Elastic Interactions of Osteon-Crack Penetration in Longitudinal Fracture

N.N.Mansor[1], R.Daud[1], K.S.Basaruddin[1], Y.Bajuri[2] and A.K.Ariffin[3]
[1]*Fracture and Damage Mechanics SIG, School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia*
[2]*UKM Medical Centre, Department of Orthopedics and Traumatology, Universiti Kebangsaan Malaysia, Jalan Yaacob Latif, Bandar Tun Razak, Cheras, Kuala Lumpur, Malaysia*
[3]*Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi Selangor, Malaysia*
nurulnajwamansor@gmail.com

***Abstract*—Longitudinal fracture of cortical bone involves complex elastic interaction between interstitial matrix, cement line, osteon and Haversian canal. Based on Kachanov theory of microcrack and hole interaction, there is effective impact interaction between different elastic moduli, and interaction between stress risers. This paper aims to numerically evaluate the effect of different Young's modulus in osteonal system structure for four-phase constituents (anterior, posterior, medial and lateral) in Haversian bone system particularly in longitudinal crack direction. The interaction between single crack and Haversian canal in crack-osteon penetration process is analysed based on linear elastic fracture mechanics (LEFM) with plain strain condition. Stress interaction intensities are compared to Brown and Srawley empirical formulation. The simulation results showed that the elastic interaction before the osteon penetration is consistent and stable**

***Index Terms*—Constituents; Heterogeneity; SIFs Parameter; Transverse-Longitudinal Crack.**

I. INTRODUCTION

Fracture in cortical bone may affect the integrity function in terms of load-bearing and may cause the injuries and mobile loss. A human cortical bone has a multiscale level that forms difference constituents. At the nano-scales, bone composed of mineralised collagen fibril matrix and extrafibrillar mineral particles named as carbonated hydroxyapatite. At the micro-scale, the lamellar layers laid down with the staggered arrangement between adjacent the most popular observations and considerations of researchers was the focus in lamellar with hollow vascular channels named as Haversian bone composed an osteon, interstitial matrix, cement line and Haversian canal [1].

Each constituent in this heterogeneous cortical bone structure has difference task, whereas, the interstitial matrix was made up from the remnants of the remodelling process, osteons is a cylindrical structure parallel to the long bone axis, and Haversian canal accommodate the blood vessel [1]. The interface between the interstitial matrix and osteon called cement line can act a toughening mechanism deflecting a crack from osteon or weakening mechanism, facilitate crack initiation [2].

Thus, the difference constituent in the microstructure gives the significant impact on the variability of bone fracture mechanical behaviour. Naturally, the bone structure is a dynamic, whereas it can repairing, remodelling and adapting itself to the surrounding environment. Moreover, bone is anisotropic in nature, the fracture toughness of bone affect the crack orientation whether in transverse, radial, longitudinal. Indeed, the osteon fracture behaviour in different Young modulus is not well described in previous studies. Thus, this study aims to investigate the osteons fracture parameters involving the stress intensity factor (SIF) near the crack tips for each constituent. The effect of material properties and crack orientation are considered throughout the Finite Element (FE) simulation.

II. MATERIALS AND METHODS

The FE simulation was divided into two cases, case A and B. Case A involved the investigation on the effect of material properties (Young's modulus), and case B regarded to longitudinal crack orientation. FE models of case A and B were created using ANSYS APDL 14.5 platform by developed macro-subroutine. The osteonal system model was approximately 1 mm in width and 1 mm in height. The model size is based on Mischinski and Ural [3].

To illustrate the idea of crack-single osteon interaction, consider the schematic diagram as depicted in Figure 1 where the crack is set to vary from 0.125 < a < 0.575 for each cortex (anterior, medial, posterior and lateral) of middle diaphysis bone. The dimension of single osteon was 0.14 mm in diameter, 0.015 mm in cement line thickness, 0.035 mm in Haversian canal diameter. This simulation considered osteon as fibre and whereas the interstitial tissue is a matrix since the osteon is circular and parallel to bone longitudinal axis [4].

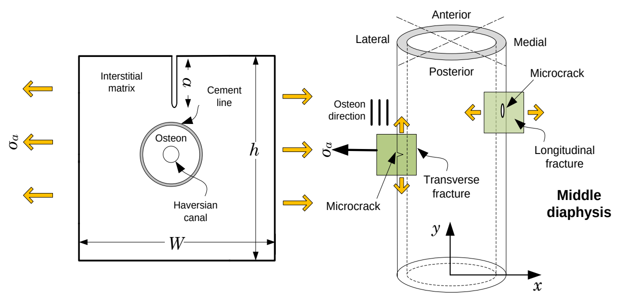

Figure 1: Schematic diagram of an osteonal system with single edge crack for longitudinal crack orientation

As suggested by Hogan [5], the model can be simplified as a single osteon and neglect the interaction between osteon. The quadrilateral meshing with eight nodes plane 183 elements were used for model meshing, as shown in Figure 2(a) and (b).

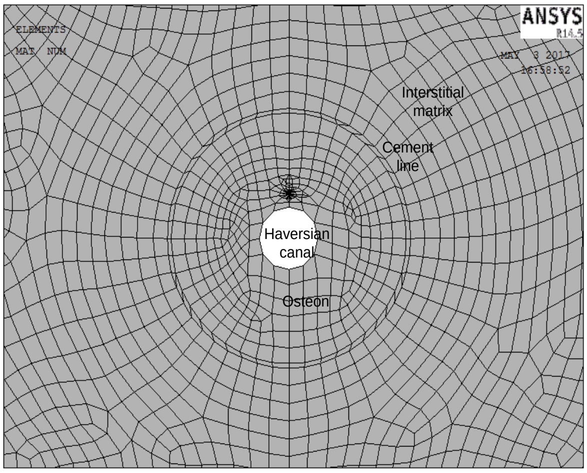

Figure 2: (a) Schematic diagram of an osteonal system with single edge crack for longitudinal crack orientation

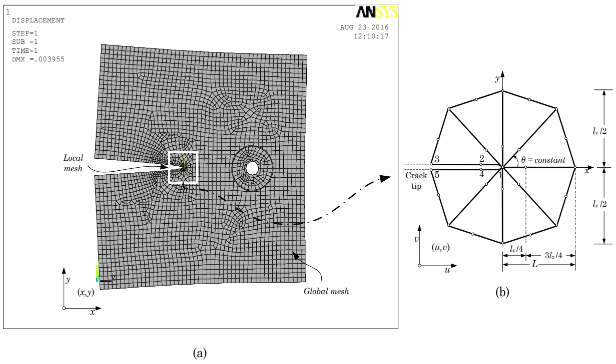

Figure 2: (b) Global and local singularity element for longitudinal crack direction

Barsoum singularity elements were employed to end tip of crack as depicted in Figure 3. The model was fixed along the y-axis at the left side model while pressure was used along the line at y-axis for the right side. The tensile loading with σ_a = 15 MPa was applied for both transverse and longitudinal crack. The constructed models were considered to be isotropic, homogenous and linearly elastic. The elastic properties were adopted from literature, and the anisotropic material properties were considered in this model as listed in Table 1.

Table 1
Materials Properties for Longitudinal Crack for Each Cortex in Femur Cortical Bone

Osteon system	Young modulus, E(GPa)				Poisson's ratio
Longitudinal crack	23.15	21.13	19.29	15.14	0.153
Cement line	6.85	6.85	6.85	6.85	6.85
Osteon	9.13	9.13	9.13	9.13	9.13

III. RESULTS AND DISCUSSION

Table 2 shows the stress intensity factor SIF in longitudinal $K_{I(LO)}$ for posterior $K_{I(LO)_P}$, anterior $K_{I(LO)_A}$, medial $K_{I(LO)_M}$ and lateral $K_{I(LO)_L}$due to variability mechanical properties for each cortex.

Table 2
Mode I SIFs for Four Cortices in Longitudinal

Crack Width Ratio	Osteonal Region	Longitudinal Mode I SIFs (N/mm^2)			
	Interstit-al matrix	Anterior	Medial	Posterior	Lateral
0.125		11.788	11.784	11.781	11.770
0.175		15.229	15.216	15.203	15.165
0.225		19.095	19.064	19.034	18.951
0.275		23.645	23.582	23.519	23.306
0.325	Cement	29.354	29.215	29.074	28.960
0.375	line	37.671	37.289	36.903	35.865
0.425	Osteon	32.103	33.058	33.946	36.059
0.475		36.662	38.472	40.272	45.332
0.525		33.745	35.271	37.762	43.470
0.575		67.824	52.796	55.423	62.539

Case A: Effect of material properties

Under tensile loading, for longitudinal crack, it is notified that the anterior cortex (E_A= 23.15 GPa) has the highest SIFs (e.g. a/W= 0.125 mm, $K_{I(LO)_A}$= 11.788 N/mm2) while the lateral cortex (E_L= 15.14 GPa) has the lowest SIFs (e.g.a/W = 0.125 mm, $K_{I(LO)_L}$= 11.770 N/mm2). It means SIF appeared to increase as Young's modulus increases. More details, the transition of material stiffness from the interstitial matrix to osteon through cement line penetration provided a significant influence on stress shielding between Haversian canal and crack tip.

For example, in the range of a/W = 0.375 to 0.425, the crack was initiated from the interstitial matrix of stiffest anterior cortex with Young's modulus (E_A= 23.15 GPa), then penetrated the cement lineE_{CL}= 6.85 GPa) before entered the osteon region (E_O= 9.13 GPa). It is observed that the unstable cracking behaviour has occurred. Due to that, approximately, the SIF parameter; (K) has increased 28% when penetrating the cement line, then decreased 17% as entering the osteon before increased again at 14%. The same unstable behaviour is experienced for all cortices.

Case B: Longitudinal Orientation

Figure 3 shows the trend of SIF for anterior, posterior, medial and lateral cortices at different a/W for longitudinal direction. Overall, SIF of cracked cortical bone increased as the a/W increased.

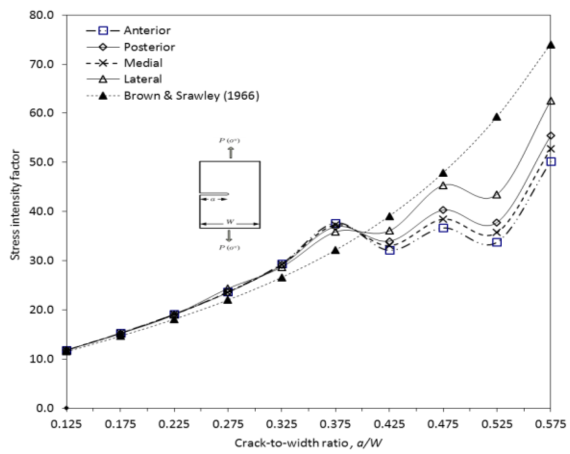

Figure 3: SIFs vs a/W for longitudinal crack orientation for four cortices

In Figure 3, the longitudinal crack showed the increased SIFs linearly for all cortices proportional to a/W approximately at a/W = 0.125 to 0.325. The trend is incrementally stable. At this stage, the stable cracking behaviour is caused by less shielding and amplification influence of cement line. The behaviour is dominantly controlled by the homogeneity material of interstitial matrix. Table 3 listed the stress shielding (%) of Mode I for every a/W.

Table 3
Mode I Stress Shielding for Four Cortices in Longitudinal Direction

Crack Width Ratio	Stress Shielding (%)			
	A	M	P	L
0.125	2.537	2.503	2.476	2.380
0.175	3.981	3.893	3.802	3.549
0.225	5.200	5.366	5.200	4.741
0.275	7.433	7.150	6.862	6.075
0.325	10.357	9.833	9.303	7.861
0.375	17.161	15.973	14.774	11.546
0.425	17.827	15.383	13.110	7.701
0.475	23.413	19.634	15.873	5.303
0.525	43.035	39.699	36.253	26.618

The interaction effect of shielding and amplification is significantly initiated in the range of a/W= 0.375 to 0.425. The SIF is peaked at a/W = 0.375 for all cortices (e.g. $K_{I(LO)_A}$ = 37.671 N/mm2) then, at a/W= 0.425 the SIF is suddenly decreased (e.g. $K_{I(LO)_A}$ = 32.103 N/mm2). The cement line interface gives the protection against the crack failure; the stress at the crack tip decreased so. Thus the SIFs decreased. A kind of split rupture that mimic the interface failure and fibre debonding is occurred [6]. This behaviour is also reflected to crack penetration from interstitial matrix to osteon through cement line at a/W = 0.525 or a = 0.0525 mm. In details, when a was nearly approach to the cement line barrier, it is more likely to deflect phenomena due to imperfections and heterogeneity of microstructure. This is due to the result of osteon's pull out process under loading.

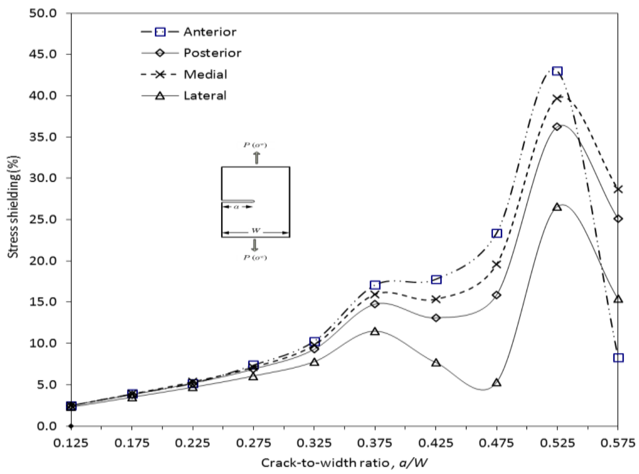

Figure 4: Mode I stress shielding vs a/W for longitudinal crack orientation of four cortices

In the final stage of cracking process in osteon, as the crack is neared to Harvesian canal for complete fracture, a sudden increased of SIF is observed at a/W = 0.575. The perfect bonding at the interface between cement line, interstitial matrix and osteons have provided radial compression shielding surround the Haversian canal to prevent.

IV. Conclusion

In this study, the longitudinal crack in tensile loading was evaluated using FE method. The relationship between different Young modulus properties of each cortex and different crack orientation with crack to width ratio is discussed. The crack in longitudinal propagates along osteon direction when crack tends to penetrate and enter the cement line in its pathway. For all cortices in the longitudinal crack, the graph trend sudden decreased when a/W =0.425 as observed due to the crack is more likely to approach the cement line region. When the crack tip was reach near to the difference Young modulus between the interstitial matrix and cement line resulted in unstable SIFs encounters the cement line constituents and the crack tip was in the osteon. The cracks propagate until a = 0.575 mm ahead of crack and tend to split, rupture and fiber debonding. For a = 0.575 mm the SIFs changes extremely increased showed that the model was rupture and failure. The influence of Young modulus in interstitial matrix significantly positive effect to the SIFs parameter, which the posterior and lateral cortex has small Young modulus compare to anterior and medial and thereby the values SIFs are tend to largely increased. Interface debonding between fiber and matrix is expected to serve toughening mechanism for longitudinal crack. When a crack penetrates into the weaker region of cement line (poorly mineralized, Burr et al., 1988), the crack was deflected and prevents catastrophic failure. However, with the condition of deflection to occur, $(G_{CL}/G_O) < (G_d/G_p)$, the results from FEM analysis was not satisfied this condition, whereas $(G_{CL}/G_O) < (G_d/G_p)$ = 0.7603 > 0.6434. Thus, this research highlight to penetrate into the osteon. This research has a limitation due to only considered one osteon and one crack in the model due to small difference modulus between interstitial matrix, osteon and cement line. This research can be further considered in plastic damage since this deformation involved in this tissue.

Acknowledgement

The authors are grateful for the research support of Ministry of Higher Education (MOHE) Malaysia and University Malaysia Perlis through awarded Fundamental Research Grants (FRGS 9003-00491) and (FRGS 9003-00578).

References

[1] S. Li, A. Abdel-Wahab, and V. V. Silberschmidt, "Analysis of fracture processes in cortical bone tissue," *Eng. Fract. Mech.*, vol. 110, pp. 448–458, Sep. 2013.

[2] P. Zioupos and J. . Currey, "Changes in the Stiffness, Strength, and Toughness of Human Cortical Bone With Age," *Bone*, vol. 22, no. 1, pp. 57–66, Jan. 1998.

[3] S. Mischinski and A. Ural, "Finite Element Modeling of Microcrack Growth in Cortical Bone," *J. Appl. Mech.*, vol. 78, no. 4, p. 41016, 2011.

[4] A. R. Najafi, A. R. Arshi, M. R. Eslami, S. Fariborz, and M. Moeinzadeh, "Haversian cortical bone model with many radial microcracks: An elastic analytic solution," *Med. Eng. Phys.*, 2007.

[5] H. A. Hogan, "Micromechanics modeling of Haversian cortical bone properties," *J. Biomech.*, vol. 25, no. 5, pp. 549–556, 1992.

[6] S. Li, A. Abdel-wahab, E. Demirci, and V. V Silberschmidt, "Inelastic

Behavior of Materials and Structures Under Monotonic and Cyclic Loading," vol. 57, 2015.
[7] A. Raeisi Najafi, A. R. Arshi, M. R. Eslami, S. Fariborz, and M. H. Moeinzadeh, "Micromechanics fracture in osteonal cortical bone: A study of the interactions between microcrack propagation, microstructure and the material properties," *J. Biomech.*, 2007.
[8] X. E. Guo, L. C. Liang, and S. a. Goldstein, "Micromechanics of Osteonal Cortical Bone Fracture," *J. Biomech. Eng.*, vol. 120, no. 1, p. 112, 1998.