

Stress Induced in Periodontal Ligament under Orthodontic Loading (Part II): A Comparison of Linear Versus Non-Linear Fem Study

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How to cite the article:

Hemanth M, Deoli S, Raghuveer HP, Rani MS, Hegde C, Vedavathi B. Stress induced in periodontal ligament under orthodontic loading (Part II): A comparison of linear versus non-linear Fem study. J Int Oral Health 2015;7(9):114-118.

Abstract:

Background: Simulation of periodontal ligament (PDL) using non-linear finite element method (FEM) analysis gives better insight into understanding of the biology of tooth movement. The stresses in the PDL were evaluated for intrusion and lingual root torque using non-linear properties.

Materials and Methods: A three-dimensional (3D) FEM model of the maxillary incisors was generated using Solidworks modeling software. Stresses in the PDL were evaluated for intrusive and lingual root torque movements by 3D FEM using ANSYS software. These stresses were compared with linear and non-linear analyses.

Results: For intrusive and lingual root torque movements, distribution of stress over the PDL was within the range of optimal stress value as proposed by Lee, but was exceeding the force system given by Proffit as optimum forces for orthodontic tooth movement with linear properties. When same force load was applied in non-linear analysis, stresses were more compared to linear analysis and were beyond the optimal stress range as proposed by Lee for both intrusive and lingual root torque. To get the same stress as linear analysis, iterations were done using non-linear properties and the force level was reduced.

Conclusion: This shows that the force level required for non-linear analysis is lesser than that of linear analysis.

Key Words: Finite element method, intrusion, lingual root torque, non-linear analysis

Introduction

Applying optimum amount of force during orthodontic treatment is a challenging task for the orthodontist. Amount of force to be applied during orthodontic treatment is one of the problems encountered in orthodontics.¹ The quantification of stress in the periodontal ligament (PDL) is an important concept, as stress in this tissue is transmitted to alveolus with subsequent bone remodeling and tooth movement.

Infinite element method (FEM) studies, the linear models are widely used. As compared to the linear static analysis, non-linear analysis gives more realistic results as they closely reflect the dynamic nature of the oral environment.²

For the present study maxillary central incisor was modeled into a three-dimensional (3D) FEM model because it undergoes the most detailed tooth movement and is at the second-highest for root resorption after the maxillary lateral incisor.³

Therefore, the purpose of this study is to analyze the stresses in PDL by applying intrusive and torque movements by a 3D FEM and to compare these stresses with linear and non-linear analyses in a maxillary central incisor model.

Aims and objectives

1. To evaluate the stress distribution in PDL on application of orthodontic load (vertical intrusive force and lingual root torque) on maxillary central incisors with a 3D FEM analysis using linear properties and then application of equivalent force magnitude using non-linear properties.
2. To compare the differences of stress distribution between linear and non-linear properties.

Materials and Methods

In this study, the 3D FEM model of maxillary central incisor used in the previous study was used to calculate the stress in the PDL by application of intrusive and torque movements and compare these stresses in linear and non-linear analyses.

Computational facilities used for the study

It was same as mentioned in part I of the same study.

Steps involved in the generation of finite element model

1. Construction of a geometric model
2. Conversion of the geometric model to a finite element model

3. Material property data representation
4. Defining the boundary condition
5. Loading configuration
6. Solving the system of non-linear algebraic equation
7. Interpretation of the results.

Construction of a geometric model and conversion of geometric model to finite element model

The same geometric model which was used in part I of the study was used, meshing was done using hypermesh and then a FEM model was created.⁴

Material property data representation

Each structure was then assigned a specific material property. The different structures in the finite element model are tooth, PDL, cortical bone and cancellous bone. The material properties used in this study have been taken from the finite element studies previously conducted.^{5,2} These material properties were linear and isotropic for linear analysis and non-linear mechanical properties were assigned for non-linear analysis (Tables 1 and 2).^{5,6}

Defining the boundary condition and application of forces

The boundary condition in the finite element model was defined at all the peripheral nodes of the bone with three degree of movement in all directions. Application of the forces (intrusion and lingual root torque) was same as the previous study.

Solving the system of linear algebraic equations

These equations are solved by frontal solver technique present in the ANSYS workbench software.

Results

The forces were applied to the maxillary central incisor for intrusive and lingual root torque movements and the equations

were solved with linear and non-linear properties by ANSYS workbench software and sequentially the stress patterns produced in PDL were analyzed.

The results obtained were divided into the following:

1. Application of intrusive force of 0.30 N using linear properties.
2. Application of intrusive force starting with 0.30 N and doing iterations using non-linear properties to get the equivalent stress as obtained using linear properties.
3. Application of lingual root torque of 1.0 N using linear properties.
4. Application of lingual root torque of 1.0 N and doing iterations using non-linear properties to get the equivalent stress as obtained using linear properties.

Application of intrusive force of 0.30 N using linear properties

When 0.30 N of intrusive forces were applied along the long axis of the tooth it produced maximum compressive stress (denoted as minus) of -0.02006 N/mm^2 at the apex of the PDL and the maximum tensile stress was 0.001528 N/mm^2 at the cervical margin.

Application of intrusive force of 0.30 N with non-linear properties

When 0.30 N of intrusive forces were applied parallel to the long axis of the tooth using non-linear properties it produced minimum compressive stresses of -0.0293 N/mm^2 at the apex of the PDL and maximum tensile stresses was 0.00264 N/mm^2 at the cervical margin (Figure 1). Force levels were iterated till 0.2 N, where an equivalent stress similar to the analysis done using linear properties was obtained (Figure 2).

Application of lingual root torque of 1.0 N using linear properties

When 1.0 N with a 15 N/mm moment load was applied using linear properties, it produced a minimum compressive stress of -0.01646 N/mm^2 and maximum tensile stress of 0.01832 N/mm^2 . This produced a lingual root torque.

Application of lingual root torque 1.0 N with non-linear properties

When 1.0 N with a 15 N/mm of moment load was applied using non-linear properties, the minimum compressive stresses was -0.0260 N/mm^2 and maximum tensile stresses was 0.0297 N/mm^2 (Figure 3). The moment value was iterated till 0.8 N, where an equivalent stress similar to the linear properties was obtained (Figure 4).

Discussion

For the non-linear analysis of PDL, elastic property in the form of a stress-strain curve was incorporated into the FEM program. The load was subdivided into a series of multiple increments and then applied to the constructed geometric

Table 1: Linear material properties used in FEM.

Material	Young's modulus (N/mm ²)	Poisson's ratio
Enamel	8.41×10^4	0.33
PDL	6.90×10^{-1}	0.45
Cancellous bone	1.37×10^4	0.3
Cortical bone	3.45×10^5	0.3

PDL: Periodontal ligament, FEM: Finite element method

Table 2: Piecewise linear mechanical property values describing non-linear elastic stress-strain behavior of PDL.

Stress	Strain
0.0000	0.0000
0.0251	0.0008
0.0473	0.0021
0.0755	0.0050
0.1009	0.0102
0.1266	0.0197
0.1526	0.0374
0.1789	0.0706
0.1883	0.0882
0.2051	0.1309

Young's modulus: $2.6 \text{ (N/mm}^2)$. Poisson's ratio: 0.45. PDL: Periodontal ligament

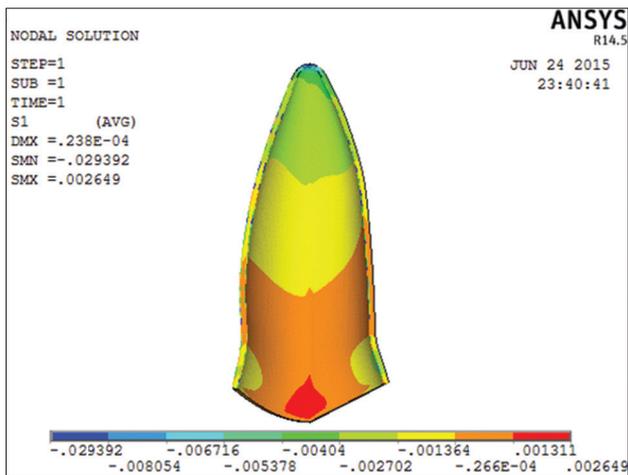


Figure 1: Distribution of principle stress in periodontal ligament on the application of the intrusive force of 0.30 N using non-linear properties.

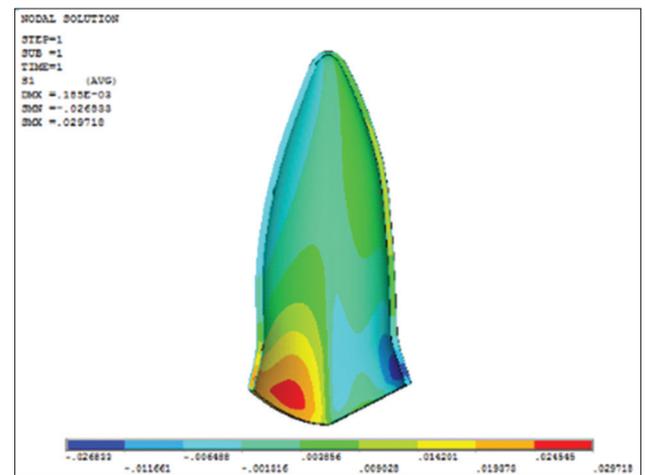


Figure 3: Distribution of principle stress in periodontal ligament on the application of lingual root torque of 1.00 N/mm using non-linear properties.

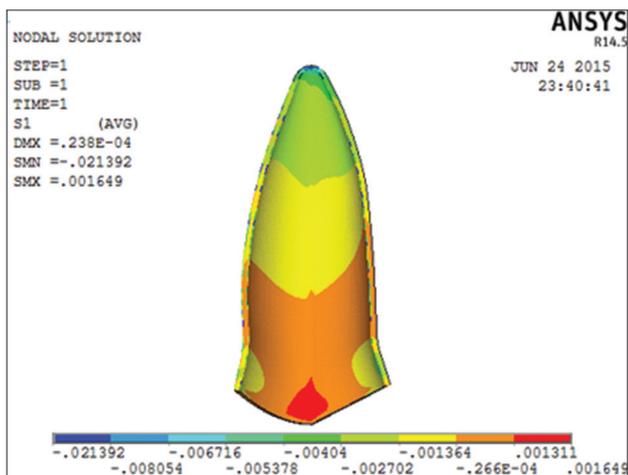


Figure 2: Distribution of principle stress in periodontal ligament on the application of the intrusive force of 0.20 N using non-linear properties.

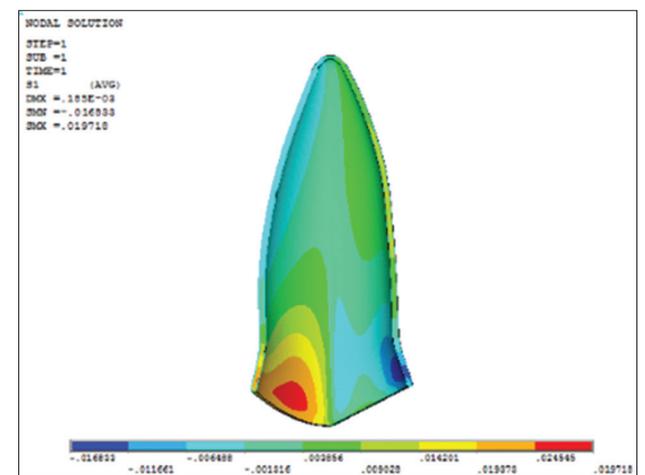


Figure 4: Distribution of principle stress in periodontal ligament on the application of lingual root torque of 0.80 N/mm using non-linear properties.

model. In each step, the program performed a linear solution and was checked for convergence. If the convergence criteria were not satisfied, the load vector was re-evaluated, and a new solution was obtained. This iterative procedure continued until the problem converged.⁷ This study shows that intrusive forces and lingual root torque produces stress at the root apex. Similar results were found in previous investigations for vertical tooth movement that used FEM.⁸⁻¹⁰

The results obtained in the part I of this study using linear properties were taken into consideration. The current study offers unique information about the non-linear elasticity of the PDL in the range of orthodontic forces for intrusion. As compared to the linear analysis the non-linear analysis is known to provide more accurate and reliable results. The use of non-linear mechanical properties for the PDL resulted in a dramatic departure from the stresses predicted by the linear models which is in agreement with the study by Toms and Eberhardt.¹¹

On application of intrusive force of 0.30 N with non-linear properties, the compressive stress was mainly concentrated at the apex whereas tensile stress was distributed throughout the PDL which is in agreement with Rudolph and Wilson.^{8,10}

Once the stresses were obtained with linear properties, the same force load was applied using non-linear properties. The minimum compressive stress was 0.0293 N/mm² and the maximum tensile stress was 0.00264 N/mm². The compressive and the tensile stress levels were increased with the same amount of load in non-linear analysis.

Therefore to get the equivalent stress as linear properties, iterations were done with non-linear properties and the force level was reduced to 0.2 N. This shows that less force is required in non-linear analysis compared to the linear analysis. The studies of Toms, Eberhardt and Durkee found the similar results.^{11,12}

Toms and Eberhardt found out that stresses at the apex with non-linear analysis was 2.4 times more than that of linear analyses for extrusion.¹¹ Durkee observed that non-linear nature of the PDL results in higher compressive stresses being generated, for both lateral and axial loading, than a comparable linear model.¹³

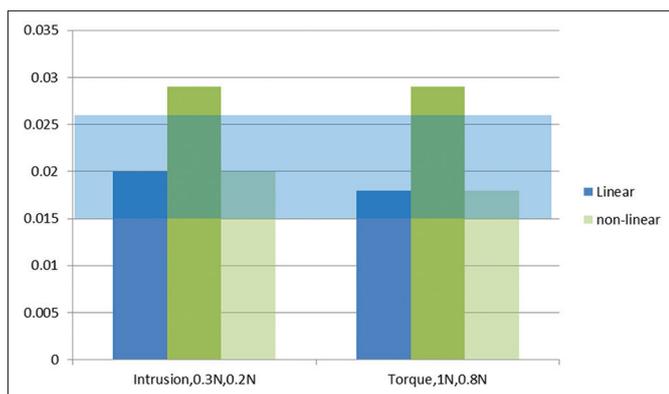
When 1.0 N/mm moment load was applied for lingual root torque maximum compressive stress was concentrated at the apex and near the buccal part of alveolar crest whereas the tensile stress was distributed at the mid region of PDL which is in agreement with Dorrow and Sander; Hohmann.^{13,14} When 1.0 N/mm of moment load was applied using non-linear properties, a minimum compressive stresses of -0.0260N/mm^2 and maximum tensile stresses of 0.0297N/mm^2 was obtained.

Therefore to get the same stress as linear, iterations were done with non-linear properties. The force level had to be reduced to 0.8 N/mm to get the equivalent stress value as linear. These results were in agreement with the study by Toms, Eberhardt, and Durkee which tells that the stresses produced in the PDL are more with non-linear analysis compared to the linear analysis with application of same amount of load.^{11,12} So, this shows that less force is required in non-linear analysis compared to the linear analysis (Graph 1).

Conclusion

Stresses in the PDL were evaluated with intrusive and lingual root torque movements by a 3D FEM and these stresses were compared in linear and non-linear analyses in a maxillary central incisor model. 0.30 N was the load applied for intrusion and 1.0 N/mm was the moment load for torque. For intrusive and lingual root torque movement distribution of stress over the PDL was within the range of optimal stress value as proposed by Lee, for orthodontic tooth movement with linear properties.¹⁵

When same force load was applied in non-linear analysis, stresses were more compared to linear analysis for both



Graph 1: The difference in the linear and non-linear stress levels.

intrusive and lingual root torque. To get the same stress as linear, iterations were done using non-linear properties and the force level was reduced to 0.2 N and 0.8 N for intrusion and torque respectively, which is within the range of optimal orthodontic force as suggested by Proffit. This shows that the force level required for non-linear analysis is lesser than that of linear analysis. Therefore in case of non-linear analysis, 1.5 times less force was applied for intrusion and 1.25 times less force was applied for torque as compared to the linear analysis.

The mobility of tooth and its recovery increases in a quasi-logarithmic manner which is suggestive of the viscoelastic nature of PDL. This property of PDL needs to be addressed in the future studies.

In FEM analysis, the simulation of materials with complex geometry and dimensions using requires the determination of elastic, plastic and viscoelastic material properties. The exact idea of stress and strain in the PDL for different types of tooth movements can be determined with the non-linear simulation. However, the non-linear FEM analysis has only been recently used in the field of orthodontics, its reliability and credibility in studying biologic structures has yet to be fully established.

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