33.8059	32.6596
0.375	60.6535	47.9797	49.4124	47.9935
0.425	87.3549	70.8341	72.7887	71.0113

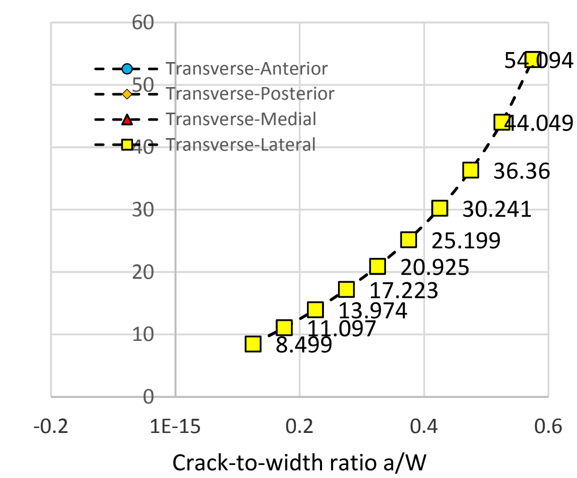

Figure-3. SIFs for transverse crack for all cortices.

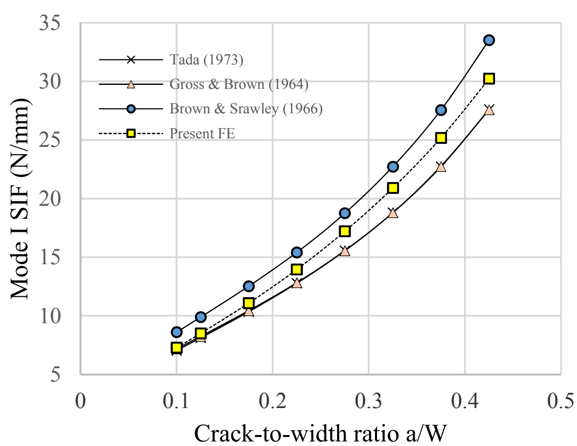

Figure-4. Comparison G_T for transverse crack in all cortices.

CONCLUSIONS

Four different cortices of finite diaphyseal fracture models in human cortical femur bone were developed to study the effectiveness of SIFs and strain energy release rate parameters subjected to tensile loading. In the present study, the transverse isotropic crack is assumed with homogenous properties. Based on the numerical results, this paper can be conclude that there has some limitation when finding the values of by using displacement extrapolation method using linear elastic fracture mechanics but for values of was changed depend on the mechanical properties each cortices. The empirical formula from Tada (1973), Gross and Brown (1966) are proved to be a reference for brittle bone crack.

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