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SENSITIVITY ANALYSIS OF THE ANNULUS FIBROSUS FIBERS INCLINATION IN A PARAMETRIC MODEL OF INTERVERTEBRAL DISC

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SUMMARY

The intervertebral disc is composed by three regions: an annulus fibrosus, a nucleus pulposus, and the terminal plates. The annulus fibrosus consist of concentric layers of collagen type I and II with fibers tilted in opposite direction in adjacent layers, the nucleus pulposus is composed of type II collagen and water. This work presents a sensitivity study of the inclination angle of the fibers of the annulus fibrosus, in terms of numerical stress analysis. Hyperplastic properties with reinforce fibers is use to model the annulus while the nucleus is consider isotropic and incompressible. The vertebral functional Unit is represented by a parametric geometry consisting in two cylinders representing the vertebrae, and two concentric cylinders representing intervertebral disc. The results indicate that an inclination of 60° yield the largest difference in displacement and 45° in stress compared to 0° inclination.

INTRODUCTION

A vertebral functional unit (VFU) is composed by two vertebrae, an annulus fibrosus, a nucleus pulposus, and two terminal plates.

The annulus fibrosus is a cartilaginosus cylinder which surrounds the nucleus and is composed by several concentric collagen layers (type I), embedded into a proteoglycans matrix. The collagen fibers of the layers are oriented on alternating angles with respect to the spine longitudinal axis (see figure 1b), the most common angle values reported on the literature are 60° [1], 45° [2], 30° [3]. The annulus is a nonhomogeneus tissue and its mechanical properties vary along its structure, particularly on the circumferential direction.

The nucleus pulposus is a semi-solid structure inside the annulus that in normal physiological conditions is pressurized, thus it behaves like an incompressible isotropic fluid.

BACKGROUND

Numerical modeling of annulus fibrosus might be approach in different ways, according to the data found in the literature. One method is to consider the annulus as an isotropic structure and manually place the fibers by using bar elements connecting nodes at surface of 3D elements [4]. Another technique implies using thin layers and simulate the fibers with shell elements [5], independent to the volume mesh.

A more complex approach is to numerically model the annulus by employing mathematical formulations base on strain energy equations. This is called the fiber reinforced composite model. Herein the annulus fibrosus can be modeled as a composite material with discrete collagen fibers embedded into an isotropic matrix [3], by using the strain tensor invariants and the fibers direction according to equation 1.

$$\Psi = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + C_{20}(\bar{I}_1 - 3)^2 + C_{02}(\bar{I}_2 - 3)^2 + C_{11}(\bar{I}_1 - 3)(\bar{I}_2 - 3) + \frac{K_1}{2K_2}\{\exp[K_2(\bar{I}_4 - 1)^2] - 1\} + \frac{K_1}{2K_2}\{\exp[K_2(\bar{I}_6 - 1)^2] - 1\} + \frac{1}{D}(J - 1)^2 \qquad (1)$$

The present work presents a sensitivity analysis of the annulus fibrosus fiber orientation in a parametric model of the intervertebral disc, using this fiber reinforced composite model.

METHODS

A cross-sectional view (coronal plane) of the parametric geometry of the VFU used in this study is shown in figure 1a; in 1b is show the annulus physiognomy. The two vertebrae (1) were considered isotropic, with E = 200 MPa, and ν = 0,3 [6], the terminal plates (2) with E = 23, 8 MPa, and ν = 0, 4 [7], and nucleus pulposus (3) with E = 0, 8 MPa, and ν = 0, 4999.

Regarding to the variation of fibers' angle, in this study the values 0°, 30°, 45°, 60° were used. The VFU was subjected to compressive loads of 500 and 1000 N. The sensitivity of the fibers orientation was characterized by the comparison of the stress and displacement distribution for each inclination angle assigned to the annulus fibrosus compared to none inclination (0°).

The finite element analysis was performed using Ansys ® v.14. To discretize the 3D geometry, 10 nodes solid element were employed. A convergence analysis of the strain energy was conducted in order to select an adequate mesh which consisted of 79132 elements.

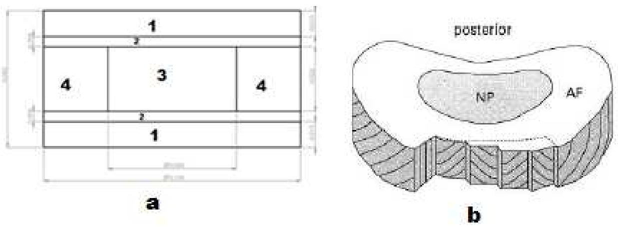

Figure 1: a) Parametric geometry of the VFU (all measures in m), b) annulus fibrosus geometry [8]

RESULTS AND DISCUSSION

Comparing the points were maximum stress is located, it is possible to notice that with a fiber angle of 30° the maximum stress is placed in the inferior surface of the annulus (see Fig 2b), just were the terminal plate and the annulus make contact, whereas when the fibers are horizontal (see Fig 2a, 0°), the maximum stress is positioned on the middle of the annulus surface.

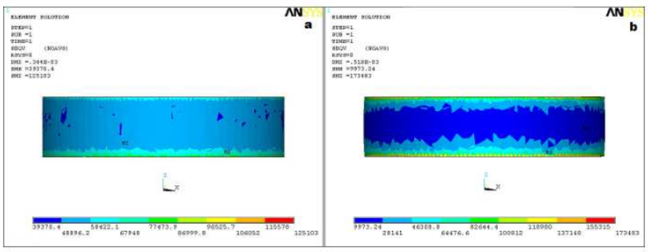

Figure 2: Stress distribution in the annulus (Pa) for a) 0° inclination, b) 30° inclination.

When no fiber inclination is consider (0°) the maximum displacement occurs on the surface were the compressive load is applied (fig. 3a), while when a fiber angle is considered the maximum displacement is located on the extern-lateral of the annulus surface (fig. 3b).

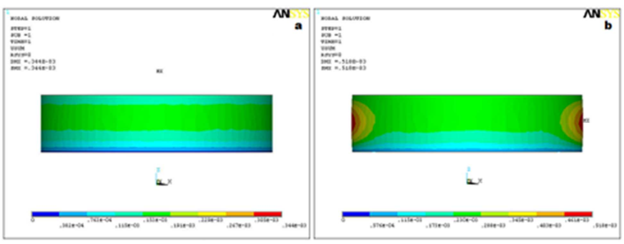

Figure 3: displacement distribution in the annulus (m) for (a) 0° inclination, (b) 30° inclination.

The differences for both stresses and displacements values were calculated for each fiber´ angle orientation, according to equation 2, where i takes value of each angle: 30º, 45º y 60º, to compare it with 0°, and the variable E takes the values of maximum displacement or stress respectively. The minimum difference in the displacement was found for 30° orientation of the fiber and the highest difference occurs for 60° (fig. 4a); for stress (fig. 4b) with 45° is obtained the highest difference the minimum difference is with an inclination of 30°.

$$\%dif = \frac{E_{0^\circ} - E_i}{E_{0^\circ}} \qquad (2)$$

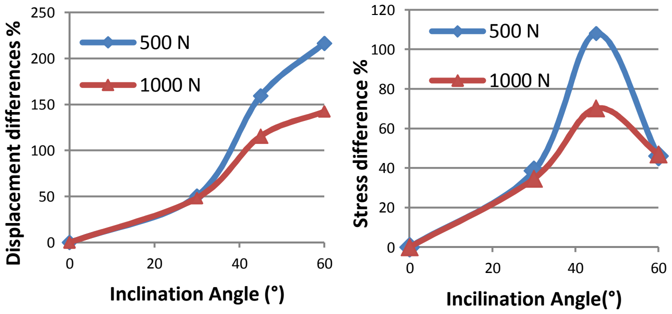

Figure 4: (a) Displacement differences vs. Inclination angle; (b) Stress differences vs. Inclination angle

From figure 4, the behavior of the displacement and stress for the different loads are the same; the differences between them are in the magnitude of the values.

CONCLUSIONS

The aim of this work was to compare the use of diverse fiber orientation angles on the annulus fibrosus modeling, based on the values reported for several researches.

It can be concluded, from the obtained results, that using fiber orientation angles significantly influences the stress and displacement values shown in the parametric VFU. It was determined if used an angle of 60°, mayor is the displacement that generate more damping with less stress.

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