Characterization of Brain Tissue under High Rate Shear Loading: a novel test method with low noise

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ABSTRACT

Recent studies suggest that the pressure changes occur at the rates of 0.5 to 1.5 kHz. Therefore, studying brain tissue at blast-rate deformations requires a test method with loading duration of about 1 ms. Although the material properties of brain tissue have been studied since 1960's, a limitation of the previous studies is that in most of them the strain rates were below 100 s^{-1}; making the results unsuitable for Blast-Induced Neurotrauma (BINT) modeling purposes. This study aimed at characterizing the material behavior of brain tissue in large deformation shear with strain rates ranging from 300 to 1000 s^{-1}. A major challenge in such test setup, due to vibration of the system, is to increase the signal to noise ratio. For this purpose, a novel test method was developed using a shock tube to drive a linear actuator with velocity of 3 to 14 m/s to deform the samples in a parallel plate shear configuration. The sample deformation was determined via high-speed imaging at the rate of 10k fps. The sample shear modulus was determined from the velocity of propagation of shear wave along the sample. The results of tests on cylindrical samples (10 mm diameter, 10 mm height) of bovine brain showed that the instantaneous shear modulus (about 6 kPa) increased about 3 times compared to the values reported in the literature. The results of this study can enhance the prediction of brain injury in finite element models of TBI in general and models of BINT in particular.

INTRODUCTION

Recently the need for understanding the material properties of brain tissue in high loading rates has been increased. While Traumatic Brain Injury (TBI) continues to be the leading cause of accidental fatality (CDC 2010), over the past decade there has been a significant increase in the number of TBI incidents among military combat personnel (Tanielian and Jaycox, 2008) as a result of prominent use of Improvised Explosive Devices (IEDs). The Department of Defense reported that over 5,500 soldiers had suffered Blast-Induced Neurotrauma (BINT) as of January 2008 (Congressional Research Service, 2008).

Blast-induced trauma is a result of several mechanisms including primary injury which is due to overpressure wave, secondary injury which is the result of propelled objects hitting the individual, tertiary injury which is caused by the individual blown into solid objects, and miscellaneous injuries, e.g., burns and inhalation of toxic materials (DePalma et al., 2005). The effects of secondary and tertiary injuries are similar in nature to the ones resulting from automotive accidents (Adams et al. 1982) which include diffuse axonal injury, subdural hematoma, and focal contusions; the mechanisms of which have been extensively studied over the past several decades (Smith et al., 2003). However the mechanisms of primary blast injury and how overpressure wave affects the brain is not completely understood at present (Elder et al. 2010). Recent studies suggest that the blast overpressure wave affect the brain tissue at the rate of 0.5-1.5 kHz (Cernak and Noble-Haeusslein, 2010) which requires a material test methodology with loading duration of about 1 ms.

A common experimental method to characterize brain tissue in high strain rates is oscillatory loading (e.g., Shuck and Advani, 1972 and Darvish and Crandall, 2001) but the frequency of loading has been limited to about 300 Hz due to inertial effects and the fact that strain amplitude in higher frequencies were infinitesimal. Step and hold experiments were generally conducted with 10 s^{-1} or lower ramp rates (e.g., Arbogast et al., 1995 and Prange and Margulies, 2002) and resulted in viscoelastic time constants of 20 ms and higher. Donnelly and Medige (1997) showed that high rate ramp tests are more appropriate to characterize the material properties of brain tissue at strain rates above 10 s^{-1}. They tested cylindrical fresh cadaveric samples in a custom made shear device at strain rates of 0 (quasi-static), 30, 60, and 90 s^{-1} up to 50% Lagrangian shear strain and reported stress versus strain responses and clearly observed a rate dependent behavior.

The highest applied strain rates on brain tissue are reported by Pervin and Chen (2009) that used a modified split-Hopkinson bar to test thin tissue slices (1.7 mm) in compression at strain rates of 1000, 2000 and 3000 s^{-1} and showed significant rate sensitivity and at least one order of magnitude higher stiffness compared to the highest results of Donnelly and Medige (1997). Since their test methodology was not validated for materials as soft as brain (they only provide validation results for Aluminum) their results should be treated with caution.

This work aimed at developing a test setup for determining the mechanical behavior of brain tissue at strain rates from 100 to 1000 s^{-1}. Development of such model ameliorates the understanding of brain tissue behavior under large deformations in a wide range of strain rates and improves the prediction of stress in computational simulations of TBI from falls and sports injuries to automotive accidents and BINT.

MATERIALS AND METHODS

Sample preparation

Cylindrical samples of bovine brain specimens from white matter (Corona Radiata region) using a 10 mm diameter boring tool. Homogeneous samples with mainly white matter were selected for this study with approximately 10 mm height. 5% gelatin gel samples with the same geometry were also tested as brain surrogate material to verify the test setup.

Experimental setup

The test apparatus consisted of an actuator (piston) that was driven by a 2-in diameter shock tube with peak over pressure levels ranging from 50 kPa to 300 kPa (Figure 1). The sample was placed between two parallel plates (fixed with super glue) with the lower plate being pushed by the actuator. The top plate was connected to a 250 gram load cell (model 11, Honerywell) recorded at 50k samples/s and the sample deformation was recorded by a high speed camera at 10 kfps (Phantom v4.2, Vision Research).

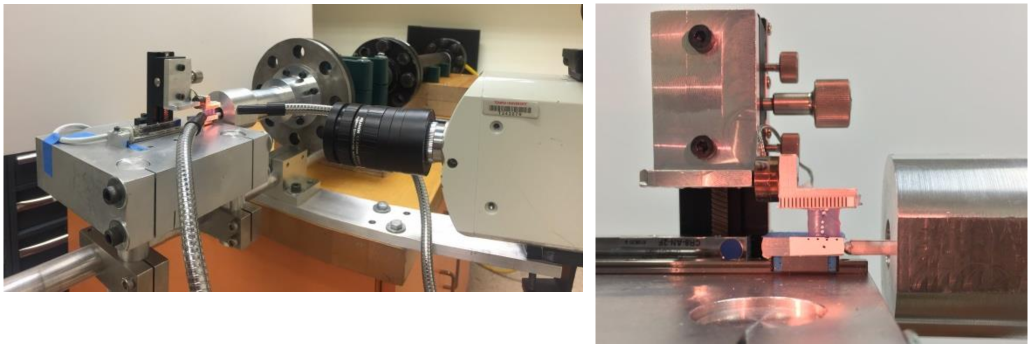


Figure 1: High rate test setup apparatus. The sample is placed between two parallel plates (right figure). The lower plate is pushed by a shock tube driven actuator (piston). The top plate is connected to a load cell and the sample deformation is recorded by a high speed camera (left figure)

Data Analysis

The effective shear modulus was calculated based on the measured propagation velocity of the shear wave front along the sample. The shear wave velocity was measured using two methods: a) quantifying the deformation captured from high speed video and b) the travel time of the shear force from the bottom plate to the t op plate. The shear wave front was identified by a sh arp change in angle of the markers placed along the length of the sample.

RESULTS AND DISCUSSION

The nominal (average) velocities of the bottom plate were 3, 6, 9, and 14 m/s that corresponded to strain rates of approximately 650, 800, 1000, and 1350 s^{-1} at 25% Lagrangian shear strain (5 mm displacement) respectively (Figure 2).

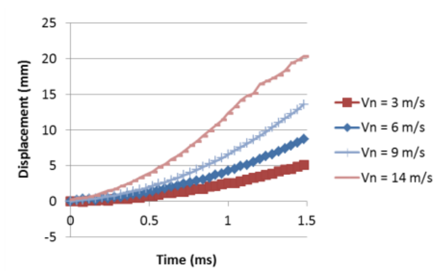
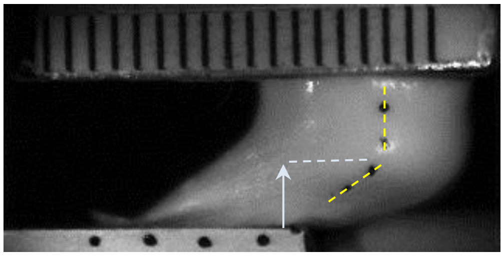


Figure 2: Kinematic characteristics of the high rate actuator for four levels of nominal velocities Vn.

The propagation of shear wave in a representative brain sample with 6 m/s nominal velocity is shown in Figure 3. The corresponding force time history is shown in the right figure, which shows the shear wave travel time, followed by a rapid rise in the force (in about 0.5 ms) and then reducing to zero as a result of sample failure.

The test results for brain and 5% gelatin gel for 6 m/s nominal velocity are summarized in Table 1. The values of shear wave velocity calculated from the two methods were in close agreement which verifies the test method. The value of shear modulus μ was estimated based on the shear wave velocity ($\sqrt{\mu/\rho}$) with the brain density assumed to be ρ = 1000 kg/m^3. The shear modulus found for 5% gelatin gel was about 40% higher than the values found from step and hold shear tests at 10 s^{-1} strain rate (Laksari et al. 2010). For brain tissue, however, the high rate shear modulus is 3 times the reported values based on step and hold tests (Laksari et al. 2012). This shows that brain tissue is highly rate sensitive at strain rates that occur at BINT.



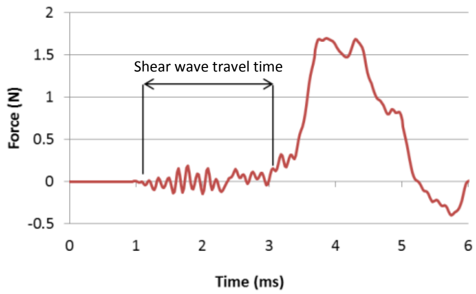


Figure 3: The effective shear modulus was calculated based on the measured propagation velocity of shear wave front (white arrow) along the sample. The shear wave velocity was measured using two methods: a) quantifying the deformation captured from high speed video (left figure) and b) the time delay (marked region) in the rise of force (right figure). The agreement of the two velocities (Table 1) verified the test method.

A critical factor in development of computational models of TBI is the material properties of brain tissue. Only few studies address the material behavior of brain tissue at high rate loading conditions applicable to modeling BINT (Donnelly and Medige, 1997 and Pervin and Chen, 2009). However, these studies either do not reach blast rate loading or lack sufficient validation. The FE models of head in blast loading developed over the past decade (Chafi et al. 2010, Taylor and Ford 2009, Roberts et al. 2009) have used material properties that were developed for automotive crash applications with viscoelastic decay rates below 100 s^{-1}, which impose a limitation on these models. In this study, a novel low-noise (non-impact) experimental setup was u tilized to determine the material behavior of brain tissue in shear at strain rates from 300 to 1400 s^{-1}. This range is higher than any previously reported results in brain shear deformation and corresponds to strain rates experienced in blast injuries. The results showed highly rate dependent behavior, providing the foundation for developing a constitutive model for bTBI.

A limitation of this study is that it is not possible to apply controlled low strain levels, i.e., the samples are failed during the test. Due to the nature of high rate dynamic tests, the inertial effects are significant and characterization of a constitutive model for the sample will require a finite element mode of the experiment.

Table 1: Average shear properties for brain and 5% gelatin gel calculated from two methods of high speed video image processing and force measurement.

Sample	Video		Force	Shear Modulus (kPa)
	Shear Wave Velocity (m/s)	Strain Rate at 15% Strain (1/s)	Shear Wave Velocity (m/s)	
Brain	2.5	635	2.5	6.3
5% Gel	1.3	635	1.4	1.7

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