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Learning Abaqus for Master's thesis project

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A short course on finite element analysis, with application to the stress distribution in teeth

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Abstract

The overall goal of my work is to gain insight into how tooth shape relates to its function. As a step towards this, I undertook an independent study project to learn finite element analysis (FEA) this semester, and to lay a foundation for my future Master's thesis project work. After solving a series of problems on paper, reading through my supervisor's work, and referring to a range of papers from the literature, I solved a series problems using FEA that helped me learn some specific methods that I believe will be useful to my research. This report contains an overview of some literature that I studied, and a summary of several finite element output plots that I found to be particularly instructive.

1. Introduction

The context in which this study was undertaken is the attachment of tendon to bone, which is a major challenge from the surgical, mechanical engineering, and tissue engineering perspectives [1-3]. For surgery, up to 94% of rotator cuff reattachments fail [4]. From the mechanical engineering perspective, the mechanisms of resilience at the insertion site are an area of ongoing research [5-11], and must overcome the free edge singularity problem [12-29]. From the tissue engineering perspective, the natural tendon to bone attachment does not grow back [4], and it is important to find ways to stabilize tissue without this attachment [20-23] and to guide regrowth of the transitional tissue [24-28]. Stabilization of tissue during healing is a topic that I am focusing on and have contributed to a conference paper on [29]. The question of resilience of tissues motivated my ongoing study of how carnivores capture and tear through flesh.

As a step towards this, I studied some basic solid mechanics this semester, including some specialized problems from the textbook by Budynas [30], and studied an introduction to finite element analysis [31].

In this report, I present a few simple finite element results that demonstrate the issues that I expect to have to overcome in my masters research.

2. Methods

The study was conducted by becoming familiar with Abaqus, a finite element analysis program, and by analyzing simple shapes that would be relevant to the Master's thesis project. The steps involved in a finite element analysis are coming up with an idealized geometry, choosing boundary conditions, making a mesh, implementing the boundary conditions, solving the equations (equilibrium, strain displacement, and constitutive equations) by a matrix-based energy minimization method, and then validating results by mesh refinement [31].

The parts used for analysis were made by Solidworks CAD program, which will later become useful when creating more complex models. Also taking MEMS 202 CAD class during the semester greatly helped improving my proficiency in Solidworks.

The problems studied here were idealized teeth on elastic foundations (Figure 1). A simple triangular model and a simple tooth shape with similar properties were used for analysis. The two models were created with a base of 4 cm and a height of 6 cm. The Young's modulus and Poisson's ratio were set to 14 GPa and 0.3, respectively. These values correspond to human cortical bone which I have used as a reference material that would allow me to gain insight [32-36]. The values that were used can be changed easily which can be later analyzed when I have a firm idea on what the actual material will be used to create the model that would assist in the human rotator cuff repair.

The teeth were placed on an elastic foundation that resisted load elastically in the vertical direction. The foundation stiffness was set to be 6000 MN/m. This represents the contribution of the periodontal ligament, the cells, and the fibrocartilage [37-39]. Although these are viscoelastic or nonlinearly viscoelastic [40-42], and teeth are highly responsive to temperature [43], simple linear elastic properties were used for my first tries at using Abaqus.

The other boundary conditions were as follow. The right hand side of the tooth was subjected to a unit load in the horizontal direction (towards the left), and was traction free in the vertical direction. The right hand side was traction free. The bottom was shear free, and, in the examples shown here, the lower left corner was restrained from moving. This last condition highlights a challenge that I will have when creating more advanced models of teeth.

The models were two dimensional, and plane strain, linear interpolation quadrilateral and triangular elements were used. In the results displayed, the elements were used without hourglass control for the purpose of highlighting the challenges expected.

Abaqus was used to refine the mesh until the strain energy and peak stress did not change more than a few percent with additional refinement. The corresponding plots of the maximum principal stress, strain tensor energy and the strain energy density will be attached.

3. Results and Discussion

The maximum tensile principal stress follows what would be expected in a cantilever beam with the boundary conditions used (Figure 1). For the curved tooth, the tensile stresses were in general higher on the loaded face, and the principal stress was zero on the back face, consistent with what is expected for flexure of a beam [30]. Two artifacts appear. The first is a stress concentration at the point that was fixed, in the lower left hand corner. This arose because of the choice made to have rollers on the bottom boundary and one fixed point. However, in other simulations where the bottom boundary was "encastre" [31], meaning that the displacement was fixed to zero, a stress concentration known as a Williams free-edge singularity appeared at that corner [44]. The stress concentrations or stress singularities can be suppressed by choosing different boundary conditions, such as a foundation that is elastic in shear or a cohesive zone model, which is used in fracture studies [31,46]. Although the understanding of these mechanisms falls under multi-scale modeling that is beyond the scope of what is needed for this study, phenomenological models can be used to account for how microstructure relates to continuum behavior [45-46]. The second is an hourglass effect [31]. Here, the oscillatory nature of the free edge singularity shows up as a series of errors in the estimation of displacements, which makes neighboring quadrilateral elements look like hourglasses [31]. The hourglass effect can be suppressed by choosing elements with "hourglass control" or by choosing triangular elements [31].

The normal strain in the vertical direction also shows what would be expected from Euler-Bernouli beam theory (Figure 2). The strains are generally tensile on the loaded face and compressive on the free face. A strain concentration is evident at the curve of the curved tooth. Both teeth also show the free edge singularity at the point that is fixed.

The final plot is strain energy density. The strain energy is particularly important because the finite element program uses the principle of minimum potential energy to estimate the displacement field. The strain energy density is dominated by the Williams singularity. However, because it is elevated over only a few of the thousands of elements, it is possible for the program to estimate a reasonable solution far away from the singularity.

4. Conclusions

I am confident that I have become familiar and somewhat proficient in using Solidworks and in Abaqus in order to create and analyze models. This skill sets that I have acquired during the semester shall contribute to laying a foundation to a Master's thesis project which is the learning objective of the study.

5. Acknowledgments

I thank my mentors Guy Genin, Victor Birman, and Stavros Thomopoulos, and also my labmate Steve Linderman, for their guidance on this study.

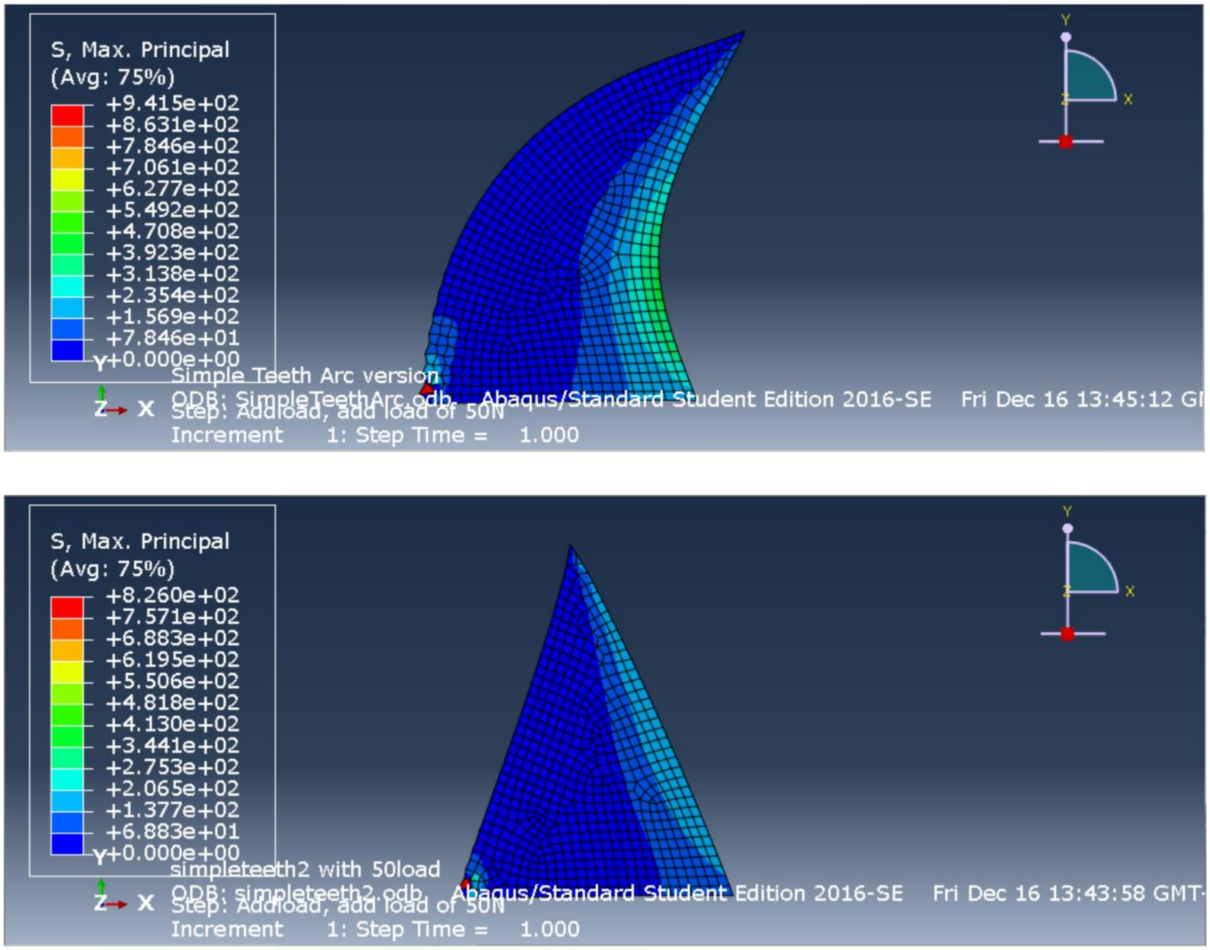

Figure 1. The maximum tensile principal stress in two simple models of teeth loaded by a horizontal unit distributed load on the right hand face. For the curved tooth, the tensile stresses were in general higher on the loaded face, and the principal stress was zero on the back face, consistent with what is expected for flexure of a beam. Two artifacts appear: a stress concentration at the point that was fixed, in the lower left hand corner, and an hourglass effect, which makes neighboring quadrilateral elements look like hourglasses.

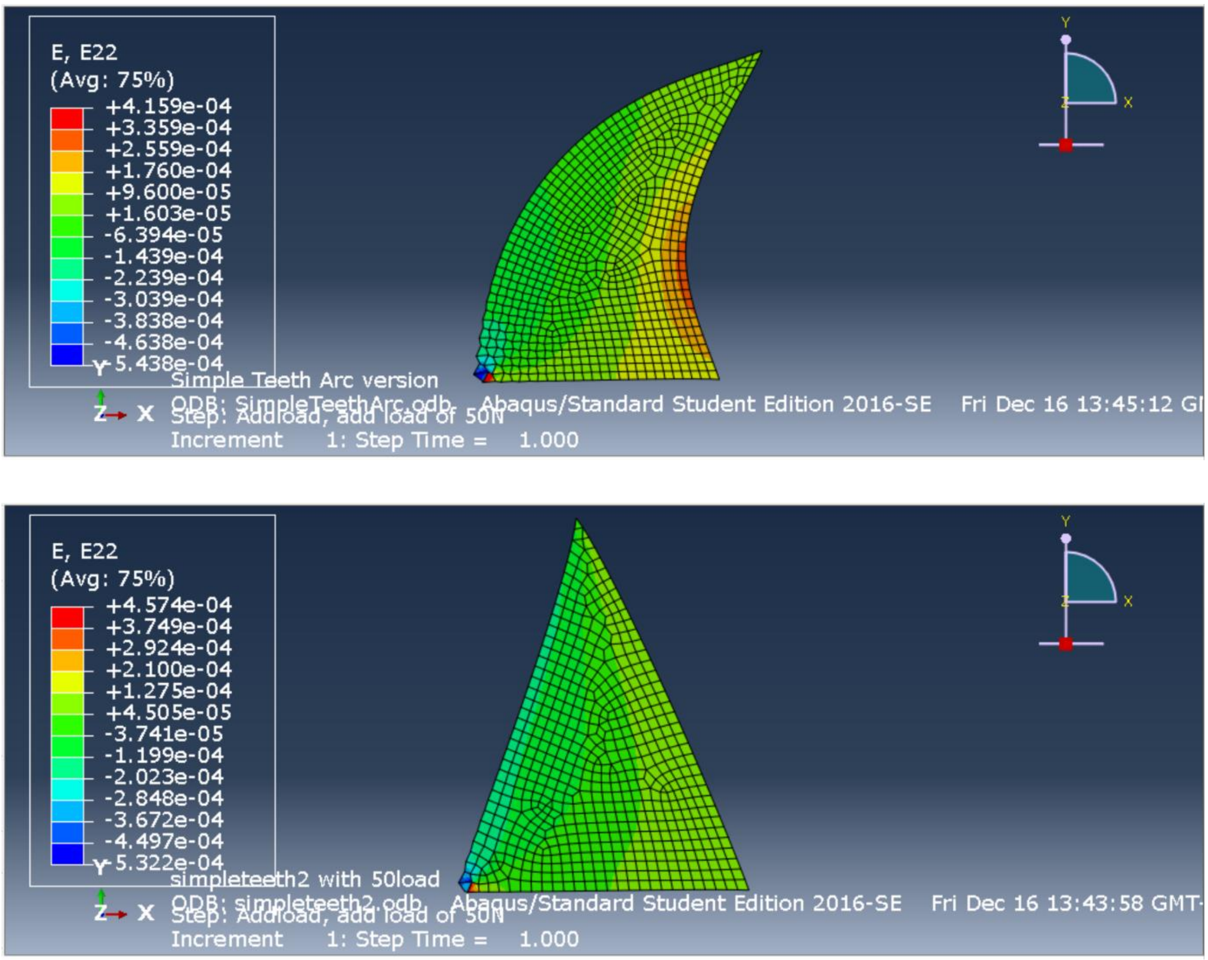

Figure 2. Normal engineering strain component in the vertical direction. The strains are generally tensile on the loaded face and compressive on the free face. A strain concentration is evident at the curve of the curved tooth. Both teeth also show the singularity at the point that is fixed.

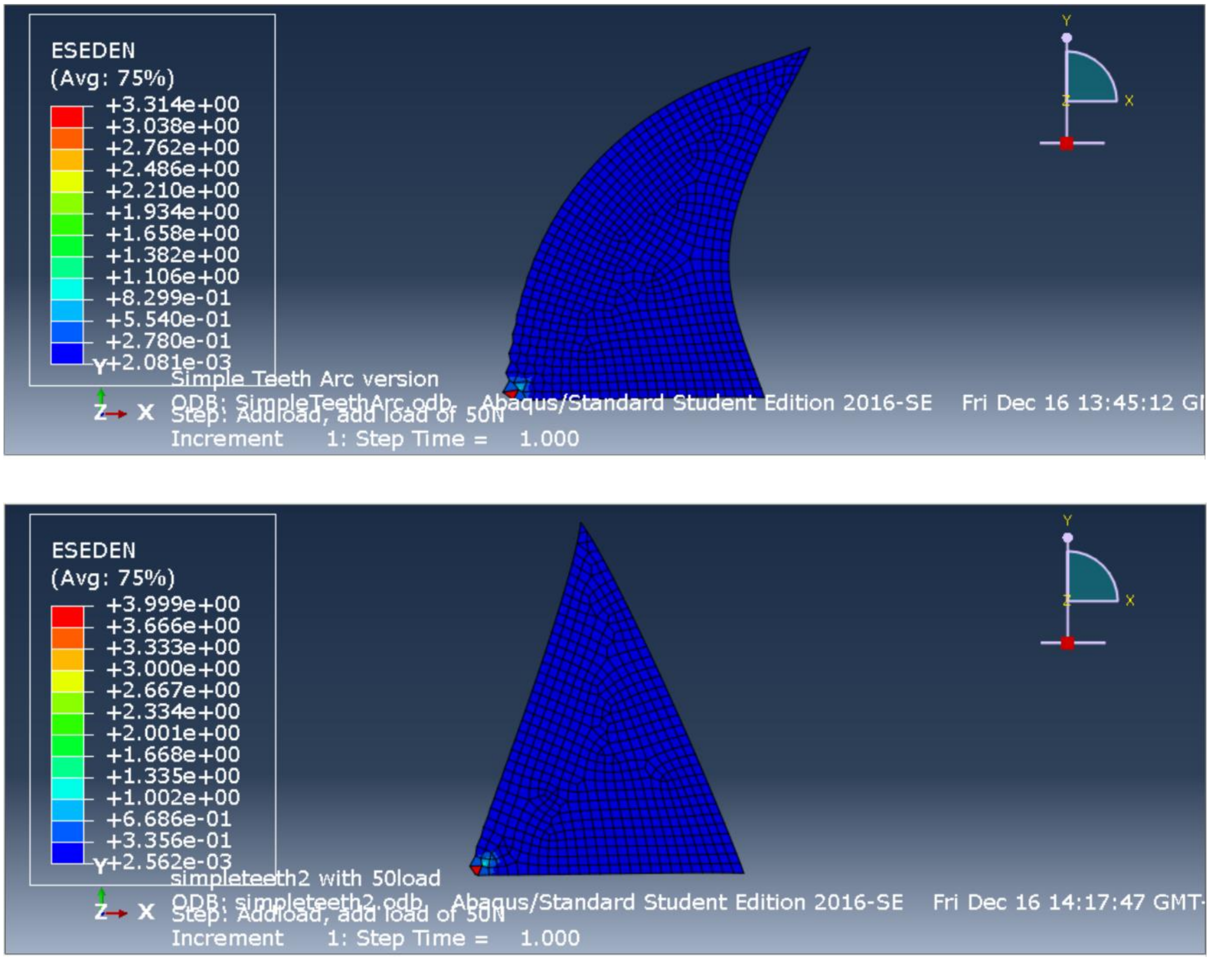

Figure 3. Strain energy density. The strain energy density is highest at the singularity associated with the pinned node.

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