Rheological behaviour and modeling of brain tissue

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INTRODUCTION

In order to understand and predict the onset of human head injury due to traumatic impact loads, there is a need to develop realistic constitutive relations so that the biomechanical response of the brain may be modeled more accurately. Although brain tissue is rather complex, possessing both fluid- and solid-like properties, it is common to find simple linear elastic or viscoelastic models in applications such as the simulation of neurosurgery. These models are, however, inadequate in many dynamic impact situations such as automobile accidents, where large strains are often encountered. For example, Bain and Meaney[1] have proposed a threshold strain criterion of nearly 0.21 for axonal injury by comparing morphological injury and electrophysiological impairment to estimated tissue strains. Troseille *et al.* [2] found that a strain above 0.15 would result in irreversible brain injury and a strain above 0.2 could be fatal. These injury criteria are clearly beyond the linear elastic limit, usually taken to be about 1% strain (Brands *et al.*[3]). Therefore nonlinear viscoelastic models must be used for brain injury modeling and prediction.

In this paper, a non-linear model first proposed by Bilston *et al.*[4] is modified and implemented into a commercial finite element (FE) code. To obtain the required model parameters, rheological tests on mechanical properties of brain tissue are performed.

MODELING, TESTING AND IMPLEMENTATION

The proposed 3-dimensional constitutive model consists of three parts: the volumetric, deviatoric and viscoelastic stress components. The long-term elastic stress is modeled by the Mooney-Rivlin rubber model, which is commonly used for hyperelastic materials under large deformation. The upper convected multi-mode Maxwell model is used for the computation of the viscoelastic stresses. The deviatoric stress terms are further modified by a damping function, which is a function of strain invariants.

The parameters in the constitutive model are determined by performing various rheological experiments such as small strain oscillation tests, shear relaxation tests, and compression tests. Porcine brain tissue samples are tested by means of a conventional stress-controlled MCR 300 Paar-Physica rheometer. Furthermore, oscillatory shear tests (both strain and frequency sweeps) and relaxation tests are performed for material property characterization.

We further implemented the 3-dimensional nonlinear constitutive model into the multi-purpose commercial explicit FE code PamCrash. The user-defined material model MAT80 was used in the program. Simulation of the shear relaxation test is performed.

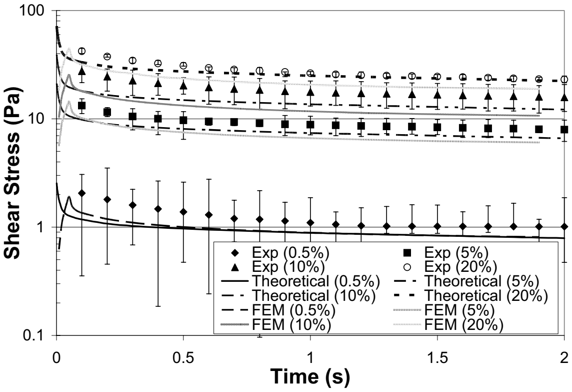

Figure 1: Shear relaxation: comparison between theoretical prediction, FE simulation and experiment

RESULTS AND DISCUSSION

Based on small strain oscillation test, a 12-mode Maxwell model is obtained by curve-fitting procedure. By applying Time-Temperature Superposition principle, the frequency regime is extended to 6 decades ($\omega = 10^{-2} \sim 10^{4}$rad/s). Shear relaxation tests with different amplitudes of shear strain are performed. A comparison between theoretical and numerical predictions and shear stress relaxation experiment is shown in Figure 1. Good agreement can be observed. Theoretical predictions are within the error bars up to a strain of 20%. Numerical predictions are slightly lower, about 20% lower than the averaged values for large strain case (20%).

CONCLUSION

A 3-dimensional nonlinear viscoelastic constitutive model for brain tissue is proposed and implemented into commercial FE code successfully. The predicted mechanical response of the brain tissue by the FE method show good agreement with shear stress relaxation test data. Combined with a proper head FE model, it is expected that the proposed brain tissue model can be used for head injury analysis.

REFERENCES

1. Bain AC, et al. *J Biomech Eng* **122**, 615-622, 2000.
2. Trosseille X, et al. 36th *Stapp Car Crash Conference Proceedings*, Seattle, WA, 1992.
3. Brands DWA et al. *Stapp Car Crash J* **44**, 249-260, 2000
4. Bilston LE, et al. *Biorheology* **38**, 335-345, 2001

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