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Material Characterization and Computer Model Simulation of Low Density Polyurethane Foam Used in a Rodent Traumatic Brain Injury Model

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Abstract

Computer models of the head can be used to simulate the events associated with traumatic brain injury (TBI) and quantify biomechanical response within the brain. Marmarou's impact acceleration rodent model is a widely used experimental model of TBI mirroring axonal pathology in humans. The mechanical properties of the low density polyurethane (PU) foam, an essential piece of energy management used in Marmarou's impact device, has not been fully characterized. The foam used in Marmarou's device was tested at seven strain rates ranging from quasi-static to dynamic ($0.014 \sim 42.86 \text{ s}^{-1}$) to quantify the stress-strain relationships in compression. Recovery rate of the foam after cyclic compression was also determined through the periods of recovery up to three weeks. The experimentally determined stress-strain curves were incorporated into a material model in an explicit Finite Element (FE) solver to validate the strain rate dependency of the FE foam model. Compression test results have shown that the foam used in the rodent impact acceleration model is strain rate dependent. The foam has been found to be reusable for multiple impacts. However the stress resistance of used foam is reduced to 70% of the new foam. The FU_CHANG_FOAM material model in an FE solver has been found to be adequate to simulate this rate sensitive foam.

Keywords

rodent head impact acceleration device; traumatic brain injury; low density polyurethane foam; compression test; rate dependency; finite element modeling

1. INTRODUCTION

Traumatic axonal injury occurs in over half of all severe cases of traumatic brain injury (TBI) and has been associated with high mortality and morbidity (Marmarou et al., 1994; Povlishock and Christman, 1995). Marmarou and his colleagues developed an impact acceleration device that is capable of producing a substantial degree of axonal injury in rodents without the complication of the focal lesions and skull fracture (Marmarou et al., 1994; Foda et al., 1994). The model utilizes rodents which are easily adapted to most

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laboratory situations and permits the comparison with other studies of alternative injury models using this species. Since the introduction of this model in 1994, it is one of the most frequently used rodent models of diffuse brain injury which has been used to increase the understanding of the pathophysiology of TBI, including changes in molecular and cellular pathways, neurobehavioral outcomes, diagnoses and treatment after TBI (Cernak et al., 2002; Fei et al., 2006; Health and Vink, 1999; Kallakuri et al., 2003; Lammie et al., 1999; Schmidt et al., 2000; Sengul et al., 2008; Stone et al., 2004; Tavazzi et al., 2005; Vagnozzi et al., 2007).

In the Marmarou model, a weight is dropped through a vertical tube onto a metallic disc (helmet) glued to an anesthetized rat resting on a piece of low density polyurethane (PU) shock absorbing foam. During impact, the foam is deformed substantially to lengthen the impact duration so as to absorb a portion of the impact energy. The stiffness of this PU foam at low loading rate (8.39 N/m) was reported by Piper et al. (1996). Marmarou et al. (1994) reported foam stiffness of 2500 N/m in their impact acceleration device using a 1-D spring-damper model. It is known that quasi-static behavior of flexible PU foam is significantly different from its dynamic behavior (Hager et al., 1992; Vorspohl et al., 1994). Besides the large discrepancy in terms of stiffness values between the studies reported by Piper et al. and Marmarou et al., PU foams have a non-linear response and thus the use of single constant material stiffness is not valid. Until now, the stress-strain behavior of the foam under impact conditions has not been characterized experimentally. This information is needed before a finite element model (FE) of rat impact injury can be used to elucidate the injury mechanism and threshold of traumatic axonal injury.

It has been reported that PU foam exhibited rate dependency, creep and stress relaxation characteristics under uniaxial compression at low and medium strain rates (Davies et al., 1999). It was also reported that under cyclical loading, the foam may undergo softening but may recover to a steady state after the first few cycles of loading. On the other hand, Rehkopf et al. (1994) observed that the PU foam continues to weaken under cyclic loading due to progressive damage to the polymer structure. To the best of our knowledge, changes in the material properties of the PU foam used in the Marmarou model under repeated loading have not been reported. The recovery rate and the reusability of the foam are essential information needed to assure reproducibility of repeatable injury severity using this rodent injury model.

The main goals of the current study were to determine the mechanical properties of the PU foam in compression due to a variety of loading rates and to quantify the stress response as a function of strain at various strain rates. A second aim was to ascertain the rate of recovery and reusability of the foam when subjected to cyclic loadings. The final aim was to implement a material model for the foam in a FE solver to validate its capability of modeling the rate dependent foam material used in the Marmarou impact device.

2. METHODS AND MATERIALS

2.1 Characterization of Foam Properties

A large piece of open-cell flexible polyurethane foam, the same foam (Type E bed) used by Marmarou's group (Marmarou et al., 1994), was purchased from Foam to Size Company (Ashland, VA). Test samples (70 × 70 × 70 mm, N = 21) were cut from foam in pre-cured shape. Constant rate uniaxial compression tests were carried out in an Instron 8500 high-speed testing machine (Instron Corp. Canton, MA, USA) at room temperature (25°C). The foam sample was impacted by the impactor plate rigidly attached to the crosshead at speeds of 1, 50, 250, 500, 1,000, 2,000, and 3,000 mm/s (Fig. 1). The corresponding nominal strain rates $\dot{\epsilon}$ at the six aforementioned speeds were 0.014, 0.71, 3.57, 7.14, 14.29, 28.57, and

42.86 s⁻¹, respectively. A new sample was used for each compression test to a nominal strain of 80%. The built-in potentiometer was used to output the actual displacement of the foam. The force was measured using load cell model 1010AJ (500 lb capacity, Interface Scottsdale, AZ) rigidly attached to a mounting base fixed to the floor. A TDAS1R4 (Diversified Technical Systems, Inc, Seal Beach, CA) data acquisition system was used to acquire force data at a sampling rate of 10 kHz. The force and displacement data were pre-filtered at 1 kHz and post-filtered with a channel frequency class 180 Hz and 60 Hz, respectively, for data analysis. Each test condition was repeated three times on three different samples. The engineering stress-strain curves from three repeated tests showed good repeatability with the coefficient of variation at 2.1%. Hence the average values of the three tests were used to represent the force-deflection response at a given loading rate. All of the stresses and strains reported in this study were engineering stress and strain. Young's moduli (E) and stiffness (k) were calculated respectively from the slopes of the stress-strain and force-deflection curves in the linear region. At the maximum compression, the final lateral dimensions of the samples ($N = 3$) tested at 1,000 mm/s were measured using a pair of calipers (0.02 mm precision). The lateral strain from each sample was calculated based on the ratio of the change in the lateral dimension to the original lateral dimension. The average strain value of results from three samples was used. Poisson's ratio was calculated by taking the ratio of the lateral strain to the longitudinal strain. The density of the foam material was determined by taking the ratio of the measured mass and volume using an electronic scale (accuracy at 0.01 gm) (Model EOD120, Ohaus Corp., Switzerland) and a pair of calipers.

2.2 Stress-Strain Rate Relationships

For strain rate dependent materials, according to Hosford and Caddell (1993), the relationship between stress σ and strain rate $\dot{\epsilon}$ at any given strain value can be described by a power law: $\sigma(\dot{\epsilon}) = C\dot{\epsilon}^n$. Where C is the strength constant that depends upon strain, temperature, and material, and n is the power coefficient for strain rate dependency. To quantify this relationship at the plateau region, stress responses at a given strain level were plotted against various strain rates on a log-log scale. The linear relationship between the stress and strain rate in the logarithmic domain was then converted to power law equations by a curve fitting (MS excel) to determine the strength constant C and the power coefficient n values.

2.3 Foam Recovery Characteristics

Recovery rate of the foam stress-strain relationship due to cyclic loading over a period of time up to three weeks was tested in compression using the same Instron machine at a constant temperature of 25°C. The specimen was first compressed cyclically five times to an 80% strain with 2 minutes recovery between cycles. The same foam was kept at a constant temperature of 25°C and was then tested at one hour (6th cycle), and one day (7th cycle). The same foam was further tested at three days (8th cycle) and three weeks (9th cycle) later to determine if further degradation of the foam properties might occur. The force-deflection results reported were the average response of three repeated tests on three samples.

2.4 FE Modeling

The uniaxial foam compression test was simulated using an explicit FE analysis solver LS-DYNA® (LSTC, Livermore, CA). The foam sample model was meshed using eight-node brick elements while the impactor plate model was defined as a rigid body. Chang and DeSilva (1998) developed a unified constitutive equation for a low-medium density foam material that possesses strain rate dependency for stress-strain responses. This material model assumes a zero Poisson's ratio. The nonlinear strain rate ($\dot{E}^N$) expressed as a function of stress and a state variable which represents the history of loading. The kinetic equation is given by

$$\dot{E}^N = \frac{\sigma}{\|\sigma\|} D_0 \exp[-c_0 \left(\frac{\text{tr}(\sigma S)}{\|\sigma\|^2} \right)^{2n_0}]$$

$$\text{tr}(\sigma S) = \sigma_{ij} S_{ij}$$

$$\|\sigma\| = (\sigma_{ij} \sigma_{ij})^{1/2}$$

where E is the Lagrangian strain tensor, N denotes the nonlinear, D_0 , c_0 and n_0 are material constants, σ_{ij} is the stress tensor, S is an overall state variable and the state variables S_{ij} are scalars. LSTC introduced this material law into LS-DYNA[®] material library as MAT_FU_CHANG_FOAM for low-density, strain rate sensitive foam materials (LSTC, Livermore, CA). This material model can be used to simulate the rate effects for a foam material by using engineering stress-strain curves determined at different strain rates as the input curves. To define the input, stress-strain curves obtained from the compression tests at four strain rates (0.014 to 14.29 s⁻¹) were combined into four combinations of input scenarios. In Case A, stress-strain curves from four different strain rates (0.014, 3.57, 7.14 and 14.29 s⁻¹) were all used for input curves. In Case B, three stress-strain curves from strain rates of 0.014, 7.14 and 14.29 s⁻¹ were used. In Case C, three stress-strain curves from strain rates of 0.014, 3.57 and 14.29 s⁻¹ were used. Finally in Case D, two stress-strain curves obtained at strain rates of 0.014 and 14.29 s⁻¹ were used to define the material input. The FE foam model was compressed by the rigid impactor model to a nominal strain of 80% at constant velocities of 1, 250, 500 and 1,000 mm/s for each material input condition. The predicted force-deflection responses by the models defined with different stress-strain curves were compared to experimental measurements made at the corresponding loading rates.

To determine the degree of agreement between model predicted force-deflection (F-D) and experimental results, an average variation in force responses was calculated by taking 40 data points (every 1.5 mm in the deflection time history) on the F-D curves of the test and FE at each given strain rate.

$$\text{Average Variation} = \frac{\sum_{i=1}^n \frac{|Test - FEA|}{Test}}{n}$$

The mean value of the average variation across all strain rates was then used to determine the best input combination defined in Cases A–C.

3. RESULTS

3.1 Stress-Strain Relationship

The measured foam density was found to be 13.8 ± 0.17 kg m⁻³. The calculated Poisson's ratio for the foam was 0.033, which is nearly zero. Experimental observation revealed that under uniaxial compression, the foam specimens underwent macroscopically uniform deformation without noticeable bulging and distortion. Figure 2 shows engineering stress-strain (σ – ϵ) curves at nominal strain rates of 0.014, 0.71, 3.57, 7.14 and 14.29 s⁻¹. The stress-strain relationships obtained at 28.57 and 42.86 s⁻¹ overlapped to that of 14.26 s⁻¹. In general, depending on the strain rate levels, a transition between linear elasticity and plateau regions occurred around 5 to 8% strain. In the plateau region between 10 and 60% strain, stress was nearly constant. A drastic rise in stress was found beyond strains of 70% with a maximum strain of 80%, indicating material consolidation. The stiffness k for the strain rate between 0.014 and 14.26 s⁻¹ ranged from 3,100 to 5,600 N/m. At strain rates of 28.57 and

42.86 s⁻¹, stiffness was 3,800 and 4,500 N/m, respectively. The Young's modulus varied from 44.75 to 78.08 kPa, respectively for strain rate from 0.014 to 14.29 s⁻¹. The E value for strain rates of 28.57 and 42.86 s⁻¹ was 63.3 and 48.5 kPa, respectively.

3.2 Strain Rate Dependency

To illustrate the degree of dependency of the stress response to applied strain rate, slope of stress-strain rate vs. strain rate in the plateau region (10 to 70% strain), the derivatives of the σ - $\dot{\epsilon}$ curve fitted by power functions were calculated as shown in (Fig. 3A, 3B). It is seen that the curve slope was much larger when $\dot{\epsilon}$ was less than 15 s⁻¹, indicating that the foam properties within the plateau region were strongly related to the strain rate below 15 s⁻¹. The calculated average values of C and n over all strain levels ($n = 7$) were 4.6 (± 0.49) and 0.11 (± 0.02), respectively. The stress (kilopascals) as a function of strain rate (reciprocal seconds) was thus best represented by $\sigma(\dot{\epsilon}) = 4.6\dot{\epsilon}^{0.11}$.

3.3 Foam Recovery Characteristics

Figure 4 shows the stress-strain response at strain rate of 0.71 s⁻¹ as a result of cyclic compression. It was noted that the stress in the plateau region exhibited significant softening beginning with the 2nd cycle in comparison to that of the first response (Fig. 4A). A minimal stress reduction was found in the subsequent 3rd, 4th and 5th cycles. When the cyclic compression test was conducted one hour (6th cycle), one day (7th cycle), three days (8th cycle) and three weeks (9th cycle) after the initial few cycles, the measured stress responses were similar to that measured in the 2nd cycle (Fig. 4B). The stresses obtained at 2nd cycle or subsequent cycles were reduced approximately to 70% of stress at the first cycle.

3.4 FE Modeling

Fig. 5A shows the correlation of the force-deflection responses from different strain rates between the model predictions for Case C and experimental measurements. Table 1 summarized the quantified variation in force responses between experimental measurements and FE model prediction at each different strain rate using different input material combinations defined by Cases A–C. It was found that average variation in force responses between the experimental results and model prediction from Cases A and B were identical at all strain rates except at strain rate 3.57 s⁻¹, average variation was slightly higher in Case B (7.8%) than in Case A (7.0%). For Case C, the worst prediction made by the model was at a strain rate of 7.14 s⁻¹, with an average variation at 5.9%. High average variations of 12.9 and 17.9% were found for Case D at strain rates of 3.57 and 7.14 s⁻¹, respectively.

Based on the overall variations (mean values) for all strain rates assessed between the model predictions and experimental results (Table 1), it appeared that foam behavior across the strain rates of 0.014 to 14 s⁻¹ could be best predicted by FE foam model using stress-strain curves defined in Case C. Two additional simulations were carried out at strain rates of 0.71 s⁻¹ and 6.79 s⁻¹. Comparison showed that the foam material model was able to predict reasonable rate dependency at strain rates where no experimental data were available (Fig. 5B).

4. DISCUSSION

In this study, a low density open-cell polyurethane foam which serves as an energy absorber in a widely used rodent axonal injury model has been subjected to uniaxial compression tests at various strain rates. The mechanical responses have been quantified to characterize the stress-strain relationships, stiffness, elastic modulus, strain rate dependency, and rate recovery for this particular foam. In general, the compressive stress-strain graph appears to have three distinct portions: an initial linear elastic regime, a plateau regime in which foam

underwent large deformation while the stress was maintained nearly constant and finally a steeply rising stress characterized as the densification regime. The strain levels at each regime were comparable with those of other flexible polyurethane foams reported in the literature (Davies and Mills, 1999; Gibson and Ashby, 1988; Mills and Gilchrist, 2000; Mills and Lyn, 2002; Youssef et al., 2005). Marmarou et al reported the stiffness of the foam was 2,500 N/m which was based on a 1-D mathematical model constructed with two sets of masses, springs and dampers. The stiffness at various strain rates obtained directly from material compression tests conducted in this study ranged from 3,100 to 5,600 N/m which was higher than that reported by Marmarou et al (1994). The foam elastic moduli E increased from 44.75 to 78.08 kPa as the strain rates increased from 0.014 to 14 s⁻¹. For the two highest strain rates (28.57 and 42.86 s⁻¹) however, the elastic moduli became lower than that at 14 s⁻¹. The exact reason as to why E decreased at the higher strain rates as compared to intermediate strain rate is unknown. In the actual Marmarou experiment, the foam is typically compressed to strain greater than 60% (plateau region). Presumably the foam behavior in elastic region (strain <8%) would have insignificant effect on the stress response occurred at large strain. However, further investigation is needed to understand this phenomenon.

Tests on PU foam should be chosen to represent the strain and strain rate condition in the actual Marmarou's experiment as close as possible. To the best of our knowledge, there was no information available in the literature that directly reported the deformation rate of the foam during rat TBI experiments. In a recent study conducted in an effort to measure the kinematics of the rat head during impact using a modified Marmarou impact acceleration device (the manuscript is in revision), video analysis of the foam deformation suggested a maximum dynamic strain rate of 40 s⁻¹ for a 2.25 m drop. The current study quantified the degree of the rate dependency of the stress for strain rates ranging from 0.014 to 42.86 s⁻¹. While the analysis revealed that the stress-strain relationships exhibited strain rate dependency both in the plateau region and at the yield point, stresses were strongly related to strain rate only up to 15 s⁻¹. The rate dependency of the stress-strain relationships observed for the PU foam were consistent with the mechanical characteristics exhibited by other polymeric foam in respond to different loading rates (Gibson and Ashby 1988).

The significant stress reduction took place from first to second loading cycles suggested that significant foam softening or foam degradation (>30% reduction) could occur after the first loading cycle. Other investigators reported similar observations in the flexible polymeric foams under cyclic loading (Vorspohl et al., 1994; Davies and Mills, 1999). This foam degradation is related to the damage to the cellular structure of polymeric matrix and plastic deformation incurred in the foam during the initial large compressive loading (Davies and Mills, 1999; Kim et al., 2002; Suresh, 1991; Rehkopf et al., 1994). From cycles 2 to 5, only gradual stress reduction (<5%) continued in the foam, presumably due to too short recovery time (2 minutes) between the cycles. It was observed that from 6th cycle and the subsequent cyclic loadings up to three weeks (9th) the foam stress responses had no noticeable differences as compared to that from second cycle. The results implied that with enough recover time, the foam not only could recover to the stress level after initial degradation but also reached a stress steady state for the subsequent cycles. The stabilized stress behavior after initial softening was also reported for high-density flexible foam under cyclic compression (Davies and Mills, 1999; Rehkopf et al., 1994).

The foam is capable of maintaining steady state stress response after multiple loadings, suggesting that the current low density PU foams are reusable up to at least three week. The results also revealed that under the cyclic loading, even with long recovery time the ability of the foam to resist deformation would never recover to its initial level. A recovery time that is too short between the tests could affect stress behavior as demonstrated between

cycles 2–5. It is largely due to the viscoelasticity of the foam. Based on the current study, the shortest recovery time required to assure the stress resistance after second cycle was found to be around one hour. Therefore, a one-hour recovery time is recommended for a repeated test to ensure consistency of the mechanical behaviors. If another test needs to be conducted in less than one hour, a piece of used foam or a piece of new foam that has been compressed at least one hour prior to the actual test could assure the repeatability of the tests conducted at different times. The use of new foam for each test is another alternative to attain repeatable results. However, care should be taken to note the difference in the stress-strain characteristics between the new and used foam in order to produce the desired mechanical response. Possible changes in stress-strain properties as a function of time beyond three weeks need to be confirmed in the future.

Material model FU_CHANG_FOAM available in the FE solver LS-DYNA has been validated against test results. The FE results suggested that the mechanical responses of the low density PU foam used in Marmarou rodent impact injury device could be best duplicated by using the stress-strain curves obtained at strain rates of 0.014, 3.57 and 14.3 s⁻¹ (Case C) as input for defining FU_CHANG_FOAM material model. The FE simulations of the compression test show that this material model is suitable for modeling the rate sensitive foam. The foam model will be used with an anatomically detailed FE model of rat head (Zhang et al., 2006; Zhang et al., 2010) to quantify the biomechanical response of traumatic axonal injury induced by Marmarou's impact acceleration device.

In conclusion, under uniaxial compression, the flexible polyurethane foam (density of 14 kg m⁻³) used in the Marmarou rat TBI model is rate dependent up to 15 s⁻¹. The foam is reusable even after multiple loadings (9 cycles). However, a one-hour recovery time is recommended for a repeated test. Care should be taken to note the difference in the stress-strain characteristics between the new and used foam in order to produce the desired mechanical response. The FE foam model defined with FU_CHANG_FOAM material have been validated against experimentally measured force-deflection responses at a range of strain rates relevant to loading conditions used in TBI tests. The quantified stress-strain relationships determined from the current study can be used as a material input to simulate the rate sensitive foam for FE modeling of Marmarou impact acceleration injury.

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Fig. 1.
Test setup for the foam compression test

Fig. 2.
Comparison of engineering stress-strain relationships tested under uniaxial compression at various strain rates (0.014, 0.714, 3.571, 7.142, 14.285 s⁻¹)

Fig. 3.
 (A) Relationship between the stress and strain-rate plotted and fitted by power functions between 10 and 70% strain, (B) Rate of the change of stress with respect to strain-rate change

Fig. 4. Comparison of the stress-strain relationship in cyclic compression (A) between the first and the next four cycles, and (B) between the second and the 6th to the 9th cycles

Fig. 5.
 (A) Comparison of force-deflection curves between model predictions from Case C and experimental measurements. (B) Predicted force-deflection response at two additional strain rates showing rate dependency by MAT 83 using input curves defined in Case C.

Percentage variation in force between experimental measurements and model predicted results at four different strain rates using input material curves combination defined in Cases A–C

Table 1

	0.0142 s ⁻¹	3.57 s ⁻¹	7.14 s ⁻¹	14.29 s ⁻¹	mean variation (%)
Case A	2.1%	7.0%	1.6%	3.2%	3.5%
Case B	2.1%	7.8%	1.6%	3.2%	3.7%
Case C	2.1%	1.0%	5.9%	3.2%	3.0%
Case D	2.1%	12.9%	17.9%	3.2%	9.0%