ME568 Lab 1: Hyperelasticity Modelling

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I. Objectives and Experimental Setup

A. Experimental Overview

The aim of soft robotics technologies is to create robots that are compliant, versatile, and precise. To ensure the suitability of materials for soft robotic applications, their mechanical behaviors - particularly under strain - must be thoroughly characterized.

This laboratory experiment centered on uni-axial stress testing, an important method for determining the limits of material deformation before failure — defined as the point at which a dog-bone shaped material sample tears or breaks under the applied force. The experiment involved incrementally applying uniaxial stress to samples of Ecoflex 00-30 and Dragon Skin 10 - two commonly used silicone polymers in soft robotics - to observe their deformation responses. The observed data from these tests were then correlated with the Neo-Hookean and Yeoh mathematical models designed to predict hyper elastic behavior. The effectiveness of these models was evaluated by calculating the Root-Mean-Square Error (RMSE) between the experimental data and the model predictions, providing a quantitative measure of model accuracy. Comparisons of experimental data were performed with peer lab groups, and the difference in results was analyzed and discussed.

B. Experimental Setup

The experimental setup for this lab was relatively simple and consisted of three main segments: mold preparation, curing, testing [1]. A cardboard, dog-bone shaped mold was created for both Ecoflex 00-30 and Dragon Skin 10 polymers. A 25mL solution of each polymer was prepared; after pouring 12.5mL of polymer into each mold, a 2cm x 4cm piece of fabric was laid into each end of the dog-bone, and the remaining 12.5mL of polymer was added to the respective molds (Figure 1).

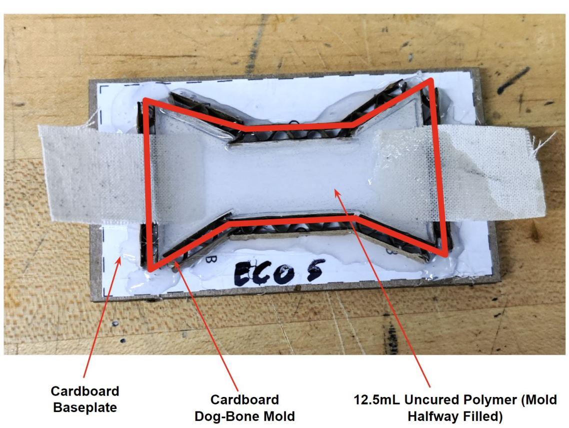

Fig. 1. Cardboard mold setup for both Ecoflex 00-30 and Dragon Skin 10 polymers. Note that 12.5mL of the uncured polymer has already been poured into the mold, and the fabric pieces have been laid down.

Both molds were cured in the oven for 20 minutes at 70°C. After curing, each sample was cut out of the cardboard mold utilizing an exacto-knife, and initial length, width, and height measurements of the cured polymers were taken (Figure 2).

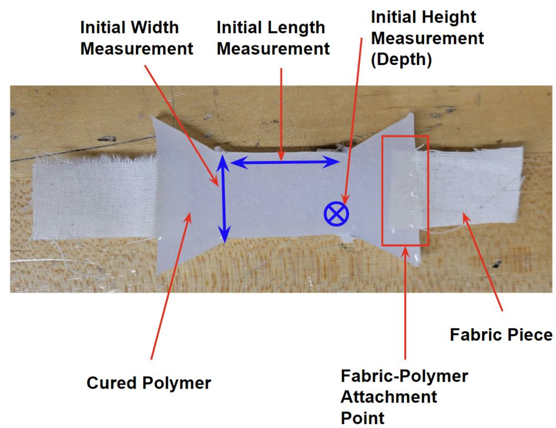

Fig. 2. Dog-bone shaped cured polymer (Dragon Skin 10).

Before testing, the cured polymer was gently stretched in order to reduce the Mullins Effect. Next, a small hole was cut into the fabric piece at one end of the dog-bone; a thread was looped through this hole and tied to an empty 2L plastic bottle, while the other piece of fabric was secured to the edge of a table with duct tape. Length measurements were re-taken and recorded after each addition of 0.1L of water to each water bottle, until either 1L of water was reached or the specimen reached its failure point (Figure 3).

The experimental data was later fit to Neo Hookean and Yeoh models of hyperelasticity via Abaqus, and was compared to results obtained by classmates. A weighing scale was used for measuring the mass of the empty bottle which was approximately 46g.

II. Data Analysis

A. Model Fitting

For the purposes of this lab, the team selected to use the Neo-Hookean and Yeoh models to model the stress strain relations of the hyperelastic materials studied in this experiment. This is driven by the fact that both of these models are valid when derived with solely uni-axial testing data.

Abaqus, the finite element analysis (FEA) software used to perform the modeling fitting in this lab, calculates both the Neo-Hookean and Yeoh models as special cases of the Reduced Polynomial Model, shown in (1) [2].

$$\sigma_u = 2(\lambda_u - \frac{1}{\lambda_u^2}) \sum_{i=1}^{N} iC_{i0}(I_1 - 3)^{i-1} \tag{1}$$

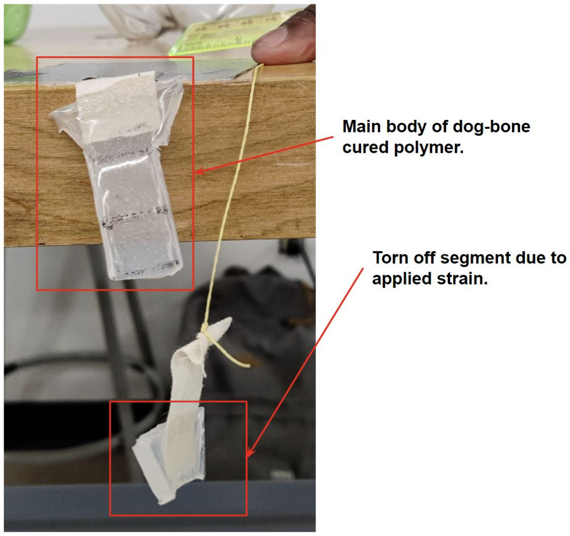

Fig. 3. Ecoflex 00-30 sample after completion of testing. Note how the dog-bone shape has torn at one end of the sample due to the applied stress from the filled water bottle.

TABLE I
CALCULATED NEO HOOKEAN MODEL PARAMETERS

Material	μ (MPa)
Ecoflex 00-30	0.021
Dragonskin 10	0.036

TABLE II
CALCULATED YEOH MODEL PARAMETERS

Material	C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
Ecoflex 00-30	0.012	-0.0007	0.0016
Dragonskin 10	0.025	0.069	-0.039

Where σ_u is the uniaxial stress, λ_u is the uniaxial stretch, C_i0 is the ith modeling parameter, and I_1 is the first strain invariant. Note that for the FEA software, the stretch λ_u is found as $\lambda_u = 1 + \epsilon_u$, where ϵ_u is the true uniaxial strain.

The Yeoh mode is found in the case where $N = 3$, giving three model parameters in the summation. The Neo-Hookean model is found in the case where $N = 1$, leading to the reduced formula in (2)

$$\sigma_u = 2\mu(\lambda_u - \frac{1}{\lambda_u^2}) \tag{2}$$

Where σ_u and λ_u match the above parameters, and μ is the singular modeling parameter calculated.

Tables I and II show the model parameters computed in Abaqus for both materials for the Neo-Hookean and Yeoh models respectively.

B. Assumptions and Error Sources

For the sake of model fitting, the team operated under the assumption that the fabric and string setup was sufficient to get uniaxial testing data, and that other process flaws like imperfections in the mold and mixing were negligible. Additionally, it is assumed that the density of the water used to weigh the sample down had a density of 1 Kg/L. To ensure the validity of the models used, only models that are derivied for uniaxial testing data, namely the Neo-Hookean and Yeoh models are used.

Sources of error causing deviations from existing models included the prescence of bubbles and tears from imperfect molds, as well as the Mullin's effect being inadequately corrected for with prestreching in the case of the Dragonskin. These error sources are discussed in greater detail in Section III.

III. RESULTS

A. Model Fitting Comparison

Root mean squared error (RMSE) is an ideal metric to assess the accuracy of a model's prediction. RMSE quantifies prediction accuracy by averaging the square root of the squared difference between predicted values and actual values, highlighting large errors. Our team went with RMSE because of its straightforwardness, consistency, and usefulness for model comparison.

The RMSE values from fitting the Neo-Hookean and Yeoh models to Ecoflex and Dragon Skin data are presented in Table III.

TABLE III
RMSE VALUES FOR ECOFLEX AND DRAGON SKIN

Material	**Neo-Hookean RMSE**	**Yeoh RMSE**
Ecoflex	0.096	0.004
Dragon Skin	0.011	0.003

As can be seen in Fig.4, the Yeoh model provides a significantly better fit for the Ecoflex data. Quantitatively, the team found the RMSE to be substantially lower ($\sim$ 24x) compared to the Neo-Hookean model. This indicates that the Yeoh model has a better fit to the data, suggesting more accurate predictions for the mechanical behavior of Ecoflex.

Similar to Ecoflex, as seen in Fig. 5, for Dragon Skin, the Yeoh model also results in a lower RMSE ($\sim$ 4x) than the Neo-Hookean model. Although the difference in the RMSE values between the models is not as large as for Ecoflex, the Yeoh model still outperforms the Neo-Hookean model, indicating it is a better fit for predicting the mechanical behavior of Dragon Skin as well.

In conclusion, the Yeoh model outperforms the Neo-Hookean model because it is better at capturing the non-linear behavior of these materials, especially under large deformation. The Neo-Hookean model, while useful for moderate deformations, is limited by its simpler formulation, which assumes a more elastic response.

B. Comparison to Soft Robotics Data Base

Marechal et al. have provided a set of guidelines for soft robotics materials testing as well as an online dataset of measured material data and an interactive model fitter in [3]. This dataset is used to compare modeling parameters for this experiment.

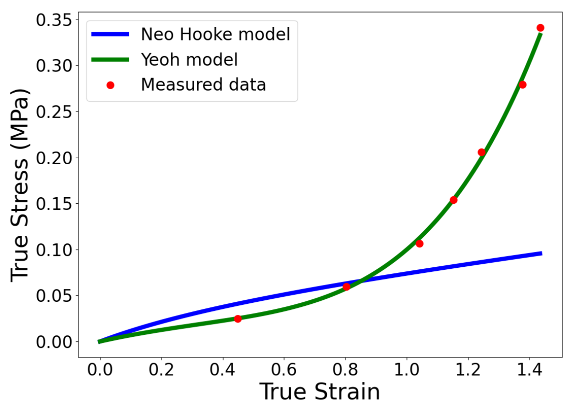

Fig. 4. Ecoflex 00-30 True Stress vs True Strain measured data and model comparison for Ogden, Yeoh, and Neo Hookean Models

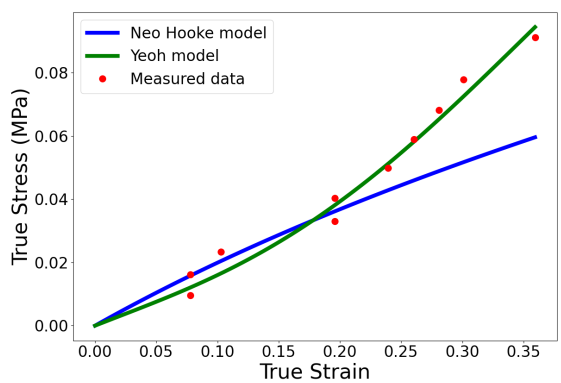

Fig. 5. Dragonskin 10 True Stress vs True Strain measured data and model comparison for Ogden, Yeoh, and Neo Hookean Models

TABLE IV
SOFT ROBOTICS DATABASE NEO HOOKEAN MODEL PARAMETERS [3]

Material	μ (MPa)
Ecoflex 00-30	0.065
Dragonskin 10	0.156

TABLE V
SOFT ROBOTICS DATABASE YEOH MODEL PARAMETERS [3]

Material	C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
Ecoflex 00-30	0.0084	0.0001	0
Dragonskin 10	0.0547	0.0002	0

Tables IV and V show the model fitting parameters found from the Soft Robotics Materials Database.

Note that the equations (1) and (2) used in Abaqus take the form of engineering strain equations, despite working with true stress and strain, since Abaqus like most FEA software works with true stress and strain. This means the equations fitted for these models are divided by a factor of λ_u to convert between true and engineering stress.

Starting with Ecoflex, there are some reasonable similarities between the the calculated fit and the ones found from the online database. The Neo-Hookean model parameters are distinct, but both are within the same order of magnitude. Given the more refined molding and testing setup used by the experimenters [3], as well as a substantially larger set of data points, these differences are reasonable. The Yeoh model parameters exhibit more pronounced differences between the team's and database's results. Both weight C_{10} similarly (same order of magnitude), and C_{20} similarly only makes up a small component of the model. However, there is a sign difference between the two models C_{20}, and the team's model favors C_{30} substantially more than the database's model. The higher order terms of the models reflect the nonlinear behavior of the system, and Figure 4 makes it clear that the Ecoflex sample used in this experiment exhibited substantial non-linearity. Given that the Ecoflex sample broke early in this experiment, it is likely that this "early nonlinear behavior" is caused by factors like flaws in the mixture (e.g. bubbles), flaws in the mold (e.g. tears serving as stress concentrates), or a combination of both. Overall, the Ecoflex 00-30 model parameters compare are relatively similar to the database's, with differences reasonably arising from a less robust testing setup in this experiment.

For Dragonskin, there are further differences in the models. For the Neo-Hookean model, the Soft Robotics Material's database has a notably higher μ then the team's measured parameters. For the Yeoh model, C_{10} are of a similar magnitude, but the team's model places much more weight in both C_{20} and C_{30}. There are a couple of likely reasons for these discrepancies. Firstly, the imprecise nature of the test setup, and particularly the measurement tools, are a recurring issue here. Dragonskin is a more rigid material than Ecoflex, meaning that over the range of data tested, there was less changes in length. Because of this, a few measurements exhibited length changes that could not be accurately measured with the ruler used, leading to repeated data points, as can be seen in Figure 5. Additionally, the range of weights used in this test do not cover a large range of strains for Dragonskin, meaning that few data points showcase the major nonlinear behavior present at larger strains. Overall, the models are reasonably similar, but with differences arising from the team's less controlled experimental setup.

C. Comparison to Classmates

As a part of this lab, each team posted their collected true stress and strain data to blackboard for comparison. Observing this data provides some interesting insights about the repeatability of the experiment, as well as potential flaws in this team's process. To start, the class broadly saw strains up to 1.2-1.3 for the Ecoflex 00-30. This is smaller than the maximum strain of 1.4 observed by this team, which notably occurred at the 7th of the 10 planned data points. This implies that the Ecoflex sample used in these measurements had notably more deformation throughout the process, likely due to flaws in the mixing, like bubbles or incorrect mixture ratio. These observations match with the discussion from Section III-B, where unexpectedly "early" nonlinear behavior was observed in the Ecoflex measurements.

Comparison of the Dragonskin 10 data provides similarly interesting insights. The team's sample had a strain of 0.35 at the final measurement, while most other teams' observed strains of up to 0.6. However, two teams did the extra credit assignment, where two different samples of Dragonskin 10 were measured, one without the recommended pre-stretching to account for Mullin's Effect. In both these cases, the team observed a maximum strain of 0.34. This result implies that the sample of Dragonskin 10 used in these measurements was not sufficiently stretched to correct Mullin's Effect. As such, our model was fit to data with the characteristic hysteresis, likely impacting the major differences observed between our data and the Soft Robotics Material database.

In all, it seems that similar results can be expected from repeated dog bone measurements if the test setups are controlled. In this case, a comparison between results was able to potentially provide explanations for mistakes in the team's experimentation.

D. Manufacturer Material Properties Comparison

Smooth-On Inc., the material manufacturer provides a set of material properties at [4] and [5] for Ecoflex 00-30 and Dragonskin 10 respectively. Particularly relevant for this experiment are the values of 100% modulus (Young's Modulus at 100% deformation) and the deformation percentage at failure.

Beginning with Ecoflex, the manufacturer provides a 100% modulus of $Y_{100\%} = 10$ psi $= 0.067$ MPa and an elongation at breakage of 900% [4]. Because of the issues present in the experimental data discussed throughout Section III, the team has opted to use the Soft Robotics database's measurements to compare with these material properties. This has the additional benefit of having more data points, as well as strains in the region of interest for Dragonskin specifically. Recall that Young's Modulus is the slope of the linear relationship between stress and strain, which in this case is centered around 100% deformation. The slope around the region (found by hand calculating the slope from the Soft Robotics Material Database between true strains of 0.9 to 1.1) is approximately 0.3. While the region used in this calculation is locally linear, it is unclear where the discrepancy between these values arises. Additionally, the database's test experienced failure at a strain of approximately 2.8 (or 280% deformation), substantially lower than the advertised 900%.

For Dragonskin, the manufacturer gives the 100% modulus as $Y_{100\%} = 22$ psi $= 0.152$ MPa and a elongation at failure of 1000% [5]. Using similarly methods as discussed previously, the Soft Robotics Database gives a comparable modulus of 1.8 MPa, which is much larger than the advertised. Similarly, the sample breaks at approximately 240% deformation.

Due to the wide range of possible deformation's before failure, Young's Modulus is not a useful metric in general for soft materials. However specific moduli defined about regions like 100% deformation, which can be qualitatively be observed to be locally linear could potentially be useful for quick calculations. It is unclear exactly where discrepancies in the values discussed above come from.

Considering now the failure strain, the observed failure strain of the team's Ecoflex sample was $\sim$1.4. The database's sample failed at $\sim$2.8. While the team did not observe the failure strain of the Dragonskin, it is expected that it would fail at a lower strain than Ecoflex, being a more rigid material overall. This expectation matches with the database's result, observing a failure at $\sim$2.4. It is again unclear how the manufacturer's advertised specifications differ so much. This is likely due to differing testing procedures.

IV. Conclusion

The primary goal of this lab was to learn how to fabricate a dog-bone polymer sample, undergo uni-axial strain testing, and utilize modeling software (Abaqus) to mathematically fit and draw conclusions from experimental data. A successful completion of this lab required the preparation of a mold that would yield an ideal sample for testing. Although the team's molds were not fabricated properly, testing and model fitting provided viable data. The lessons learned within this lab are critical for future applications because they provide a foundation for understanding the critical aspects of a common materials test meant to characterize the properties of a material. Additionally, the comparison between the team's measurements, the Soft Robotics Materials Database, and the manufacturer specifications have illuminated the importance of both more robust material modeling and shared testing standards, as discussed in depth in [3]. As seen in Section III-D, the metrics provided by sellers are insufficient for the ranges of deformation desired in Soft Robotics applications. In addition, the issues in the teams' data due to experimental setup further highlight the importance of shared measurement standards, as different setups can lead to unforeseen errors, and therefore deviations, between the models. The lessons learned here will be critical when developing soft robots in the future with complex fabrication methods and body compositions.

References

[1] *ME568 Lab 1 - Hyperelasticity Modelling*.

[2] ABAQUS theory manual (v6.6). [Online]. Available: https://classes.engineering.wustl.edu/2009/spring/mase5513/abaqus/docs/v6.6/books/stm/default.htm?startat=ch04s06ath124.html

[3] L. Marechal, P. Balland, L. Lindenroth, F. Petrou, C. Kontovounisios, and F. Bello, "Towards a common framework and database of materials for soft robotics," vol. 0, no. 0, p. null.

[4] Ecoflex™ 00-30 product information | smooth-on, inc. [Online]. Available: https://www.smooth-on.com/products/ecoflex-00-30/

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