Universiti Teknologi MARA
Cawangan Perlis
Jurnal Intelek

Volume 13 Issue 1 (2018)

Interaction Study of Muscle Laceration and Cortical Bone Fracture in Opened Fracture

M.S. Salim[a], N.A.A. Azizan[a], A.F. Salleh[a], R. Daud[a]

[a]*School of Mechatronics Engineering, Universiti Malaysia Perlis (UniMAP), Arau, Perlis, Malaysia.*

ABSTRACT

Generally, open fracture is classified when there is an observable open wound on the region of broken bone. Initially, this research was carried out to dig out answers and solutions for problems and issues that had arises for centuries. One of the problems is the difficulty to observe the mechanical properties attained by the four layers when the samples of bone and muscle are difficult to be handled. On the other hand, there is no research has been conducted yet to analyse the behaviour of bone fracture and muscle laceration during opened fracture. The primary objective of this research is to develop a two-dimensional (2D) model of human muscle and cortical bone segment by using finite element software (ANSYS 14). Upon the development of this multilayer model, the mechanical properties of cortical bone and muscle were considered. Moreover, this research was to determine and analyse the parameters of stress intensity factor, strain-energy release rate and Von Mises stress when three-point bending test is applied on the developed 2D multilayer model that consist of muscle and cortical bone layers by using continuum mechanics approach. By referring to the previous research papers, the dimension of the model is determined and the construction of 2D numerical model was done. Different loads and crack-to-width ratios were two manipulative variables applied in this research in order to evaluate the required corresponding variables. It is found that the stress intensity factor and strain-energy release rate obtained from finite element analysis were increased due to the increasing of crack length and applied loads. Furthermore, the Von Mises stress gained from the developed numerical model also have the same pattern, which increased with the increment of crack lengths.
Keywords: *cortical bone fracture; finite element modelling; muscle layer; j-integral; von mises stress*

1. Introduction

Bones can be categorized as individual organs that are comprised of manifold tissues which include connective tissue, bone, cartilage and hematopoietic tissue. Jammed-packed with inorganic salts, which are mainly the calcium salts such as calcium carbonate and calcium phosphate, have made the bone to become a dense type of connective tissue. Based from the research paper published by Clarke (2008), bone propose some of superpower functions in the body which include locomotion, soft tissues protection and support, the storage of calcium and phosphate, and locomotion of the body. Research paper published by Anthony Ciarallo et al (2006) stated that mammals usually consist of two types of bone which are cortical and cancellous bone. The cross-section of bone is illustrated in Figure.1.

Muscle fibres made the muscle. Within muscles are the interior parts of the cells that consist of myofibrils. Sarcomeres are the individual contractile units of myofibrils, which are made up of actin and myosin. All of the single muscle cells that are available line up Endomysium. The muscle cells are affiliated together by perimysium into bundles called fascicles (Lorant, 2018). Next, these bundles are then assigned into group together to form muscle and are lined by epimysium. Muscle spindles are distributed throughout the muscles and provide sensory feedback information to the central nervous system.

ISSN: 2231-7716

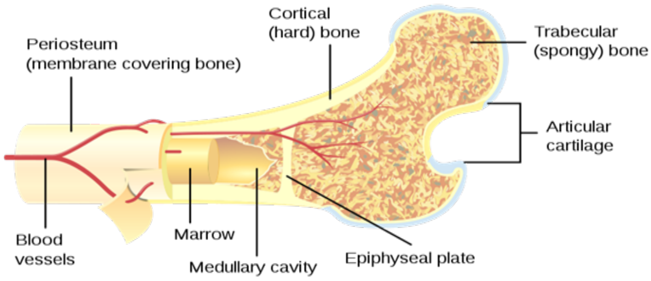


Fig. 1 Cross-section of bone, (Lorant, 2018)

It is acknowledged that the mineral content of bone itself affects mechanical properties of bone. Fung (1993) had stated that cortical bone is approximately linear elastic, transversely isotropic, and relatively homogenous. The mechanical properties possessed by cortical bone can be observed in Table 1.

Table 1. Mechanical properties of linear and elastic materials, (Fung, 1993).

	Elastic Modulus	Poisson's Ratio
Cortical bone	17 GPa	0.30
Cancellous bone	350 MPa	0.25
Cartilage	12 MPa	0.45

Muscle possessed hyperelastic property. The capability of large deformation endurance when undergo small loads and retain initial structure and configuration without permanent deformation after removal of load is the specialty possessed by hyperelastic materials. According to Aimedieu et al. (2003), hyperelastic materials contain a highly non-linear of stress-strain behaviour. Hence, the elastic behaviour characterization of these nonlinear materials proposed a significant importance. Mechanical properties of hyperelastic materials can be referred in Table 2 where μ and α are the coefficient from Ogden model.

Table 2: Mechanical properties of hyperelastic materials, (P. Aimedieu et al, 2003).

Hyperelastic materials	μ	α	Density (kg/m2)
Adipose	$1.70x10^3$	23	1100
Muscle	$2.20x10^4$	4.5	920
Skin	$2.20x10^6$	12	1100

Advanced research for a further understanding on fracture behaviour of bone is fundamental in order to prevent and reduce the percentage of diagnosis of trauma. When the fracture of the bone propagates to the muscle layer, it is called muscle laceration. A laceration is a wound produces by a tearing of soft body tissue. To achieve this, the study that related to mechanical properties of bone and muscle, such as its fracture toughness is also necessary. Li et al. (2013) has published a research paper with the main objective is to conduct and compare the results obtained from experimental study and numerical simulations of the bovine femoral cortical bone tissue upon the occurrence of fracture process. The experiment is conducted by characterizing fracture toughness possessed by bone tissue. This method is implemented in order to obtain the prime understanding of anisotropy and spatial variability of cortical bone resistance to fracture and its relation to foundation microstructure.

Figure 2 shows a dimensional geometry of layered cylindrical puck that was designed to allow the effective experimental validation cost (Payne et al, 2015).

ISSN: 2231-7716

Fig. 2 Dimension of four human's main layers, (T. Payne et al, 2015).

An open fracture is a type of fracture when the punctured skin from the fractured bone can be inspected by naked eyes. Advanced research for a further understanding on fracture behaviour of bone is fundamental in order to prevent and reduce the percentage of diagnosis of trauma. According to Song et al. (2017), linear elastic fracture mechanics (LEFM) can be defined as primer fracture theory, which represents the relationship of elastic bodies that contained sharp cracks. Any material that possesses an elastic and isotropic property is applicable for this theory, except in a vanishingly small region at the crack tip (assumption of small scale yielding), quasi-brittle or brittle fracture, and stable or unstable crack growth. Usually, the derivation of most formulas for either plane strains or the plane stresses in Linear Elastic Fracture Mechanics are related to three basic modes of loadings on a cracked body, which are opening, sliding, and shearing/tearing. The crystal-clear diagram of these three basic mode is illustrated in Figure 4. Foremost, Mode I is the opening mode. In this mode, the locomotion of crack surfaces is directly apart, comparable to an edge dislocation. Next, Mode II is the edge-sliding mode, in which, in this mode, the locomotion of the crack surfaces is normal to the front of the crack front. Moreover, it will remain fixed in the crack plane and analogous to an edge dislocation. According to the shear mode (Mode III), the parallel mobility of the crack surfaces to the front of the crack will remain fixed in the crack plane. Mode III is analogous to dislocation of screw.

The strain energy release rate quantifies the rate of change of the potential energy of a cracked elastic solid as the crack grows (Hawkins, 2015). The relationship between stress intensity factor, K and strain energy release rate, J is significant because it means that the condition of crack extension is a necessary and sufficient criterion for crack growth since it embodies both the stress and energy balance criteria. The relationship between K-value and J-integral is proven by the equation 1.0 shown below:

$$J_{IC} = G = K_{IC}{}^{2}\left(\frac{1-v^2}{E}\right) \tag{1}$$

where,
J_{IC} = J-integral (for linear elastic) for mode I
G = Energy release rate
K_{IC}= Stress Intensity Factor
v = Poisson's Ratio
E = Young's Modulus

Finite element analysis is a computer based numerical method to deduce engineering structures' strength and behaviour. It is a cumbersome and interactive method to use in order to obtain solution for complicated boundary conditions problems, complex shapes and material properties. However, finite element methods provide solutions that are approximate but acceptable solutions to certain problems. To begin with, R. Courant (1943), the pioneer of the minimization of variational calculus and numerical analysis of Ritz method, had developed the Finite Element Analysis (FEA).

According to Judex et al. (2007), bending tests are very useful in order to characterize the miniature experimental animals such as mice bones' mechanical behaviour that belongs to distinct strain, which the skeleton may be affected. Three-point bending test is an analysis of mechanical structural because it examines the 'whole bone' properties as a single structure. At the beginning point of the test, the undeformed state of bone will be positioned between two displacement supports base and a uni-pronged loading device will be enforced on the opposite at a precise point in the middle between the two supports of the bone surface. When the ultimate load is applied on the loading point, a fracture of bone can be observed at this region. The illustration of three-point bending test can be observed on Figure 3.

ISSN: 2231-7716

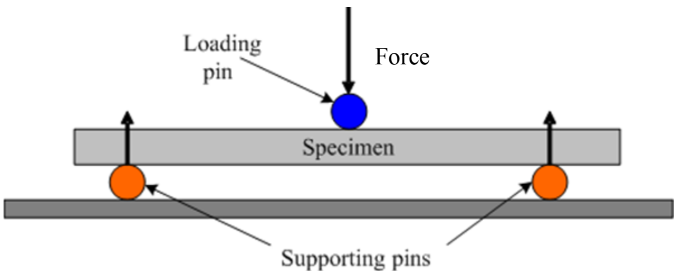


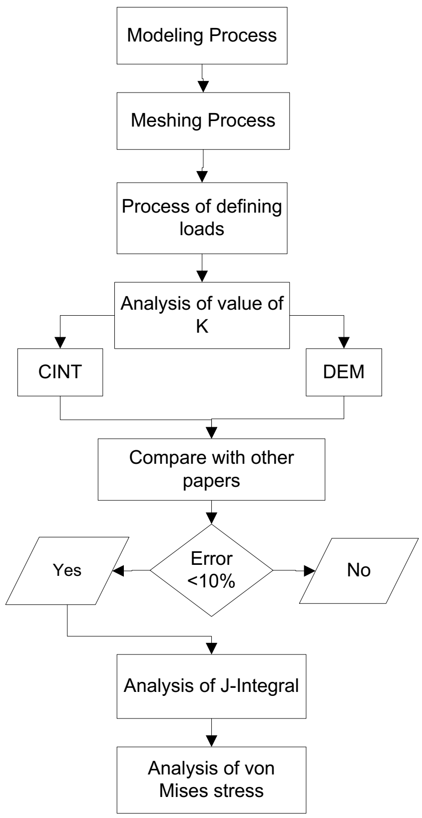
Fig. 3 Illustration of three-point bending test (Judex et al, 2007).

Initially, this research was carried out to dig out answers and solutions for problems and issues that had arisen for centuries. One of the problems is the difficulty to observe the mechanical properties that attained by muscle and bone when the samples of bone and muscle are no longer fresh. Another problem is the fact that any research to analyse the behaviour of bone fracture and muscle laceration during opened fracture has yet to be conducted. The fact is, this analysis would be conducive for surgeons, as it would rule out any unnecessary pain, aid in proper fixation of the bone and in worst incident is the re-surgery to retune the fracture. Furthermore, the encyclopedic detail on the area of development for finite element analysis application, especially in bone biomechanics, will ensure the enhancement for patient treatments.

2. Methodology

2.1 Modeling process

The dimensions of the multilayer model are referred according to Figure 2. The width of the multilayer model is said to be 4W, which is four times the value of thickness of multilayer model, 0.24m. First, make sure to confirm that you have the correct template for your paper size. The first term of Ogden hyperelastic model was referred in order to assign the muscle property. The constant parameters of Ogden used for muscle layer can be referred from Table 2. However, the constant parameters for the second layer, which is cortical bone, can be referred to Table 1. The procedure on finding J – Integral and von Misses stress under Mode I loading is shown in Figure 4.



ISSN: 2231-7716

Fig. 4 Process on finding J-Integral and Von Mises stress.

The radius of the first row of elements (DELR) was specified with the value of 0.003617, while the number of elements around circumference (NTHET) chosen was six. Two displacement supports were respectively positioned on the edge of base surface of the multilayer model. The surface load was placed tangential to the surface of multilayer model, on a precise point that was aligned to the crack tip. The model was set in solid plane strain, isotropic quadrilateral elements (8 node PLANE 183) with singularity elements and around the crack tip having 8 nodes throughout the analysis. The 2D Cartesian coordinate were constructed where the axis of (x,y : 0,0) were set as reference corresponding coordinate at the cross-sectional of cortical bone layer. A number of elements were created and density of elements was controlled based on height to width basis (Mischinski & Ural, 2011). The illustration of three-point bending test performed in FE simulation on multilayer model is shown on Figure 5.

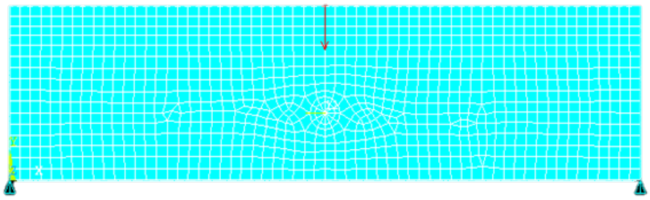


Fig. 5 Three-point bending test performed on multilayer model.

After the three-point bending test was performed on the developed multilayer model, deformed shape of the multilayer model could be observed in Figure 6. It can be seen that the crack opening has occurred parallel to the line of the applied load that been given.

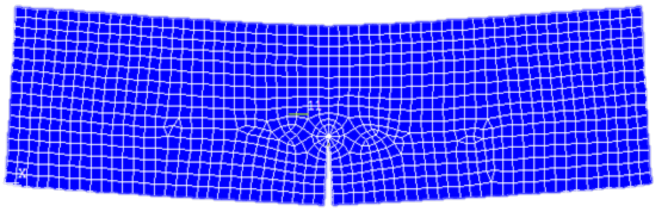


Fig. 6 Deformed shape of the multilayer model.

3. Results and discussions

3.1 Comparison values of SIF between DEM, CINT and Srawley's expression for one layer bone model

The purpose of this investigation is to compare the values of stress intensity factor (SIF), K, obtained through Displacement Extrapolation Method (DEM) and Constraint-Complex Integration Method (CINT) with the theoretical expression proposed by Srawley (1976). The Srawley's expression is shown below:

$$\frac{KB\sqrt{W}}{P} = \frac{3\left(\frac{S}{W}\right)\sqrt{a}[1.99 - a(1-a)(2.15 - 3.93a + 2.7a^2)]}{2(1+2a)(1-a)^{\frac{3}{2}}} \qquad (2)$$

where,
K = Stress intensity factor of crack tip
P = Load exerted on the crack surface of the specimen
B = The thickness of the specimen
W = The width of the specimen
a = The crack length
S = Span length of the specimen

Based from the plotted graph in Figure 7, it can be seen that the line graph increses linearly. As the crack-to-width ratio, *a/W,* increased, the stress intensity factor also increased. However, the line graph obviously shows that K_{CINT} approach is much closer to K_{Srawley} compared to K_{DEM}. To be more specific, starting from *a/W* = 0.125 until *a/W* = 0.6259, K_{CINT}, K_{DEM} and $K_{Srawley}$ were very close to each other. Nonetheless, at *a/W* = 0.962963, K_{DEM} started to increase, going apart from the theoretical value of

ISSN: 2231-7716

$K_{Srawley}$. Meanwhile, K_{CINT} remain constant to closely approach the $K_{Srawley}$. Hence, CINT method gives much better accuracy of identification of parameters in ANSYS compared to DEM.

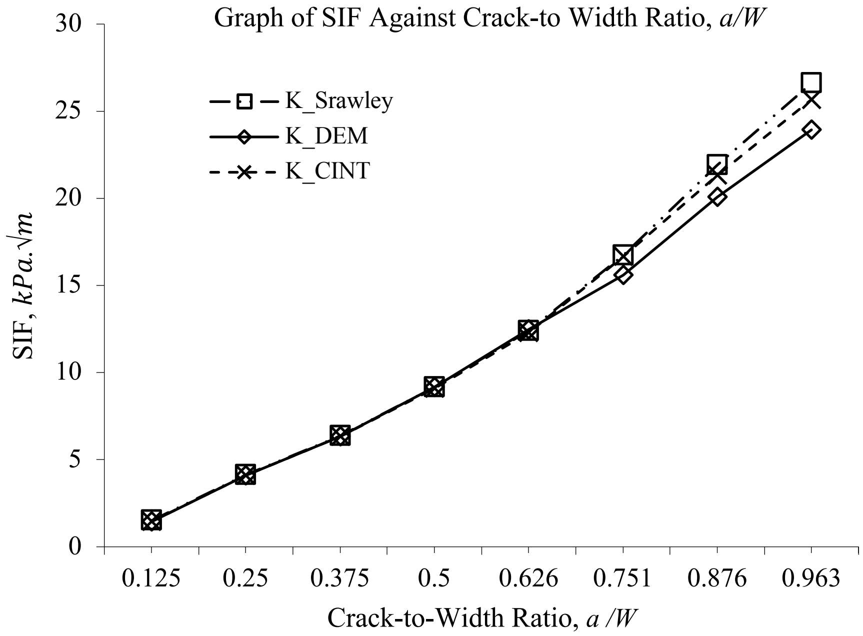


Fig. 7 Analysis to compare the theoretical SIF values with SIF values obtained from different approaches in ANSYS.

3.2 Analysis of J-Integral on different applied loads and crack-to-width ratio, a/W

The purpose of this analysis is to observe the increment pattern of strain energy release rate, *J,* when the same load is applied on the multilayer model at different crack-to-width ratio, *a/W*. From the plotted graph in Figure 8, the correlation between strain energy release rate, J-Integral and the crack-to-width ratio, a/W is clearly displayed. All of the line graphs plotted show that *J*-Integral displays a nonlinear increment at the end of bone fracture layer. All of the line graphs show a constant increment of *J*-Integral values on muscle layer. However, when the crack-to-width ratio, *a/W* was extended to the bone layer, the *J*-Integral rose extremely. This drastic change could be affected by the elastic property possessed by cortical bone. Moreover, it was realized that graph of 5000 N possessed the largest increment of *J*-Integral as the value was 12244.3333. In opposite, the lowest maximum of *J*-Integral obtained when the load exerted was 1000 N in which the value of *J*-Integral was 476.1733. Regardless of any value of loads exerted, the *J*-Integral values would still escalated when the crack-to-width ratio is raised. Thus, it can be concluded that both increment in the exerted loads and crack-to-width ratio affect the strain energy release rate, *J* on neither elastic nor hyperelastic material.

ISSN: 2231-7716

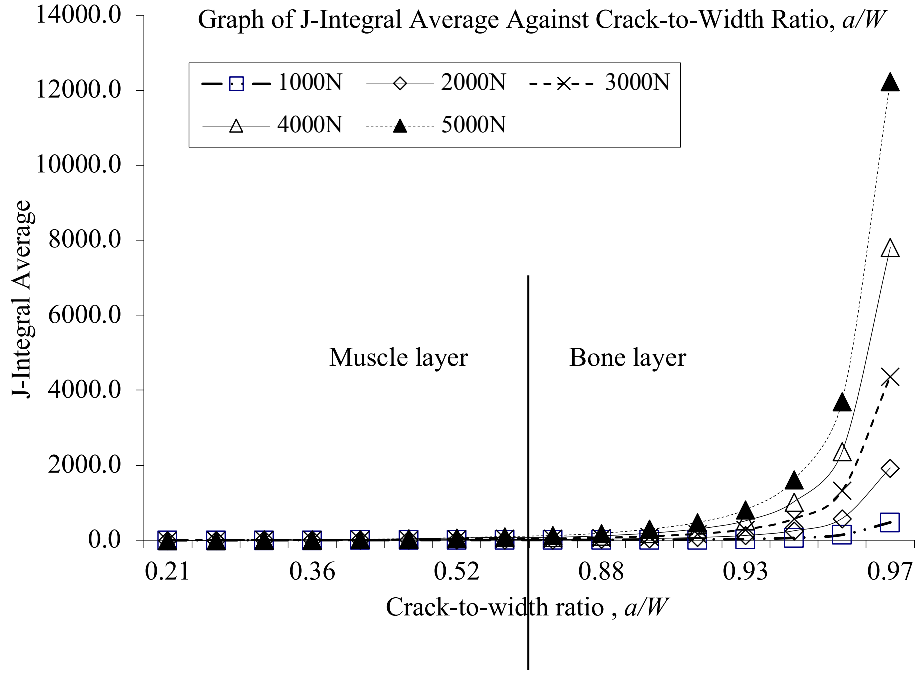


Fig. 8 Graph of different loads applied to different crack-to-width ratio, *a/W*.

3.3 Analysis of von Mises stress when different forces applied on model

The main goal of this analysis is to evaluate the von Mises stress of the multilayer model that consists of muscle and bone when different forces are applied on the model. Based from Figure 9, the values of von Mises stress, when the crack-to-width ratio, a/W was appointed on muscle layer shows slightly decrement and increment. This scenario can be observed for all value of loads exerted on the model. To conclude, it can be said that the von Mises stress also depends on the properties of the materials. In linear material especially in bone layer, the von Mises stress increases when the crack-to-width ratio, a/W increased. In opposite, the slightly decrement and increment of von Mises stress will be obtained in material with nonlinear property even though the a/W is increased.

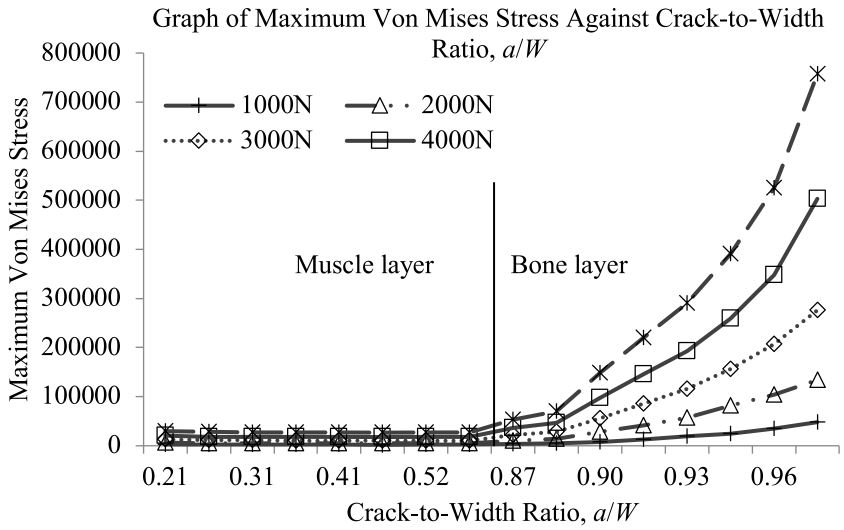


Fig. 9 Graph of Von Mises stress with different crack-to-width ratio, a/W.

ISSN: 2231-7716

4. Conclusion and Recommendations

Several case studies analysed and discussed in this research have clearly shown that finite element analysis (FEA) is a powerful and impressive tool that can be implemented for the purpose of investigating the mechanical properties such as stress intensity factor, strain energy release rate, J and von Mises stress of muscle and cortical bone. Even though any researcher has yet to publish this kind of research, the results obtained by using the approach of finite element analysis (FEA) will help others in understanding the mechanical behaviour of bone fracture and muscle laceration. Based from the line graph plotted in Figure 7, it is found out that CINT method gives better accuracy compared to DEM method where it was closer to the theoretical expression by Srawley. Next, the analysis of different applied loads with the same crack-to-width ratio, a/W had demonstrated the increment of strain energy release rate, J when the amount of loads that exerted on the numerical model is raised. Hence, this study can be concluded that as the crack-to-width ratio a/W increased, the strain energy release rate, J-Integral also increased. Moreover, the analysis of von Mises stress on different values of applied loads produced the same trend of increment when the crack-to-width ratio, a/W is raised.

References

Aimedieu, P., Mitton, D., Faure, J. P., Denninger, L., & Lavaste, F. (2003). Dynamic stiffness and damping of porcine muscle specimens. *Medical Engineering and Physics* 25, p. 795.

Ciarallo, A., Barralet, J., Tanzer, M., & Kremer, R. (2006). An approach to compare the quality of cancellous bone from the femoral necks of healthy and osteoporotic patients through compression testing and microcomputed tomography imaging. *McGill Journal of Medicine: MJM* 9, p. 102.

Clarke, B. (2008). Normal bone anatomy and physiology. *Clinical journal of the American Society of Nephrology* 3, p. S131.

Fung, Y. C. (2013). *Biomechanics: mechanical properties of living tissues*. Springer Science & Business Media.

Hawkins Jr, D. A., & Haque, A. (2015). Strain energy release rate and mode-I delamination growth in carbon-graphene/epoxy hybrid nanocomposites. *Procedia Engineering* 105, p. 829.

Judex, S., Lei, X., Han, D., & Rubin, C. (2007). Low-magnitude mechanical signals that stimulate bone formation in the ovariectomized rat are dependent on the applied frequency but not on the strain magnitude. *Journal of biomechanics* 40, p. 1333.

Lorant, J., Saury, C., Schleder, C., Robriquet, F., Lieubeau, B., Négroni, E., & Ledevin, M. (2018). Skeletal muscle regenerative potential of human MuStem cells following transplantation into injured mice muscle. *Molecular Therapy* 26, p. 618.

Li, S., Abdel-Wahab, A., & Silberschmidt, V. V. (2013). Analysis of fracture processes in cortical bone tissue. *Engineering Fracture Mechanics* 110, p. 448.

Mischinski, S., & Ural, A. (2011). Finite element modeling of microcrack growth in cortical bone. *Journal of Applied Mechanics* 78, p. 041016.

Payne, T., Mitchell, S., Bibb, R., Waters, M. (2015). The evaluation of new multi – material human soft tissue simulants for sports impact surrogates. *Journal of the Mechanical Behaviour of Biomedical Materials* 41, p. 336.

Song, C., Ooi, E. T., & Natarajan, S. (2017). A review of the scaled boundary finite element method for two-dimensional linear elastic fracture mechanics. *Engineering Fracture Mechanics*.

Srawley, J. E. (1976). Wide range stress intensity factor expressions for ASTM E 399 standard fracture toughness specimens. *International Journal of Fracture* 12, p. 475.

ISSN: 2231-7716