Calibrating Rate - Dependent Shear Properties of an Artificial Brain Tissue Stimulant Using a Reverse Engineering Approach

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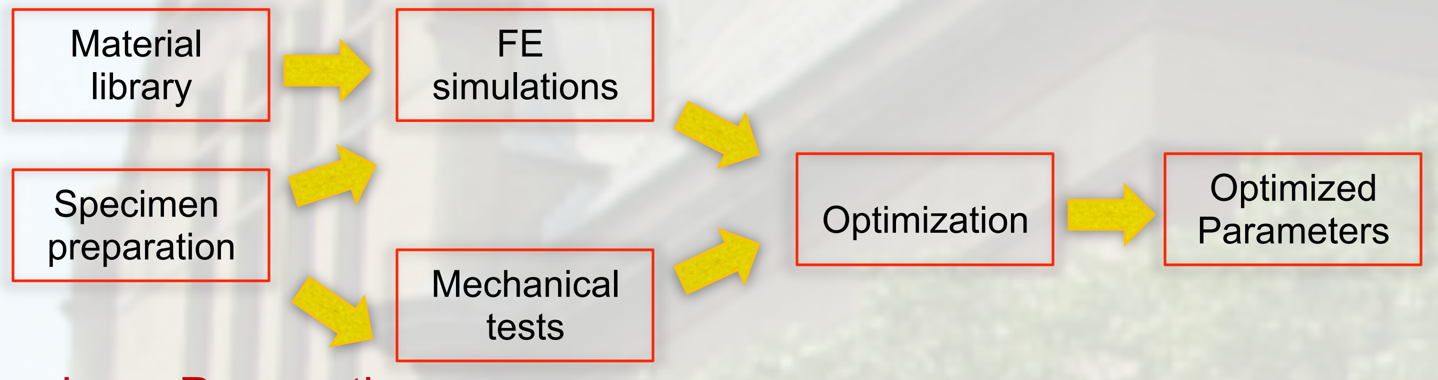
1. Introduction

- The high-rate mechanical response of human brain tissue is of the current interest of academic and clinic community.
- Cadaver tests are expensive and the data are widely scattered, depending on the age, gender, and physical conditions of the subjects.
- Silicone gel is an ultra-soft medium which has similar mechanical properties as brain tissues and then has been used as the brain simulant.
- Currently, a number of compression and oscillation shear tests have been conducted to calibrate the dynamic behavior of silicone gel.
- These tests are not able to reach very high strain rates and obtain the shear modulus directly.
- This study proposes a reverse engineering based methodology to identify the shear properties of silicone gel at a wide range of strain rates. The highest strain rate is 1000/s.
- Ogden material model is chosen to describe the dynamic behavior of gel.
- This new approach can be used to identify the material parameters of soft biological tissues or engineering materials with a relatively small number of samples.

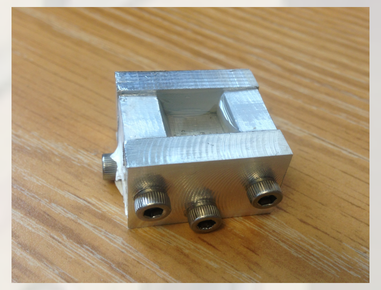
2. Methods

Flow Chart



2.1 Specimen Preparation

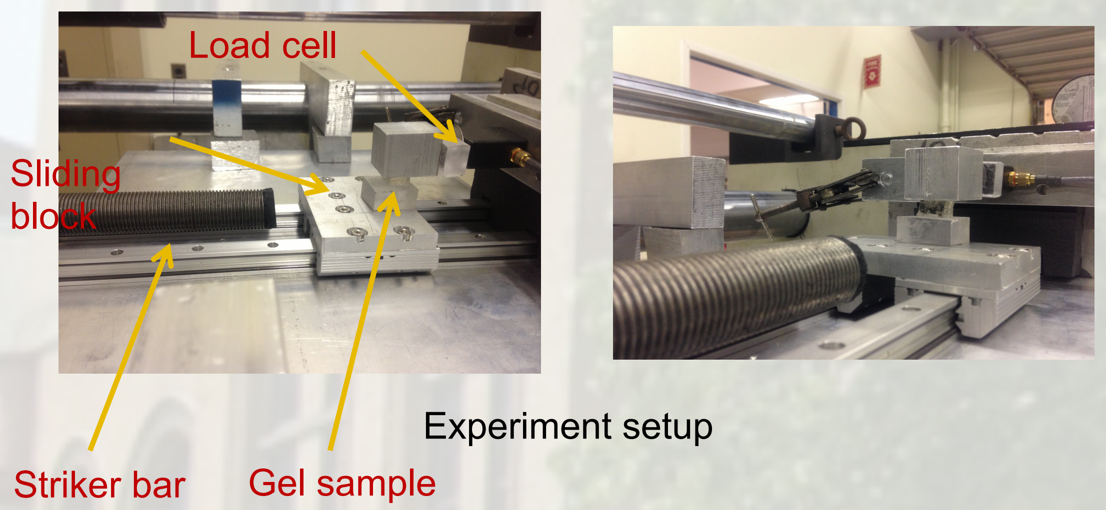
Shear tests were conducted on 12 x 12 x 8 mm Sylgard 527 (Dow Corning, Midland, MI) specimens. The gel is a mixture of two chemical agents A and B at the ratio of 1:1.



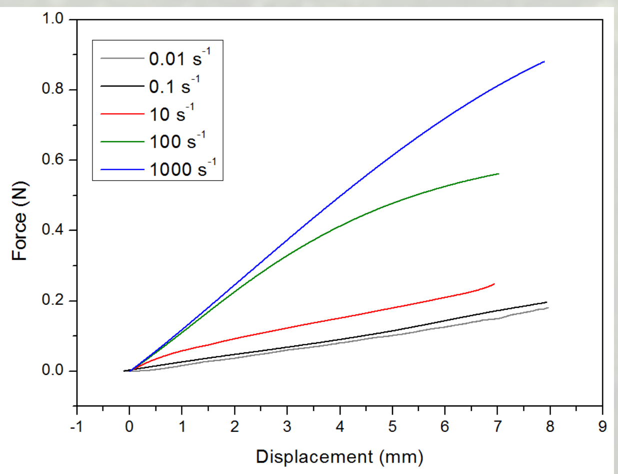
Specimen Preparation

2.2 Mechanical test

Shear tests were performed on the gel samples at 0.01/s, 0.1/s, 10/s, 100/s, and 1000/s strain rates using an Instron machine.



Experiment setup



Typical force – displacement curves

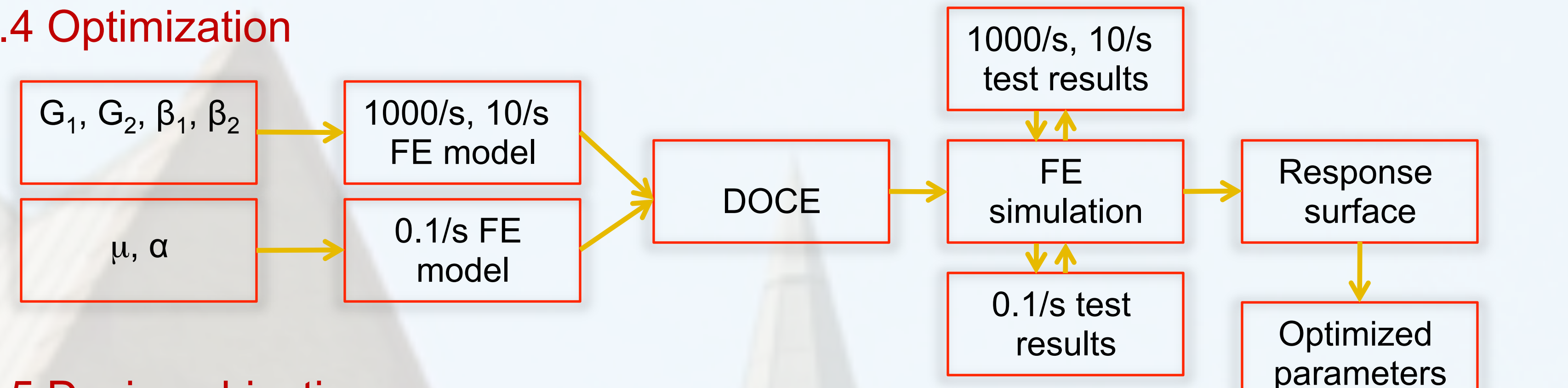
2.3 FE modeling

The rate dependent behavior of sylgard gel is described using a visco-elastic material law – Ogden rubber. Its constitutive model:

$$W^* = \sum_{i=1}^{3}\sum_{j=1}^{n}\frac{\mu_j}{\alpha_j}\left(\lambda_i^{*\alpha_j}-1\right)+K\left(J-1-\ln J\right) \qquad g(t)=\sum_{i=1}^{n}G_i e^{-\beta_i t}$$

where g(x) is relaxation function, W* is strain energy, μ is shear modulus, α is exponent, K is bulk modulus, J is relative volume, G_i is shear relaxation modulus, β_i is decay constants, and t is time.

2.4 Optimization



Validation with 0.1/s, 10/s, 100/s, 700/s and 1000/s, rate test results

2.5 Design objective

$$Obj = \left|\frac{F_s - F_e}{F_e}\right| \quad --> Min.$$

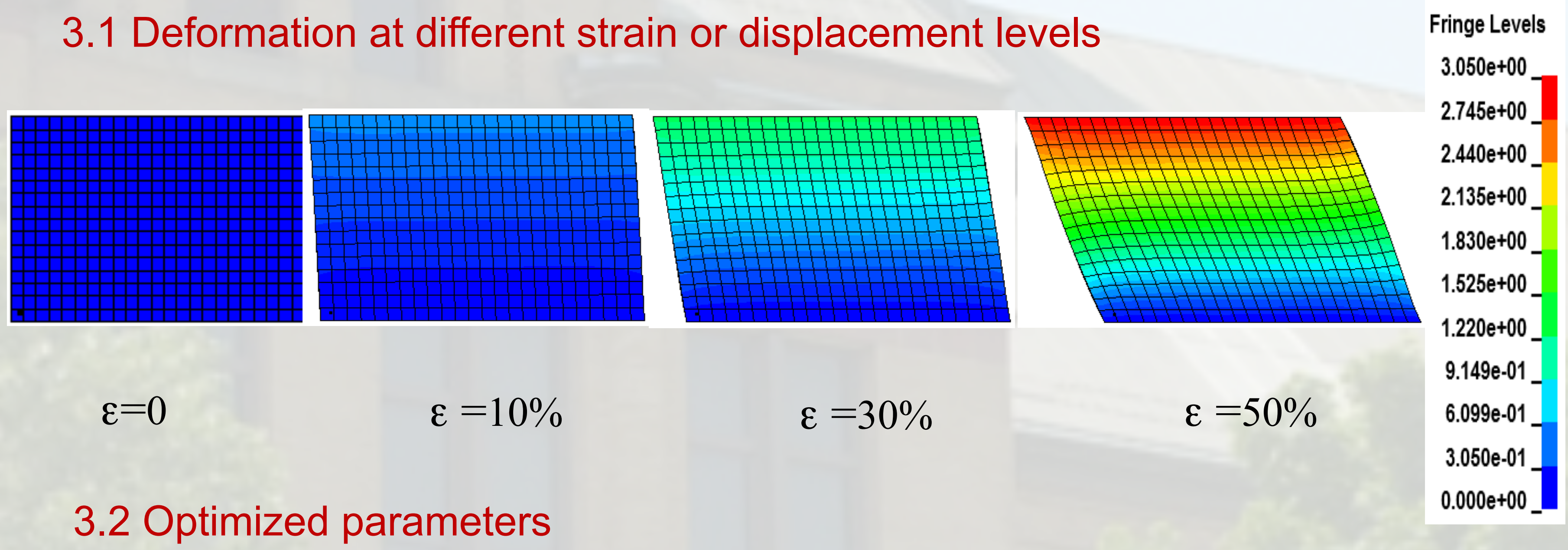
F_s: Simulated force
F_e: Measured force

2.6 Response surface function

Obj=19.81-7.01 β_1-94.26β_2-1.70G_1-4.59G_2+21.57β_1^2+1043.66β_2^2+0.33G_1^2+1.56G_2^2-14.98$\beta_1\beta_2$-4.21$\beta_1 G_1$+0.69$\beta_1 G_2$-4.41$\beta_2 G_1$-32.82$\beta_2 G_2$+0.89$G_1 G_2$ where G_1, G_2 are in kPa

3. Results

3.1 Deformation at different strain or displacement levels

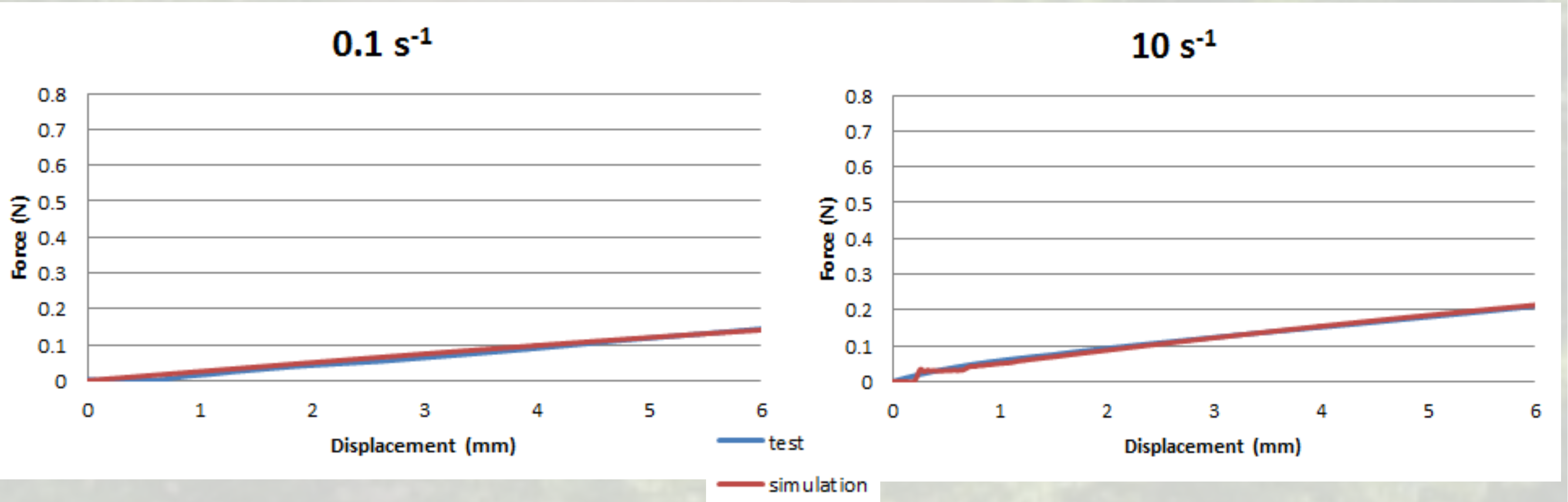


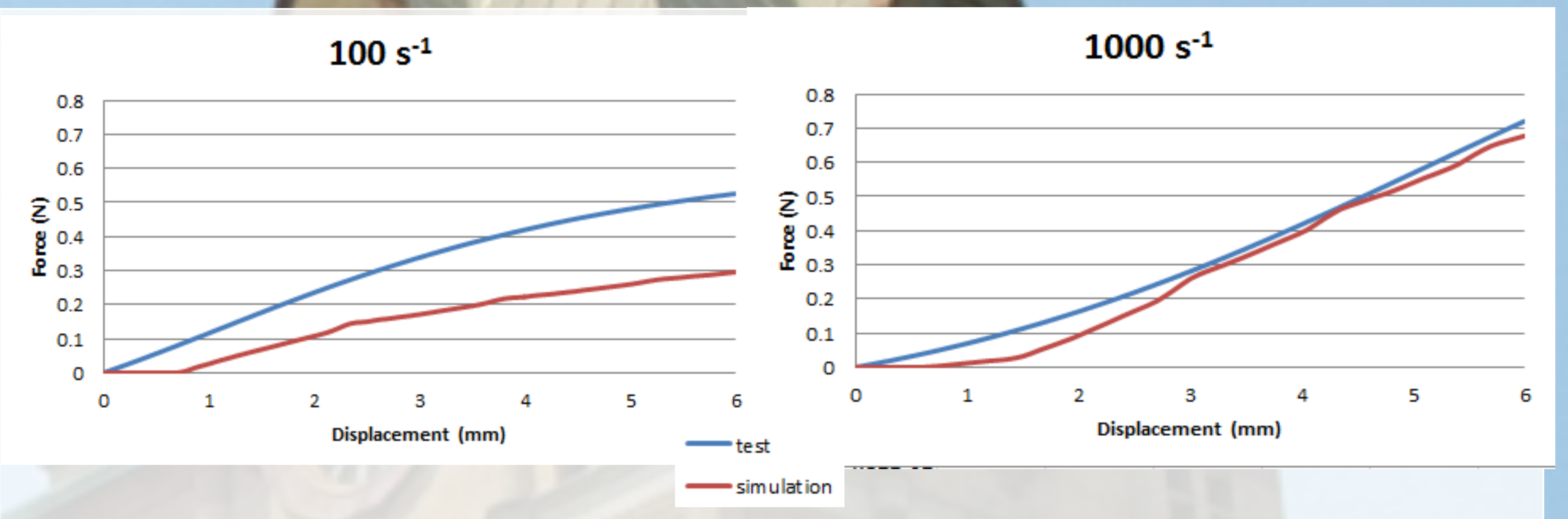
ε=0 ε =10% ε =30% ε =50%

3.2 Optimized parameters

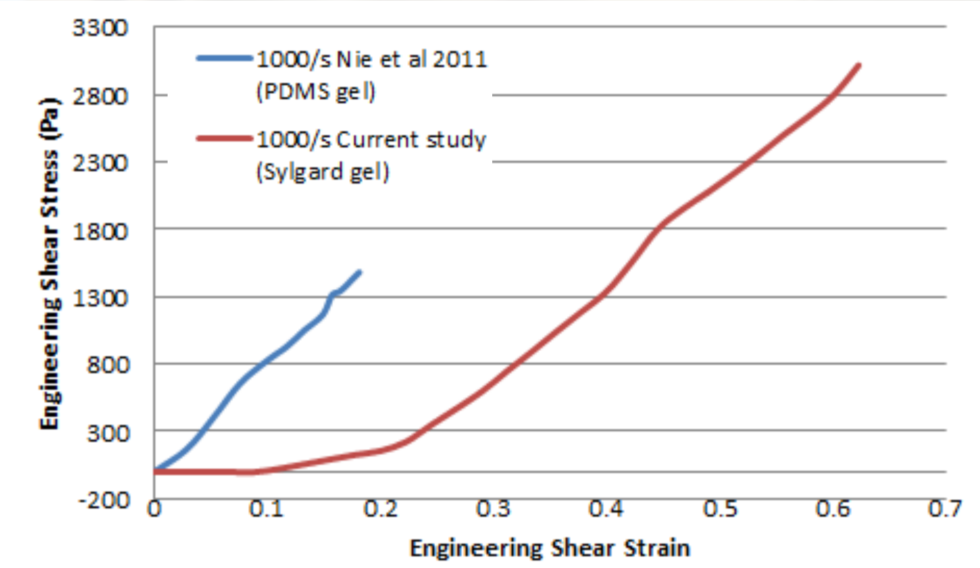
G_1(kPa)	G_2(kPa)	β_1(s^{-1})	β_2(s^{-1})	α	μ(kPa)	PR
5.61	4.64	7.51	0.44	0.80	3.60	0.4999

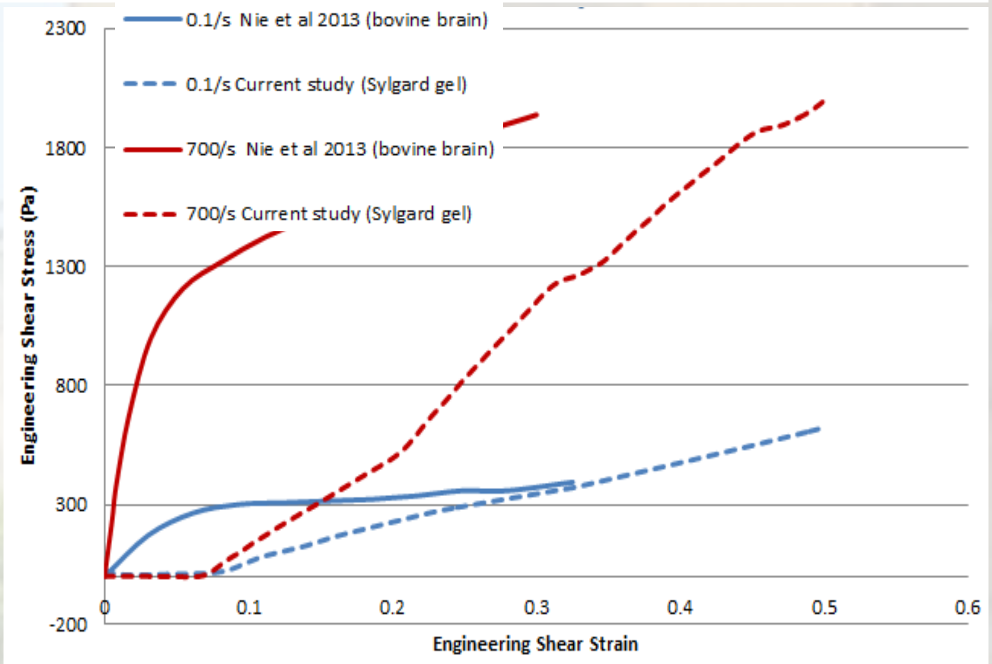
3.3 Comparison of the test and simulation results





4. Comparison with similar studies





- Shear tests on the PDMS gel and bovine brain tissue have been conducted using a modified Kolsky bar (Nie et al. 2011, 2013).
- The strain levels in (Nie et al. 2011, 2013) are much lower than those in the present study.
- PDMS gel shows a linear response while bovine tissue exhibits a non-linear strain hardening behavior.
- Sylgard gel has a much softer response than PDMS gel and bovine tissue.
- An evident inertia effect can be observed in the computational simulation of the Sylgard gel.

5. Conclusion

- Shear tests of a brain tissue simulant at the high strain rates up to 1000 s^{-1}
- Rate dependent property calibration using a reversed engineering based approach
- Optimization of the material parameters until the simulated response matches the measured ones
- Reasonable agreement between computational results and experimental data

6. References

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2. F. Zhu, X. Jin, F. J. Guan, et al. Identifying the properties of ultra-soft materials using a new methodology of combined specimen-specific finite element model and optimization techniques. Materials and Design, 2010; 31:4704-4712.
3. X. Nie, R. Prabhu, W. W. Chen, et al. A Kolsky torsion bar technique for characterization of dynamic shear response of soft materials. Experimental Mechanics, 2011; 51:1527-1534.
4. X. Nie, B. Sanborn, T. Weerasooriya, et al. High-rate bulk and shear responses of bovine brain tissue. International Journal of Impact Engineering, 2013; 53:56-61.