Material Properties of Brain Tissue under Complex Shear and Compression Loading

Mehdi Shafieian[1], Kaveh Laksari[2], Kurosh Darvish[2], Jeff Crandall[1]

[1]*Center for Applied Biomechanics, University of Virginia, Charlottesville, VA*

[2]*Department of Mechanical Engineering, Temple University, Philadelphia, PA*

Abstract– *During an impact scenario brain tissue undergoes a complex loading condition and therefore for modeling purposes material properties of brain tissue have been characterized under different modes of loading; however it has been shown that a constitutive model developed under one mode of loading (e.g. shear) may not necessarily predict the behavior of the tissue under another mode of loading (e.g. compression). In this study a viscoelastic constitutive model for brain tissue was developed that is capable of predicting the behavior of the tissue under multiaxial loading. The developed model was compared with previously developed models and it showed a close agreement with them in their corresponding mode of loading, while having the advantage of modeling multiaxial loading as well.*

I. INTRODUCTION

Improving the knowledge of brain tissue material properties has been a key element in developing more realistic FE models of the head–brain complex. A large degree of the variability of brain tissue material properties reported in the literature can be associated partly with the differences in experimental methods, i.e., modes of loading and loading rates.

Material properties of brain tissue have been mostly characterized under a specific type of loading and the derived constitutive equations represent the tissue material properties under one loading condition and do not necessarily predict the behavior of tissue under another mode of loading, e.g. Miller and Chinzei [1] developed a constitutive model for brain tissue under compression and later on showed this model does not predict the brain behavior under tension [2]. Several physical models and FE simulations of brain tissue under loading conditions that results to TBI have been developed [3, 4, 5] and showed that the brain tissue undergoes a complex combination of loading modes during impact, which signify the need for a comprehensive constitutive model for brain tissue suitable for multiaxial loading.

This study proposes a Quasi-Linear Viscoelastic (QLV) constitutive model for brain tissue to predict the response of the tissue under shear and compression deformation.

II. MATERIAL AND METHOD

52 cylindrical samples with approximate diameter of 10mm and height of 8mm were acquired from fresh bovine brain tissue from a local slaughterhouse. In order to maintain the ionic balance and water content, the brains were kept in Phosphate Buffered Saline (PBS) solution immediately after purchase and kept at 0-5°C prior to the experiments.

Two modes of loading were implemented in the experiments, a group of samples underwent shear (n=30) and the second group were tested under compression (n=22). For a detailed account of the compression tests, the reader is directed to study the report by Laksari et al. [4]. For the shear tests a custom-made testing device that consisted of two parallel plates with the lower plate attached to a high-speed linear actuator (WM60, PT-USA, VA) and the upper plate attached to a precision load cell (GSO10, Transducer Technique, CA). For compression tests the configuration setup of the test device was reoriented to apply vertical load. Figures 1 show the shear and compression test setup. A step-and-hold input was applied and the displacement and resulting shear force were recorded. The relationship between the measures of stress σ(t) and strain ε(t) were modeled using the QLV theory [7] which can be written as:

$$\sigma(t) = \int_0^t G(t-\tau)\frac{\partial\sigma^e(\varepsilon)}{\partial\varepsilon}\frac{\partial\varepsilon}{\partial\tau}d\tau$$

where $\sigma^e(\varepsilon)$ is the instantaneous elastic function and G(t) is the reduced relaxation function. A discrete spectrum approximation in the form of Prony series was assumed for G(t):

$$G(t) = G_\infty + \sum_1^4 G_i e^{-\beta_i t}$$

The sample deformation for shear tests was assumed to be a combination of simple shear and uniaxial compression with the following deformation gradient:

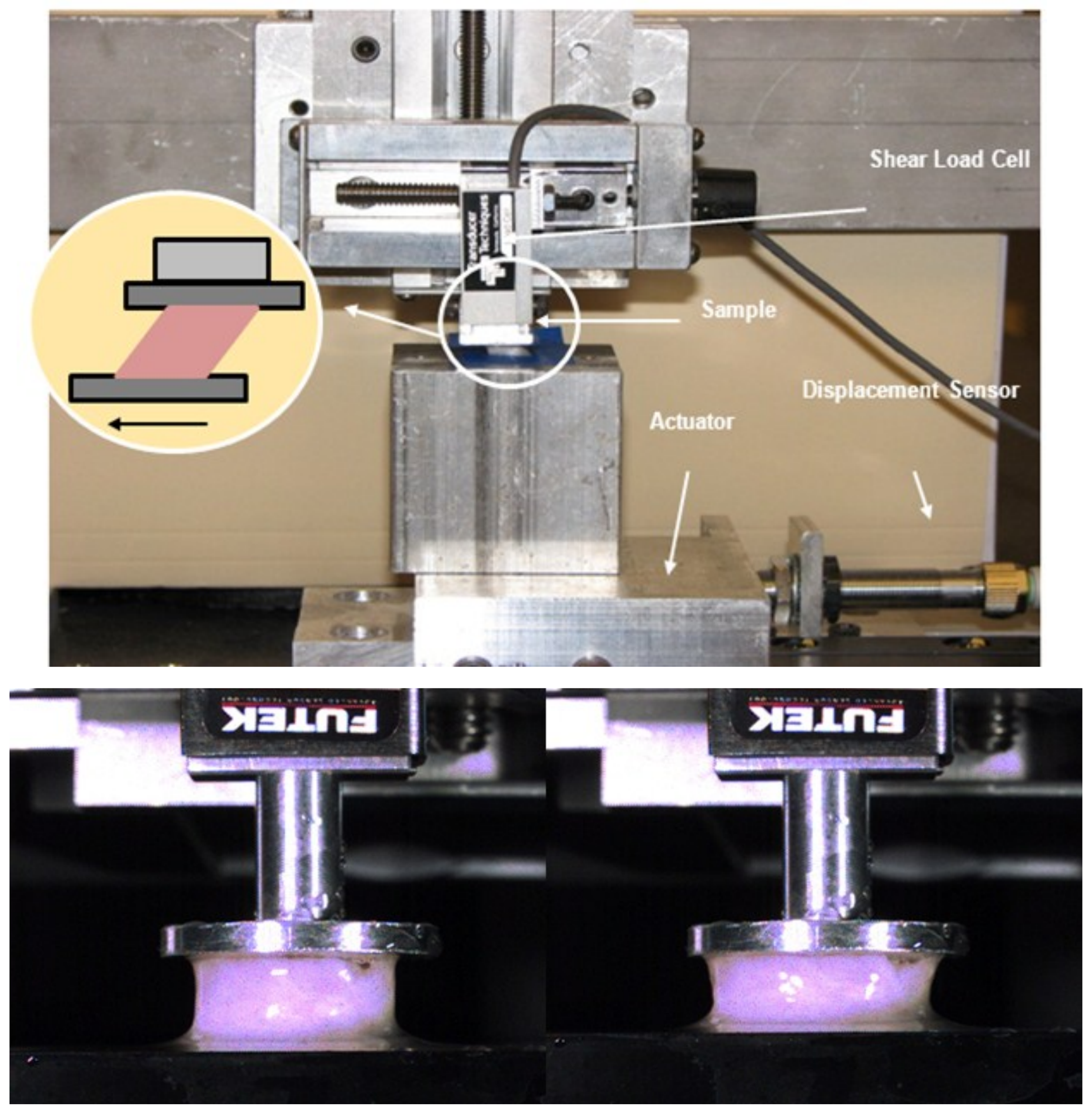

Figure 1. The shear (top) and compression (bottom) experimental setup

$$F_s = \begin{bmatrix}\lambda_1 & k\lambda_2 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_1\end{bmatrix}$$

Assuming samples to be homogenous and isotropic, a generalized Rivlin model was assumed for the strain energy function:

$$W = C_{10}(I_1-3) + C_{01}(I_2-3) + C_{11}(I_1-3)(I_2-3)$$

Considering the applied 10% compression preload to shear tests, P_{12} was written as:

$$P_{12} = 3.24\,C_{11}k^3 + (1.8C_{10} + 2C_{01} + 1.267C_{11})k$$

In case of compression the normal stress (P_{22}) was written as:

$$P_{22} = 6\,C_{11}\lambda^2 + (2C_{10} - 6C_{11})\lambda + 2C_{01} - 6C_{11} + \frac{6C_{11} - 2C_{10}}{\lambda^2} + \frac{6C_{11} - 2C_{01}}{\lambda^3} - \frac{6C_{11}}{\lambda^4}$$

P_{12} and P_{22} were fitted to the data using the same material parameters (C10, C01, C11) by minimizing the sum of squared errors (SSE) and material parameters were determined.

III. RESULTS AND DISCUSSION

Figure 2 shows a representative of experimental data and model fitted in shear and compression under 20% strain. The shown models are both resulted from the same sets of material parameters (Table 1) and successfully captured the experimental data. The slight difference between model and experimental data at peak stress is due to the inertial effect.

The predicted elastic response in this study for a complex mode of loading is in close agreement with previous studies. The stiffer response can be attributed to the significantly higher applied ramp in this study (10 s^{-1} versus 0.5-4 s^{-1}).

Table 1. The parameters of instantaneous elastic response and reduced relaxation function for brain tissue. All material parameters

Instantaneous Elastic Response		Reduced Relaxation Function	
C_{10} (kPa)	-7.723 ± 0.500	G_∞	0.143 ± 0.143
C_{01} (kPa)	8.274 ± 0.536	$G_1(\beta_1=0.1/s)$	0.116 ± 0.116
C_{11} (kPa)	0.133 ± 0.009	$G_2(\beta_2=1/s)$	0.103 ± 0.103
		$G_3(\beta_3=10/s)$	0.187 ± 0.187
		$G_4(\beta_4=100/s)$	0.451 ± 0.451

V. CONCLUSIONS

This study developed a constitutive model that predicts the tissue behavior under complex loading conditions. Also, the validity of QLV assumption under shear and compression in high deformation rates was validated.

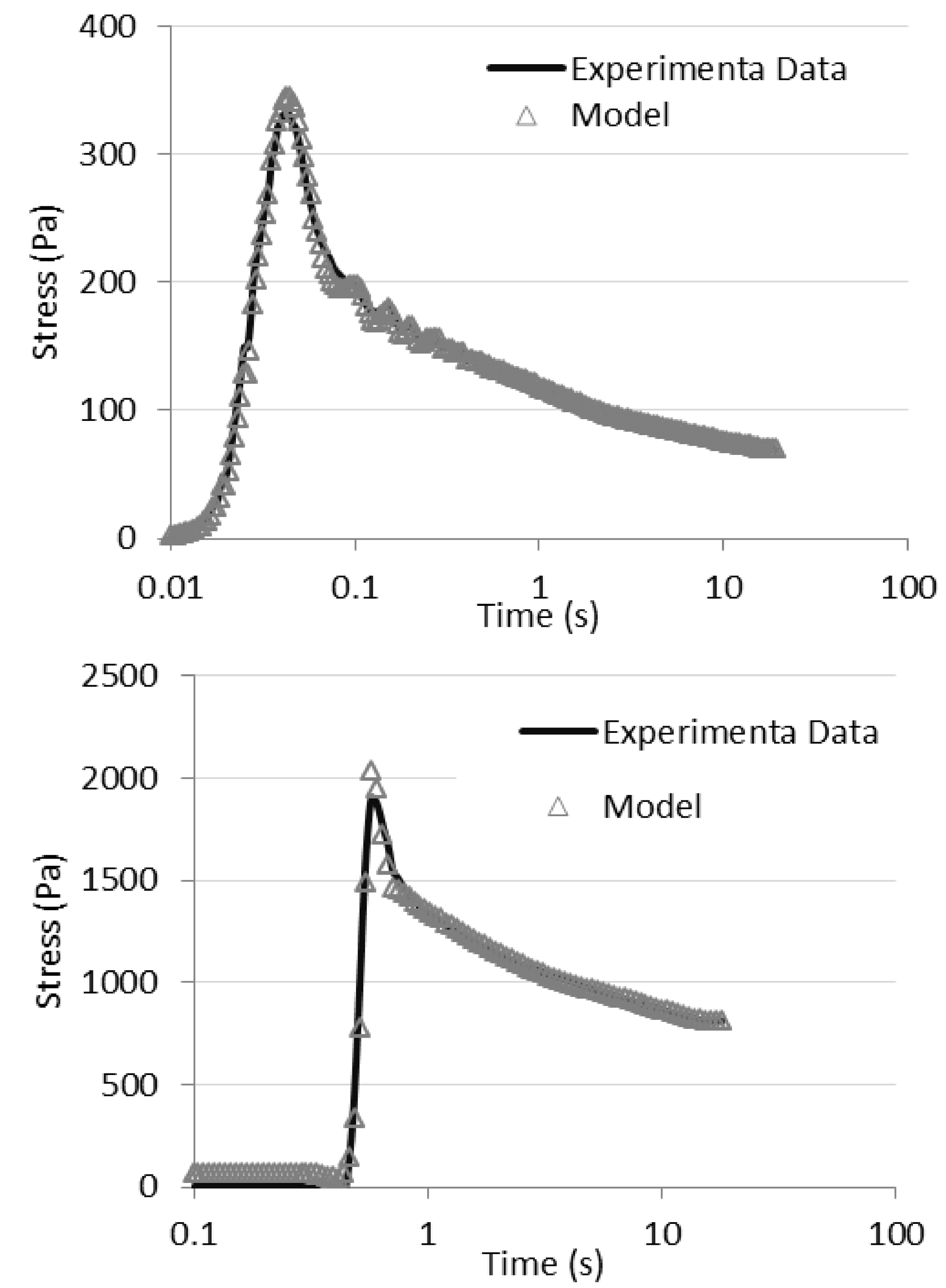

Figure 2. Experimental data and fitted model to shear (top) and compression (bottom).

REFERENCES

[1] Miller K., Chinzei K., 1997, Journal of Biomechanics, 30, 1115-1121.

[2] Miller K.,Chinzei K., 2002, Journal of Biomechanics, 35, 483–490.

[3] Thibault L. E., Margulies S.S, Gennarelli T. A., 1987, Proceedings of the 32th Stapp Car Crash Conference, 267-272.

[4] Viano D., Aldman B., Pape K., van Hoof J., von Holst H., 1997, International Journal of Crashworthiness, 2, 2, 191-206.

[5] Zhang L., Yang K. H., King A. I., 2001, Journal of Neurotrauma, 18, 21-30.

[6] Laksari K., Shafieian M., Darvish K., 2012, Journal of Biomechanics, 45, 4, 642-646.

[7] Fung Y. C., Biomechanics: Mechanical properties of living tissues. Springer, New York.