A STUDY OF ANISOTROPIC DEPENDENT TOUGHENING MECHANISMS OF CORTICAL BONE UNDER MONOTONIC LOADING

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2021

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July 2021

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of requirement to graduate with honours degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School Of Mechanical Engineering

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DECLARATION

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ACKNOWLEDGEMENT

In the present world situation that has been spared challenges due to the affected pandemic issue, to be able to proceed with the final year project in this uncertain situation is such a big blessing to all, on a positive note, this hundred percent of simulation work could also be a platform that bridging connections between theoretical and experimental work. By that, firstly I would express my deepest gratitude to God the Almighty for lighting me to complete this thesis until the end.

My heartfelt recognition to my supervisor, Dr. Norwahida Binti Yusoff for the endless support, be it academically and mentally. The flexibility that she offered undoubtedly soothed the simulation process, if looking at a bigger perspective, she has inspired me to learn, never once did she leave me in despair in self-confusions, this encouragement always kept me warm and motivated to ask and explore this research field more. The journey feels way much easier with the trust and help from my proficient supervisor.

Besides, I am highly obliged to thank the course coordinator, Dr. Muhammad Fauzinizam Bin Razali for the seminar and online writing enhancement sessions provided by the university library team, which nevertheless brushed up my thesis writing skills. All in all, my appreciation for everyone I had encountered throughout my final year project progress. My colleague Mr. Syamim for always encouraging me to work smart, also to the presentation examiner, Ir. Dr. Feizal Yusof, that eventually had me advised to be better. This piece of research truly would not be an accomplishment without encouragement from all.

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LIST OF SYMBOLS

α	Relative Crack Length
a	Crack Length
W	Specimen-Width
a / W	Crack-length to Specimen-width ration
K_I	Stress Intensity Factor
$K_{I\ (average)}$	Average Stress Intensity Factor
E	Young’s Modulus
v	Poisson Ratio
$\boldsymbol{\varepsilon_{max}^{0}}$	Maximum Principal Strain

LIST OF ABBREVIATIONS

XFEM	Extended Finite Element Method
CT	Compact Tension
BMD	Bone Mineral Density
Mode I Fracture	Tensile-opening Loading
Mode II Fracture	In-plane Shear Loading
Mode III Fracture	Out-of-plane Shear
MAXPE	Maximum Principal Strain Criterion
QUADE	Quadratic Nominal Strain Criteria
CPE4R	Four-node Plane Strain Element with Reduced Integration
CAE	Complete Abaqus Environment
ASTM E 399	American Society for Testing and Materials in 399 Version
USM	Universiti Sains Malaysia

KAJIAN MEKANISME KEBERGANTUNGAN ANISOTROPIK TERHADAP KETAHANAN BON KORTIKAL DI BAWAH BEBAN MONOTONIK

ABSTRAK

Ketahanan patah tulang kortikal dalam kalangan manusia dipengaruhi oleh penyakit seperti osteoporosis yang terbukti keberkaitannya seiiring dengan peningkatan usia. Tulang penuaan lebih cenderung kepada masalah berpori, menjadi asbab tulang terdedah kepada kejadian retak sejurusnya berupaya mengakibatkan patah tulang. Literatur yang mengetengahkan hubungan antara tulang kortikal dan kekuatan tulang kortikal di bawah beban Mode I melalui prosedur simulasi ternayta masih kurang. Demikian, kajian ini mengutarakan pendekatan simulasi lantas meneliti hubunga antara struktur mikrostruktur tulang kortikal dan faktor intensiti tekanan, K_I sebagai ukuran kuantitatif ketahanan tulang. Untuk mengemukakan subjek yang berkenaan, tulang dimodelkan sebagai sebuah specimen ketegangan padat (CT) dengan variasi bilangan mikrostruktur, dan pelbagai ukuran retak lantaran menerangkan sifat rintangan tulang kortikal terhadap fenomena retak dan patah tulang. Lebih-lebih lagi, gerakan pertumbuhan retak di sepanjang lintasannya juga dikaji dalam menekuni penyebaran retak sebagai tindak balas terhadap struktur mikro tulang kortikal yang berbeza. Keputusan analisis telah mengukuhkan kenyataan bahawa faktor intensiti tekanan meningkat setara dengan peningkatan bilangan struktur mikro dan ukuran retak, sekaligus mengetengahkan fungsi struktur mikro tulang kortikal sebagai satu elemen penting yang mempengaruhi retak dan juga sebagai satu faktor mekanisme ketahanan tulang kortikal. Perbandingan hasil kajian dilakukan dan yang dikemukakan ialah selaras dengan terbitan literatur.

A STUDY OF ANISOTROPIC DEPENDENT TOUGHENING MECHANISMS OF CORTICAL BONE UNDER MONOTONIC LOADING

ABSTRACT

The fracture resistance of human cortical bone is adversely influenced by diseases such as osteoporosis that are age-related. Aging bones are prone to be porous in return making them easily exposed to bone fracture occurrence. Cortical bone toughening mechanisms are known to be dependent on its microstructure that is affected by cortical porosity considering void volumes within the cortical bone volume. There are abundant published works of literature that measure the relation between cortical bone and fracture toughness under Mode I loading via experimental procedures, however, simulation is, apparently on the contrary. The aim of this study is to investigate the relationship between the cortical bone microstructural properties and stress intensity factor, K_I as the quantitative measure of bone fracture toughness. To address the subject mentioned, the bone is modelled as a compact tension (CT) specimen with crack size variations as also to investigate the toughness properties of the cortical bone concerning the crack size. Moreover, the motion of crack growth along its trajectory is also explored in highlighting the crack propagation in response to different cortical bone microstructures. The finite element analysis shows that the stress intensity factor increases as the number of microstructures and the crack size increase, besides, the presence of microstructure also does influence crack deflection as a matter of enhancing the cortical bone's toughening mechanism, which is consistent with that reported in published literature.

CHAPTER 1

INTRODUCTION

1.1 Background

The weight of human skeletal bone is filled with 80% of cortical bone [1], because of its ability to self-repair and adaptive to variations in mechanical usage patterns, it has become a distinctive and widespread subject in engineering materials.. Porous bone leading to osteoporosis has been the primary factor of osteoporotic fracture [2], especially in elderly women. Clinically, osteoporosis is diagnosed based on the measurement of bone mineral density (BMD) which deteriorates with age [3]. Nonetheless, this clinical method is argued insufficient to predict the bone fracture risk as the bone fracture toughness is regulated not only by bone mass but also strongly dependent on bone quality, which is essentially determined by bone porosity and its constituent microstructures [4].

In the framework of a mechanical viewpoint, cortical bone is conveyed as a composite material from its complex anisotropic and hierarchic microstructure which its heterogenous microstructure provides a protective toughening mechanism preventing catastrophic failure and bone breakdown [4]. The main microstructure features of bone at the nanoscale, as shown in Figure 1.1. A cylindrical osteon structure of 0.003 – 0.007 mm thickness formed by concentric lamellae. With a diameter of 0.03 – 0.05 mm, these lamellae structures encircle the Harversian Canals, besides covering the external boundary separating the osteons from an interstitial matrix that termed as cement lines [5]. The space embedded in the osteons is composed with a disordered tissue of interstitial matrix. Microcracks are studied to form not just within the osteons, but also within the interstitial bone, reaching cement lines. [6].

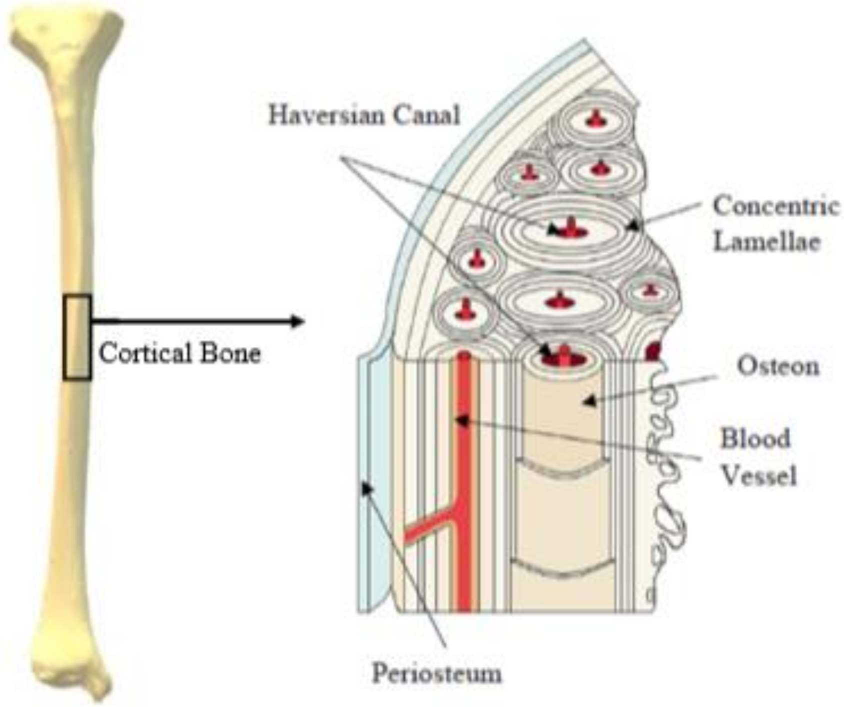


Figure 1.1 : Microstructure of Human Cortical Bone [7]

The bone's fracture toughness is a material parameter that describes the resistance to crack propagation [8]. The fracture toughness of cortical bone is better represented by the Stress-Intensity Factor (K_I). Most suitably, a linear-elastic fracture is applied when characterising cortical bone that any inelastic behaviour is only restricted to the tip region limit, also the stress and displacement fields are associate to the tip of a pre-existing crack. Meanwhile, the stress-intensity values may be defined and classified as illustrated in Figure 1.2; Mode I (tensile loading), Mode II (in-plane shear loading), and Mode III (out-of-plane shear loading).

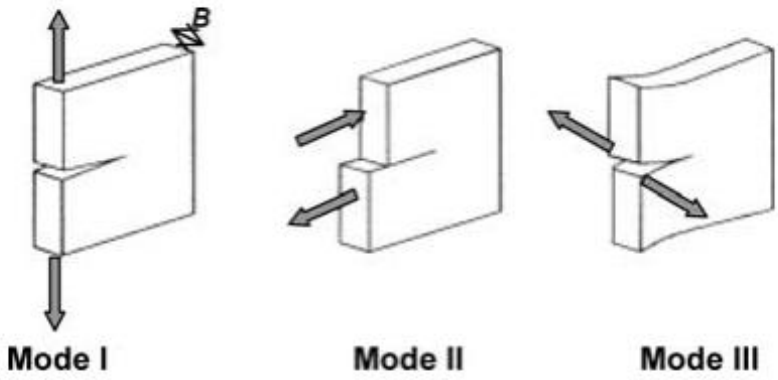


Figure 1.2 : Modes of Fracture

1.2 Problem Statement

Concerning bone fracture is a prominence effect from its physiological factor of aging human cortical bone that makes it prone to multiloading, nevertheless including Mode I of tensile loading fracture. Abundant of studies has focused on the fracture when the bone model is subjected under a mono-fracture loading condition, Mode I, also the influence of cortical bone microstructures as a part of its fracture properties. However, the impact of each layer of cortical bone microstructures on crack propagation is still a challenge in experimental analysis, and the roles of the microstructures in resisting crack propagation is less studied. Furthermore, the essential requirement of specimen size geometry in simulation could also affect the analysis outcome.

Therefore, this current study primarily **aims to study the anisotropic dependent toughening mechanisms fracture toughness of cortical bone in Mode I fracture with various crack lengths using finite element analysis**. The roles of bone microstructure as the toughening mechanisms that would retain the toughness properties of the bone and prevent it from fracture are investigated. This study further examines the influence of the microstructural properties on fracture toughness and toughening mechanisms, when the simulated model is subjected to Mode-I loading condition with different crack lengths. The relation between bone microstructure and its toughness, quantified by K_I, is examined through the means of finite element analysis.

1.3 Objectives

1. To assess the impact of cortical bone microstructures on fracture properties for Mode I loading in measures of stress intensity factor.
2. To evaluate the influence of crack length on the stress intensity factor with regard to cortical bone fracture properties under Mode I loading.
3. To examine the pattern of crack propagation of cortical bone in response to its microstructural properties under Mode I loading.

1.4 Scope of Work

This paper is highlighting on fracture properties of human cortical bone when it is subjected to Mode I loading. Both aspects of qualitative and quantitative were carried out to evaluate the resistance of cortical bone towards the fracture load applied, which in relative to that, leading to its toughening mechanism and fracture properties which are as schematically outlined in Figure 1.3.

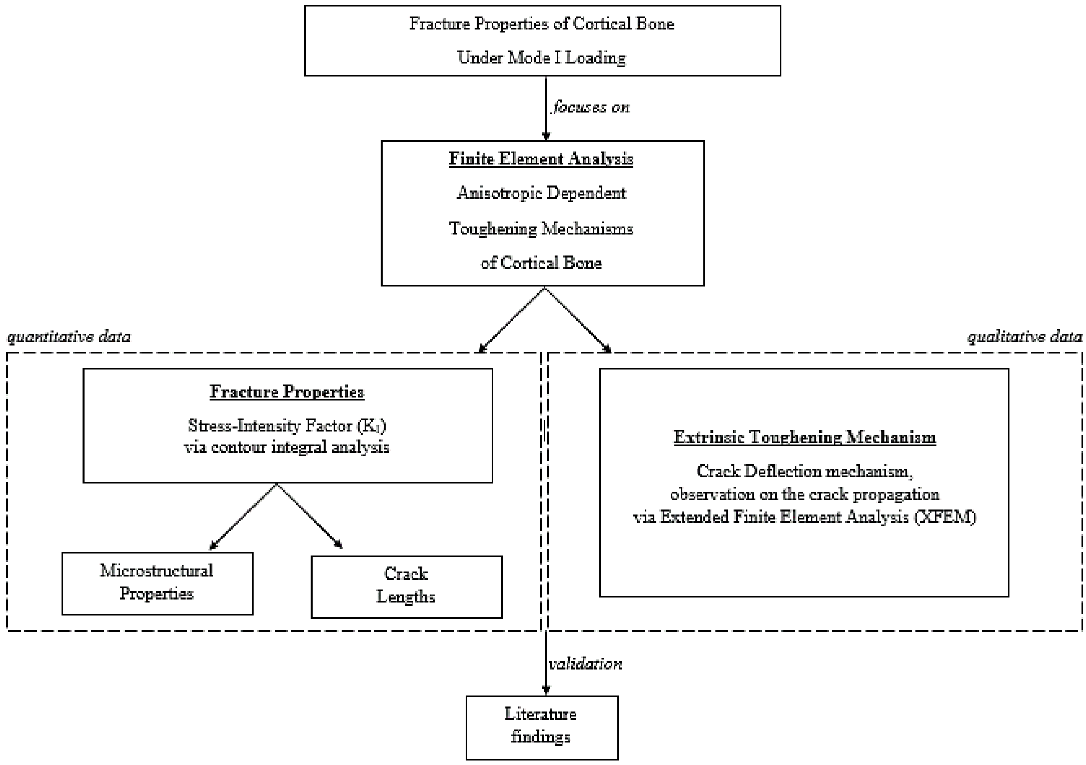


Figure 1.3 : The scope of the research work

CHAPTER 2

LITERATURE REVIEW

2.1 Stress Intensity Factor and Fracture Toughness

A common numerical requirement in fracture mechanics to study the behavior of cracked bodies is termed as stress intensity factor, K. The stress intensity factor, K predicts the stress state near the tip of a crack or notch caused by a remote load or residual stresses [9]. It is a theoretical construct that is applicable to a homogeneous, linear elastic material widely known for providing a failure criterion for brittle materials [10], therefore in this context of human cortical bone.

Stress intensity factor describes the stress state at a crack tip, which can be expressed in few forms. The stress intensity factor for single-edge-cracked specimens giving out the overall intensity of the stress distribution, is expressed as [11]:

$$K_I = \sigma\sqrt{\pi\, a} \qquad (1)$$

where σ is stress, a is relative crack length and W is the width of the specimen. A critical measure that is used in design a plane-strain fracture toughness to analyse the material's ability to withstand crack tip stresses up which the crack propagates rapidly [11] is termed as the critical value of stress intensity, K_{IC}, that is calculated by:

$$K_{IC} = Y\, \sigma\, \sqrt{\pi\, a} \qquad (2)$$

This critical stress intensity factor is a measure of material toughness [11] which the Y refers to the geometrical factor that is dependent to the crack length a. The geometrical factor will be further addressed in the next section on this paper.

2.2 Cortical Bone Microstructure and Fracture Toughness

In conjunction with the topic of human cortical bone fracture, fracture toughness usually is addressed in terms of few quantitative measurements, such as the strain-energy release rate (G), work of fracture (W), and the most common is the stress-intensity factor (K). Utilising linear-elastic fracture mechanics, the work of fracture is obtained from the load-displacement curve while the strain-energy release rate and the stress-intensity factor can be calculated using theoretical equations [5]. Traditional studies on bone fracture have always relied on linear-elastic fracture mechanics in determining single-value fracture toughness (K or G), however Resistance-curve (R-curve) analysis is nevertheless important to differentiate the intrinsic and extrinsic toughening mechanisms involved in fracture.

Silva et al. on his paper studied that when the cortical bone specimen was subjected under a mixed-mode I and II, the specimen showed an increasing trend at the R-curve, upon the fracture process, followed by a plateau, which the strain-energy release rate was ranged 1.6-1.9 N/mm [12].

Relating fracture toughness and the microstructure of cortical bone, Abdel-Wahab et al. had shown a significant effect of cement lines on fracture toughness on his numerical simulation [13]. The results showed that the homogenous cortical model (Model A) deformed the quickest, followed by Model B (model with cement lines) then Model C (model without cement lines). Besides, Model C required 17.5% higher applied stress for microcracks to start growing, while Model B required 16.9%, leaving Model A the lowest. This finding indicates that the presence of cement lines markedly increases the fracture toughness of the cortical bone.

Apart from that, Gauthier et al. claimed that a higher area of osteon fraction in the specimen model leads to lower fracture toughness [14]. This can be seen by more microdamage found in the radial diaphysis, as compared to the femoral diaphysis and femoral neck when the anatomical site of cortical bones was subjected under quasi-static loading condition. A higher volume fraction of micro-cracks, as observed in the radius, results in a higher quantity of energy dissipated and thus a slowdown of the main crack propagation. This is affected by bone microstructure like the osteons. This finding experimentally agrees with Zhai et al. [15], in which the stress-intensity factor (K) increased as the osteon orientation changed from in-plane longitudinal to out-of-plane transverse, followed by the in-plane transverse. Results developed an average fracture toughness of ~1.2 MPa $m^{1/2}$ for in-plane longitudinal, ~2.1 MPa $m^{1/2}$ for in-plane transverse, while for out-of-plane transverse falls in between the range.

On the contrary, Bokam et al. examined that the fracture properties of cancellous bone, and found that the fracture toughness is influenced by the porosity and pores orientation [16]. However, the standardised error was found to be 40% for stress intensity factor (K), this was due to uncertainties that stress-intensity values were influenced by the presence of pores near the crack tip while the crack initiates at the maximum load.

Yan et al. also studied the fracture toughness in cancellous bone via a three-point bending test [8]. Due to a large error calculated, the JMAN method of finite element analysis was carried out to evaluate the two-dimensional displacement field. The critical stress intensity factor (K_{IC}) was estimated by linear extrapolation on the observed stress intensity factor and load, obtaining 0.14 MPa $m^{1/2}$. The reliability of this measurement may be assessed by comparison from the literature, in which the data on the fracture toughness of trabecular bone are still limited.

2.3 Crack Length and Bone Toughness

As mentioned in 2.1, the crack length a, is hugely related to alpha, α stands for the relative crack length which is also defined as the function of the ratio of the effective crack length, a, and the effective specimen width, W [17]. This can be expressed by:

$$\alpha = f\ \frac{a}{W} \tag{3}$$

Bowie in his study has numerically proved on single-edged cracked specimen and found that that the stress intensity factor is significantly dependent on the specimen geometry size [18]. In fact, the potential for size-dependence is evident from the context of geometric correction factors applied in the stress intensity factor calculations [19] in fracture mechanics.

Relative crack length is crucial as it is a standard specimen size requirement in fracture testing. The assumed linear elastic can only be applicable if the extent of Mode I plasticity is relatively small compared to the test-piece dimensions. The test piece must be sufficiently thick so that most of the deformation will occur under plane-strain conditions [20]. Using this standard approach that the crack length, a, must be larger than the plastic zone size as the consideration is set to be [20] :

$$0.45 < a/\mathrm{W} < 0.55$$

Any unmet condition of the standard size geometry may lead to fracture instability in other words, can be said to affect the coincident plane-strain fracture toughness.

2.4 Toughening Mechanisms

Toughening mechanisms occur significantly largely due to the anisotropic microstructure of cortical bones, which are mainly the osteons, interstitial matrix, Haversian canal, and cement lines, as illustrated in Figure 1. Magnifying at a microscopic scale, the resistance of cortical bone against fracture can be evaluated by looking at the toughening mechanism the bone has experienced when it undergoes crack propagation, which is classified into two: intrinsic toughening mechanism and extrinsic toughening mechanism.

Ritchie et al. [5] did evaluate the mechanistic approach of intrinsic toughening mechanism to the failure of cortical bone and demonstrated that cement lines provide a weaker path for fracture, by having a lower intrinsic toughness in orientations where the crack runs along the cement lines. However, this finding contradicts with Gustafsson and Wallin proving that increased porosity resulted in straighter crack propagation through osteons, instead of along cement lines [21]. From this, it is said that the alteration of the interstitial matrix of the cortical bone tissue microstructure could as well affect the intrinsic toughness.

Besides, Gustafsson, Khayyeri, et al. [6] found that the extrinsic toughening mechanism on cortical bone such as crack deflection has slowed down the crack propagation. However, the toughening mechanisms occurring at smaller length scales were not well captured, as these appeared as plastic mechanisms only at larger scales. Due to that, cohesive damage law was introduced to capture the crack deflection. Failure occurs only after a critical amount of damage has accumulated to the specimen model, propagating damage may be arrested by structural features such that additional load is required to precipitate catastrophic failure [22]. Therefore, to predict load carrying capability, it is necessary to capture the damage propagation and corresponding stress redistributions up to the failure of the bone model. [6] was then found that in weaker cement lines, the crack had propagated the cement line and penetrated around the osteons, while in stronger cement lines, the crack penetrated the cement line and propagated through the osteons. It was also highlighted that the osteon orientation and the presence of Haversian canal inhibit crack deflection, which means by having crack penetrating the cement line and reach the canal, the bone may lead to a complete fracture. The simulation proved that the presence of a canal in the osteon longitudinal model had an interface 50 times weaker for a complete deflection around the osteon, while in longitudinal models without canals it was just 7 times.

One study was done to investigate the influence of mechanical loading and anatomical location of cortical bone on the extrinsic microcracks toughening mechanism. Cortical bones were experimentally tested under quasi-static and fall-like loading conditions. [14] found a significant number of microcracks formed during the fracture process, however anatomical-wise, only radial diaphysis had larger volume of microcracks, which did not experience by the femoral diaphysis and the neck diaphysis. From this, it was claimed that if microcracks is an effective extrinsic toughening mechanism for the radius, means not only 'dissipating energy' play a role during the crack propagation. Other possible mechanisms might as well affect crack propagation like crack deflection, which explains the reason crack deflection being the most dominant extrinsic mechanism being explored in works of literature.

Zhai et al. on his paper did evaluate the effect of three different osteon orientations on the toughening mechanisms. The severity of crack deflection was at a decreasing trend, starting from the in-plane transverse osteon orientations, out-of-plane transverse osteon orientations, followed by the in-plane longitudinal osteon orientations [15]. The in-plane transverse osteon orientations also showed obvious crack twist and unbroken-region bridging whereas the opposite occurred for the in-plane longitudinal osteon orientations [15].

2.5 Crack Characterisation

Crack characteristics are highly dependent on the microstructure of a cortical bone, which can be described in terms of crack initiation, crack growth, crack propagation, crack path, and crack trajectory [5]. Gustafsson, and Wallin, et al. [23] examined this on five specimen models with different porosity. It was determined that low porosity specimen experienced a shorter crack path, specimen with intermediate porosity had a longer, and high porosity specimen model had a straighter crack path. This is because the crack instead penetrated the cement line interfaces and propagated through the osteons. This means that, the cracks propagated through osteons instead of deflecting along the cement lines. The crack growth rate was also affected by the microstructure. Models with no or low porosity experienced rapid crack growth. Moreover, the simulation has proved that the microstructure influenced the propagating crack using two distinct mechanisms: Haversian canals attracted the crack causing smooth crack patterns, and the cement line deflected the cracks causing sharp turns in the crack path.

In conjunction with crack propagation, Baptista et al. [1] examined the influence of osteon distributions on crack, evaluating if they could attract and arrest the crack. Models with one osteon and several osteons were numerically modelled. The osteon did attract cracks in softer osteon while stiffer osteons and harder cement lines decrease the attraction tendency. Furthermore, Gauthier et al. [14] did an experiment on the same topic too. However, the author took different osteon from different anatomical locations of human cortical bone. It was demonstrated the differences in crack profiles. In-plane transverse osteon orientation portrayed more rugged crack paths, and the fracture surfaces were more torturous than the other two directions. The concentric lamellae were aligned perpendicular to the crack path and the osteons were mostly cut through directly in transverse by the crack, and crack deflection occurred as it crashed the cement lines. On the contrary, the in-plane longitudinal osteon orientation had the smoothest and straightest crack trajectories, with the crack propagated straight through the microstructure and the fewest crack deflections. It was also the crack growth was higher in the in-plane transverse specimen, followed by the out-of-plane transverse direction and in-plane longitudinal specimen.

Besides osteons, Abdel-Wahab et al. [13] also studied the effect of cement lines on crack propagation. The model with cement lines had changed the upper path between two osteons, while the model without the cement lines had resulted in kinks. In detail, the model with cement lines showed two different paths, the upper microcrack went straight away between two osteons and split until it reached the Haversian canal while the lower microcrack deviated towards an osteon and tried to split it, but the cement line arrested the microcrack. It was also found that the additional Haversian Canal microstructure affects the distribution of maximum principal stress that, which influences the microcracks propagation trajectories.

2.6 Summary

Combining all areas of interest, it is commonly noticed in works of literature that a quasi-static loading was applied to create a crack on a specimen or model, particularly Mode I tensile loading direction. However, studies that make full use of simulation are yet to be lacking. Many were focusing on experimental approaches such as the Single Leg Bending test instead. Hence showing that a numerical model on cortical bone subjected under Mode I tensile loading is remarkably less studied.

There are bundle studies on fracture toughness, which is commonly represented in terms of fracture toughness, K, and fracture energy values, G. The fact that the Resistance-curve is proven to display a more accurate differentiation between intrinsic toughening mechanism and extrinsic toughening mechanism. Straightforwardly, crack deflection is the most common topic being explored. Others such as microcracking are progressively making a place in recent studies however it is seen to be insignificant due to data limitations.

The anisotropic dependence of cortical bone contributing to its toughening mechanisms has attracted the attention of many. It is no longer an infrequent subject field of fracture mechanics, specifically on the human skeletal system. For instance, if cement lines deflected microcracks [6] and osteons had triggered crack to bridge further [15], which toughening mechanism seems to be dominant if all microstructures are fully defined. Although many studies have shown a significant impact of cortical bone microstructures on its fracture properties, however, the presence of each microstructure on crack propagation, the question of why the material phases are persistently resistant to the crack propagation resisted are still a potential. In response to this, there are few findings considering each layer of the complex cortical bone microstructural properties such as the osteon, and the cement lines, as the manipulative or independent variable. Not only that, the relation of toughening mechanisms in bone significantly because of its microstructures is yet to be explicitly addressed.

Therefore, the anisotropic dependent toughening mechanisms of a two-dimensional human cortical bone model subjected to Mode I loading are assessed in this thesis. The influence of microstructures is analysed in response to its fracture toughness and toughening mechanisms. The application of brittle and linear-elastic fracture mechanics will be fully utilised to an extent that the relative crack length, will be evaluated to analyse the impact of different relative crack lengths on the size-dependence plain-strain fracture toughness. In this present paper, the outcome portraying the cortical bone's fracture properties are in the sense that, the stress intensity factor, K_I as a measure of fracture toughness, and the crack propagation as a measure of bone's toughening mechanisms are presented.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Bone Modelling

A closely resembled cortical bone with its microstructures including circular Haversian Canal encircled by osteons composed in an interstitial matrix and surrounded by cement lines were modelled as a standard Compact Tension (CT) specimen. Twelve two-dimensional bone models were created on Abaqus 6.12 Complete Abaqus Environment (CAE), with different number of microstructures and crack-length to specimen-width ratios. All models were constructed using a plane strain 4-node bilinear elements with reduced integration (CPE4R) with hourglass control provided in the Abaqus finite element code. Inclusive of the linear-elastic material of cortical bone, the modelling code on Abaqus was automatically set to be first-order element. Additionally, among other considerations that were kept constant, two different Abaqus approach were used for two purposes; Abaqus Contour Integral was utilised to compute the Stress Intensity Factor (K_I) as the main measures of fracture toughness, also the Extended Finite Element Analysis (XFEM) on the other hand was used to aid the crack propagation evaluation.

3.2 Microstructure Geometries

The four material properties representing Haversian Canals, osteons, cement lines, and interstitial matrix were defined as anisotropic linear-elastic materials, the model constructed is as shown in Figure 3.1 [6]. Alliance to aging people, a model that matches a 70-year-old male tibial bone was obtained from a prior study [24] and applied to the current simulation, the mechanical properties of each physiological materials [23] were as in Table 1.

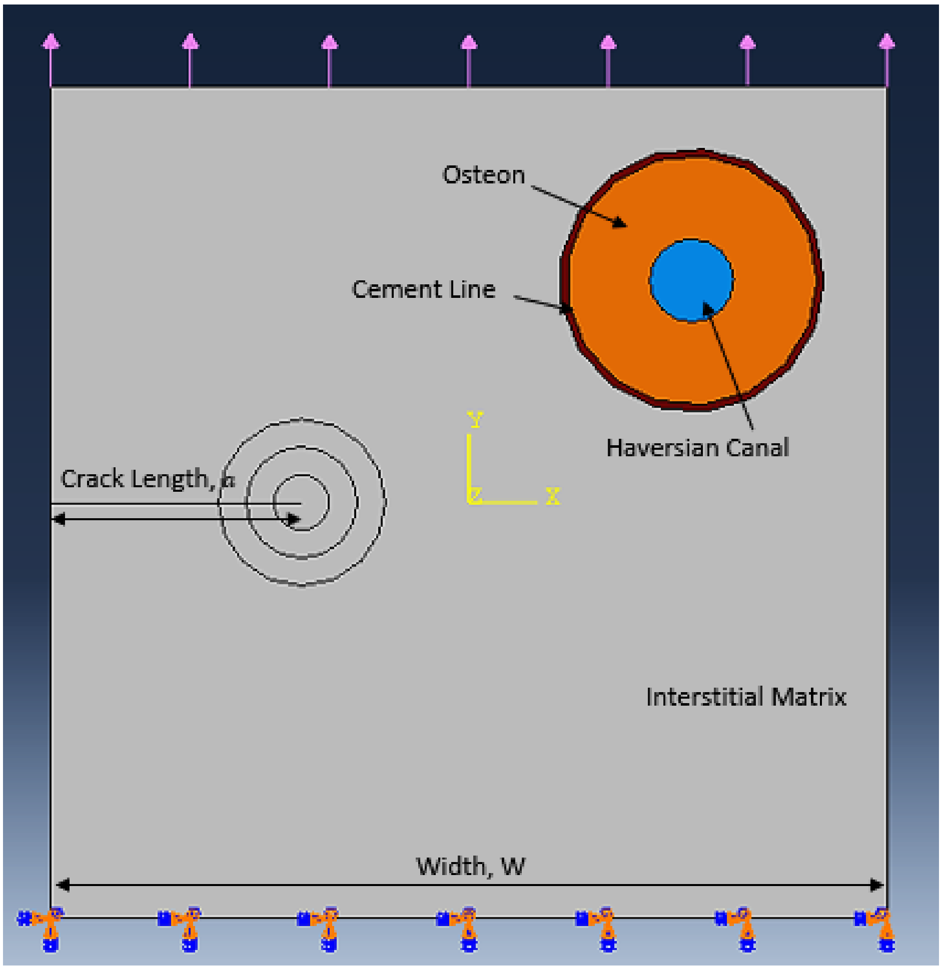


Figure 3.1 : The cortical bone microstructure modelling.

Table 3.1 : Material properties for interstitial matrix, osteon, Haversian canals and cement lines.

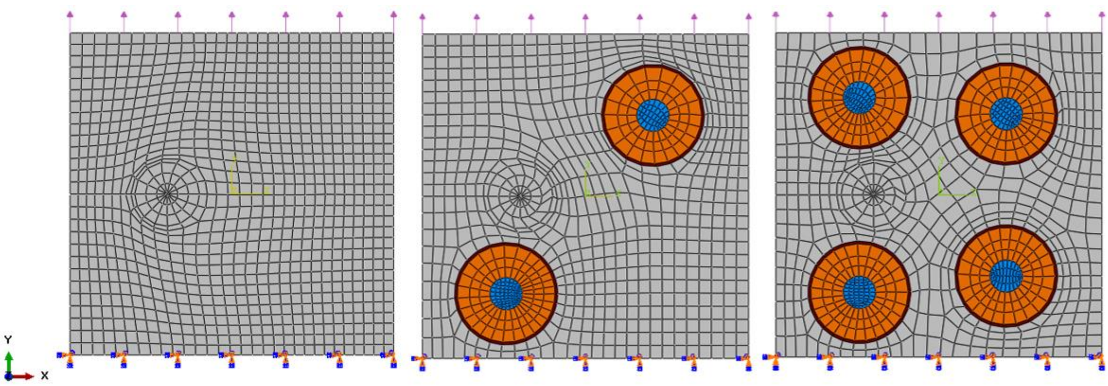
	Young's Modulus, E (MPa)	Poisson Ratio, $\boldsymbol{v}$	Maximum Principal Strain, $\boldsymbol{\varepsilon^{0}_{max}}$
Haversian Canal	10	0.3	0.004
Osteon	12000	0.3	0.004
Cement Line	18000	0.3	0.004
Interstitial Matrix	15000	0.3	0.004

3.3 Computing Stress Intensity Factor (K_I)

3.3.1 Model Description

Simplified compact specimens of cortical bone were modelled complying ASTM E 399 [9], a standard procedure of fracture toughness measurement, in which the specimen size considering the crack length and the width are the important measures. Three crack-length to specimen-width ratios (a/W) were set; 0.3, 0.5 and 0.8. As in literature findings, the a/W of 0.3 represents a thin specimen, 0.8 for thick specimen, leaving the 0.5 in between as an ideal deep crack and thick specimen [25]. For each a/W, the number of microstructures were defined differently by a factor of two; 0, 2, and 4. Hence, there were nine models of cortical bone in total.

Model 1; A compact specimen of 0.6 mm x 0.6 mm square dimensions embedded with interstitial matrix was created. A surface traction of 20 MPa was applied on top [7] with its vector that was normal to the top plane indicating the presence of Mode I tensile loading, while the bottom was kept fixed, as indicated in Figure 3.2. Due to the requirement a shorter crack (a/W = 0.3), a 0.18 mm of edge crack was defined using contour integral crack feature available in Abaqus Standard.



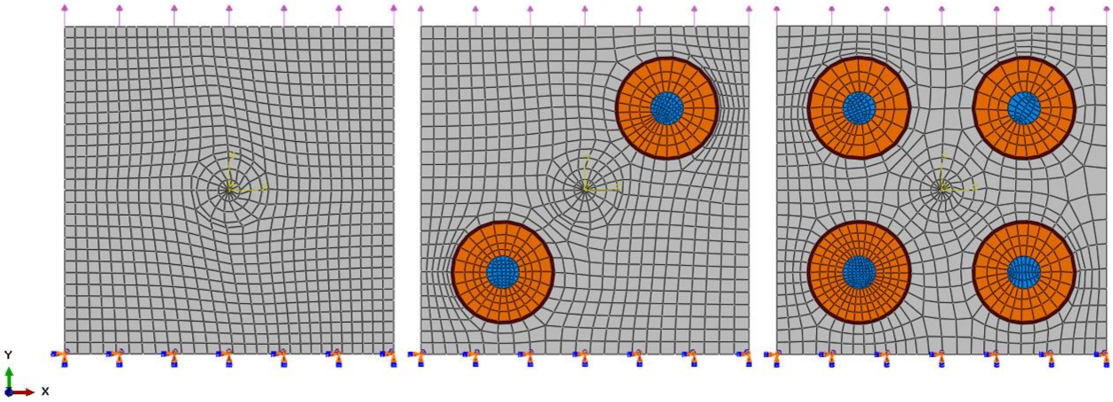
(a) (b) (c)

Figure 3.2 : Models with a/W = 0.3
(a) Model 1 (b) Model 2 (3) Model 3

Model 2 and Model 3; The same specimen geometry with additional of cortical bone isotropic microstructures that loaded of interstitial matrix, with 0.06 mm diameter of Haversian Canal in most middle, followed by an osteon of 0.18 mm diameter, which then followed by a 0.005 mm thickness of cement lines. Utilising the same 0.3 of a/W to portray a short and shallow crack, a model of cortical bone with two osteon structures were created for Model 2. The four material phases representing the cortical bone microstructure were similar as stated in Table 1. Same geometries were applied in Model 3 except that at this state four osteon structures were formed implementing the variable of osteon microstructures that increases by a factor of 2. Both models are pictured in Figure 3.2.

Model 4; The same dimension that built up the model as in Figure 3.1 was created. Without no osteon and other microstructures, a compact model of cortical bone specimen with a/W of 0.5 was constructed. 0.3 mm of crack was defined measuring from the edge as shown in Figure 3.3. Similarly, the same 20 MPa of traction was applied on top indicating the Mode I of fracture. This model significantly represents the most suitable deep crack (a/W = 0.5) that leads to a reliable stress intensity factor as an important quantitative data for fracture toughness.

Model 5 and Model 6; With the same deep crack requirement, a model with two osteon structures was modelled, followed by a model with four osteon structures. The models were diagrammed as in Figure 3.3.

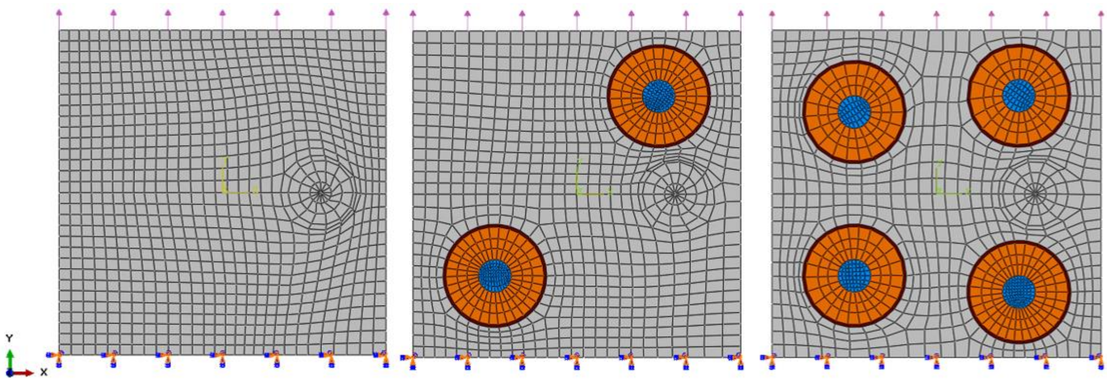


(a) (b) (c)

Figure 3.3 : Models with a/W = 0.5
(a) Model 4 (b) Model 5 (3) Model 6.

Model 7; A compact specimen of 0.6 mm x 0.6 mm with a deeper and longer crack was created. A crack tip region was sketched to be 0.48 mm from the edge of the model, hence the requirement of having a/W = 0.8 was achieved. Maintaining the fixed bottom as the boundary condition, as displayed in Figure 3.1, also a traction of 20 MPa was applied on top while the bottom was kept fixed.

Model 8 and Model 9; With the same long crack requirement, similarly, a model with two osteon structures followed by a model with four osteon structures were modelled. Model 7, Model 8 and Model 9 were created as in Figure 3.4.



(a) (b) (c)

Figure 3.4 : Models with a/W = 0.8
(a) Model 7 (b) Model 8 (3) Model 9.

3.3.2 Contour Integral Finite Element Analysis

On all nine models created, the crack was defined as contour integral, which is inclusive of the crack tip region, and the closest two contour region surrounds it, as modelled in Figure 3.5. The crack extension was made normal to the crack plane, with a vector of (1, 0, 0). The properties of second-order mesh option; 0.25 of Singularity portraying a linear-elastic fracture with $1/\sqrt{r}$ approach and Single Node Collapsed Element Side [26] to degenerate element control at the crack tip region. However due to the first-order solid continuum elements of the plane strain 4-node bilinear elements (CPE4R) designated, the second-order settings were auto-generated be ignored by Abaqus setting.

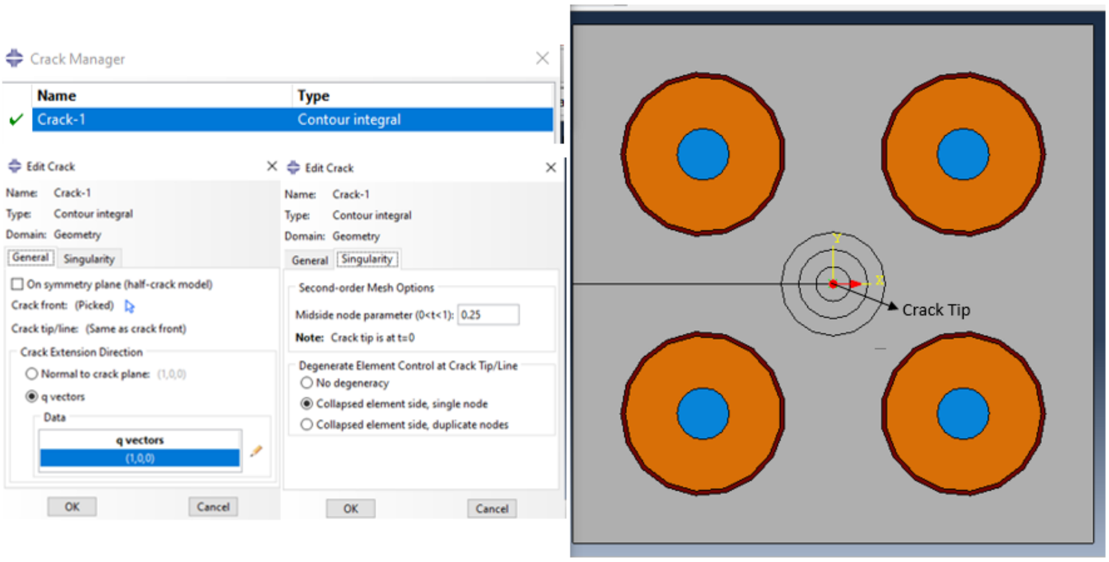


Figure 3.5 : The Contour Integral Crack

Besides, the contour integral type of crack was also defined by setting the maximum tangential stress as its contour domain with finite domain of 7 number of contours with the crack extension direction that was normal to the crack plane, the contour integral was expanded into an area integral at each location along the crack, implementing a divergence theorem that as a result errors in computing the value of stress intensity factor were reduced [27]. The maximum tangential stress criterion is suitable to execute the stress intensity factor for homogenous, isotropic elastic materials such as cortical bone.

Once crack was created, meshing took place by selecting the microstructures to be meshed with quad-elements at their medial axes, leaving only the crack front in sweep element type. The global seeds were set as 0.02, give out a defined meshing effect. This method is robust and explicitly mesh the defined crack to the geometry, hence the final visualisation results generate the stress intensity factor (K_I) around the crack tip when the models were subjected under 20 MPa of Mode I tensile load. Along with that, as shown in Figure 3.6, the magnitude of spatial displacement of 0.01 m was also obtained for the purpose of XFEM which will be explained in the following next sub-chapter.

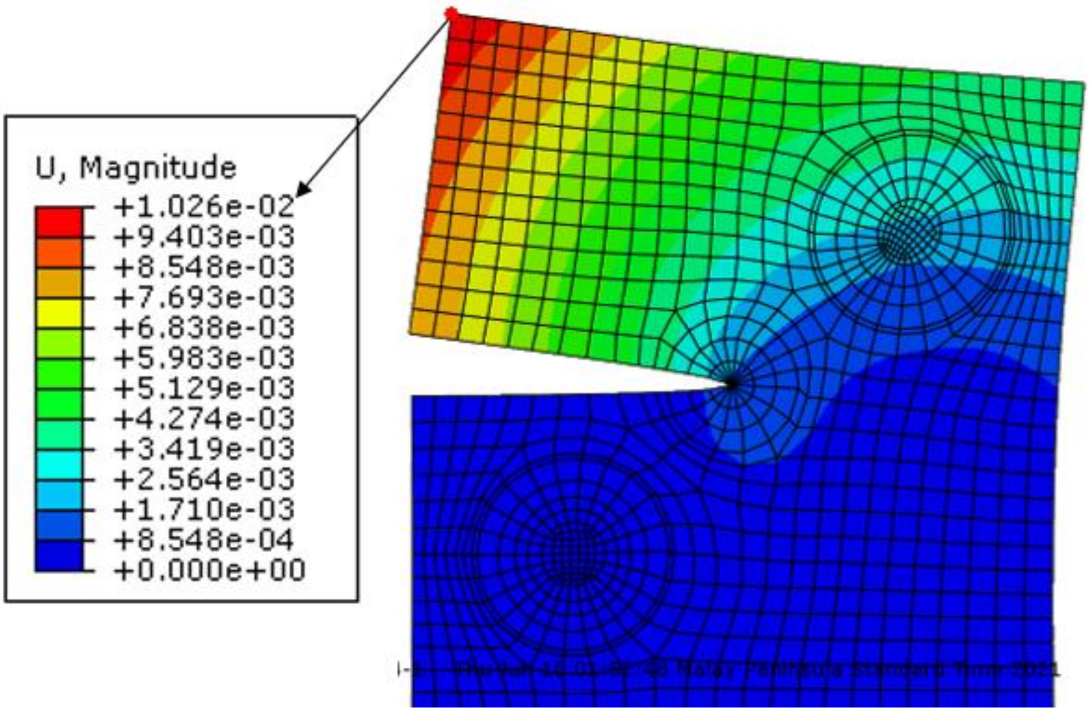


Figure 3.6 : The displacement magnitude used in XFEM

3.4 Toughening Mechanisms

Considering only the ideal crack length requirement of 0.5, three models were created using a different approach, extended finite element analysis (XFEM). This method is utilised to evaluate crack propagation, focusing on a closer magnification on the crack growth and crack trajectory.

3.4.1 Cohesive Damage Model Description

Model 10; A compact specimen of 0.6 mm x 0.6 mm embedded with interstitial matrix complying the ideal deep crack having a/W = 0.5 was constructed. A crack line was defined 0.3 mm from the most left of the bone face, as illustrated in Figure 3.7. When applying load, again the bottom was made constant to be zero, but as an addition, the fixed boundary condition was also applied to both left and right of the model. This enhances the distortion effect on the model's simulation not to forget a 0.01 m of displacement boundary condition was applied on top representing the Mode I of fracture. As mentioned, the maximum spatial displacement magnitude was obtained directly from the numerical analysis generated from previous contour integral analysis, as illustrated in Figure 3.6.

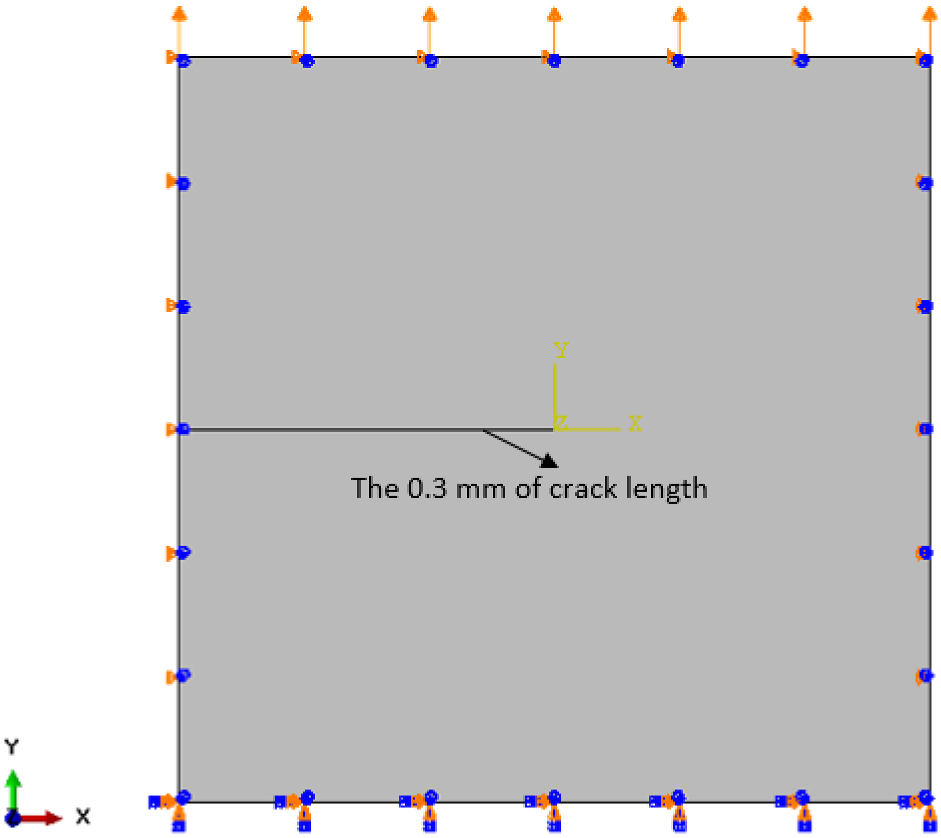
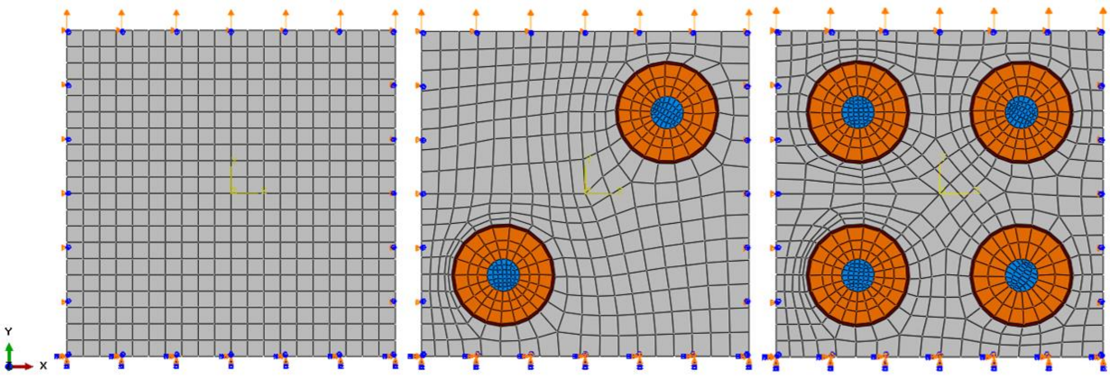


Figure 3.7 : The XFEM Model

Model 11 and Model 12; The cohesive damage criterion was taken into consideration when defining the cortical bone microstructure in XFEM, in which the maximum principal strain (MAXPE) was utilised in defining the crack propagation, as tabulated in Table 3.1, with other mechanical properties followed the same procedures as before. The three crack propagation models are as shown in Figure 3.8.



(a) (b) (c)

Figure 3.8 : Crack Propagation models in (a) Model 10 (b) Model 11 (c) Model 12.