Reverse-Engineering of Contact Lens Mechanical Properties from an In Situ Compression Test

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Abstract: Contact lenses correct the optics of the ocular system by placing a refractive element over the cornea. Modern lens materials are comprised of 30-90% water and exhibit viscoelasticity, hyperelasticity and thermal dependencies. Contact lens materials have traditionally proven to be extremely difficult to characterize for a number of reasons, primarily because the properties are dependent upon the processing conditions of the lenses themselves and the size and geometry of contact lenses makes them unsuitable for use in standard test apparatuses. In order to better characterize our contact lens materials we have developed an In Situ lens compression testing instrument, wherein a lens is placed in solution and compressed between two flat surfaces while applied force is recorded. Contact lens geometries are reverse-engineered with CAD software (Dassault Systèmes CATIA), Finite Element Analysis software (Dassault Systèmes Abaqus) is used to model the force response of the lens and the optimization and data matching capabilities of a process integration and optimization software package (Dassault Systèmes Isight) are used to modify the material model parameters in order to match the test and model curves of force vs. displacement. This experimental system has allowed us to develop a much greater understanding of our own lens materials and those of our competitors, and it has provided new insights into the behavior of the materials vary with both temperature and the rate of loading.

Keywords: Biomechanics, Biomedical, Contact Lens, Abaqus, Abaqus/CAE, Isight, Hyperelasticity, Non-linear Elastic, Modulus, Material Properties, Reverse-Engineered, Material Matching, Optimization

1. Introduction

Modern soft contact lenses are made from hydrogel and silicone hydrogel polymeric materials that are known to exhibit highly nonlinear elastic properties. These materials are gas-permeable in order to allow oxygen to reach the cornea, and they are porous with water content that ranges from 25% to 80%. Characterizing the mechanical properties of contact lens materials has proven difficult for a number of reasons; the lenses are not well suited to placement in standard test fixtures, the lenses must remain hydrated during testing. The properties are dependent on: temperature, strain rate, strain and salinity. Samples cut from a lens will be doubly curved and have non uniform thickness. Any changes to the standard molding process will impact the material properties (for instance casting sheets or molding dog-bones will lead to samples with different properties than those of a contact lens of the same material) therefor our samples cannot have a regular rectangular cross-section The traditional approach to testing is to stamp a dog bone sample from the center of a contact lens, clamp it and test it in an axial tension tester while submersed. Due to the aforementioned problems with this approach the method leads to significant error, and

lateral contraction is typically not measured so the Poisson's Ratio of contact lens materials has not been measured and has instead been assumed to be 0.5 (i.e. that the materials are incompressible).

In order to allow for material characterization directly from intact contact lenses the authors have developed an *in situ* compression testing device. This device is composed of a submersion cell, a heat exchanger, a thermocouple, a pedestal to hold the lens, a force transducer and a plunger to deform the lens, and a camera to obtain a side-view of the compression test. The system is shown schematically in Figure 1.

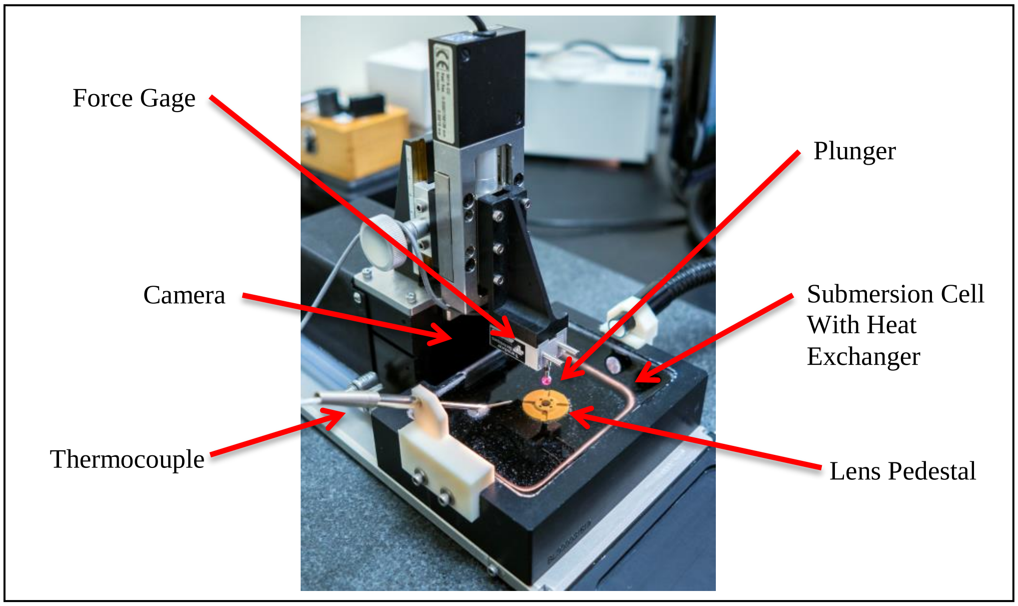

Figure 1: In Situ Testing Apparatus

The testing device allows a contact lens to be placed in a temperature-controlled bath and compressed between of a variety of fixtures (typically a flat surface or a ball-end probe). During compression the displacement of the plunger and the reaction force on the gage are recorded. Because the specimens are analyzed intact, at the desired temperature (typically room temperature and body temperature), and fully hydrated this method addresses many of the difficulties associated with characterizing contact lens materials. However, the device makes necessary a means of correlating the test data with the material properties. For this purpose the authors developed an Abaqus finite element model of the lens and compression fixture and an Isight system optimization scheme to optimize the material properties in order to match the FE prediction with the test data.

The test was performed to a compression level that put portions of the lens in the same strain regime that is believed to occur when the lens is conformed to the front surface of the wearer's eye, which is necessary if material data developed from it is to be used to evaluate on-eye performance of lenses. Test data shown is for a contact lens material in development that is not yet commercially available.

2. Finite Element Model

An Abaqus/CAE model was developed of a contact lens in the test apparatus, which is shown schematically in Figure 2. The lens geometry was reverse-engineered from nominal dimensions measured from the test lenses (outer diameter, center thickness, sagittal depth, etc.) and the plunger and pedestal were drawn in Abaqus/CAE from dimensions on the engineering prints. Contact was applied between the convex [anterior] lens surface and the plunger and between the concave [posterior] lens surface and the pedestal, and the plunger was translated toward the lens, in the positive Y direction to apply the compressive load of the test. Abaqus/Standard was used to solve the model.

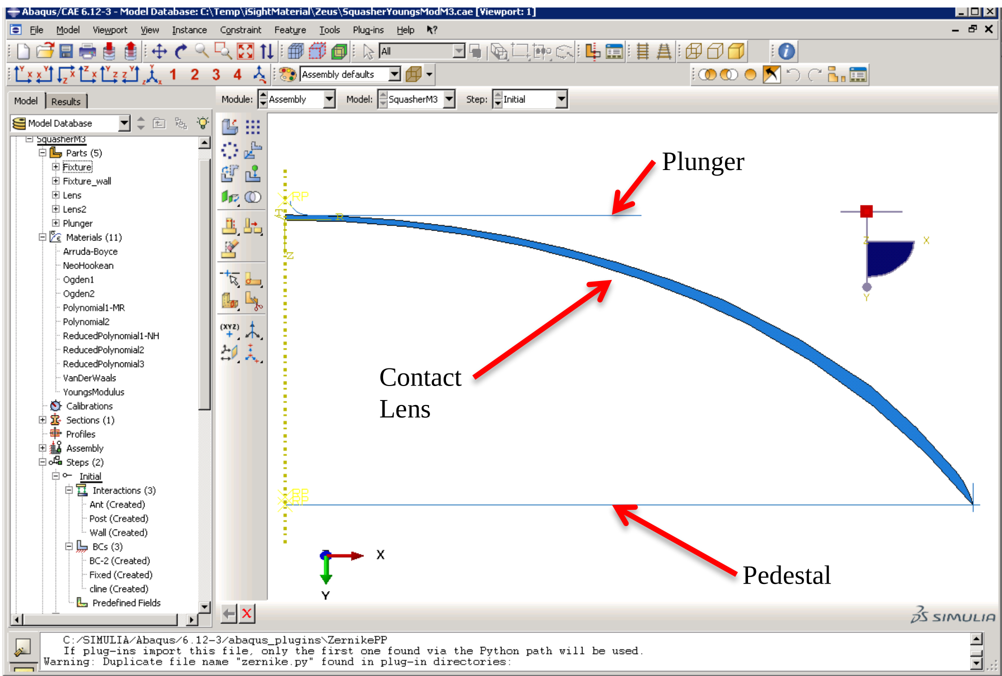

Figure 2: Abaqus/CAE Model of Lens in Test Apparatus

3. Material Matching Model

Isight was used to build a system model that would optimize material property constants (Elastic Modulus and Poisson's Ratio in the case of a linear elastic material model) in order to match the force vs. displacement data from the Abaqus model to the original test data. The Isight workflow is detailed in Figure 3 below. Test data was read into array variables of force and displacement from Microsoft Excel with the Excel component, and an Optimization component was created that contained the Abaqus model, a Data Exchanger component and a Data Matching component. As contact lenses are developed in families for treating a wide range of spherical corrections, two distinct contact lens powers were included in the optimization. This allows us to incorporate the effects of geometric nonlinearities in the original test, with the intention of discovering one optimized material model that will provide outputs that accurately predict the physical performance of the lens design across the range of our actual product geometries.

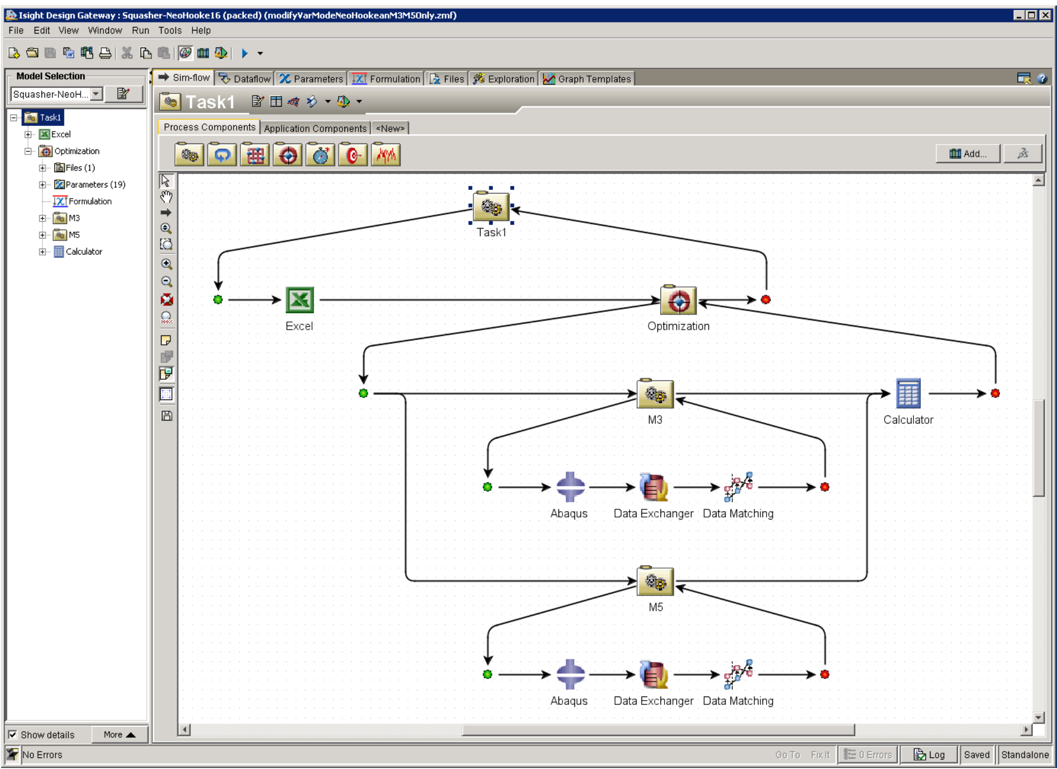

Figure 3: Isight System Optimization Model

The inputs to the optimization model are the test data for each lens, the material type, the optimization parameters (which are dependent upon the algorithm chosen but typically include each parameter in the material properties and upper and lower bounds), and the goal criteria. For

this work the DownhillSimplex technique of Isight was used. Since we had no a priori knowledge of which material model might yield the best fit to the data, several models were set up and evaluated independently (including linear elastic, Reduced Polynomial Hyperelastic, Neo-Hookean Hyperelastic).

4. Results

The data matching optimization model in Isight consistently led to material properties that provided a good match between the test data and the model data. This is demonstrated in Figures 4 and 5 below, where applied force is plotted against displacement for both lens powers.

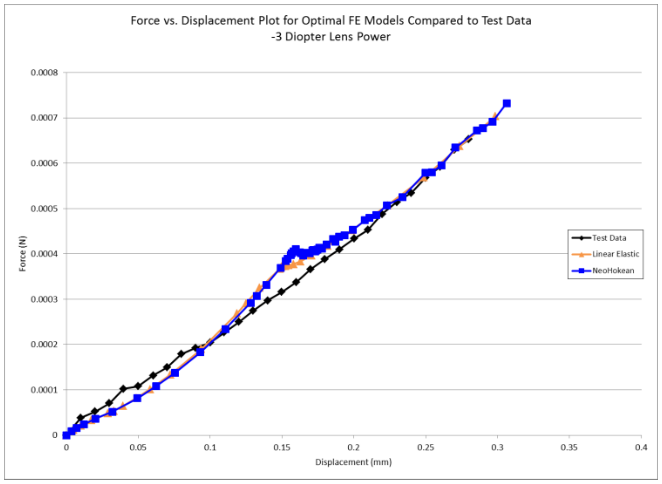

Figure 4: Force vs. Deflection Plot, Optimized Material Models (-3 Diopter Lens)

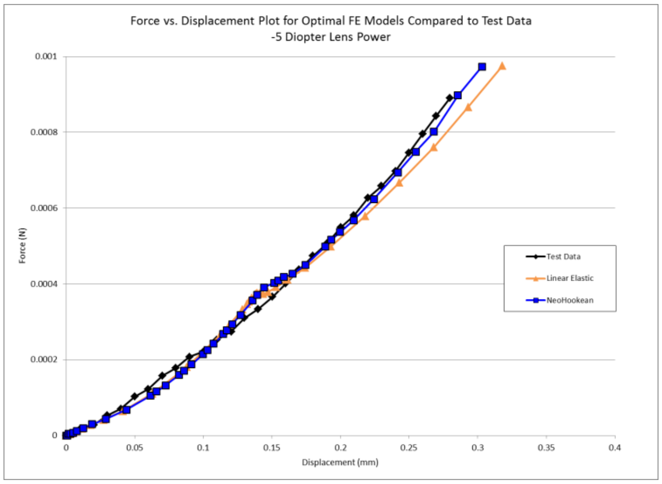

Figure 5: Force vs. Deflection Plot, Optimized Material Models (-5 Diopter Lens)

Of the various material models evaluated the Neo-Hookean model yielded the best fit to the experimental data, which can be seen in the Goal Plot in Figure 6. In this figure the optimization goal is plotted versus iteration number for both the linear elastic and Neo-Hookean models.

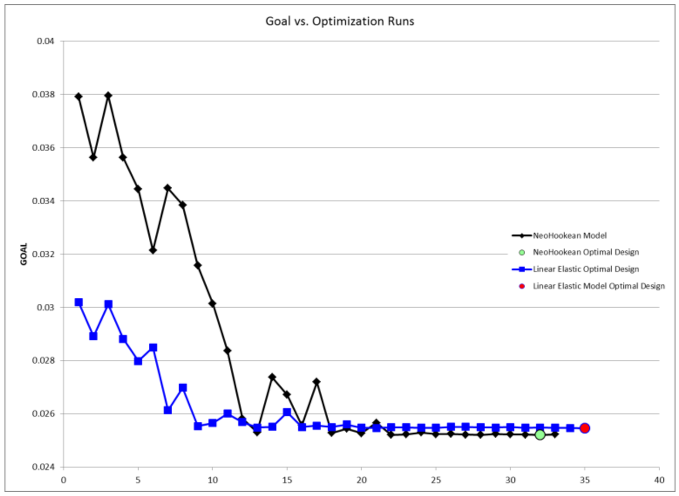

Figure 6: Isight Goal Plot For Linear Elastic and Neo-Hookean Optimizations

As a general check of the results, the compression plot was evaluated visually and compared to the image acquired during the original test. The agreement between the two is demonstrated below in Figure 7. Attention was specifically focused on the 'oil canning' buckling mode and the separation from the plunger.

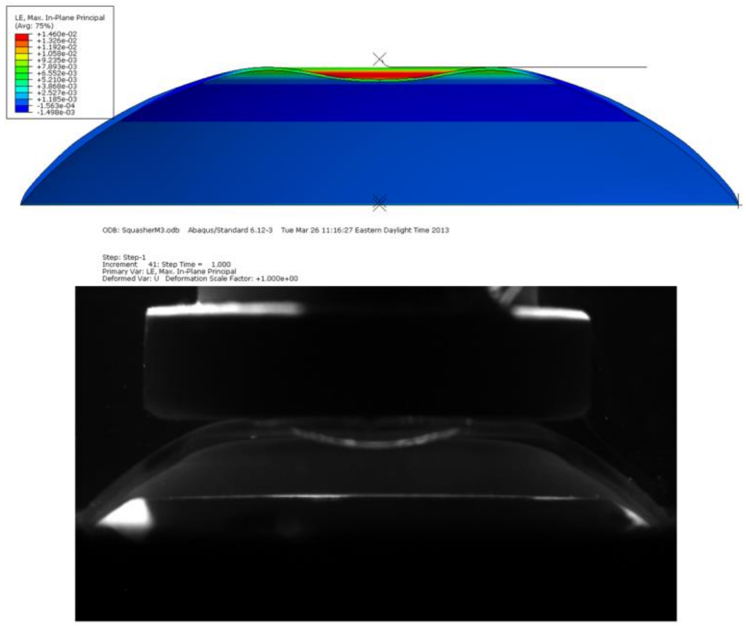

Figure 7: Visual Comparison of Lens Compression in Model and Bench Test

5. Conclusion

Abaqus/CAE and Isight were used successfully to develop a system to optimize material properties to match FE model output to physical test data from an *in situ* contact lens compression tester. To our knowledge this system has provided the first characterization of a contact lens material taken directly from an intact lens at body temperature, and the ability to test various material models against test data for varying lens geometries has provided tremendous insight into the non-linear elastic behavior of these materials.