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Research paper

Stress Cracking Behavior of Interstitial Matrix and Cement Line Interface Deflection

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Abstract

Bone can be noticed as a complex hierarchically organized structures at several length scales, which has both metabolic and mechanical functions. One of the major type of bone is known as cortical bone as it comprises of distinct microstructures including osteons, interstitial bone, and cement line which play an important role in examining the fracture behavior in cortical bone. Microcracking of these unique features may lead to bone fracture. To date, there are a few of studies have been done regarding to its special microstructures. However, the mechanical properties of cement line is absently described to predict the cracking behavior at micro-scale level. This study aims to determine the stress distribution of cement line deflection in single osteon using finite element (FE) method. A FE analysis were performed to simulate the secondary osteon model under mode I, mode II and mixed-mode loading. The finding of this study propose the stress is accumulated near to the cement line. The maximum stress may be found to be high at the longest crack. The study concluded that the stress cracking behavior of cement line deflection is influenced by different mode of loading.

Keywords: *Cortical bone; Cement line deflection; Finite element analysis; Maximum stress; Mode of loading.*

1. Introduction

Bone is known as a unique hierarchical composite material that can be considered at multi length-scale from nanometer scale to the macroscopic level. Some factor of ageing and disease can altered the mechanical properties of bone which increasing the tendency of bone to be fractured [1]. Figure 1 shows schematic diagram of cortical bone microstructures. At the microscopic level, the microstructures of cortical bone are comprises of osteons, which consist of Haversian canal that surrounded by lamellae and cement line that bounded the osteons. Besides, the bone strength and fracture behavior are provided by these distinct microstructure, and not been completely understood [2].

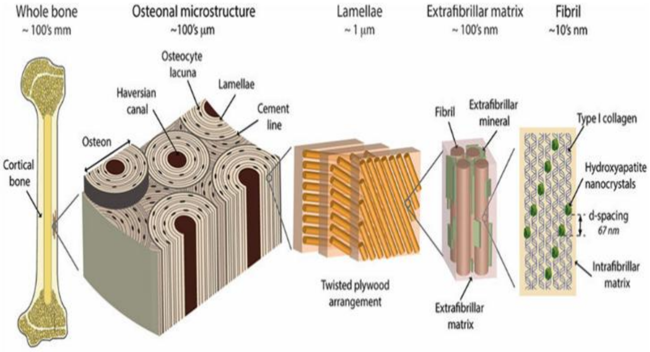

Fig. 1: Schematic diagram of cortical bone microstructures. Adopted from [3].

Basically, there is a stage in which microcracking occurs, before the bone fractures as an outcome of imposed strains being more than it can bear [4]. The several factors such as bone loss, heterogeneous microstructure, variation of its material properties and accumulation of microcracks were influenced a fracture process in a cortical bone tissue [5]. Thus, the fracture processes need to be understand in order to develop the strategies for the prevention and treatment.The previous study on the crack propagation and microstructure of the cortical bone, which mainly cement line displayed that the microcracks were arrested at the cement line [6]. This finding showed that the cement line was plays a role to inhibit the propagation of microcracks. Nevertheless, the mechanical behavior of how the microcracks arrested at the cement line is not well discussed. Thus, further efforts are required to simulate how the cement line involved in inhibiting the microcracks at the microscale level.The crack deflection plays a main role, which mostly increase bone toughness by increasing the work of fracture [7]. The crack path was changed by altering the crack angle from the minimum energetic configuration. This is due to the osteon and cement line mechanism which acts as barriers along with their size and density [8]. The study on the mechanism of crack propagation in the single osteon and the role of cortical bone microstructure revealed that the crack growth was prevented or slowed down due to the obvious effect of cement line that acts as a barrier [9]. This past study also suggested that the future investigations can be performed in details to examine the phenomenon of crack deviation by adding more the effect of osteons.

Although the special microstructures of cortical bone in particular cement lines area have been studied enormously [6][8][7][9], there is still lack of study about the mechanical properties of cement line in predicting the cracking behavior at micro-scale level. Therefore, the purpose of this study to determine the stress distribution of cement line deflection in single osteon using finite element (FE) method.

2. Finite Element Modeling

Two-dimensional FE model of a single osteon was designed in ANSYS Parametric Design Language (APDL) (version 16.1). At micro-scale level, four distinct constituents including osteons, cement line, interstitial matrix and Haversian canal are considered [10]. The microstructure of cement line followed by interstitial matrix and Haversian canal is built into this model to simulate crack deflection into cement line. The model was simulated using three mode of loading: mode I (tension), mode II (shear) and mixed-mode. The dimension of the model is height, H = 1 mm x width, W = 1 mm[10]. The osteon and Haversian canal are constructed at the center of the model with the average value of diameter is 200 µm and 80 µm, respectively. The osteon is surrounded by the cement line with the thickness of 2 µm. All the dimensions data were used based on the average values stated in literature [6][3].

Table 1: The mechanical properties of cortical bone Adopted from [6] [11][12].

Model	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 this study, only the interaction of single osteon is emphasized. The crack is introduced into the model with eight different points (1-8) for each type mode of loading (mode I, mode II and mixed-mode) in order to simulate the crack initiation and propagation. For mode I, the loading was applied at upper corner of the model dimension. Meanwhile, the loading was applied at left corner of the model dimension for mode II. For mixed-mode, the loading was applied at both upper and left corner of the model dimension. The simulations are performed in displacement control mode by constraining both along Y-axis and X-axis.

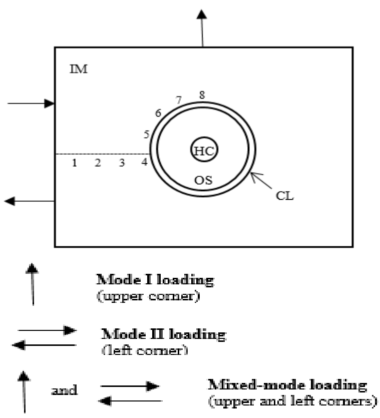

Fig. 2: Schematics diagram of finite element model of single osteon (IM = Interstitial matrix, HC = Haversian canal, OS = Osteon, and CL = cement line). Note that the number 1-8 are crack point. The arrows represent the location and direction of applied loading, which applied pressure = 10 MPa. Adopted from [13].

The stress distribution is evaluated based on von-Misses stress σ_e, which can be expressed as:

$$\sigma_e = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \quad (1)$$

where:
σ_1 = 1st principal stress
σ_2= 2nd principal stress
σ_3 = 3rd principal stress

Figure 3 shows the convergence test analysis based on different meshing size. In this work, the convergence of von-Mises stress is achieved at 1.26 µm of meshing size which has been used throughout this study. Thus, the accuracy of the following iteration results may be increase as the convergence test is performed on the FE model of osteon. The size of element may also be reduced [14].

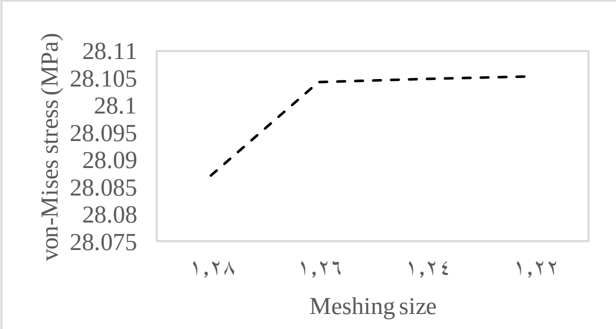

Fig 3: von-Mises stress versus meshing size.

3. Results and Discussion

The three mode of loading: mode I (tension), mode II (shear) and mixed-mode were applied to a single osteon model to investigate stress behavior of cement line deflection in cortical bone. The FE analysis showed that the crack growth pattern of stress distribution for the three modes of loading are approximately similar to each other. However, the results indicated that the maximum value of stress distribution for each crack point are different for each type mode of loading. Hence, it is presented that cracking behavior of cement line deflection were influenced by the three modes of loading. The finding presented that the accumulation of stress are increased from point 1 to point 4, which the initial crack propagates to the cement line. However, the accumulation of stress started to decrease from point 4 to point 5, which the initial stage of crack deflection into cement line. This phenomenon might be occurred due to the first attempt of crack to deflect from the cement line. The properties of cement line might be also involved in this phenomenon. The previous study demonstrated that cement line is able to resist the microcrack path due to it acts as microcrack deflector[15]. Thus, the microcrack will not able to penetrate the osteon in the presence of cement line. Furthermore, the accumulation of stress was begin to increase from point 5 to point 8. Figure 5, 6 and 7 shows the example of stress distribution for the three modes of loading started from point 1 to 8. In this study, the different mode of loading for each crack point showed the different stress distribution as well as the different crack length and cracking behavior of cement line deflection.

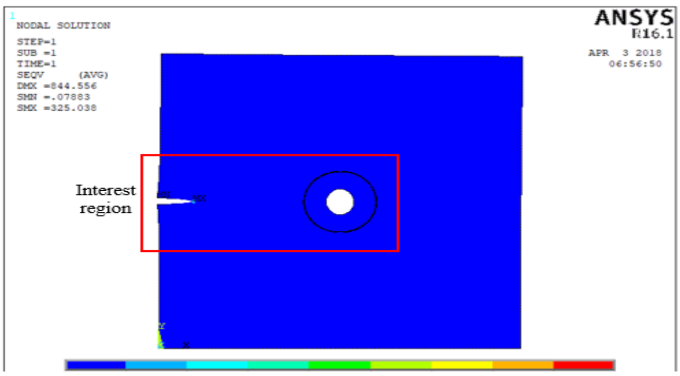

Fig. 4: Example of stress distribution for crack point 1 which applied by mode I loading with interest of region.

Figure 8 shows the example of maximum stress distribution which located at point 8 near to cement line. It can be seen that point 8 was the longest crack that deflected from cement line compared to point 5. The crack length is also the longest at point 8 compared to point 1 to 7. As expected, the longest crack has shown to produce the highest maximum stress in this study. The von-Mises stress value for mode I, mode II and mixed-mode loading at point 8 are 2132.640 MPa, 978.095 MPa and 2458.160 MPa, respectively. This results obviously showed that the stress distribution was increases as the crack was propagated far away.

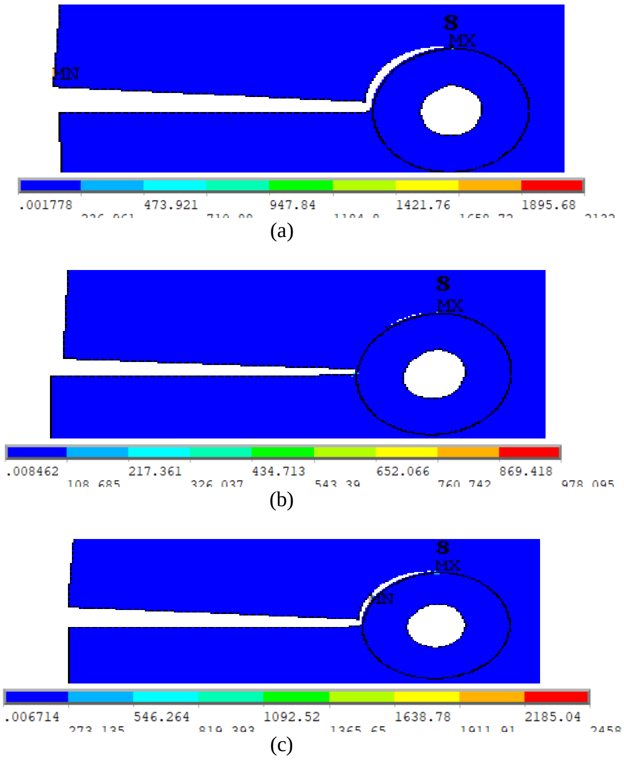

Fig. 8: The maximum stress distribution which located at point 8 near to cement line (a) mode I, (b) mode II and (c) mixed-mode loading.

Figure 9 shows the relationship between von-Mises stress versus crack point (1-8). It can be seen that the graph plotted is proportionally linear. In this work, the stress distribution for mixed-mode at point 8 presented as the highest when among of the mode of loading were been compared. It is due the combination mode of loading, which both mode I and mode II are been applied to the model. Apart from that, the simulation results indicated that stress accumulation was lower at point 8 in mode II loading compared to mode I loading. Due to bone is anisotropic material, the bone can be fractured slowly in compressive and tension strength rather than shear strength [16]. The respond of the bone influenced by the directions of load. Thus, the bone fractured in mode II produced lower stress compared to another.

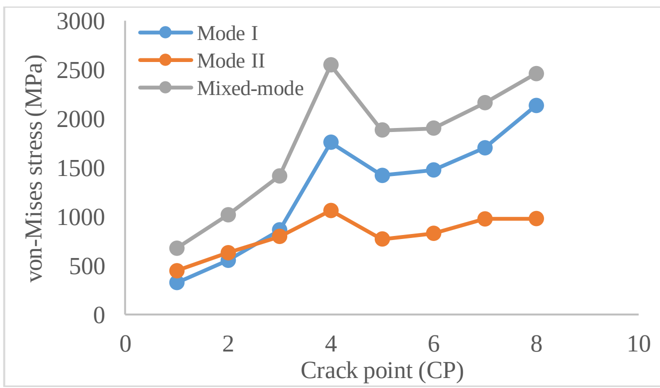

Fig. 9: von-Mises stress versus crack point (1-8).

When the cement line acts as a barrier, there has a clearly effect exhibited the growth of crack was slowed down and prevented [9]. The past study proposed the crack deflection plays an important role, predominantly in increasing the bone toughness by increasing the work of fracture [7]. A study from Mischinski and Ural [13] identified that the cement line required less than one-third of the strength of matrix in order for crack to be deflected. Hence, the study on crack deflection by cement line is crucial to be explored to predict the crack growth behavior that can be applied to understand the fracture and failure of human cortical bone.

4. Conclusion

The stress distribution of cement line deflection in single osteon was studied using 2D FE model affected by three dissimilar modes of loading. The stress have shown to accumulate nearby the cement line and the maximum stress is predicted to be the highest at the longest crack. The obtained results established that the different stress distribution showed the different cracking behaviour for dissimilar mode of loading. The developed model will provide additional information on how stress behavior of cement line deflection in a single osteon through FE modeling approach that cannot be directly accessed via experiments. However, future investigations can be performed in details to a better understanding the mechanical properties of cement line.

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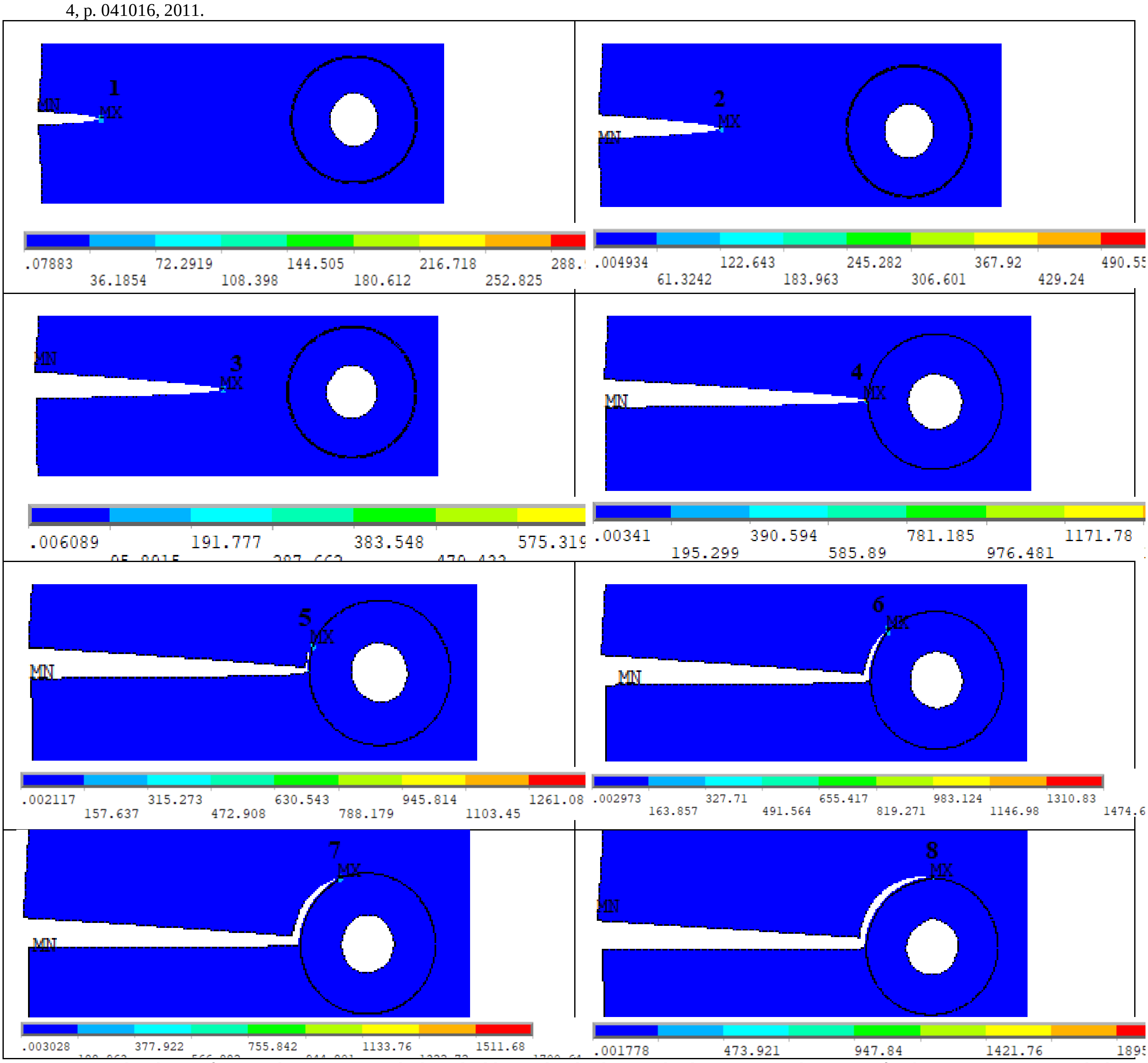
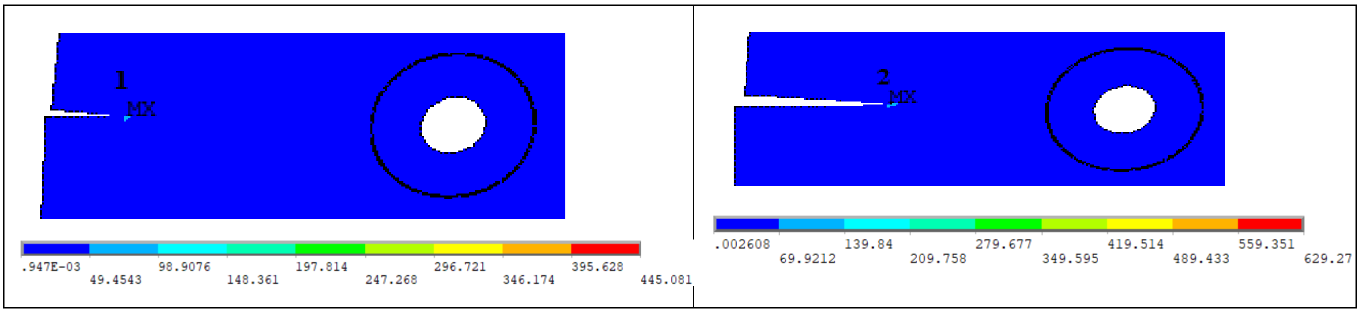


Fig. 5: Stress distribution from crack point 1 to 8 which applied by mode I loading. Red color represents the interest for the von-Mises stress with the value to be selected.



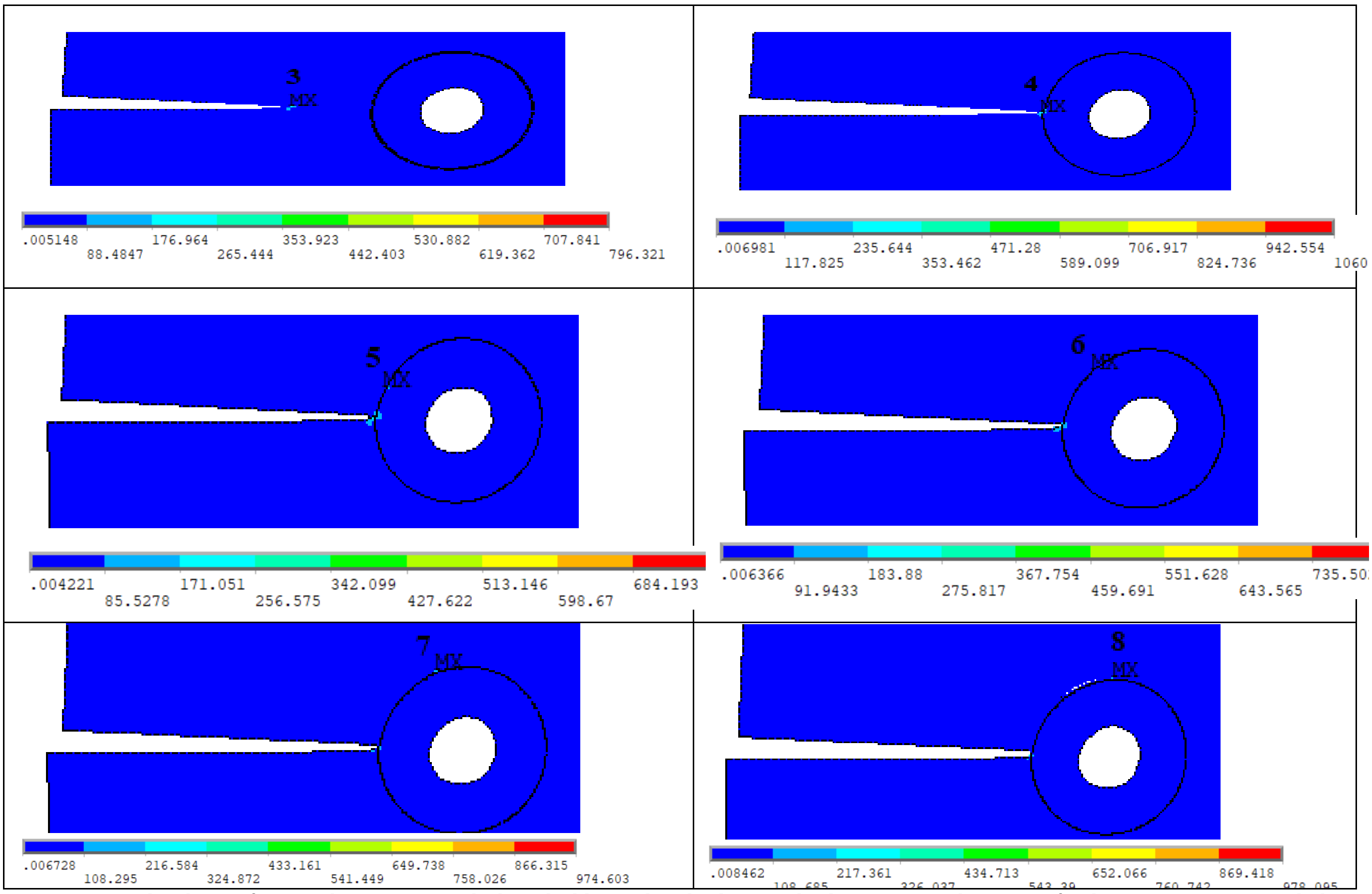
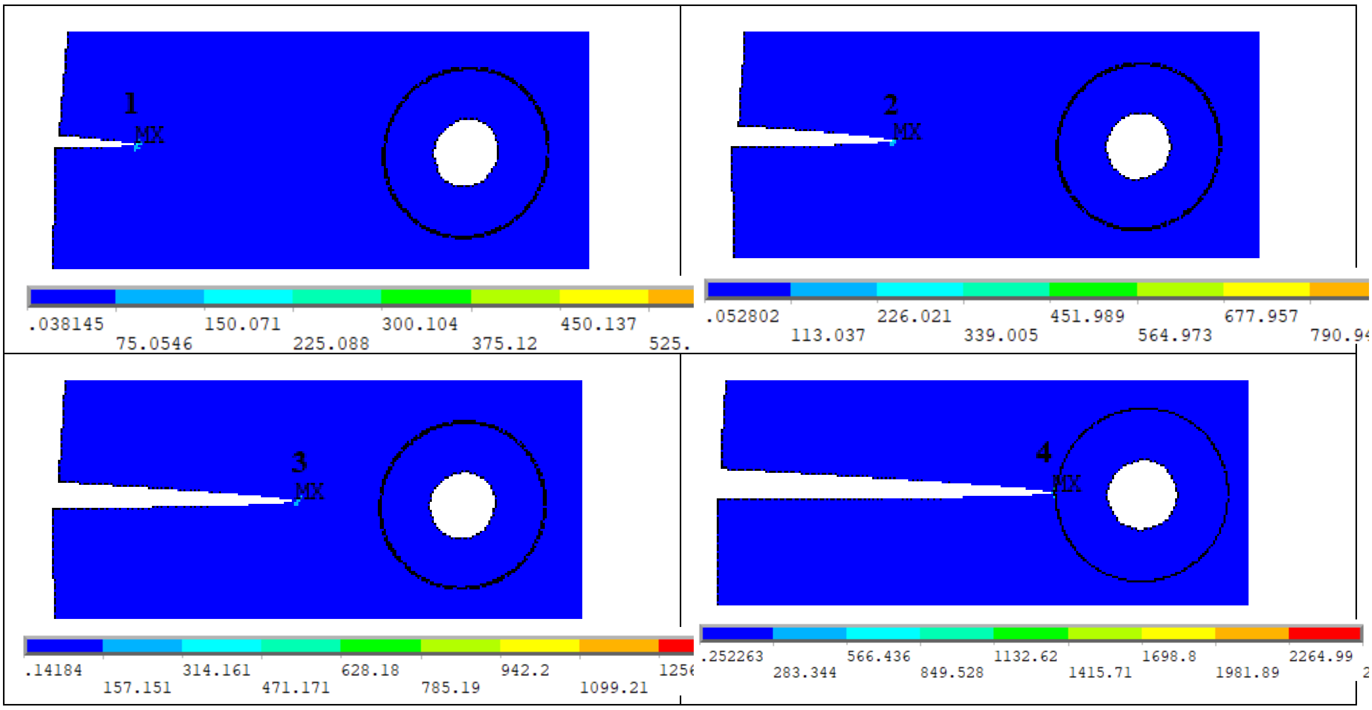


Fig. 6: Stress distribution from crack point 1 to 8 which applied by mode II loading. Red color represents the interest for the von-Mises stress with the value to be selected.



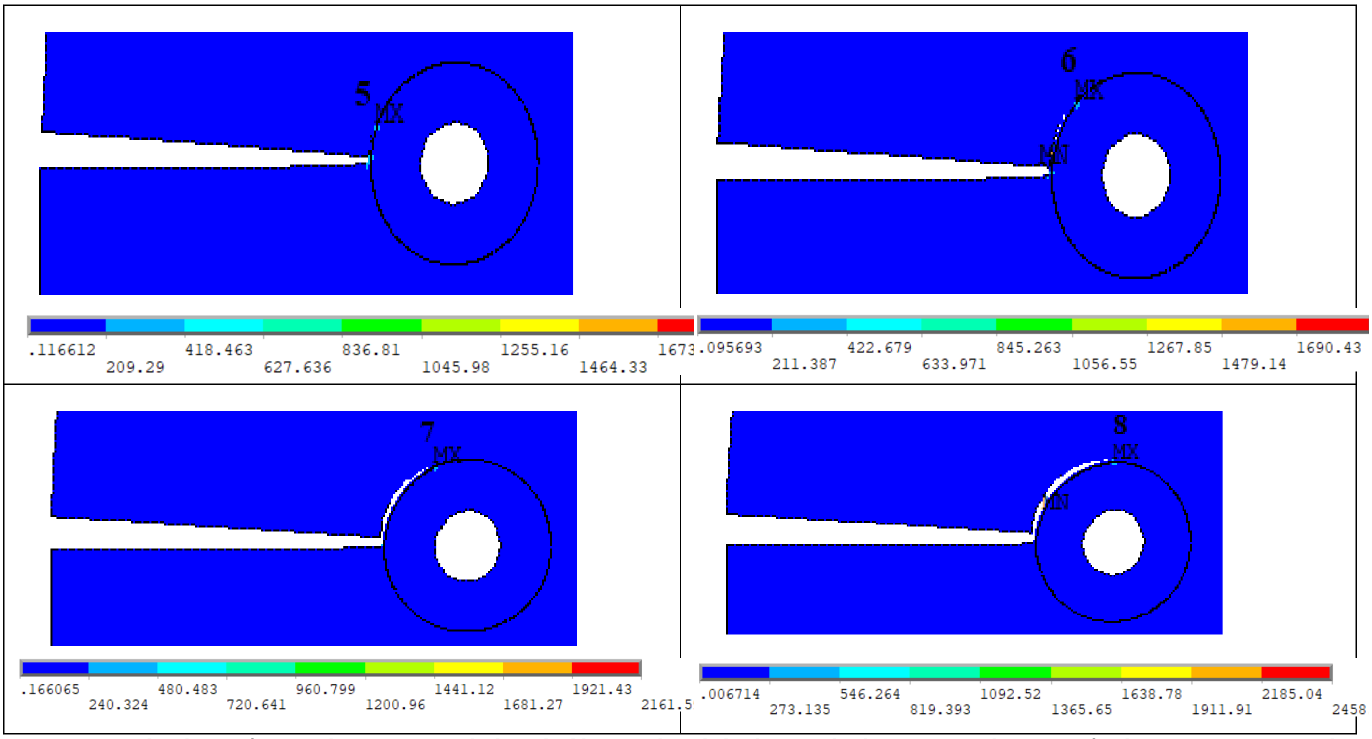


Fig. 7: Stress distribution from crack point 1 to 8 which applied by mixed-mode loading. Red color represents the interest for the von-Mises stress with the value to be selected.