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Research Article

Fracture Mechanics Analysis of Fourth Lumbar Vertebra in Method of Finite Element Analysis

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ABSTRACT

Objective: In this paper, finite element model of the L4 vertebra subjected to combination of compression and flexion loading in isotropic and anisotropic cases is investigated. **Methods:** In both cases, the vertebra is considered homogeneous. Also, the body of vertebra is divided to cancellous and cortical sections in anisotropic model, but the process is assumed isotropic such as isotropic model. The maximum Von Mises stress on the fourth lumbar vertebrae is obtained. Also, the stress intensity factor is analyzed with placing a small crack on the critical region of the model from view point of fracture mechanics. Furthermore, the required force for the fracture of fourth lumbar vertebrae is obtained through increasing the applied force for assumed model. **Results:** The results show that the highest stress value and its position is 7.237MPa in the upper pedicle region for anisotropic property of vertebrae. At the end of this article, stress intensity factors in different aspect ratios of crack for anisotropic vertebrae under combination of flexion and compression loading are plotted.

INTRODUCTION

It is always assumed in fracture mechanics that each piece has some flaw and small cracks. In fact, since no phenomenon in nature is ideal, this assumption can always be true and the used equations in strength of materials can be replaced with equations of fracture mechanics. In this way, the stress intensity factor can be considered as a basis criterion for analysis in both real and critical state.

Because of the body weight and daily activities such as sitting, standing, walking, etc, forces and moments will be applied to all vertebras of spine. Lumbar spine as a strong support always plays an important role in tolerating daily life pressures, such as static and dynamic activities. These activities can be a little impact due to sliding, running, or sudden lifting a heavy weight. So regardless of the disc hernia ion or swelling, fracture in vertebrae due to unwanted cracks should also be taken into consideration. Nowadays with progression of technology, laboratories and experimental stations in field of Biomechanics, try to produce exact and nearly true models for simulating behaviors and analyzing forces acting on human body parts such as the sensitive part of lumbar spine. This section consists of five vertebrae, inter vertebral discs, muscles, etc., which are connected to thoracic spine from the top side and to sacrum from the bottom side. Recognizing the critical failure position can be performed clinically or experimentally that this is the approach of orthopedic specialists, But another way to distinguish the critical failure position, is analytical and engineering approach that has more variety and lower cost than the previous method. Finite element analysis is one of the most advanced simulation techniques and has been used in orthopedic

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biomechanics for many decades (Kayabasi and Ekici 2008). Up to now, many finite element (FE) simulations both in vivo and in vitro studies have been conducted for biomechanical analysis of the lumbar spine (Kuo et al., 2010). They can also be successfully applied for the simulation of biomechanical systems (Odin et al., 2010). FE methods have become an important tool to evaluate mechanical stresses and strains in bone (Hernandez et al., 2001) and have been widely used to investigate the mechanical behavior of bone tissue (Herrera et al., 2007). Finite element analysis of the three-dimensional model of the forth vertebrae was developed to clarify the mechanical causes of low back pain. The stresses in a modeled lumbar structure were then analyzed as solid cortical bone, as a hollow shell of cortical bone and with its inner cancellous bone structure.

In all cases, material properties have been supposed as isotropic. The results show large stress concentrations were found in the superior and inferior facet region and on the central surfaces of the vertebral body. Higher stress concentrations were also found in the cortical shell of the vertebrae (Nabhani and Wake, 2002).

Zulkifli and Ariffin (2012) have studied lumbar vertebrae under compression load with isotropic properties. They have been obtained the maximum stress at the upper region of the pedicle with value of 4.5 MPa. Also the value of stress intensity factor was obtained 0.525MPa$\sqrt{m}$ at their research, and the fracture toughness has been presented 1.46MPa$\sqrt{m}$. Various values of K_c and G_c for bone has been found from different orientations and sizing conditions (Isaac and Graham, 2011).

In this study fourth lumbar vertebra with regard to statically activities is investigated. For simplicity, the effect of inter vertebral disc, another lumbar vertebras, muscles and ligaments are not included. The purpose of this paper is to determine the maximum Von Mises stress and stress intensity factor (SIF) and the required force for fracture of the fourth lumbar vertebra due to the combined loading in two cases. In the first case, material properties of vertebrae are supposed as isotropic and in the other case, true model of the vertebrae is considered as the different anisotropic properties for the cortical and cancellous and isotropic property for the process. Also using finite element analysis, stress distribution and the stress intensity factors have been studied in two cases at the fourth lumbar vertebrae, under combination of flexion and compression loads, i.e. isotropic and anisotropic properties for vertebrae materials. In all states of body position, these two kinds of loading are always applied to the lumbar spine. Because if we consider the weight of the trunk, we should not forget the moment caused by the body's gravity center. The gravity center of the body lies in the mid-sagittal plane (due to anatomic symmetry) and somehow upside the sacral spine. It is reported to be 4 cm in front of the first sacral vertebra in the standing anatomic position (White and Panjabi, 1990). Results of a survey showed that the pedicle is a critical region (Nabhani and Wake, 2002). So, we put the considered crack in this region (Zulkifli and Ariffin, 2012).

Certainly, current study contributes to orthopedic specialists in the detecting failing potential region in fourth lumbar vertebrae with an analytical and engineering point of view.

2. MATERIALS AND METHODS

A vertebra is composed of six components which are: vertebral body, spinous process, transverse process, lamina, pedicle, and facet joints. Point cloud model of vertebra has been provided from biomechanics department of BRNO University. Then, the three dimensional model of vertebrae was constructed in Catia and Inventor software's and was imported by Abaqus 6.12 software for the analysis. Figure 1 shows the anatomy of the fourth lumbar vertebrae. The vertebrae's body has two layers, consist of cortical and cancellous bone, and each of these two sections have different properties. In fact, the surface of the lumbar vertebra is not smooth.

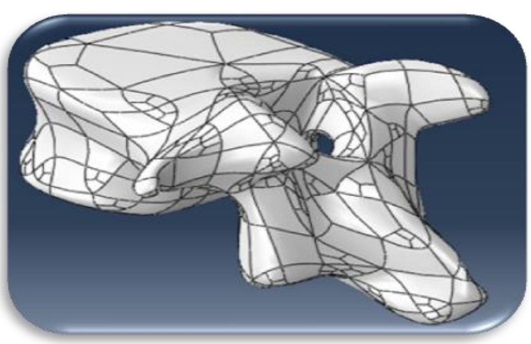

Figure 1:
Anatomy of the fourth lumbar vertebrae

2.1. Loading and boundary conditions

To evaluate the effect of the compression condition, a simple compressive loading is applied to the vertebral model. At first, to obtain the critical region of the fourth lumbar vertebrae, a force of 578 N including head weight, trunk weight, arms weight and a box weight that, person picks it up, was applied to the lumbar vertebrae. According to Figure 2, we can determine pressure and moments which have been exerted on vertebrae by weight of the box, head, trunk, hands, and calculating the distance between each of them from the vertebra (Kurtz and Edidin, 2006).

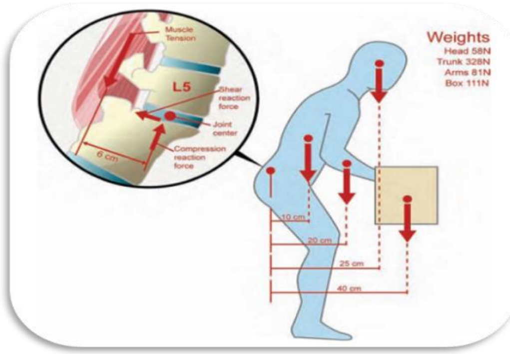

Figure 2:
View of forces and the distances from each part to L4 (Kurtz and Edidin, 2006)

Table 1 shows the weight of each segment and its distance from the vertebrae. The load is divided to 70% on the upper vertebral body and 30% on the facets joint (Ahmad and Arifin, 2010).

Table 1:

Head	58	weight (N)
	25	distance (cm)
Trunk	328	weight (N)
	10	distance (cm)
Arms	81	weight (N)
	20	distance (cm)
Box	111	weight (N)
	40	distance (cm)

Also, 70% of load bearing surface has been assigned to the body and 30% to the facet joints and the loading conditions is assumed uniform. For considering the flexion effects, a concentrated moment of 108 N.m is applied to reference point which is located on the geometric center of the upper part of the vertebral body by kinematic coupling (Weisse et al., 2012). For applying the boundary conditions, the lower vertebral body is fully constrained in all degrees of freedom (Ahmad and Arifin, 2010). Figure 3 shows applied loads and boundary conditions. Areas which are measured in Catia software have been presented in Table 2.

Table 2:
Area of surfaces on body and facet joints

Body	1284.7 (mm^2)
Facet joints	248 (mm^2)

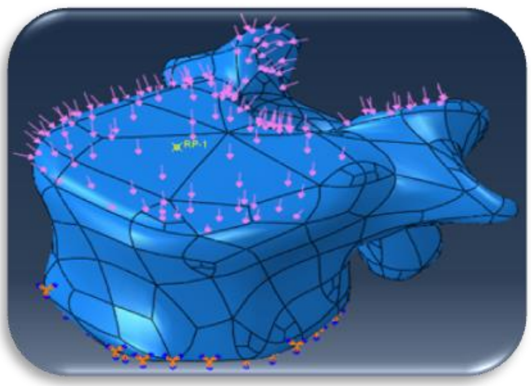

Figure 3:
View of the loading and boundary conditions

2.2. Mechanical properties

Human vertebra is a non-linear, inhomogeneous and anisotropic material and varies in the boundary regions between cortical and cancellous bone (Xia et al., 2006). In this paper, for loading conditions, two cases are considered by using the finite element analysis. In the first case, for simplicity, the vertebra is considered as isotropic material and in the second case; true material properties of vertebrae are considered. For applying appropriate material properties to different parts of vertebrae, the vertebra has been separated from pedicles. Thus, we can choose each part of vertebrae as a separate cell. Assigned properties to the fourth lumbar vertebrae in the two cases are presented in tables 3 and 4 (Chena et al., 2009).

Table 3:
Material properties of isotropic vertebrae (Ahmad and Arifin, 2010)

E(GPa)	12
ν	0.3

Table 4:
Material properties of anisotropic vertebrae (Chena et al., 2009)

	cortical	cancellous	process	
E_x (MPa)	11300	140	**E (MPa)**	**υ**
E_y (MPa)	22000	200	3500	0.25
E_z (MPa)	11300	140		
G_x(MPa)	5400	48.3		
G_y (MPa)	3800	48.3		
G_z (MPa)	5400	48.3		
$υ_{xy}$	0.203	0.315		
$υ_{yz}$	0.484	0.315		
$υ_{xz}$	0.203			

2.3. Applying finite element mesh to the model

Applying the finite element mesh to the geometry, the vertebra is divided into a grid of elements which form the finite element model. Once the finite element model has been created, the next step is to identify the type of element that will be used for meshing various partitioned volumes. The model can use more than one element type. Generally, the simplest element type should be used for modeling the problem. In this study, it was decided to use three-dimensional, solid, linear, tetrahedral elements for all parts. This decision was based on the complexity of model shape and this type of element was able to give a good accurate rendition of the surface geometry. Also, the approximate size of each element has been altered to get an optimum converge in a specific stress value.

4. Results and Discussion

As previously mentioned, in this study, critical region of vertebra, in conjunction with the value of Von Mises stress and stress intensity factor were found, unlike other papers. At continuing this discussion, the results and the relating points will express in two models of anisotropic and isotropic. Figure 4 shows the stress distribution of the fourth lumbar spine for evaluating the Combination of compression and flexion forces in anisotropic case. It was found that the highest stress concentration points were at the upper pedicle region, with Von Mises stress value 7.237 MPa. So, this area is a critical region of the fourth lumbar vertebrae.

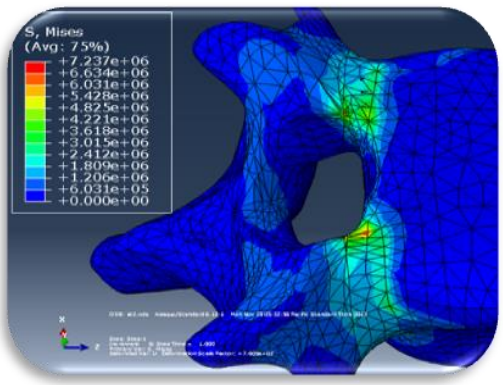

Figure 4.
Von Mises stress distribution in anisotropic vertebrae under combination of flexion and compression loadings (in un-cracked model)

As mentioned in the introduction part, due to the criticality of the pedicle and opening mode, crack has been put at the upper part of the pedicle (Zulkifli and Ariffin, 2012). According to the mathematical theory of fracture mechanics, the shape of crack growth is an ellipse, even though the first shape of crack is not an ellipse (Parker, 1981). So the crack has been modeled in a shape of ideal half- ellipse, respectively, with 3 and 2 millimeters in length and width. Fig. 5 shows stress distribution and crack opening in isotropic vertebrae under flexion and compression forces and the contours represent the level of Von Mises stress.

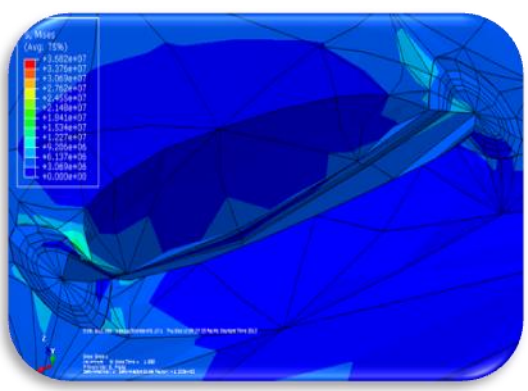

Figure 5:
Von Mises stress distribution and crack opening in isotropic vertebrae under combination of flexion and compression loadings

We could see that the highest stress concentrations are at the top of the pedicle and around the crack, with Von Mises stress value 36.82 MPa. This suggests that pedicle is a high potential region for the failure. This critical region of the pedicle tends to act as a pivot when another load is applied to the facet joints and creates a bending effect. A longer distance between the facet joints and the vertebral body causes an increase in the bending moment, and also a stress concentration region. The value of stress intensity factor (K_I) at deepest point of crack is 0.261469MPa√m. It should be noted that the number of contours around the crack tip is considered 5.

Figure 6 shows Von Mises stress distribution and crack opening in anisotropic vertebrae under combination of flexion and compression forces. It is found that like the pervious case, the highest stress concentration is at the upper pedicle region, but with Von Mises stress value of 34.89 MPa. The value of stress intensity factor (K_I) at deepest point of the crack is 0.304445MPa√m.

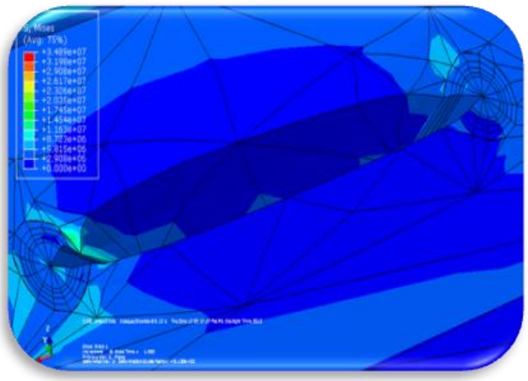

Figure 6:
Von Mises stress distribution and crack opening in anisotropic vertebrae under combination of flexion and compression loadings

For obtaining the required force for the fracture of lumbar vertebrae, we increased the value of applied force and then computed the corresponding stress intensity factors and compared them with the reported fracture toughness by literatures and a force of 2250 N obtained as a critical force.

Figure 7 shows the stress distribution of the fourth lumbar vertebrae under the mentioned load. It's been found that similar to previous cases, the highest stress concentration is around the crack, but with Von Mises stress value of 163.8 MPa.

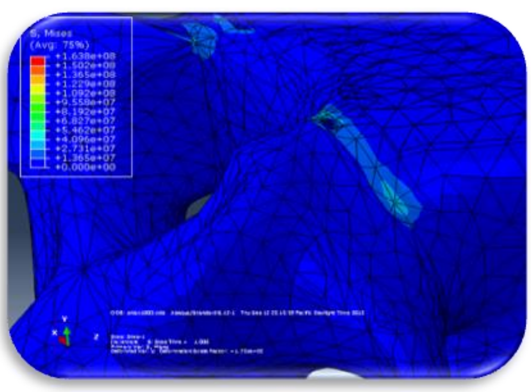

Figure 7:
Von Mises stress distribution in anisotropic vertebrae under a load of 2250N

In Fig. 8, the crack opening is visible. The value of stress intensity factor (K_I) at deepest point of crack is 1.4296MPa√m.

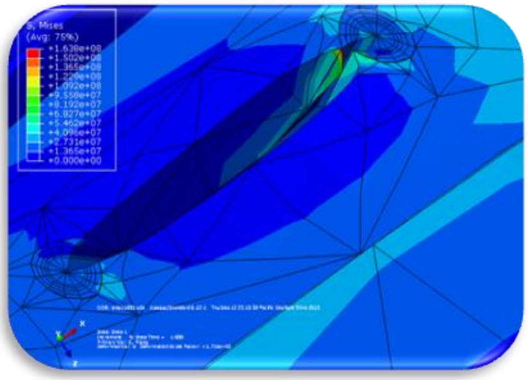

Figure 8:
Crack opening in anisotropic vertebrae under a load of 2250N

It is important that real properties and actual loading conditions have been considered for analysis purpose.

We are looking at this subject that whether the crack has been extended or not during a static loading. Therefore, the stress intensity factor and fracture toughness values have been required to compare with each other. In the first two cases, cracks are still far from reaching a critical stage. But in case with larger load, we've been very close to the critical region. This fact shows that it must be avoided to lift loads with a large amount.

Table 5 compares these mentioned cases in summary. Stress intensity factor values obtained in the first two cases show that the vertebrae tolerated under applied load, because the stress intensity factor values is lower than fracture toughness. Table 6 shows fracture toughness limits K_c and the thicknesses used for the biomechanical testing of the some specimens.

Table 5:
Summary of stress and stress intensity factor values

	stress intensity factor	**maximum stress**
isotropic with a load of 111N	0.261469 (MPa√m)	36.82 (MPa)
anisotropic with a load of 111N	0.304445 (MPa√m)	34.89 (MPa)
anisotropic with a load of 2250N	1.4296 (MPa√m)	163.8 (MPa)

Table 6:
Summary of Fracture toughness limits K_c and the thicknesses used for the biomechanical testing of the specimens (Isaac and Graham, 2011)

Study	**Direction**	**Thickness (mm)**	K_c $MPa\sqrt{m}$
Norman et al., 1994	Longitudinal	2	4.69 ± .65
	Longitudinal	3	4.48 ± .89
Bonfield et al., 1978	Longitudinal	1.5	2.1 - 4.7

According to the above discussion, two cases arise for rupturing: the length of crack should be larger with same load value, or a bigger load is needed for failing with same size of crack. Actually, when value of SIF reach to value of fracture toughness, the vertebra will fail and the crack will spread in critical region. This is what leads to the movement modification. After the crack detection by X-ray photos, Orthopedics specialists based on amount damage, prescribe instructions to help to modify daily actions and prevent increasing damage. Also, Figure 9 shows stress intensity factors in some aspect ratio of crack under second loading case (flexion and compression loadings) for anisotropic vertebra. It's been observed that with increasing aspect ratio ($^a/_b$), the stress intensity factor increases.

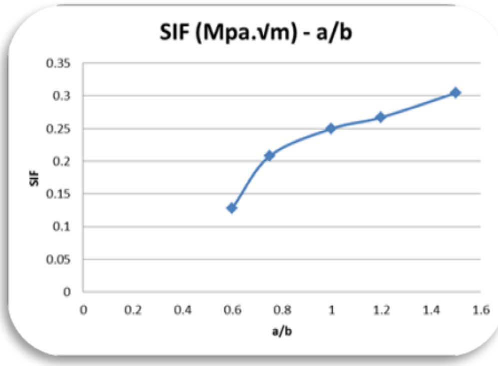

Figure 9:
Stress intensity factors in some aspect ratio of crack for anisotropic vertebrae under combination of flexion and compression loadings. (a=crack length, b=crack depth)

3. Conclusion

This paper has studied the use of the finite element model to determine the maximum stress and stress intensity factor and the required force for the fracture of fourth lumbar vertebrae under combination of compression and flexion forces in isotropic and anisotropic cases, regardless of inter vertebral discs, muscles and other vertebras. The results indicated that the maximum Von Mises stress value was in anisotropic case and at the upper pedicle region, with Von Mises stress value of 7.237 MPa. Hence, placed assumed crack on this region and computed corresponding value of SIF. Also, according to above condition, it was observed that the value of stress intensity factor in this region was 0.304445MPa√m.

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