STRESS ANALYSIS OF VERTEBRA USING PHOTOELASTIC AND FINITE ELEMENT METHODS

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In this study, both the photoelastic, as well as the finite element methods, are used to study the stress distribution within human vertebra (L4) under forces similar to those that occur during normal life. Two & three dimensional models of vertebra were created by the software AutoCAD [1]. The coordinates obtained were fed into a computer numerical control (CNC) tensile machine to fabricate the models from photoelastic sheets. Completed models were placed in a transmission polariscope and loaded with static force (up to 1500N). Stresses can be quantified and localized by counting the number of fringes. In both methods the Principle stresses were calculated at different regions. The results noticed that the maximum von-mises stress on the area of the extreme superior vertebral body surface and the facet surface with high normal stress (σ) and shear stress (τ). The facets and other posterior elements have a load-bearing function to help support the weight of the upper body and anything that it carries, and are also acted upon by spinal muscle forces. The numerical FE results have been compared with the experimental method using photoelasticity which shows good agreement between experimental and simulation results.

Keywords: Photoelasticity, Stress, Load, finite element,

1. Introduction

The vertebrae are bone structures sustain biomechanical overload and it is believed that these stresses are the determinant factor to define the vertebrae microstructure. These changes in the microstructure in response to external overloads are adaptive, and in high-stresses regions, the bone tissue becomes more tough and strong. If the porosity is low, with 5–30% of bone volume occupied by nonmineralized tissue, the tissue is termed
**cortical bone.** Bone tissue with a relatively high porosity, with 30% to greater than 90% of bone volume occupied by nonmineralized tissue, is known as spongy, **cancellous,** the porosity of bone is of interest because it directly affects the mechanical characteristics of the tissue. With its higher mineral content, cortical bone is stiffer, so that it can withstand greater stress, but less strain or relative deformation, than trabecular bone. Because trabecular bone is spongier than cortical bone, it can undergo more strain before fracturing.

However, there are some medical conditions such as lordosis, kyphosis, scoliosis, spondylolysis and osteoporosis in which these adaptations fail, resulting in vertebral fractures. [2]

There are two main types of stress analyses. The first is conceptual, where the structure does not yet exist and the analyst is given reasonable way to define geometry, material, loads, and so on. The permanent way of doing this nowadays is with the finite element method (FEM). The second analysis is where the structure (or a prototype) exists, and it is this particular structure that must be analyzed. Situations involving real structures and components are, by their very nature, only partially specified. These problems are usually handled by a combination of analytical methods and experiments are used to measure some of the unknowns, and guesses/assumptions are used to fill in the remaining unknowns. [3]

Photoelastic provides quantitative evidence of highly stressed areas and peak stresses at surface and interior points of the structure and often equally important, it discerns areas of low stress level where structural material is utilized inefficiently. When photoelastic model is subjected to force, optical properties change in direct proportion to the stresses developed. The material becomes “birefringent” and a colorful interference (fringes) pattern is observed. These fringe patterns can be interpreted to give information on the magnitudes of the principal stresses which are present in the model and then, by using a simple formula, the stresses in the actual component can be determined [3].

**2. Materials and Methods:**

**2.1 Photoelastic Method:**

Photoelasticity is based on the stress-optic effect, which for plane stress analysis is governed by the following stress-optic law [4]:

\[
\sigma_1 - \sigma_2 = \frac{N f_\alpha}{h}
\]  

(1)

Where \(N\) represent the number of fringes, \(f_\alpha\) is the material fringe constant and
\( (\sigma_1 - \sigma_2 ) \) is the difference in the principle stresses,  
\( (h) \) is the thickness of the model [4].

### 2.1.1 Photoelastic Models

Three types of two-dimensional models of human L4 vertebra were fabricated:
- Model (I) side view.
- Model (II) front view
- Model (III) top view.

The coordinates obtained were fed into a computer numerical control (CNC) machine to fabricate the models from polycarbonate plastic sheet [1]. These models cut with a cold water jet. The water jet process created smooth edges and left very little residual stress on the models (Figure 1, 2 and 3).

### 2.1.2 Experiments:

A Transmission circular polariscope was used as the experimental instrument. It consists of a light source, two polarizing plates, and a quarter-wave plate (Fig.4) [5].

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Fig.1 Model of side view L4

Fig.2 Model of front view L4

Fig.3 Model of top view L4

Fig.4 Transmission circular polariscope and loading frame.
Before loading procedures were initiated, the models were placed in the polarscope to determine if any stress was produced during model preparation. In the loading test the loads were applied in the vertical distributed compression loads (0N, 20N, 40N, 60N, 80N, 100N, 120N, 140N, 160N) which equal when transferring it by a factor to the normal loadings 700N, 1000N, 1200N & 1500N. The stress distributions in the loading models were observed and photographed. The photoelastic polycarbonate used was calibrated and had an optical Constant of 6.9 N/mm fringe.

2.2 Finite Element Models:

A three dimensional human L4 vertebra were created at Autodesk Inventor CAD system, using common geometry and material properties of the cortical bone of the vertebra models (E=12000 GPa, v=0.3). Then, CAD models are imported to the ANSYS software (V.15). The finite element mesh was obtained using a plane quadrilateral element with four nodes. Mesh were pre-analyzed and refined on the stress concentration region. Table (1) shows the number of knots and elements used in the whole models.

<table>
<thead>
<tr>
<th>Type of Vertebra</th>
<th>Number of Element</th>
<th>Number of Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4</td>
<td>122211</td>
<td>207630</td>
</tr>
</tbody>
</table>

3. Result:

The photoelastic analysis and the FE method were used to assess and compare the distribution of stress in the L4 vertebra. Under (0N, 20N, 40N, 60N, 80N, 100N, 120N, 140N, 160N) vertical loading, the following findings were recorded from the numerical results of the F.O. of experimental models. Figures (5), (6), (7) and (8) show the distribution of the stresses in the side view of L4 vertebra by using photoelastic and 3D finite element analyses. In order to demonstrate the similarity of the values obtained in the experimental and numerical techniques, a comparison of the values of the principle stresses for each point was carried out showed in figures (9), (10), (11), and (12). Also Figures (13), (14), (15), and (16) show the distribution of the stresses in the front view of L4 vertebra by using photoelastic and 3D finite element analyses.
A comparison of the values of the principle stresses for each point was carried out, according to the regions analyzed in figures (17, 18, 19 and 20).

4. Discussion:
Stress is produced within a structure as a result of load acting upon it. The direction of the load applied and the shape of the structure influence the nature of the distribution of stress within the structure.

In this study, Photoelastic testing was used to provide qualitative solution. Material was used within the elastic region and thus, the stress fields are only dependent on the geometry and loading condition. In the experiment, pictures of the isochromatic fringe patterns were taken under different loads. Eventually, the load of (700,1000,1200 & 1500) N were selected for this study because of this load magnitude allowed observation to be done easily, that overlapping stress concentration areas within this range do not occur and this range of loads do not causes damaging the model.

Figures (5), (6), (7) & (8) shows that when the load is increased from 700N, 1000N, 1200N & 1500N the points of interest become so obviously shown & it give us a good description on the distribution of stresses in the vertebra from the top to the bottom and where its concentrated more & what is the most fragile & convenient areas to be damaged even if the load was lower.

The results noticed that the maximum von-mises stress on the area of the extreme superior vertebral body surface and the facet surface with high normal stress (σ) and shear stress (τ). [6, 7]. The facets and other posterior elements have a load-bearing function to help support the weight of the upper body and anything that it carries, and are also acted upon by spinal muscle forces.

The Comparison between experimental and numerical results showed a relatively small difference. There is some possible reasons for these differences between experimental and numerical results. Such as:

- May be some error in the calculation of the material fringe constant
- The fringe order at contact point is very high because of the localized contact load and, therefore, the fringe order exactly at the contact point can never be measured accurately.
**Fig (5):** Distribution of the stresses in L4 Vertebra by application of a vertical load of 700 N. (a) Using Photoelasticity (b) Using finite element

**Fig (6):** Distribution of the stresses in L4 Vertebra by application of a vertical load of 1000 N. (a) Using Photoelasticity (b) Using finite element
**Fig (7):** Distribution of the stresses in L4 Vertebra by application of a vertical load of 1200 N. (a) Using Photoelasticity (b) Using finite element

**Fig (8):** Distribution of the stresses in L4 Vertebra by application of a vertical load of 1500 N. (a) Using Photoelasticity (b) Using finite element
**Fig (9):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (700N).

**Fig (10):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1000N).

**Fig (11):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1200N).

**Fig (12):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1500N).
Fig. 13 Distribution of the stresses in L4 Vertebra by application of a vertical load of 700 N. (a) Using Photoelasticity (b) Using finite element

Fig. 14 Distribution of the stresses in L4 Vertebra by application of a vertical load of 1000 N. (a) Using Photoelasticity (b) Using finite element
Fig. 15 Distribution of the stresses in L4 Vertebra by application of a vertical load of 1200 N. (a) Using Photoelasticity (b) Using finite element

Fig. 16 Distribution of the stresses in L4 Vertebra by application of a vertical load of 1500 N. (a) Using Photoelasticity (b) Using finite element
Comparing points of interest we found the following results:-

**Fig (17):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (700N).

**Fig (18):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1000N).

**Fig (19):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1200N).

**Fig (20):** Comparison of stresses in points of interest determined by photoelastic and finite element analysis in L4 (1500N).
5. Conclusion:
Within the limitations of the present study, the results indicate the following:
1. The photoelastic approach provides a clear visual and qualitative picture of the stress distribution for the applied scientist, whereas the finite element approach provides a more detailed evaluation of the complete state of stress in the model for the researcher.
2. Peak stresses were concentrated at upper vertebral body but the body of Vertebra is made to sustain such loading while there are fragile & convenient areas to have damaged even if the load was lower.
3. The stress distribution obtained for the plane-stress model by a photoelastic analysis is usually independent of the elastic constants. So that the magnitude of the stresses in real vertebra different from those in a models. However, the location and general standard of these stresses are similar.
4. The comparison between numerical and experimental results showed reasonably agreement for both the location and magnitude of stresses.

6. References:
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