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Determination of Friction Coefficient in Unconfined Compression of Brain Tissue

Badar Rashid^a, Michel Destrade^{b,a}, Michael Gilchrist^{a*}

^a*School of Mechanical and Materials Engineering, University College Dublin, Belfield, Dublin 4, Ireland*

^b*School of Mathematics, Statistics and Applied Mathematics, National University of Ireland Galway, Galway, Ireland*

**Corresponding Author*

Tel: + 353 1 716 1884/1991, + 353 91 49 2344 Fax: + 353 1 283 0534

Email: Badar.Rashid@ucdconnect.ie, michael.gilchrist@ucd.ie, michel.destrade@nuigalway.ie

Abstract Unconfined compression tests are more convenient to perform on cylindrical samples of brain tissue than tensile tests in order to estimate mechanical properties of the brain tissue because they allow for homogeneous deformations. The reliability of these tests depends significantly on the amount of friction generated at the specimen/platen interface. Thus, there is a crucial need to find an approximate value of the friction coefficient in order to predict a possible overestimation of stresses during unconfined compression tests. In this study, a combined experimental – computational approach was adopted to estimate the dynamic friction coefficient μ of porcine brain matter against metal platens in compressive tests. Cylindrical samples of porcine brain tissue were tested up to 30% strain at variable strain rates, both under bonded and lubricated conditions in the same controlled environment. It was established that μ was equal to 0.08 ± 0.04 , 0.1 ± 0.05 , 0.15 ± 0.05 and 0.15 ± 0.04 at strain rates of 1, 30, 60 and 90/s, respectively. The test conditions (lubricant used, biological tissue, loading velocity) adopted in this study were similar to the studies conducted by other research groups. This study will help to understand the amount of friction generated during unconfined compression of brain tissue for strain rates of up to 90/s.

Keywords *Tissue, Computational, Ogden, Dynamic, Specimen, Lubricant*

1 Introduction

Traumatic brain injury (TBI) is recognised as a leading cause of death and disability and, as such, has been the focus of extensive research for at least 50 years. The complex mechanical behavior of brain tissue due to a sudden impact on the head is still under extensive investigations. Several research groups have developed numerical models which contain detailed geometric descriptions of the anatomical features of the human head, in order to simulate and investigate internal dynamic responses to multiple loading conditions (Ho and Kleiven, 2009; Horgan and Gilchrist, 2003; Kleiven, 2007; Ruan et al., 1994; Zhang et al., 2001). However, the fidelity of these models is highly dependent on the accuracy of the material properties used to model the biological tissues.

Several research groups investigated the mechanical properties of brain tissue in order to establish constitutive relationships over a wide range of loading conditions. Mostly dynamic oscillatory shear tests were conducted over a frequency range of 0.1 to 10000 Hz (Arbogast et al., 1997; Bilston et al., 2001; Brands et al., 2004; Darvish and Crandall, 2001; Fallenstein et al., 1969; Ho and Kleiven, 2009; Hrapko et al., 2006; Nicolle et al., 2004; 2005; Ning et al., 2006; Peters et al., 1997; Prange and Margulies, 2002; Shen et al., 2006; Shuck and Advani, 1972; Takhounts et al., 1999; Thibault and Margulies, 1998) and unconfined compression tests (Cheng and Bilston, 2007; Estes and McElhaney, 1970; Franceschini et al., 2006; Miller and Chinzei, 1997; Pervin and Chen, 2009; Prange and Margulies, 2002; Tamura et al., 2007), while a limited number of tensile tests (Franceschini et al., 2006; Miller and Chinzei, 2002; Tamura et al., 2008; Velardi et al., 2006) were performed.

Unconfined compression tests are convenient to perform on cylindrical samples of brain tissue to determine mechanical properties as compared to tensile tests because they allow for homogeneous deformations. Tensile tests are typically conducted on glued cylinders, because of the fragile nature of brain tissue, which cannot easily be cut into dog bone specimens and clamped. The resulting deformation is then inhomogeneous (see Miller and Chinzei, 2002). However, the generation of undesirable friction at the specimen/platen interface is unavoidable during compression tests at quasi-static and dynamic loading conditions. Williams and Gamonpilas (2008) derived analytical solutions for the compression of cylinders with bonded surfaces and with Coulomb friction conditions at the interfaces. It was shown that the apparent moduli were strong functions of Poisson's ratio and of the Coulomb friction coefficients. A mathematical model for the realistic friction contact

conditions with non-linear characteristics was also developed by Oden and Pires (1983) and Zhong (1989), which is available for use in the finite element analysis code ABAQUS 6.9/Explicit. Various research groups (Estes and McElhaney, 1970; Miller and Chinzei, 1997; Prange and Margulies, 2002; Tamura et al., 2007) have tried to reduce the effects of friction in their experimental results during unconfined compression of brain tissue. The reliability of unconfined compression tests does indeed depend significantly on the amount of friction generated during the tests. Thus, there is a crucial need to estimate an approximate value of the friction coefficient in order to quantify the overestimation of stresses during unconfined compression tests, particularly for soft biological tissue.

Therefore, in this study, unconfined compression tests were conducted on cylindrical specimens of porcine brain tissue at strain rates of 1, 30, 60, 90/s in order to estimate the friction coefficient, μ at the brain specimen/platen interface. Tests were conducted both under lubricated conditions (nearly pure slip condition) and bonded conditions (no slip condition). A combined experimental – computational approach was adopted to estimate the friction coefficient, μ at variable loading conditions. This study will provide further insight regarding brain tissue behavior and variation of friction coefficient, μ at different loading conditions during unconfined compression tests.

2 Materials and Methods

2.1 Specimen Preparation

Twelve fresh porcine brains were collected from a local slaughter house and tested within 3 h postmortem. Each brain was preserved in a physiological saline solution at 4 to 5°C during transportation. Then, 24 specimens were excised from 12 porcine brains (2 specimens from each brain). The dura and arachnoid were removed and the cerebral hemispheres were first split into right and left halves by cutting through the corpus callosum. Cylindrical specimens (15.0 ± 0.1 mm diameter and 5.1 ± 0.1 mm thick) composed of mixed white and gray matter were prepared using a circular steel die cutter. The time elapsed between harvesting of the first and last specimens from each brain was 10 ~ 12 minutes for the unconfined compression tests (lubricated and bonded tests). The specimens were not all excised simultaneously, rather each specimen was tested first and then another specimen was extracted from the cerebral hemisphere. All samples were prepared and tested at a nominal room temperature of 22 °C and relative humidity of 34 – 35%.

2.2 Experimental Setup

A custom made test apparatus was used in order to perform unconfined compression tests at strain rates $\leq 90/s$, as schematically shown in Fig. 1. The experimental setup was also calibrated to confirm uniform velocity during tests. An electronic actuator (speed: 500 mm/s, stroke: 50 mm, LEY 16 A, SMC Pneumatics, Ireland) was used to ensure uniform velocity during compression of brain tissue. A GSO series ± 5 N load cell (rated output of 1 mV/V nominal, Transducer Techniques, USA) was used for the measurement of compressive force. The load cell was calibrated against known masses and a multiplication factor of 13.62 N/V was used for the conversion of voltage to load. An integrated single-supply instrumentation amplifier (AD 623 $G=100$, Analog Devices) with a built-in single pole low-pass filter having a cut-off frequency of 10 kHz was used, with a sampling frequency of 10 kHz. The linear variable displacement transducer (LVDT) with a range ± 25 mm (ACT1000A, RDP electronics) was used to measure displacement during the unconfined compression phase.

2.3 Lubricated and Bonded Compression Tests

24 brain specimens were excised from 12 porcine brains (2 specimens from each brain) to perform bonded and lubricated unconfined compression tests. 6 bonded and 6 lubricated tests were performed at each strain rate of 1/s and 60/s (results at 30/s and 90/s strain rates were obtained from our previous study (Rashid et al., 2012)). Since two specimens were extracted from the same brain, one specimen was utilized for the lubricated unconfined compression tests while the other was used for the bonded unconfined compression tests. The tests were performed on mixed white and gray matter on cylindrical specimens up to 30% strain. The top and lower platens were thoroughly lubricated with Phosphate Buffer Saline (PBS) solution warmed at 37° C to minimize frictional effects and to ensure, as much as possible, uniform expansion in the radial direction. All samples were tested at a room temperature of 22 °C. Each specimen was tested once and then discarded because of the highly dissipative nature of brain tissue. The velocity of the compression platen (top platen) was adjusted to 300 mm/s to achieve a strain rate of 60/s using the test apparatus shown in Fig. 1. However, in order to achieve a strain rate of 1/s (300 mm/min), a standard universal tensile testing machine (Tinius Olsen) was used for the tests. In the bonded tests, the surface of the platens was first covered with a masking tape substrate onto which a thin layer of surgical glue (Cyanoacrylate, Low-viscosity, Sigma-Aldrich) was applied. The application of glue was

very effective to fully restrict lateral expansion of the top and bottom surfaces of the brain specimen during the compression phase.

3 Results

A combined experimental and computational approach was adopted in order to estimate the amount of friction generated during unconfined compression of brain tissue. The experimental data as discussed in Section 2.3 was utilized to estimate the friction coefficient. The cylindrical brain specimens were compressed up to 30% strain at different strain rates (1, 30, 60, 90/s). Preliminary force - time data obtained at each strain rate was recorded at a sampling rate of 10 kHz through a data acquisition system. The force (N) was then divided by the surface area measured in the reference configuration in order to compute the compressive engineering stress (kPa). The engineering stresses determined experimentally under both lubricated and bonded conditions are shown in Fig. 2 and the maximum stress values at 30% strain at each strain rate are shown in Table 1.

The experimentally determined stresses (lubricated and bonded) were used as two extreme references for the numerical simulations performed in ABAQUS 6.9/ Explicit. The density 1040 kg/m^3 and element *C3D8R* were used for the simulations. The *kinematic contact method*, *tangential behaviour* (as *surface interaction property*) and *penalty* option was selected to estimate the stresses at various values of friction coefficient, μ . The platen surface was selected as *master* and the brain as *slave* surfaces. The numerical simulations were performed up to 30% strain. Several iterations were performed by assuming $\mu=1$ and arbitrary one-term Ogden material parameters (G = infinitesimal shear modulus (Pa) and α = stiffening parameter). After a small number of simulations, excellent agreement was achieved between the bonded (experimental) and numerical stresses at $G = 2500 \text{ Pa}$, $\alpha = 1.7$. Thereafter, these material parameters were kept constant and only μ was varied until numerical stresses were in good agreement at $\mu = 0.08 \pm 0.04$ against stresses obtained under lubricated conditions $3.83 \pm 0.34 \text{ kPa}$ (mean \pm SD) at 1/s strain rate as shown in Fig. 3. A similar procedure was also adopted to estimate μ at strain rates of 30, 60, and 90/s. The numerical stress profiles at various values of μ at different strain rates are shown in Fig. 3. It is observed that μ decreases with the decrease in strain rate; however, it remains unchanged from 60 to 90/s strain rate. The estimated values of μ , which are in agreement with the stress

profiles obtained under lubricated conditions (Fig. 3) and the adjusted Ogden material parameters (G, α) at each strain are summarized in Table 2.

There is a 25% and 50% increase in μ with the increase in strain rates (1/s to 30/s) and (30/s to 60/s), respectively. The range of μ varies from 0.04 (minimum) to 0.2 (maximum) over a strain rate range of 1/s to 90/s. The good agreement of numerical stresses with the experimental stresses (both lubricated and bonded conditions) was also analyzed statistically using one way ANOVA test as shown in Fig. 4. It is observed that there is no significant difference between the average experimental stress profiles (lubricated) and the numerical stress profiles ($p=0.5980 \sim 0.9554$) at various values of μ as shown in Table 2. Similar agreement between the stresses is also observed under bonded condition ($p=0.7588 \sim 0.9355$) as shown in Fig. 4.

4 Discussion

Practically, it is experimentally impossible to generate a perfect frictionless condition during unconfined compression tests. Therefore, it was essential to estimate an approximate value of the friction coefficient μ , particularly focusing on unconfined compression of brain tissue. A combined experimental - computational approach was adopted to determine μ at variable loading conditions. Before numerical simulations, it was essential to perform both lubricated and bonded unconfined compression tests under the same controlled environment. The values of μ estimated in this study (as shown in Table 1) at various strain rates (1, 30, 60, 90/s) indicate that the experimental results are affected more at higher loading velocities because of the associated higher values of the friction coefficient ($\mu = 0.15 \pm 0.05$ at 60 and 90/s strain rates). As discussed before, there is a significant rise in μ (25% increase) with the increase in strain rate from 1/s to 30/s. The test conditions (lubricant used, biological tissue, loading velocity) adopted in this study were similar to previous research conducted on brain tissue (Estes and McElhaney, 1970; Miller and Chinzei, 1997; Prange and Margulies, 2002; Tamura et al., 2007) as mentioned in Table 3. An approximate amount of friction which may exist during unconfined compression of brain tissue can be assumed based on the similarity of test conditions.

The apparent elastic modulus, E (strain range: 0 – 0.10) at a strain rate of 1/s (lubricated test) is 6.35 ± 0.134 kPa (mean \pm SD); this is in the same approximate range (5.7 ± 1.6 kPa at a strain rate of 1/s) as estimated by Tamura et al., (2007). Similarly, E is

approximately equal to 3.0 ± 0.3 kPa at a strain rate of 0.64/s, calculated from the experimental data of Miller and Chinzei (1997). However, a similar increase in E of the present study was also observed at a strain range of 0.20 – 0.30 after comparing results with Tamura et al., (2007) and Miller and Chinzei (1997).

The mesh density greatly reduces or increases the simulation time. The mesh is said to be convergent when further mesh refinement produces a negligible change in the solution. In the present study, mesh convergence was achieved when there was a negligible change in the numerical solution (0.3%) with further mesh refinement and the relative simulation time noted was 50 s. Moreover, the magnitudes of various energies of the numerical model were also analyzed for hourglass stiffness effects. The artificial strain energy as a percentage of the total strain energy was $\sim 0.063\%$ to 0.34% at all strain rates. The significant low percentage of artificial strain energy ($\leq 0.34\%$) indicates that hourglassing is not a problem during simulations to determine the friction coefficient.

Wu et al., (2004), suggested that the stress levels of soft tissues can be overestimated by 10 – 50% during unconfined compression tests; however the main limitation of the study was the reference stress response curves (at zero friction) obtained after fitting to experimental data, which does include frictional effects. Thus there was a strong possibility of overestimating the real values. However, in the present study, a combined computational – experimental approach was followed to estimate values of the friction coefficient at variable strain rates. This will help to quantify any error in the magnitude of the stresses or the overestimated values of experimental stresses during unconfined compression tests.

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FIGURE CAPTIONS

Fig. 1 – Schematic diagram of complete test apparatus for unconfined compression of brain tissue.

Fig. 2 – Experimental engineering stress (kPa) both in bonded and lubricated conditions at different strain rates.

Fig. 3 – Agreement of numerical stress profiles at various values of μ with experimental stress profiles (bonded and lubricated) at various strain rates.

Fig. 4 – One way ANOVA tests indicates no significant difference between the numerical stresses values (obtained at various μ) and the experimental stresses (bonded and lubricated) at various strain rates.