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FINITE ELEMENT ANALYSIS OF MID-DIAPHYSEAL TRANSVERSE FRACTURE BASED ON CORTICAL BONE HETEROGENEITY

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ABSTRACT

The failure of bone may cause from accumulation of micro cracks, and will affect the micro structure features. The composition in cortical bone can be in the composite structure which has variety in material properties and play a role to macroscopic fracture behavior of whole bone structure. The composition in bone can be demonstrated as heterogeneous material properties which considered as constituents of osteon, cement line, interstitial matrix and Haversian canal. It is hypothesize that linear stress interaction exist and growth to intensify the interaction between constituents. This paper presents a finite cortical bone model based on continuum mechanics theory to identify the linear elastic interaction between four constituents and evaluate its model based on the standard analytical model for brittle fracture. Finite element method is employed to calculate the interaction fracture parameter, stress intensity factor (SIF) and energy release rate for four anatomical positions in cortical bone which are posterior, anterior, medial and lateral are considered due to different variability of bone properties. The results demonstrates the highest value of SIFs at posterior cortex and found lowest at lateral cortex. It is identified that numerical data is in good agreement with analytical model for brittle fracture.

Keywords: diaphyseal fracture, heterogeneity, SIFs, finite element method.

INTRODUCTION

Biomechanical study demonstrates that the behavior of whole bone structure is depending to cortical bone [1]. Due to complex microarchitecture of cortical bone, it has significant effect in mechanical and fractured properties due to different loading modes and orientations. Bone failure may affect from arrangement of microstructure cortical bone such as porosity, mineralization, orientation, diameters and spacing of collagen fiber. Cortical bone's mechanical property is not only effect by microstructure but also the direction of crack microstructure due to deformation of crack length and fracture behavior of cortical bone tissue by considering different loading modes (longitudinal and transverse crack) and orientations of four anatomical quadrant positions (posterior, anterior, medial and lateral).) The distinctions of anisotropy and variability of mechanical properties in four quadrants of bovine cortical bone under tension and compression using experimental procedure is studied by [2]. By experiment, [3] consider studying the elastic-plastic behavior in different directions, transverse and longitudinal axis and mechanical properties for 4 different cortices using the experimental procedures. More details, [2] 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. Few finite element models were used to model and analyzed the fracture behavior of microstructural cortical bone tissue. In example, [4] used a cohesive finite element modeling to investigate the mechanism that effect crack penetration into osteons or deflection into cement line [5] modeled the Haversian cortical bone using linear elastic fracture theory in order to investigate the interaction of microcracks and osteon. [6] introduced multiple scale method for modeling multiple crack growth in cortical bone under tensile loading by using extended finite element (FE) method, X-FEM Matlab/Gmsh for discretized the final geometry. In another attempt, [7] study the influence of porosity, osteon bone, and orientation of Haversian system on macroscopic elastic moduli and Poisson's ratio of cortical bone. The osteon in cortical bone can be promoted or retarder is dependent on ratio elastic modulus of osteon towards the interstitial matrix studied by [1]. This study aims to investigate the effect of cement line, interstitial matrix and osteon with difference material properties in cortical bone structure that caused transversial fracture.

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].

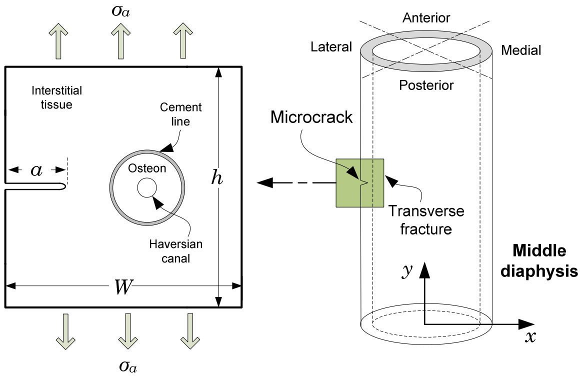


Figure-1. Middle diaphysis loading and boundary condition.

Table-1 summarizes the properties used in this numerical simulation. The material properties of this micro-structural and heterogeneous property which regard to bone axis and transverse crack are obtained from experimental data [3].

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

Cortices	E_T Interstitial matrix (GPa)	Poisson ratio, v
Posterior	E_{T_P} = 10.20	0.153
Anterior	E_{T_A} = 13.20	0.153
Medial	E_{T_M} = 14.122	0.153
Lateral	E_{T_L} = 11.18	0.153

Table-2. Young's modulus and poisson ratio for 4-phase constituents' model.

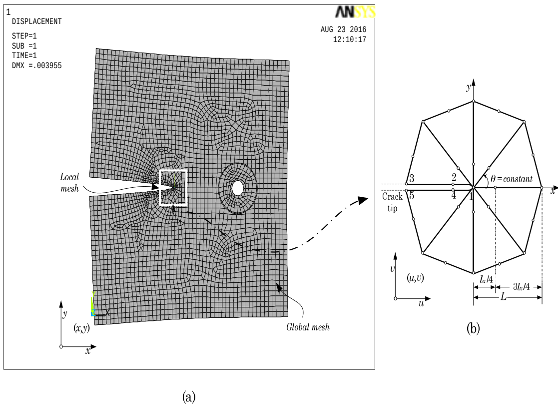
Cortical bone segment	Young's modulus (GPa)	Poisson ratio, v
Osteon	9.13	0.17
Cement line	6.85	0.49
Interstitial matrix	14.122	0.153
Haversian canal	-	-

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). Meshing scheme of 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. SIFs for Mode I and Mode II are evaluated using displacement extrapolation method (DEM) which defined by

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

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

where, $E(E_A,E_P,E_M,E_L)$ is Young Modulus for posterior, anterior, medial and lateral cortices for 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.



(b)

(a)

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 isotropic heterogeneous materials, Equation. (1) can be expressed as Stress intensity factor (SIF) for brittle transverse isotropic heterogeneous materials, Equation. (1) can be expressed:

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

RESULT AND DISCUSSIONS

Table-3. SIFs for Mode I and Mode II for four cortices in transverse crack.

Crack width ratio a/W	**Mode I SIF** (N/mm^2), K_{I_T}			
	Posterior K_{I_P}	**Anterior** K_{I_A}	**Medial** K_{I_M}	**Lateral** K_{I_L}
0.100	7.12294	7.1794	7.1657	7.2120
0.125	8.4396	8.3864	8.3718	8.4212
0.175	11.0130	10.9560	10.9400	10.9930
0.225	13.8880	13.8310	13.8150	13.8690
0.275	17.1430	17.0910	17.0760	17.1250
0.325	20.8610	20.8220	20.8110	20.8480
0.375	25.1580	25.1440	25.1390	25.1530

Crack width ratio a/W	**Mode II SIF** (N/mm^2), K_{IIT}			
	Posterior K_{II_P}	**Anterior** K_{II_A}	**Medial** K_{II_M}	**Lateral** K_{II_L}
0.100	1.90E-04	1.89E-04	1.89E-04	1.90E-04
0.125	5.51E-05	5.48E-05	5.47E-05	5.50E-05
0.175	1.81E-04	1.80E-04	1.80E-04	1.81E-04
0.225	8.50E-05	8.46E-05	8.45E-05	8.45E-05
0.275	5.63E-05	5.60E-05	5.59E-05	5.62E-05
0.325	2.85E-05	2.83E-05	2.83E-05	2.84E-05
0.375	1.90E-03	1.90E-03	1.90E-03	1.90E-03

Various crack to width ratio a/W = 0.1 - 0.375 were considered in FE simulation. Table-2 shows the different values of and due to variability mechanical properties for each cortex. For Mode I transverse fracture, the result indicates the posterior cortex has highest value of K_{IP} = 25.158 N/mm2 at a/W = 0.375 and the lowest for the medial cortex K_{IM} = 25.1390 N/mm^2. This is due to the lowest Young modulus (E_P) in posterior. The relationship of transverse Mode I SIF and was shown in Figure 3(a) and (b). Results indicated that, for fixed transverse loading, the will increase significantly along with the increasing crack to width ratio. The errors between four anatomical positions is relatively small in the range of 0.02 - 0.7%. In this case, since the position of osteons is fixed, it is revealed that elastic interaction parameters determined by Equation. (1-3) is reliable, and the effect of is more significant as increased near to the cement line.

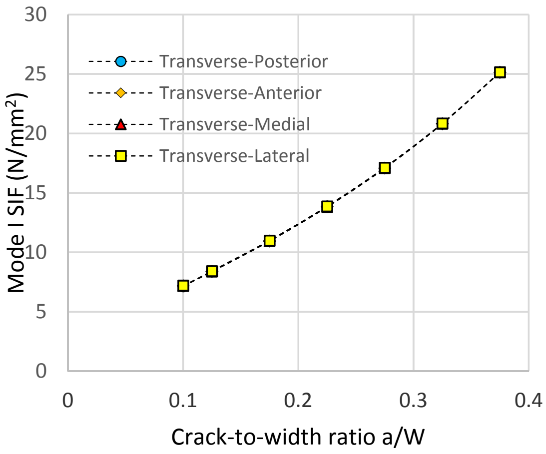


Figure-3(a). Stress intensity factor for transverse crack in all cortices for mode I.

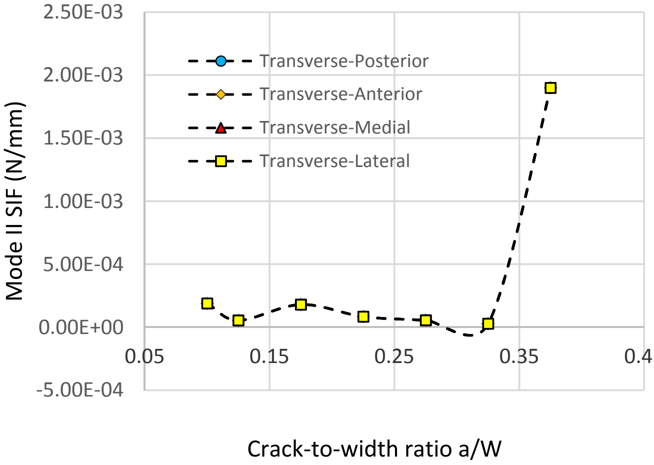


Figure-3(b). Stress intensity factor for transverse crack in all cortices for mode II.

Table-3 also shows the results of Mode II SIF K_{II_T} relative to a/W = 0.1 - 0.375. Figure-3(b) shows the relationship trend as a/W increased. It can be seen, the Mode II seems to have no significant effect to the interaction between cracks and osteons, hence can be neglected. However, while the a/W transition from 0.325 to 0.375, K_{II_T} seems to fluctuated rapidly peak at 1.90E-03 N/mm^2 for all cortices. This trend shows significant elastic interaction as the crack tip near to the cement line of osteons.

Table-4. SIFs between numerical and analytical data.

Crack width ratio a/W	Mode I SIF (N/mm^2) from empirical formula		
	Tada (1973) K_{I_T}	Gross & Brown (1964,1966) $K_{I_{GB}}$	Brown & Srawley (1964) $K_{I_{BS}}$
0.100	7.1040	7.1808	8.5400
0.125	8.1627	8.2558	9.8481
0.175	10.3278	10.4400	12.5464
0.225	12.7130	12.8252	15.4998
0.275	15.4689	15.5624	18.8541
0.325	18.7462	18.8045	22.7867
0.375	22.7248	22.7344	27.5445

For results validation, the results were compared with Tada (1973)Y_T, Gross and Brown (1966) Y_{GB} and Brown and Srawley (1964, 1966)Y_{BS}. Table 4 shows the variation of SIFs subjected to transverse loading. Tada (1973) and Gross and Brown (1966) formulation show a good agreement to present K_{I_T} , as shown in Figure-4.

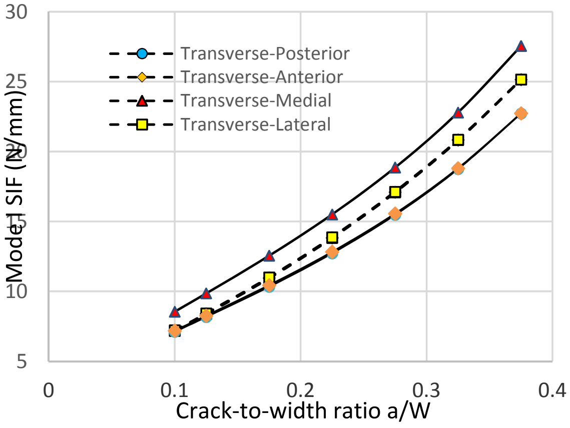


Figure-4. SIF for mode I four phase of cortices under tensile loading in transverse crack.

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 heterogeneous properties (osteon, cement line and interstitial matrix) considering four cortices; posterior, anterior, medial and lateral. Based on the numerical results, this paper can be concluding that the values of K_{I_T} and K_{II_T} are different for each cortex due to effect of different mechanical properties of Young modulus, E. For comparison between numerical model and empirical formula, can be concluded that Tada (1973) and Gross and Brown (1966) can be as reference of brittle fracture.

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