Effect of the Lacuna Distribution on Stress and Strain in Single Osteon

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***Abstract*—In order to understand bone behaviour and bone failure behaviour, this study aimed to investigate stress distribution and strain developed in a single osteon with a different number of lacunae when a compressive load was given. Finite element (FE) analysis of single osteon was developed, one osteon with no lacuna (Model A) and three osteon models with a different number of lacunae (10 lacunae = Model B, 8 lacunae = Model C, 6 lacunae = Model D). The single osteon is developed as a semi-circle due to symmetric structure, with the presence of Haversian canal at the centre in each model. Stress distribution in Model B, Model C and Model D were shown to yield the highest stress at the lacuna near the given load and Model A was shown to yield maximum stress near the Haversian canal. The maximum strain of Model B, Model C and Model D were measured at the ellipse lacuna near the load while the maximum strain of Model A was shown at lamella near Haversian canal. These investigated results for the stress distribution and strain in the osteon can be used in the study to determine the yield region in osteon in bone fracture study.**

***Index Terms*—Lacuna; Single Osteon; Stress Distribution; Strain.**

I. INTRODUCTION

Bones are complex hierarchical structures that form support in vertebrae. Studies suggested that bone microstructures are related to the micro-crack formation and growth in the bone [1-2]. The bone structures at different levels eventually affect how it reacts to the pressure given to its structure. At nano-scale structure, bone is made up of organic material, inorganic material and water. At sub-micro-scale, the mineralised collagen fibrils were arranged in a circumferential direction to made up lamella (3-5 µm), which eventually form the osteon. Also, there is a structure known as a lacuna, the ellipse-shaped cavity, which located between thin and thick lamellae interphase. Lacuna contains bone cells (osteocytes), and the dimension of the structure is 22 µm × 9 µm × 4 µm. At micro-scale, lamellae are arranged into concentric cylinders forming osteons approximately 200 – 300 mm in diameter. Each osteon has a canal at the centre, called a Haversian canal, through which the blood vessels run into the bone [3– 5].

A study done by Brien *et al.* [6] found that osteons act as barriers to crack in the bone. However, some of the cracks that can break into the cement line, which made the osteon to act as a weak point and facilitate crack propagation in the bone. Apart from that, the study suggests that micro-cracks propagation will eventually stop once they reach the region of high osteon density in bone. Najafi *et al.* [7] also found that micro-crack growth is affected by the osteons and the crack follows a path between the osteons. This path is also affected by the distance between the osteons. A study by Ebacher *et al.* [8] shows the unique structure of lamellae, and the osteons distribution within the bone play a role in controlling the process of bone fracture. From the literature, it can be concluded that the osteon plays an important role in maintaining the bone toughness, give strength to the bone and also delaying the bone from fracture.

Apart from that, the sub-micron structure of osteon, which is lacuna, was suggested to act as a stress riser in the osteon. A study found there is strain amplification at lacuna in osteon of the bone. Reilly [9] suggested the lacuna may act as a site for micro-crack formation. The local strain that is high enough can cause the initiation of micro-crack in the osteon structure [10]. According to Currey, stress is the resistance in the object that prevents it from deforming, and strain is the measure of deformation in the object [11]. Previous studies of the osteon were limited to experimental observation [7- 10] and the progressive damage in single osteon considering the presence of lacunae in the model [3, 11]. The relationship between the micro-cracks formation and bone microstructure has not yet been fully understood and need further quantitative investigation.

This present work aims to identify the effect of lacunae number in the single osteon on stress distribution and strain concentration at a given load. In this study, finite element (FE) analysis was adopted for the analysis of stress distribution in single osteon with a different number of lacunae distribution, but the locations of lacunae were fixed in every model. Even though these studies neglecting many other properties of a cortical bone microstructure such as cement line and an interstitial matrix, this model gives the understanding of stress and strain yield region in the single osteon with the presence of the lacuna.

II. FINITE ELEMENT MODELING

The osteon was built as a heterogenized model, which consist of 17 thick lamellae and 17 thin lamellae. The thickness of thick lamella and thin lamella were set to 2.4 µm and 0.8 µm respectively. The centre of the osteon was left empty, which resemble the presence of Haversian canal. The model was displayed as semicircle due to its symmetrical structure as shown in Figure 1. The radius of the canal was set to 40 µm. Hence, the total radius for osteon model was 74.4 µm [16].

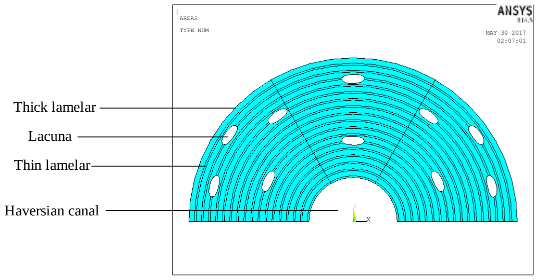

Figure 1: Model of half osteon

Regardless of the complexity of osteon micro-structure, it was modelled as a heterogeneous hollow cylinder neglecting the presence of cement line. The geometrical parameters used in this study were derived from the value in literature, and the model geometry was adapted from the model in a study done by Giner *et al.* [16]. According to Giner *et al.*, the distribution of lacunae was based on the average density of lacunae in cortical bone, which is 460 lacunae per mm^2 and average lacunae area is 30-40 µm^2. Based on this data and some image correlation from the literature, Giner *et al.* included 10 lacunae in half-model osteon. In this study, there are four different models with a different number of lacunae were constructed according to the osteon micro-structural characteristic. In Model A, no lacuna was created. Model A was included to compare the stress distribution and strain in the osteon structure without any lacunae, with the model with the lacuna. In Model B, 10 lacunae were included following the literature [3,13], while in Model B and Model C, there 8 and 6 lacunae respectively, the number of lacunae were changed slightly to investigate the effect of lacunae number on stress distribution and strain (see Figure 2). The locations of lacunae were created randomly.

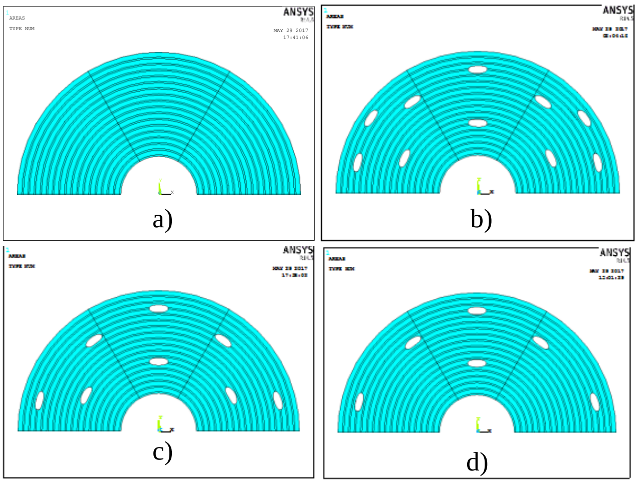

Figure 2: Three models of half osteon consisting of thick and thin lamellae with the Haversian canal at the centre and different number of lacunae (a) Model A = No lacuna (b) Model A = 10 lacunae (c) Model B = 8 lacunae (d) Model C = 6 lacunae

The element type used is plane 183 solid elements in plain strain condition. The material property of the model is chosen as structural, linear, elastic and isotropic. The elastic modulus (E) and Poisson's ratio (v) of osteon in Table 1 were adopted based on the literature data by Abdel Wahab et al. [17] and Liu et al. [3].

Table 1
Elastic Modulus and Poisson's Ratio of Thick and Thin Lamellae

Type	Elastic Modulus (GPa)	Poisson's Ratio
Thick lamella	20.0	0.17
Thin lamella	15.7	0.17

The simulation was conducted using finite element software ANSYS Mechanical APDL 14.5. Type of meshing element was set as a quadrilateral. The simulations were performed in displacement control mode by constraining the translation along Y-axis and translation on X-axis was set at a node in the centre of the canal. The applied radial pressure was set to 5 MPa at the beginning and up to 60 MPa. The pressure was applied along 60° of the arc (Figure 3), following the procedure is done by Giner et al. [16].

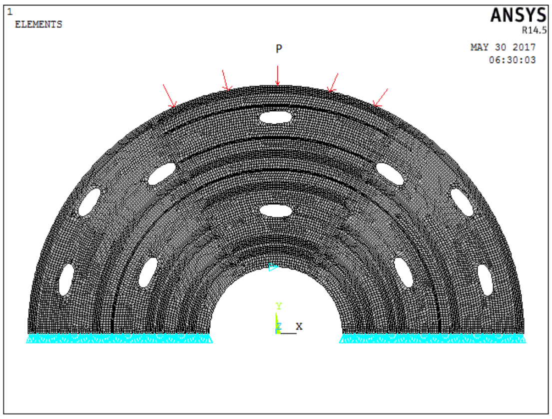

Figure 3: Boundary conditions on semi-osteon and loading (red arrows along the 60° arc of osteon)

III. Results and Discussion

The maximum von Mises stress regions were shown in Figure 4 for the four models. In Model A, the maximum Von Mises stress was seen to yield at the lamella near the Haversian canal. However, in models with lacuna (Model B, Model C and Model D) were shown to yield the maximum stress at the lacuna near to the applied load. The results show that the Haversian canal and lacuna in the osteon actually act as the potential stress riser.

Figure 5 shows the magnified area of maximum von Mises stress region. It is clearly seen that the maximum stress was yielded near the Haversian canal in the model with no lacuna while near the lacuna in the model with lacuna as these two structures in bone (Haversian canal and lacuna) are hollow that eventually can act as the stress riser [10].

In Figure 6, the graph showed that the maximum stress increase as the pressure increase. The maximum stress was highest in Model A, followed by Model B and then Model C and Model D. The results show that the maximum stress is highest in Model A, which is the osteon without lacuna. It can be said that the Haversian canal alone actually yields higher stress. In the presence of lacuna, as in Model B, Model C and Model D, the maximum stress shown to be slightly lower compared with Model A. The yield stress might be distributed at the lacuna in the Model B, Model C and Model D. The lacunae and Haversian canal are the discontinuity in the osteon structure that raises the stress locally [11]. However, the number of lacunae seems not to affect much the maximum stress value in Model C and Model D.

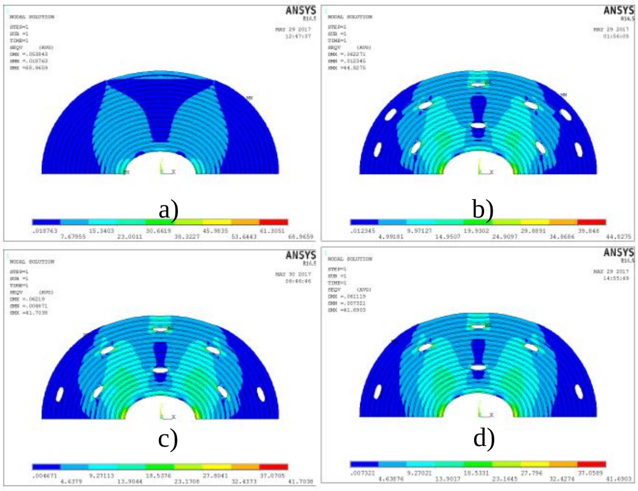

Figure 4: Von Mises stress distribution in (a) Model A, (b) Model B, (c) Model C and (d) Model D

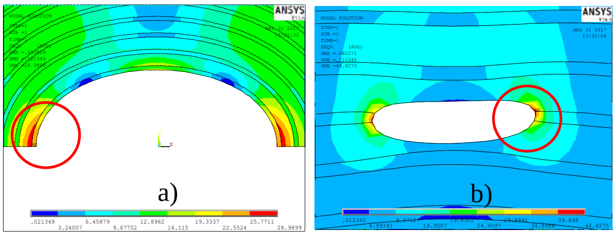

Figure 5: Zoom in the maximum stress (a) Model A, (b) Model B (representative of models with lacuna)

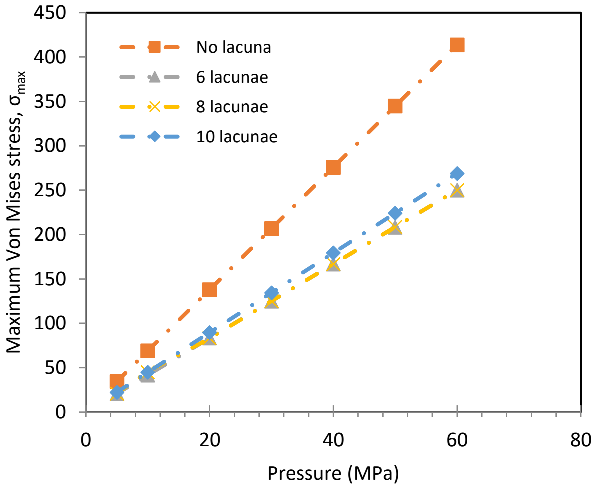

Figure 6: Graph of maximum Von Mises stress versus pressure (MPa)

The maximum strain regions for the models were shown in Figure 7. The maximum strain is seen near the Haversian canal in model A, while the maximum strain is seen at the end of ellipse lacuna in Model B, Model C and Model D. The results agree with the previous study where the strain was high near the tip of the ellipse lacuna [10]. The maximum strain trends in all models were corresponding to the maximum von Mises stress trend. However, the regions of maximum strains were noticed to oppose the region of maximum stress (compare Figure 5 and Figure 8).

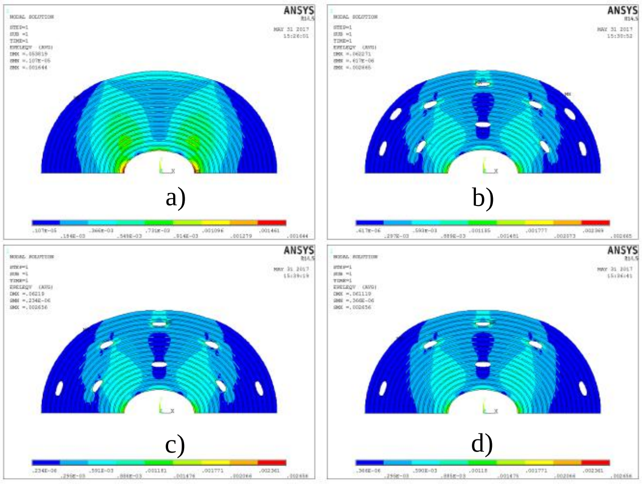

Figure 7: Strain concentration in (a) Model A, (b) Model B, (c) Model C and (d) Model D

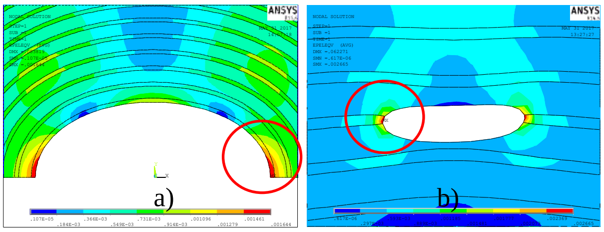

Figure 8: Zoom in the maximum strain (a) Model A (b) Model B (representative of models with lacuna)

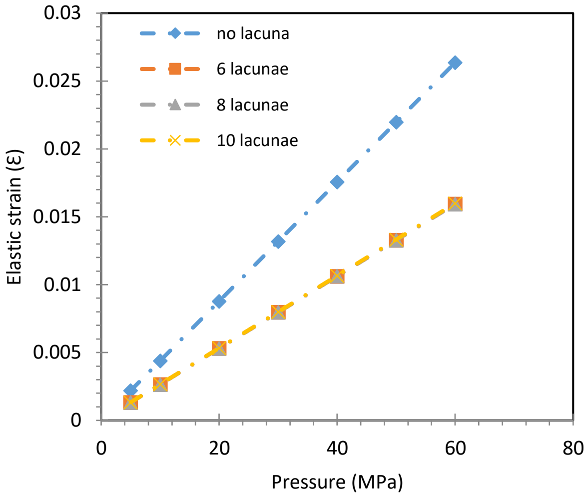

Figure 9: Graph of maximum elastic strain versus pressure (MPa)

The maximum strains shown in Figure 9 for the models were plotted against pressure applied to the model. The strain was shown to increase as the pressure increase. The yield strain may eventually result in the damage of the bone [18]. The micro-crack might start in this region. Thus, from the plotted results, it is shown that Model A will have the greatest damage as it had the highest maximum strain compared to other models. Other from that, it was obvious that the maximum strains for all the models with lacuna (Model B, Model C and Model D) almost equivalent to each other. From the results, it is obvious that the number of lacunae was not really affecting the maximum strain in the osteon model, but the lacunae presence seems to lower the maximum strain in the osteon model. This might be due to the resistance in the osteon structure to prevent the osteon from deforming in Model B, Model C and Model D is the same in three models.

IV. CONCLUSION

FE analysis approach is employed to analyse the effect of lacunae number on stress distribution and strain concentration in osteon. The result of the stress distribution revealed that when the boundary condition and pressure are same, the maximal von Mises stress in Model A is highest. It is noticeable that the maximum stress increase as the pressure increase. The maximum stress is highest in Model A, followed by Model B, and Model C and Model D. The maximum von Mises stress for Model C and Model D did not show much difference. The maximum Von Mises stress region for Model A is at the lamella near the Haversian canal, while the maximum von Mises stress region for Model B, Model C and Model D is at the lacuna near to the load. Same goes for the results of maximum strain. The maximum strain increases as the pressure increase. The strain is highest in Model A, while Model B, Model C and Model D showed almost equivalent maximum strain value. The number of lacunae did not affect the magnitude of maximum strain. The results show a preliminary study of micro-crack initiation of the osteon. The high stress and strain region may indicate the starter to micro-crack.

ACKNOWLEDGEMENT

The authors are very grateful for the research support of Ministry of Higher Education (MoHE) Malaysia and Universiti Malaysia Perlis through awarded Fundamental Research Grant (FRGS 9003-00578).

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