MATERIAL MODELING AND ANALYSIS FOR THE DEVELOPMENT OF A REALISTIC BLAST HEADFORM

S. G. M. Hossain
University of Nebraska at Lincoln, smgmamur@yahoo.com

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MATERIAL MODELING AND ANALYSIS FOR THE
DEVELOPMENT OF A REALISTIC BLAST HEADFORM

by

S. G. M. Hossain

A THESIS

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Blast traumatic brain injury (BTBI) has become an important topic of study because of the increase of such incidents, especially due to the recent growth of improvised explosive devices (IEDs). This thesis discusses a project in which laboratory testing of BTBI was made possible by performing blast loading on experimental models simulating the human head. Three versions of experimental models were prepared – one having a simple geometry and the other two having geometry similar to a human head. For developing the head models, three important parts of the head were considered for material modeling and analysis – the skin, skull and brain. The materials simulating skin, skull and brain went through many testing procedures including dynamic mechanical analysis (DMA). For finding a suitable brain simulant, several materials were tested under low and high frequencies. Step response analysis, rheometry and DMA tests were performed on materials such as water based gels, oil based mixtures and silicone gels cured at different temperatures. The gelatins and silicone gels showed promising results toward their use as brain surrogate materials. Temperature degradation tests were performed on gelatins, indicating the fast degradation of gelatins at room temperature. Silicone gels were much more stable compared to the water based gels. Silicone gels were further processed using a thinner-type additive gel to bring the dynamic modulus values closer to those of human brain matter. The obtained values from DMA were compared to the values for human brain as found in literature. Then a silicone rubber brain mold was prepared to give the brain model accurate geometry. All the components were put together to make the entire head model. A steel mount was prepared to attach the head for testing at the end of the shock tube. Instrumentation was implemented in the
head model to obtain effective results for understanding more about the possible mechanisms of BTBI. The final head model was named the Realistic Explosive Dummy Head or the “RED Head.” The RED Head offered potential for realistic experimental testing in blast loading conditions by virtue of its material properties and geometrical accuracy.
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1 INTRODUCTION

1.1 About Blast TBI

Various processes that may damage the brain after trauma, singly or in combination, are referred to in the literature as traumatic brain injury (TBI) [1]. These mechanisms which are responsible for the occurrence of TBI can vary, but they are broadly categorized as impact TBI and blast TBI. For both categories, the trauma can lead to disability or death. The primary TBI (induced by mechanical forces) can result in injuries such as injury to scalp, fracture of skull, surface contusions or lacerations, intracranial hematoma, diffuse axonal and vascular injury and injury to cranial nerves and pituitary stalk.

Impact-induced TBI resulting from head impacts caused by automotive accidents [2-4] or sports-related accidents [2,5,6] happen mostly among the civilian population, and this phenomenon has been extensively studied, primarily through animal testing and analyses of human trauma data [2,7]. On the other hand, blast-induced TBI gained its importance for study because of the recent increase in the use of improvised explosive devices (IED) as weapons which have the unifying characteristic of inflicting widespread death and massive trauma with a single explosion [8]. According to Ford and Taylor (2008), injuries sustained from blast exposure have been categorized into three major types: primary, secondary and tertiary [9, 10]. Primary blast injury is associated with direct exposure of the head and body to the blast wave. In secondary blast injury, debris is accelerated into the individual, while in tertiary injury the victim is thrown into stationary objects by the blast. Now, both the latter mechanisms are comparable to mechanical trauma whereas the primary blast exposure in the development of TBI remains less well
understood [10, 11]. Damage of brain tissues due to blast exposure has been explained by some proposed mechanisms, such as the bulk acceleration of the head [2, 12] and load transmission through orifices in the skull and compression of the thorax generating vascular surge into the brain [2, 13]. Skull flexure issues were also considered in the research of Moss et al. [2] because of blast wave propagation through and around the skull.

In this research, the objective was to develop a fair amount of understanding on this blast TBI phenomenon and use this knowledge for enabling design of effective protection measures against them.

1.2 Anatomy and Material Properties of Human Head

The human head is a very complex structure consisting of numerous objects having various mechanical properties. In this case of blast response analysis, certain components were given more importance due to their bulk existence and for their mechanical properties. The head consists of a facial area and cranial skull surrounded by the scalp [14]. For studying TBI, the facial area is not highly important to consider. Rather, other specific components of the head were studied more rigorously. These components were: scalp, skull, brain and cerebospinal fluid (CSF).

Fig. 1.1 Anatomy of human head according to [15] – left: the coronal section, right: sagittal section.
1.2.1 SCALP

Scalp is the outermost layer of the human head that covers the skull and absorbs and distributes external energy from direct impact. The thickness of the scalp ranges from 5 to 7 mm [16]. Scalp consists of five layers, where the innermost layer is attached to the skull. Its name was developed due to the five layers that create SCALP: S for Skin, C for (sub)Cutaneous connective tissue, A for Aponeurosis, L for Loose areolar tissue and P for Pericranium. Fig. 1.2 describes a cross section view of the scalp.

Fig. 1.2 Sectional view of scalp [17].

Researchers have investigated the mechanical properties of scalp, for example, the stress-strain curves obtained by static loading. In 1965, Gadd found that for human scalp, pork skin, soft polyvinyl butyral and napa goatskin, stress-strain curves were concave upward and did not have a linear portion whose slope could be used as Young’s modulus [18]. According to Galford and McElhaney in 1970, a typical dynamic modulus value for monkey scalp obtained from free
vibration experiments is found to be 223 psi (1.54 MPa) [19]. The creep compliance was not altered significantly by stress level, which indicated that the scalp could be adequately described by linear viscoelastic theories over the range of stress and time encompassed by their tests.

1.2.2 SKULL

The skeletal structure of the head is divided into three major parts: neurocranium (housing of the brain), face and base. Neurocranium is made of eight bones: frontal, two parietal, two occipetal, sphenoid and ethmoid [16]. The following figures illustrate these bones making up the human skull [17].

![Diagram of the human skull](image)

Fig. 1.3 Norma occipitalis (posterior view of the skull) [17].
Fig. 1.4 Norma verticalis (view of skull from above) [17].

Fig. 1.5 Norma lateralis (view of skull from lateral position) [17].
Skull material study is important in this research as the skull is one of the barriers the blast pressure waves have to pass though to enter into the brain and cause damage. Also, skull flexure created from blast loading on the head might be a mechanism of TBI. Moss et al. found from their numeric hydrodynamic simulations that non-lethal blasts can induce sufficient skull flexure to generate potentially damaging loads in the brain – even without the presence of a head impact [2]. Fig. 1.6 shows some sample outcomes of their research on skull flexure.

Fig. 1.6 Pressure and skull motion for impact and blast simulations as in Moss et al. (2009): (a) angled impact at maximum deceleration; (b) blast wave propagating past the simulated victim 5.6 ms after detonation; (c) expanded view of the head as the blast wave [2].
1.2.3 BRAIN

Human brain is made of mainly two types of cells: neurons and glia. Neurons are the cells that enable the nervous system to carry out all the complex computational functions. A typical human brain weighing 1.3 kg and with a size of 1.5 liters contains an estimated number of 20-100 billion neuron cells. The glial cells are described as the supporting cells for the nervous system; those play an important role of allowing the nervous system to work properly. The estimated number of glial cells in an average human nervous system is 10 times the number of neuron cells [20].

Fig. 1.7 Various parts of a human brain as in [21].
The cerebral cortex of the brain can be divided into several lobes according to their relative positions covering the corresponding cranial bones. The gray matter, containing the neuron cell bodies, dendrites and final parts of axons, is a very thin layer (2 mm thick) on the surface of the cerebral hemisphere. The white matter is essentially the cabling that joins the different parts of the cortex and other parts of the brain together. Fig. 1.8 illustrates the positions of white matter and gray matter in a human brain.

Fig. 1.8 Stained coronal section taken through revealing the cortex and other parts of the human brain according to Bruni et al. [22].

The soft brain tissue is securely held together by three layers of connective tissue: dura mater, pia mater and arachnoid mater. These three layers together are known as meninges. Dura mater is a
highly fibrous layer that lies next to the skull. The pia mater is connected to the brain itself and closely follows the contours of the folded surface of the brain. The arachnoid mater is situated in between the dura mater and pia mater [20].

Brain matter has undergone numerous tests performed by many researchers to obtain its material properties. In 2002, Miller et al. performed in vitro, uniaxial tension tests on swine brain tissue in finite deformation and also proposed a hyper-viscoelastic constitutive model for the brain tissue. Experimental results for two loading velocities corresponding to two strain rates (0.64 and $0.64 \times 10^2 \, s^{-1}$) were presented. A strong stress-strain rate dependence was found from the results because the tissue response stiffened as the loading speed increased [23]. In 1997, Donnelly and Medige performed transient, single-pulse high-rate shear displacement tests on brain samples collected from fresh cadavers. They fitted the experimental data to a nonlinear, viscoelastic standard solid model (obtained by adapting a standard solid linear viscoelastic model). The shear stress and finite shear strain were compared. It became apparent from their tests that the stress versus strain response of the human brain tissue did not increase linearly with strain rate as a solid Kelvin-Voigt model would predict. The three-element standard solid also has the desirable characteristic of zero stress at zero strain regardless of the strain rate. The nonlinear model was found to fit the experimental data well [24]. In 2000, Miller et al. also performed in vivo tests on swine brain tissue and concluded from the numerical analysis that the linear, viscoelastic model of brain tissue is not appropriate for modeling brain tissue deformation even for moderate strains [25]. Donnelly and Medige also provided a collection of brain material properties those were obtained by different researchers at different times. Some relevant data out of that study is provided in Table 1.1.
Fig. 1.9 The three-parameter linear viscoelastic model proposed by Donnelly and Medige [24]. This model was adapted to develop a nonlinear viscoelastic model.

Table 1.1 Summary of brain tissue shear properties - partially obtained from [24].

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Storage Modulus (kPa)</th>
<th>Loss Modulus (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koeneman (1966) compression 80 – 350 Hz</td>
<td>2.7 – 5.0</td>
<td>0.5 – 3.2</td>
</tr>
<tr>
<td>Galford and McElhaney (free axial vibration) 34 Hz</td>
<td>22.2</td>
<td>8.7</td>
</tr>
<tr>
<td>Estes and McElhaney (1970) constant strain rate compression</td>
<td>4.7</td>
<td>0.28 – 2.8</td>
</tr>
<tr>
<td>Shuck and Advani (1972) oscillating torsion 10 – 60 Hz</td>
<td>8.0 – 16.0</td>
<td>3.2 – 8.6</td>
</tr>
<tr>
<td>Wang and Wineman (1972) in vivo probe data</td>
<td>19.5</td>
<td>11.2</td>
</tr>
<tr>
<td>Green et al. (2008) gray matter 90 Hz</td>
<td>3.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Green et al. (2008) White matter 90 Hz</td>
<td>2.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Galford et al., decades earlier, performed a series of creep and relaxation experiments on scalp, brain and dura from both human and monkey. They proposed a four-parameter Maxwell-Kelvin model to fit the creep data. Also free vibration tests were performed to obtain complex modulus values in the frequency range of 10-40 Hz [19]. They concluded from the creep compliance curves of dura and scalp that they did not alter significantly with the stress level, which indicated that these materials could be modeled by linear viscoelastic models over the time and stress ranges encompassed by their tests.

![Four-parameter Maxwell-Kelvin model](image)

Fig. 1.10 The four parameter Maxwell-Kelvin model proposed by Galford et al. for creep [19].

In a recent report from Sandia National Laboratory, the brain material properties used were found as Tables 1.2 and 1.3 as follows [10]. They used a generalized three-term Maxwell viscoelastic model for the shear response:

\[ G(t) = G_n + (G_0 - G_n)e^{-\beta t} \]

where \( t \) is time, \( G_0 \) is the short term shear modulus, \( G_n \) is the long term shear modulus and \( \beta \) represents the viscous decay constant.
Table 1.2 Elastic material properties for skull and brain [10].

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cc)</th>
<th>Initial Bulk Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>Yield Stress (MPa)</th>
<th>Strain to Failure (%)</th>
<th>Fracture Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull</td>
<td>1.412</td>
<td>4.82</td>
<td>0.22</td>
<td>95</td>
<td>0.8</td>
<td>77.5</td>
</tr>
<tr>
<td>White Matter</td>
<td>1.04</td>
<td>2.37</td>
<td>0.49</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Gray Matter</td>
<td>1.04</td>
<td>2.37</td>
<td>0.49</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 1.3 Viscoelastic material properties for brain [10].

<table>
<thead>
<tr>
<th></th>
<th>Short-term Shear Modulus $G_o$ (KPa)</th>
<th>Long-term Shear Modulus $G_\infty$ (KPa)</th>
<th>Decay Constant $\beta$ (sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Matter</td>
<td>41.0</td>
<td>7.8</td>
<td>700</td>
</tr>
<tr>
<td>Gray Matter</td>
<td>34.0</td>
<td>6.4</td>
<td>700</td>
</tr>
</tbody>
</table>

R. van Noort et al. obtained human dura mater’s mechanical properties under tensile loading. Tests were performed on samples collected and processed from cadaver. Each sample was removed from the cadaver within twelve hours of death and kept refrigerated up to five hours [26]. The stress-strain curve produced by their experiments is presented in Fig. 1.11.
1.2.4 CEREBROSPINAL FLUID (CSF)

CSF is a liquid with an approximate specific gravity of 1.008 kg/m³ which occupies subarachnoid space, fissures, sinuses and ventricles. This is a colorless clear liquid which maintains uniform pressure within the cranium in a normal head. Its volume inside the head is about 140 mL, which is nearly 10 percent of the intracranial volume [16]. CSF can be an important material to consider in this context due to the pressure-related issues inside the human head, because of its fluidity.
1.3 **Epidemiology of Blast TBI**

All these experiments and research works discussed in the previous sections indicate the importance of understanding more about human head. This knowledge is necessary to take proper actions against the growing incidence of traumatic brain injury throughout the world. For example, the estimated yearly incidence of traumatic brain injuries in the United States was found to be 1.4 million people with 50,000 deaths and 235,000 hospitalizations [10, 28]. An average rate of fatal plus non-fatal hospitalized brain injuries reported in all United States studies was approximately 150 per 100,000 per year [1].

These blast injuries have emerged as a leading cause of battlefield morbidity and mortality recently in Operation Iraqi Freedom (OIF) and Operation Emerging Freedom (OEF) [29-31]. Primary blast overpressures generated from explosive detonations affect the gas-filled organs such as lungs, gastrointestinal tracts, auditory system etc. with lung injuries being predominant in
cases where blast occurs in confined spaces [31-34]. From OIF and OEF casualty data, blast is now recognized as the major cause of injuries to the brain [11, 31, 35-37]. 35% of the battlefield casualties evacuated to the National Naval Medical Center from April 2003 to October 2005 required neurosurgical consultation and treatment, with the majority of these injuries resulting directly or indirectly from blast propagated by improvised explosive devices (IEDs) [37, 38].

According to a Wall Street Journal (March, 2010) report, “Improvised explosive devices, or IEDs, have become the signature weapon of the Afghan war, as they were in Iraq. The number of IED attacks in Afghanistan rose to more than 8,000 last year from 2,677 in 2007. They are the single biggest killer of U.S. and North Atlantic Treaty Organization troops, accounting for 275 of the 449 coalition fatalities in Afghanistan in 2009. So far this year, Afghan IEDs have killed 68 NATO troops, including 39 Americans” [39].

The rise in the number of these incidents reflects the necessity for more research to prevent them in effective ways to reduce the number of injuries to a lower level. To design protective measures, it is important to understand the mechanism of the response of human organs to such blast loadings. For this reason head models could be used to simulate such blast incidents.

1.4 Existing Head Models

Headforms have wide use mostly in the automobile industries as crash test dummies. In such usage, these models generally simulate and measure consequences due to head impact in automobile collisions. However, there have been few headforms developed and tested for the purpose of predicting blast loading response. Some of the instrumented head models which were studied before designing our headform are discussed in the following [40].
1.4.1 HYBRID III

General Motors developed the Hybrid III anthropomorphic test device (ATD) in 1973 for assessing automotive safety. The headform was good for rigid body kinematics simulation of the human head because of its similarity in mass characteristics with that of a human head. It had a flexible neck structure that could simulate the movement of the neck in response to loading. However, the model was not suitable enough for blast wave propagation cases because of its material choice. This ATD’s skull was manufactured from aluminum and the exterior skin from vinyl rubber. The response of aluminum to shock wave is not similar to that for skull because of the difference of material properties and wave propagation properties. Fig. 1.14 shows a 50th percentile Hybrid III headform.

Fig. 1.13 Hybrid III headform by General Motors [40].
1.4.2 MABIL HEADFORM

Manikin for Assessing Blast Incapacitation and Lethality (MABIL) headform was developed by DRDC Valcartier for evaluating personal protection measures against blast threats. It consisted of a solid urethane head with detailed ear and facial features and a simplified torso. The torso surrogate membrane is made from Shore A 70 (PU70) polyurethane. This viscoelastic material has been used in the past to represent the behavior of the human thorax under dynamic loading caused by behind-armor blunt trauma [41,42]. It contained a pressure sensor in the mouth and another in the ear canal, as well as a photo diode in its eye to measure light intensity of the blast. The model was compared with numerical simulation results. This model focused more on injuries in air-containing organs such as lungs, auditory system, and gastrointestinal tracts rather than any TBI assessment.

Fig. 1.14 (a) MABIL headform by DRDC Valcartier [40]; (b) the torso with the headform [42].
1.4.3 DERAMAN HEAD

The Dynamic Event Response Analysis Man (DERAMan) is another smart dummy head developed by UK Defence Evaluation and Research Agency (DERA). This head model was designed to suffer car crashes, boxing blows, sports collisions and firing from ejector seats [43]. Its flesh is made of a special polymer, the outer skin was custom made polyurethane, the skull of hard plastic and brain of another type of polyurethane. The head was fitted with 40 piezoelectric polymer pressure sensors located within the brain, 45 piezoelectric ceramic pressure sensors on the inner surface of the skull, two accelerometers and one three-dimensional force gauge for a total of 90 inputs. It has also been used for blast trials [40].

Fig. 1.15 DERAMan Headform by UK Defence Evaluation and Research Agency (DERA) [40].
1.4.4 JHU HEADFORM

The Applied Physics Laboratory (APL) of Johns Hopkins University is developing a headform to be tested under blast loading to evaluate protective capabilities of helmets. Little to no data has been published yet about this headform, but the initial prototype contains a head with a flexible neck attached to it. The instrumentation is being done to investigate pressure and acceleration response due to blast loading [44].

Fig. 1.16 The JHU Headform at the Applied Physics Laboratory of Johns Hopkins University [44].

1.5 The Approach of the Research

After a rigorous literature survey, it was possible to plan the research so as to discover more about this yet unknown blast TBI mechanism. The initial goal of this collaborative research was to know as much as possible about these mechanisms so that at the final stage it would be possible to improve the design of protective devices such as helmets to protect lives from IEDs.
The broad overview of this project covered the design of an instrumented surrogate head (named Realistic Explosive Dummy Head or RED Head) which would respond in blast loading in a way similar to a real human head. Then this dummy head would be tested in the shock wave generation facilities prepared for this collaborative research. Shock tubes are used to simulate free-field explosions in a laboratory environment. After the tests, the results would be validated with the numerical results obtained by another group. The analyzed results would be used to design helmets or other equipment for protection against IEDs and other explosion incidents.

For the material selection portion, the research was divided into several steps to facilitate obtaining valid data out of this yet unknown and complex phenomenon of blast TBI. As we find from the anatomy of human head, it is very complex to model every single detail. The initial target was to find the correct material for the skin or scalp, skull and, most importantly, brain. The cerebrospinal fluid (CSF) is composed mostly of water (99%) [45]. So it was decided to use water for modeling the CSF – especially in the later phases of the head model. The work plan for this research is presented below for better understanding.
Fig. 1.17 Work plan for the RED Head development. After this division, the research proceeded bottom to top to reach the final goal of developing the dummy headform.

The tests were performed on some selected materials which had potential to be close to tissue properties in the blast loading regime. The materials were modeled either as simple elastic or viscoelastic and the experimental results were fitted to these models. The data were also compared to the properties of the corresponding tissues obtained either from tests performed by another group of the collaborative research team or from available literature.
2 BRAIN SIMULANT MATERIALS: LOW FREQUENCY SCREENING TESTS

2.1 Material Selection

Choosing the proper brain simulant material for the headform was the biggest challenge for this project. As the main objective was developing better understanding about traumatic brain injury, the synthetic brain needed to be as close as possible to real human brain in terms of its properties in blast loading situations. Brain consists of several parts as shown in Figs. 1.1 and 1.7, and the mechanical and viscoelastic properties of these different parts vary. Simulating every single detail of the brain is a very complex job because of these dissimilarities, and for that reason it was decided to prepare the brain out of a single homogeneous material. With this constraint, the part of the brain containing the largest volume of tissue was considered as the one to be simulated by a synthetic material. That is, the properties of brain cortex including the gray matter and white matter was chosen to be matched. As we find from Tables 1.2 and 1.3 that the elastic and viscoelastic material properties for gray and white matter do not vary to a large extent, it seems sufficient to find a material having similar properties to either or both of these.

Initially to choose a pool of materials, some general properties of brain cortex were considered, such as that the material should exhibit viscoelastic behavior, it should not flow as a liquid (but may do so when shear load is applied), and it should not be brittle. Another consideration in this phase of material selection was that it should be easy to mold, as it would be placed inside the skull and preferably be molded into a shape similar to that of a human brain. Colloidal materials were chosen for brain simulants because of the similarity of such materials to biological tissues. We find such similarities from work by Fredberg et al. in 2007 where the biological cells’ fluidization behavior under application of shear has been compared to that for some inorganic
colloidal materials such as toothpaste, shaving foam, tomato ketchup etc. [46]. Gelatin and toothpaste were chosen to be tested because of being colloidal and their potential for having desired viscoelastic properties.

After choosing the materials, sample preparation was performed carefully. Soft materials are not easy to prepare as samples with accurate geometry and size because of the manifold problems related to their handling. Each type of test required a different size and shape of samples, and the sample preparation procedure is described in the corresponding sections.

The materials went through a process of screening according to their responses to applied low-frequency loading. As the response to blast waves is a very high frequency phenomenon, the final goal would be the materials’ responses at excitation frequencies as high as 1MHz. But it is not easy to analyze response of viscoelastic materials at such high frequencies. Also, the details of such responses are largely unknown, as most of the available literature on the testing of brain materials and their simulants covers much lower frequencies than 1MHz. So lower frequency loadings were performed as an initial approach so that the responses would be sure to have some similarity to the quasi-static responses, those being much easier to handle and compare. High-frequency tests were planned to be performed after a firm understanding was developed by performing the low-frequency tests.

### 2.2 Load Tests on Gelatin and Toothpaste

Gelatin and toothpaste were chosen as potential brain simulants for their colloidal nature. The first type of gelatin was a store-bought food product. It contained less than 2% carrageenan carob gum as an active ingredient. The second and third types were custom-made gels, and it was possible to vary the thickness and hence stiffness of the resultant gel by varying the concentration of the gelatin powder in the water solution. These gels are water based, which finds similarity
with brain matter’s water content. The toothpaste, also store-bought, had active ingredients of sorbitol, cellulose gum and PEG 32. This was also a water-based gel.

These materials went through cyclic loading of 1 Hz, 10 Hz and 40 Hz with displacement as input and load as output. The goal was to compare the input and output to understand whether the materials had any phase difference which would indicate their damping effect and hence enable quantifying their viscoelastic behavior.

2.2.1 SAMPLE PREPARATION

For the ready-made gelatin, a rectangular cross-section sample was cut. This sample was easy to handle because of its higher stiffness. The custom gels were prepared by mixing the powdered gel into boiling water and then cooling it in a conventional refrigerator. Then after 24 hours of cooling, the gel was collected and rectangular cross-section samples were cut. Plane surfaces were difficult to achieve for this type of gel as it was not as stiff as the first type of gel. Moreover, as the sample was collected from a refrigerated condition and tests were performed at room temperature, the samples degraded relatively quickly and lost their shape somewhat. The toothpaste sample was made as a square cross-section by mixing the gel and cutting it to shape.

2.2.2 TEST SETUP AND PROCEDURE

For the load testing of these materials, a BOSE ElectroForce® 3200 load testing device was used. The samples went through compressive loading in between two flat metal platens. The device applied displacement using its electromagnetic drive, and the load was recorded in the load cell with 225 N maximum load capacity. Fig. 2.1 shows the device, the samples attached to the platens along with the load cell, and ready-made gelatin from which rectangular samples were cut.
Fig. 2.1 (a) The BOSE ElectroForce® 3200 load testing device; (b) the load cell testing gel sample; and (c) the ready-made gel.

2.2.3 RESULTS AND ANALYSIS

From these tests, the low-frequency displacement of 1 Hz showed some tangible results, whereas the 10 Hz and 40 Hz frequencies showed results with less recognizable significance. In case of the ready-made gel at 1 Hz, the input and output both are very much in phase, and hence it shows elastic behavior or almost no viscous behavior. For the viscous element in the material, the output typically lags behind the input as the viscous element causes loss or dissipation of energy. The thicker custom-made gel showed a similar behavior for this 1 Hz case. However, the less thick custom-made gel possibly showed some appreciable viscous behavior, as we can see that its output is out of phase with its input. Rather than being a clean sinusoidal curve like the input, one can notice high-frequency noise in it. Because of such noise, or as the output does not show clean sinusoidal behavior, we could not derive acceptable results from this outcome. However, for the toothpaste as in Fig. 2.2 (a), the result was better and showed a clear sinusoidal output with a
phase lag. This included some noise too, but it was at such a level that the original sinusoidal waveform could be easily recognized. From the plot, we get that the value for $\tan \delta$ can be found as follows:

$$\tan \delta = \tan \left(\frac{2\pi \Delta t}{T}\right)$$

where $\Delta t$ is the time difference as in Fig. 2.2 (a), and $T$ is the time period.

From the plot, $\Delta t = 0.18$ sec, and $T = 1$ sec. So, we get $\tan \delta = 0.02$. The value of $\tan \delta$ indicates dynamic viscoelastic behavior of internal friction or mechanical damping. A zero value would indicate that the material is purely elastic. Based on this outcome, we can conclude that this material is viscoelastic.
The 10 Hz data for all the gels show very unusual waveforms for both input and output. For toothpaste, the waveform was closer to sinusoidal, and this showed a phase change as well. For 40 Hz, neither the input nor output exhibited any 40 Hz signal; rather, the signals were exhibiting lower values, e.g. 11 Hz, 18 Hz etc. The frequency range of the instrument was up to 200 Hz, so this failure of reaching the assigned frequency indicates inaccurate control, command or procedure followed while performing these tests.

The ready-made gelatin was quite stable at room temperature. It was observed that this gel starts degrading significantly after being in the open air at room temperature for about a week. However, the custom gels did not show good temperature stability, as they rapidly degraded (lost bulk stiffness) after being removed from the refrigerator. For both the high- and low-thickness samples, ramp load was applied, and the time and temperature data were recorded along with the
load cell’s load-deformation data. The relations between stiffness and temperature change were plotted. The refrigerator temperature for the gels was kept at 40 degrees Fahrenheit. The stiffness dropped very quickly after taking them out to room temperature. The room temperature was 74 degree Fahrenheit. During testing, the less thick gel warmed up to 71.5°F, and the thicker gel reached 69°F.

The processed data is presented below:

Table 2.1 Temperature degradation data for the low-thickness gel.

<table>
<thead>
<tr>
<th>Time, t (min)</th>
<th>Temperature, T (F)</th>
<th>Stiffness, E (K Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>69</td>
<td>0.1653</td>
</tr>
<tr>
<td>8</td>
<td>71</td>
<td>0.0809</td>
</tr>
<tr>
<td>28</td>
<td>71.5</td>
<td>0.1338</td>
</tr>
<tr>
<td>43</td>
<td>71.5</td>
<td>0.1072</td>
</tr>
<tr>
<td>63</td>
<td>71.5</td>
<td>0.0749</td>
</tr>
</tbody>
</table>

Fig. 2.3 Temperature degradation plots for low thickness gelatin: (a) stiffness - temperature plot (linear fitting); and (b) stiffness - time plot (quadratic fitting).
The first plot trend refers to the decrease of stiffness as the temperature increases. The temperature becomes steady at 71.5°F, whereas the stiffness keeps decreasing. The second plot trend shows the decrease in stiffness as time elapses. It was close to a logarithmic decrease, and the majority of the loss in stiffness occurred within 30 minutes.

Table 2.2 Temperature degradation data for the high-thickness gel.

<table>
<thead>
<tr>
<th>Time, $t$ (min)</th>
<th>Temperature, $T$ (°F)</th>
<th>Stiffness, $E$ (K Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>68</td>
<td>1.322</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>1.0256</td>
</tr>
<tr>
<td>18</td>
<td>70</td>
<td>0.9481</td>
</tr>
<tr>
<td>43</td>
<td>69</td>
<td>0.6814</td>
</tr>
<tr>
<td>73</td>
<td>69</td>
<td>0.6279</td>
</tr>
<tr>
<td>163</td>
<td>69</td>
<td>0.3507</td>
</tr>
</tbody>
</table>

Fig. 2.4 Degradation plots for high-thickness gelatin sample: (a) stiffness vs. temperature plot (linear fitting); and (b) stiffness vs. time plot (quadratic fitting).

In the case of the thicker gelatin, the stiffness decreases at a slower rate compared to the less thick gelatin. The temperature becomes steady at 69°F, whereas the stiffness keeps decreasing. Based
on the oscillation between 69 and 70°F, it appears that the resolution of the temperature measurement was about 1°F.

The second plot trend shows the loss of stiffness as time elapses. It was clearly a logarithmic decrease, and the majority of loss in stiffness occurred within 30 to 40 minutes.

### 2.3 Load Tests on Oil-Based and Alginate Samples

Ramp loading and stress relaxation tests were performed on a sample of sodium alginate gel and two oil-based mixtures. The gelling properties of alginate are dictated by its block structure. Alginate sources such as durvillea and ascophyllum species tend to be high in mannuronic acid and hence form softer gels, whereas laminaria hyperborea stems tend to have a higher guluronic acid content and hence form much more rigid gels [47,48]. This is helpful in preparing the gel according to the desired rigidity. The Young’s modulus of the gel is known to be proportional to the square of alginate concentration, which is also very useful to produce the desired gel to simulate human brain matter [49].

Oil-based mixtures were tested for stress relaxation. As water-based materials may have time-varying properties due to water loss through evaporation, the hypothesis was that oil-based mixtures or gels could serve better in this respect.

#### 2.3.1 SAMPLE PREPARATION

Alginate gel was prepared from calcium chloride and sodium alginate. The initial samples were alginate gel spheres with a maximum of 10 mm diameter. The spheres were cut carefully into cylindrical shapes as final samples. The tested sample had 1.5% sodium alginate. Samples with lower concentrations were too small in diameter to prepare adequate samples, so they were omitted from load tests.
Sample “CFOSG” was prepared using corn flour mixed with canola oil and then incorporating shaving gel in it. The mixture was kept inside a plastic pipe and then was extruded out into a cylindrical shape. Finally it was cut down to the desired height.

Sample “CFOT” was prepared the same way as CFOSG, but instead of shaving foam, gel toothpaste was used as the third ingredient.

2.3.2 TEST SETUP AND PROCEDURE

For these tests, the BOSE ElectroForce® 3200 load testing device was used, and the samples went through compressive loading in between two flat metal platens just as in section 2.2.2.

2.3.3 RESULTS AND ANALYSIS

For the ramp loading, creating up to 3.5% strain, a plot was obtained and Young’s modulus (with an assumption of elastic behavior) was found to be 6.4 kPa; this is still larger than the desired value corresponding to human brain matter. The overall result included a lot of noise in it, and it would be preferable to perform viscoelastic tests on this material rather than treating it as elastic. The fast degradation of the sample was the main barrier to performing any such test.
Sample CFOSG showed viscous properties to some extent, but it did not show good elastic behavior (there was some tendency towards viscoplastic behavior). Sample CFOT also showed viscous properties to some extent, but again it did not show good elastic behavior. While the displacement was linearly increased and then held fixed for a while (for both of these samples), the load seemed to drop gradually, which shows a trend of stress relaxation. However, this trend is misleading here because the cross-sectional area of the sample kept increasing as excessive strain (up to 20%) was applied. As a consequence of this, the stress value gradually decreased because of its inverse relationship with cross-sectional area of the sample.

Fig. 2.5 Ramp load test plot for 1.5% sodium alginate gel sample.
Fig. 2.6 Stress relaxation test for an oil based mixture: (a) strain vs. time; and (b) stress vs. time plots.
2.4 Initial DMA Tests

Dynamic mechanical analysis (DMA) was performed on some material samples to understand their viscoelastic behavior under loading in changing frequencies. The BOSE ElectroForce® 3200 load testing device was used, and the samples went through compressive loading in between two flat metal platens.

2.4.1 SAMPLE PREPARATION

Six materials were tested with DMA. The gelatin sample was cut from ready-made gelatin dessert. Two types of custom-made pudding samples were prepared. They contained albumin as an ingredient, which is a colloidal component and remains as the standard of comparison for colloids [50]. The two pudding samples were prepared such that their stiffness varied. Three oil-based mixtures were used – the first sample (CSO) contained corn starch and canola oil as ingredients. In the second one (CSOG), gluten was an additional component. The third one (GO) was only gluten with oil. After mixing the ingredients in a way such that the resultant dough would have desired stiffness close to the gelatin samples (as this stiffness was supposed to be close to brain matter’s stiffness), cylindrical samples with nearly 14 mm diameter were obtained by means of extrusion through a hollow cylinder.

2.4.2 TEST SETUP AND PROCEDURE

The BOSE ElectroForce® 3200 load testing device was used in these experiments. The integrated DMA software was used to directly plot storage modulus, loss modulus and the overall complex modulus as functions of applied frequency. The frequency was varied up to 200 Hz.
2.4.3 RESULTS AND ANALYSIS

The plots obtained from the tests are presented below:

(a) Plot for ready-made gelatin

(b) Plot for thick pudding
(c) Plot for thin pudding

(d) Plot for corn starch/oil sample
Fig. 2.7 DMA plots obtained from different materials to simulate brain matter.

The loss modulus values for some samples appear to gradually increase with frequency, but for some samples they entered the negative region, which indicated negative values for the viscous component which generally dissipates energy rather than storing or generating it. This behavior is very unusual, and for this reason the obtained data was not considered entirely trustworthy. The
storage modulus values for most of the samples remained in the negative region, which indicated releasing energy rather than storing, which is also a very unusual behavior. Although negative storage modulus values are available in literature [51], these were at very high frequencies (more than 15 MHz). Also, none of the available data on brain matter’s modulus indicate negative values. The hypothesis is that this is a software glitch. It was concluded that tests should have been performed in such a way so that the modulus values could be obtained step by step rather than using the software to directly get the plots. This approach would eliminate obtaining any result that is highly dependent on any possible default values or initializations used by the software which may not be relevant to our particular test conditions. Another important thing was that samples might have gone through high strains which resulted in such outcomes. The tests were done in compression, and for such materials, shear is a much better option to obtain high-quality results and compare with existing data in literature.

2.5 Rheometry Analysis

Five samples – one gelatin, two silicone gels and two corn starch based mixtures – were tested under shear loading created inside a rheometer. The strain level was kept very low so that obtained data would not enter a non-linear region, in which case it would be difficult to validate the data. The rheometer had the facility of maintaining a set temperature, which was utilized to perform tests at human body temperature in order to replicate in vivo human brain conditions.

2.5.1 SAMPLE PREPARATION

Corn starch samples were prepared using the same procedure as in section 2.4.1. The gel samples were cut into a cylindrical shape using a knife. Silicone gels came as two-part liquids and were
mixed thoroughly together and then cured at room temperature to solidify. For gel 527, the curing time was 1 week and for gel 3-4190, it was 24 hours.

2.5.2 TEST SETUP AND PROCEDURE

A rheometer from TA Instruments® was used, which had two parallel cylindrical metal platens to hold the material. The temperature was kept at 37.4 °C, which is typical human body temperature. Frequency was varied up to 90 Hz, and tests lasted for 194 seconds. Strain was kept within 0.01% to be comfortably inside the linear region. Dynamic shear modulus was obtained as the final outcome, and loss and storage shear modulus values came out from software calculations. Fig. 2.8 shows the rheometer and the sample placed on the rheometer.

Fig. 2.8 (a) The TA Instruments® rheometer with temperature control; and (b) placement of the sample in between the platens of the rheometer.
2.5.3 RESULTS AND ANALYSIS

Fig. 2.9 Storage shear modulus plots with frequency.

Fig. 2.10 Loss shear modulus plots with frequency.
From the plots, it is understandable that the pizza dough and corn starch mixture samples showed much higher stiffness values (two to three orders of magnitude) than the gels. From similar experiments performed by Brands in 2002, it can be found that for porcine thalamus tissue, the dynamic shear modulus value varies from 0.3 to 2 kPa on a frequency range of 0 to 100 Hz [14]. Here, the gels, especially gel 527 and gelatin, show this value from 0.4 to 3 kPa on a frequency range of 0 to 90 Hz. However, the thing that made these data not exactly comparable to that literature was that in our case the maximum allowed strain was 0.01% whereas in case of [14] it was 1%. Another important issue was the initial load applied to the specimen. The initial load was not consistent across all the samples; rather, different values were used for different material samples. Also, the silicone gel sample was not prepared with very high quality geometry, as the process to prepare nicely shaped samples for this type of gel had not been perfected at that time.
In the shear tests performed later, this problem was solved by preparing silicone gel samples with consistent and uniform shape and size. It should be mentioned here that the silicone gels were very hard to cut by knife because of their stickiness. For this reason, the samples contained irregular surfaces and uneven geometry. From this experiment, the corn starch and pizza dough samples were eliminated from the list of potential as brain simulants, as the data suggested undesirably high stiffness values. At this point, the materials which were still showing potential were gelatin and the two types of silicone gels, especially gel 527.

2.6 Step Response Analysis

A method of finding material properties was developed using the principles of step response analysis. A constant load was applied to the sample material, causing decaying oscillation in the material. This step response represents both the elastic and viscous properties of the material, and it is possible to find these individual components by comparing the experimental values with mathematical models. For this reason a mathematical model was developed with spring, mass and damper components. Linear simulation and nonlinear optimization were performed on this system to find out correct viscous and elastic component values for the materials in the experiment using the assumption of a standard linear viscoelastic solid. Four types of materials were used in these experiments – pizza dough, corn starch dough, gelatin and silicone gel.

2.6.1 SAMPLE PREPARATION

Pizza dough and corn starch dough samples were cut out of the bulk dough by means of a cylindrical cutter or punch. The surface were made as smooth as possible for better experimental results. The samples tended to deform very quickly under their own weight and go from the actual cylindrical shape into a more tapered shape. So tests were performed as soon as possible after the sample preparation. Also these samples were desiccating, so the curved surfaces of the
samples were covered by pieces of paper soaked in water. Gelatin samples were cut out from the ready-made gelatin. These samples were more stable and retained their shapes for a long time. This was true for the silicone gel samples too. Silicone gel samples were prepared in a special procedure because of their adhesive behavior which obstructed the cutting out of the sample from bulk. First of all, 1-inch diameter aluminum cylinders were prepared and were wrapped with tape to hold the gel inside. The two parts of the gel mixture were added and mixed thoroughly together. A release agent was sprayed inside the holder so that it would be possible to release the sample out of it. Gel solution was poured inside up to certain level, and it was kept at room temperature to cure it over the course of a week. The tape was then peeled off to get the cylindrical silicone gel sample ready to be tested. Fig. 2.12 shows two silicone gel samples prepared in this manner.

Fig. 2.12 Silicone gel samples prepared on aluminum cylinders.

2.6.2 TEST SETUP AND PROCEDURE

The final setup for this test was very simple but achieved good accuracy. In the initial tests, a cylindrical metal weight was touching the upper surface of the sample and then was released on
the sample manually to initiate the step response procedure. This method was not accurate, as observed from the ARAMIS® high-speed video system. Stickers with white dots were put on the front surface of the weight to track its movement at different points. ARAMIS® setup required the calibration of the position of the sample by adjusting the distance between the sample and video cameras. Two cameras were used and kept at an angle relative to each other to capture three-dimensional perspective. The movement of the weight on the sample should have been perfectly vertical, as this was intended to be a uniaxial test. But in this setup, the markers moved in all three dimensions, indicating the possibility of errors in the results based on unwanted reaction forces in the material. Fig. 2.13 shows the initial procedure with the unwanted movement.

Fig. 2.13 The primary setup for step response test of gelatin and the vertical displacement reading captured by ARAMIS® video system.
Because of this limitation, the system was upgraded by designing a weight that could be tied to a string and held up by a clamp. Two weights of the same dimensions were prepared from steel and aluminum to vary the weight. It was first decided to insert the weight through a linear ball bearing as depicted in Fig. 2.14. But it was found from experiments that this bearing made the direction one dimensional at the cost of free movement of the weight. The weight experienced friction too high to be neglected, which caused an alternate procedure to be sought.

![Fig. 2.14 (a) The linear ball bearing CAD model; and (b) the weight setup with the linear ball bearing.](image)

A very simple but improved procedure was developed to maintain the one-dimensional movement of the weight on the sample. The weight touched the upper surface of the sample while hanging from the clamp by a cotton string. Then the string was set on fire so that it became suddenly disconnected and thus initiated the free movement of the weight on the sample in the vertical direction. The string was not cut by any mechanical tool because that could induce motions in off-axis directions. The ARAMIS® video showed that this system was much better
than the previous one and produced cleaner response data. Fig. 2.15 shows the upgraded test setup and the camera positioning.

Fig. 2.15 (a) Upgraded test setup for step response analysis; and (b) ARAMIS® cameras ready to take video.

2.6.3 RESULTS AND ANALYSIS

A sample plot acquired directly from ARAMIS® is provided in Fig. 2.16. This shows the captured image of the weight on the sample and the obtained displacement plots for some of the points on the weight. In this case, three reference points were chosen on the weight.
Fig. 2.16 The improved setup for step response test of gelatin and the vertical and transverse displacement reading captured by ARAMIS® video system.

To find the material properties, these plots can be compared to a mathematical model believed to describe the same system. So, a third-order mathematical model was proposed that could be depicted as in Fig. 2.17(a). The step response produced from a model like this can be expressed as in Fig. 2.17(b). This can express the movement of the weight on the viscoelastic material samples. By adjusting the values of the model components, the simulated curve is reshaped.
Fig. 2.17 (a) The linear model of the third-order system; and (b) step response from the model.

The model was described mathematically as follows:

A vertical downward (weight) force is applied to the mass component $m$, with two springs having spring indices $k_r$ and $k$ and a damper with damping coefficient of $c$, with element interconnections as shown in Fig. 2.17(a).

The displacements for springs $k_r$, $k$ and damper $c$ are described by $x$, $y$ and $z$ respectively. We can write for these displacements:

$$ x = y + z $$

$$ \dot{x} = \dot{y} + \dot{z} $$

$$ c\dot{z} = ky $$

.......... (1)
Also, from boundary conditions,

\[ \dot{x}(0) = 0 \]

\[ \ddot{x}(0) = 0 \]

\[ \dddot{x}(0) = 0 \]

From force balance in the components, we find:

\[ ky + k_x x + m \dddot{x} = m g \]  \hspace{1cm} (2)

From (1),

\[ c \dddot{z} + k_x x + m \dddot{x} = m g \]

\[ F = m g \]  \hspace{1cm} (3)

From (2),

\[ y = \frac{1}{k} \left[ mg - k_x x - m \dddot{x} \right] \]

\[ \dot{y} = \frac{1}{k} \left[ -k_x \ddot{x} - m \dddot{x} \right] \]

From (3),

\[ c \dddot{z} + k_x x + m \dddot{x} = m g \]

\[ c \left( \dddot{x} - \dot{y} \right) + k_x x + m \dddot{x} = m g \]

\[ c \dddot{x} - \frac{c}{k} \left[ -k_x \ddot{x} - m \dddot{x} \right] + k_x x + m \dddot{x} = m g \]
Taking the Laplace transform of both sides of Equation (4), we get:

\[ F(s) = \frac{mc}{k} s^3 X(s) + ms^2 X(s) + \left( c + \frac{ck_r}{k} \right) s X(s) \]

So the transfer function is:

\[ TF = \frac{X(s)}{F(s)} = \frac{1}{\frac{mc}{k} s^3 + ms^2 + \left( c + \frac{ck_r}{k} \right) s + k_r} \]

Now, this was considered as the mathematical model to which the experimental curve should be fitted. The value for the mass, m was constant (the weight made of aluminum was used). (Because of the material’s mass, that value of m was slightly lower than the effective mass in this case.) Using this final equation on a linear system simulation and using a nonlinear optimization routine in Matlab®, values of m, kₐ, k, and c were found. These values represented the stiffness and viscosity components for the material model. “fmincon” optimization routine was used where the values of the variables were minimized to target values where the linear simulation plot would fit the experimental plot. The upper and lower bounds for this minimization routine were set in such a way so that the minimized values would fall in relevant ranges. The variable values were scaled so that they could be used both in the function prepared for linear simulation and the function containing the experimental data. In one function the values were scaled whereas in the other one it was scaled back to the original. The outcome of curve fitting for the four types of samples is presented below.
2.6.3.1 Sample: Pizza Dough

For this sample, the viscosity index was high, which resulted in fast damping. The value of $k_r$ was found from the steady-state response value, as that represented the single spring component in the model. The material underwent a moderate maximum strain of $8.17\%$. The steady-state strain was the same as the maximum strain. We can observe the outcomes in Table 2.3 and Fig. 2.18.

Table 2.3 Step response test data for pizza dough sample.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>$k_r$</th>
<th>Optimized values</th>
<th>Height of sample (mm)</th>
<th>Maximum displacement (mm)</th>
<th>Maximum strain</th>
<th>Steady State (mm)</th>
<th>Steady state strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.69</td>
<td>120.71</td>
<td>32.74</td>
<td>429.36</td>
<td>0.0480</td>
<td>1.05</td>
<td>0.0817</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Fig. 2.18 Linear simulation plots for pizza dough sample.
2.6.3.2 Sample: Corn Starch Dough

Corn starch dough showed less viscous behavior compared to the pizza dough sample. It showed a slightly higher value for the spring in series with the damper. Maximum and steady-state strain values were 5.48%. It did not show any overshoot, just like the pizza dough sample, but had less damping effect.

Table 2.4 Step response test data for corn starch dough sample.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>k_r</th>
<th>Optimized values</th>
<th>Height of sample (mm)</th>
<th>Maximum displacement (mm)</th>
<th>Maximum strain</th>
<th>Steady State (mm)</th>
<th>Steady state strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.69</td>
<td>191.13</td>
<td>5.25 500 0.0580</td>
<td>10.95 0.6 0.0548</td>
<td>0.6 0.0548 0.6 0.0548</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2.19 Linear simulation plots for corn starch dough sample.
2.6.3.3 Sample: Gelatin

The ready-made gelatin was tested for its step response, and this showed low viscosity or damping effect. For this, the motion appeared more vibratory than the previous two samples even though the optimized value for \( k \) was much lower. The lower value of \( c \) compensated for that value. The strain was higher than the previous two samples, and maximum strain reached up to 11.06\%, whereas the strain at steady state was 10.09\%. The value of \( m \) was much more dominant than for any other tested samples.

Table 2.5 Step response test data for gelatin sample.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>( k_r )</th>
<th>Optimized values</th>
<th>Height of sample (mm)</th>
<th>Maximum displacement (mm)</th>
<th>Maximum strain</th>
<th>Steady State (mm)</th>
<th>Steady state strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.69</td>
<td>143.35</td>
<td>2.70 92.27 0.0985</td>
<td>7.93</td>
<td>0.88</td>
<td>0.1106</td>
<td>0.80</td>
<td>0.1009</td>
</tr>
</tbody>
</table>
2.6.3.4 Sample: Silicone Gel (Gel 527)

Silicone gel showed higher viscosity than the gelatin but less than the pizza and corn starch dough samples. The mass effect was comparable to that for the first two samples. The mass was supposed to be the effect of the mass inserted plus the effect of the sample’s mass. However, the optimized values (showed in kg in tables) were much higher than those values. Further investigation is required to elucidate this phenomenon. From the plots, it is obvious that there was no overshoot like that observed with the gelatin sample. Strain in maximum displacement and steady-state were 10.02%.

Fig. 2.20 Linear simulation plots for gelatin sample.
Table 2.6 Step response test data for silicone gel sample.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>k</th>
<th>Optimized values</th>
<th>Height of sample (mm)</th>
<th>Maximum displacement (mm)</th>
<th>Maximum strain</th>
<th>Steady State (mm)</th>
<th>Steady state strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.69</td>
<td>76.45</td>
<td>7.44</td>
<td>379.83</td>
<td>0.048</td>
<td>14.97</td>
<td>1.50</td>
<td>0.1002</td>
</tr>
</tbody>
</table>

Fig. 2.21 Linear simulation plots for silicone gel sample.
3 **BRAIN SIMULANT MATERIALS: HIGH-FREQUENCY SCREENING TESTS**

3.1 Final DMA Tests

After the low-frequency screening tests, it appeared that silicone gels were the best possible options within the availability of the tested materials. To confirm the viscoelastic properties of the silicone gels, they went through a series of dynamic mechanical analyses (DMA). The tests were performed in compression and shear. Data were obtained using a frequency sweep. The storage and loss modulus values for both compression and shear were recorded. The two types of silicone gel samples were prepared by performing room temperature curing (which was a slower process) and high temperature curing (a faster process) to investigate the difference in material properties due to these two different processes. They were also tested for different amplitudes of oscillations and different pre-load values. Later, two other types of silicone gel samples were prepared by varying the stiffness to match its properties closer to that of human brain matter. All the test results are presented below with resulting analysis of the obtained plots.

3.1.1 SAMPLE PREPARATION

The silicone gel (from Dow Corning®) samples were prepared as 3-4.5 mm thick and 12.5-14 mm diameter cylinders. A special procedure was followed to prepare nicely shaped samples for obtaining accurate results. Silicone gel solution was prepared by thoroughly mixing the two parts of the gel solution (A and B). Aluminum cylinders were prepared having one-inch diameter with one surface polished using sandpaper and alumina polish. This was done so that the gel sample would have a smooth surface finish. The cylinder was wrapped with heat resistant tape in such a
way so that it could hold the liquid solution. A release agent was sprayed inside the holder, and gel solution was poured in to a level of 3-4.5 mm. For room temperature curing, it was set aside to cure at approximately 70°F, whereas for high temperature curing, it was heated inside an oven up to a certain temperature (150°C) which was kept constant for a specified length of time depending on the type of the gel (35 minutes for gel 527 and 4 minutes for gel 3-4190). After curing, half-inch diameter samples were cut from the one-inch diameter gel sample using a custom-made cutter that was very similar to a biopsy punch which is generally used to cut soft tissue. Fig. 3.1 shows the copper biopsy punch, samples being cured and the cut-out samples.

![Image of biopsy punch and gel samples](image.png)

(a) (b)

Fig. 3.1 Sample preparation for DMA analysis: (a) biopsy punch and curing samples; and (b) samples ready for testing. The two solutions can be seen at the background; those were mixed to prepare the gel solution.

3.1.2 TESTS ON ROOM TEMPERATURE CURED GEL 527 IN COMPRESSION

The compression tests on room temperature cured gel show a gradual increase in the storage modulus until 100 Hz and then a sudden drop. Loss modulus shows nearly exponential rise with the increasing frequency. For both modulus values, pre-load variation does not show any significant difference in those outcomes.
Fig. 3.2 DMA compression test: storage modulus plots for room temperature cured gel 527.

Fig. 3.3 DMA compression test: loss modulus plots for room temperature cured gel 527.
3.1.3 TESTS ON ROOM TEMPERATURE CURED GEL 527 IN SHEAR

In the case of shear, the room temperature cured gel 527 shows a gradual increase of shear modulus until 100 Hz and then a sudden rise. This set of data was obtained only for one oscillation displacement magnitude, but later shear tests were performed for multiple values.

Fig. 3.4 DMA shear test: storage shear modulus plots for room temperature cured gel 527.
3.1.4 TESTS ON HIGH TEMPERATURE CURED GEL 527 IN COMPRESSION

The pre-load on the samples was varied for performing the compression tests, and the responses were recorded and plotted to understand the comparison among them. The pre-load was from 0.1-0.5 N with 0.1 N intervals. From the gel 527 plots, it is obvious that for storage modulus, the value goes up with pre-load. This increment occurred up to about 100 Hz, but after that the values fell sharply. Loss modulus showed almost exponential rise with frequency in the entire range.
Fig. 3.6 DMA compression test: storage modulus plots for varying load condition for gel 527.

Fig. 3.7 DMA compression test: loss modulus plots for varying load condition for gel 527.
3.1.5 TESTS ON HIGH TEMPERATURE CURED GEL 527 IN SHEAR

The oscillation amplitude was varied to find out how this affected the modulus values. The amplitudes used were 1, 2, 5 and 10 µm. These values did not show any specific trend for any of the gels. For low frequencies, the modulus values showed similarity, while for high frequencies they showed some differences but without following any relation that could be clearly discerned from these plots. The storage modulus values remain nearly constant until 40 Hz and then a rise is observed. At very high frequencies, a sharp rise is observed. The fall of a data point below zero could be due to an irregularity in the sample or to DMA software-related issues at high frequencies. For loss modulus, the values are also constant until 40 Hz and then they rise pretty consistently at higher frequencies.

Fig. 3.8 DMA shear test: storage shear modulus plots for high temperature cured gel 527.
Fig. 3.9 DMA shear test: loss shear modulus plots for high temperature cured gel 527.

3.1.6 TESTS ON ROOM TEMPERATURE CURED GEL 3-4190 IN COMPRESSION

For room temperature cured gel 3-4190, the storage modulus values for compression show gradual increase and then suddenly drop after 100 Hz. Loss modulus values show near-exponential increase across the whole frequency range.
Fig. 3.10 DMA compression test: storage modulus plots for room temperature cured gel 3-4190.

Fig. 3.11 DMA compression test: loss modulus plots for room temperature cured gel 3-4190.
3.1.7 TESTS ON ROOM TEMPERATURE CURED GEL 3-4190 IN SHEAR

In shear, this gel showed constant values both for storage and loss modulus up to about 70 Hz, but then a sudden fall followed by a sudden rise are observed for storage modulus, and a logarithmic-type increase for loss modulus. The fall of the data point below zero could be due to DMA software issues while handling high frequencies, or irregular response of the sample at those frequencies.

Fig. 3.12 DMA shear test: storage shear modulus plots for room temperature cured gel 3-4190.
3.1.8 TESTS ON HIGH TEMPERATURE CURED GEL 3-4190 IN COMPRESSION

These tests show gradually increasing values of storage modulus with frequency. The very low modulus for 0.1 N preload may represent possible errors in the experiment, which may be true for certain loss modulus values too. The loss modulus shows near exponential increase, except for a few data points displaying unusual deviation from this trend.

Fig. 3.13 DMA shear test: loss shear modulus plots for room temperature cured gel 3-4190.
Fig. 3.14 DMA compression test: storage modulus plots for high temperature cured gel 3-4190.

Fig. 3.15 DMA compression test: loss modulus plots for high temperature cured gel 3-4190.
3.1.9 TESTS ON HIGH TEMPERATURE CURED GEL 3-4190 IN SHEAR

Two pre-loads (specific values unrecorded) were used to obtain shear modulus values in this case. Storage modulus displayed very slow increase up to 100 Hz followed by a sudden rise and some unusual values between 100 and 200 Hz. Loss modulus values remain constant until 40 Hz and then show sudden rises and falls. This unusual behavior can again be due to DMA software-related issues as in some of the previous tests and in the initial DMA analyses discussed in Chapter 2.

![Storage Shear Modulus for High Temperature Cured Gel 3-4190](image)

Fig. 3.16 DMA shear test: storage shear modulus plots for high temperature cured gel 3-4190.
3.1.10 TESTS ON ROOM TEMPERATURE CURED GEL 16.67 IN COMPRESSION

Gel 16.67, prepared by mixing 16.67 volume % of “200 fluid” with gel 527, was cured at room temperature and tested for compression. The storage and loss modulus values showed very slow increase with frequency. Storage modulus values rose quickly after about 100 Hz and then showed a sharp fall, probably because of software issues handling high frequencies. Loss modulus values increased almost exponentially after about 30 Hz. Pre-loads used in these experiments were 1, 2 and 5 N.
Fig. 3.18 DMA compression test: storage modulus plots for room temperature cured gel 16.67.

Fig. 3.19 DMA compression test: loss modulus plots for room temperature cured gel 16.67.
3.1.11 TESTS ON ROOM TEMPERATURE CURED GEL 16.67 IN SHEAR

In the case of shear, both storage and loss modulus showed steady values until nearly 100 Hz, and then they showed unusual values for high frequencies as discussed in the previous sections. Oscillation amplitudes were varied as 1, 2, 5 and 10 µm.

Fig. 3.20 DMA shear test: storage shear modulus plots for room temperature cured gel 16.67.
3.1.12 TESTS ON ROOM TEMPERATURE CURED GEL 25 IN COMPRESSION

Gel 25 was prepared by mixing 25 volume % of “200 fluid” with gel 527 and was cured at room temperature. Pre-loads of 1, 2 and 5 N were used. Compression tests on this sample showed behavior very similar to gel 16.67. Even the values obtained for 5N pre-load were higher, just as for gel 16.67.

Fig. 3.21 DMA shear test: loss shear modulus plots for room temperature cured gel 16.67.
Fig. 3.22 DMA compression test: storage modulus plots for room temperature cured gel 25.

Fig. 3.23 DMA compression test: loss modulus plots for room temperature cured gel 25.
3.1.13 TESTS ON ROOM TEMPERATURE CURED GEL 25 IN SHEAR

Tests performed for shear on gel 25 provided similar results to gel 16.67 too, with oscillation amplitudes of 1, 2, 5 and 10 µm. However, the values obtained for 1 µm amplitude displayed some deviation from the trends followed by other values.

Fig. 3.24 DMA shear test: storage shear modulus plots for room temperature cured gel 25.
Fig. 3.25 DMA shear test: storage shear modulus plots for room temperature cured gel 25.

3.1.14 COMPARISON OF THE RESULTS

The resultant values of the storage and loss modulus both for compression and shear for the two types of silicone gels cured at room and high temperature and two thin gels cured at room temperature can be presented graphically as Fig. 3.26. These data were also compared in this chart to the real human brain data found in the literature [52]. It can be concluded from this comparison that the modulus values obtained by means of compression are much higher than those obtained by shear and also than the available value for human brain in the literature. In the case of shear, the room temperature cured “Gel 527,” both types of “Gel 3-4190” and the thin gels show close modulus values with the values for human brain. By preparing brain simulant materials having lower modulus values than these obtained values as in the case of gel 16.67 and gel 25, it was possible to match these modulus values to those for human brain. For this reason,
the existing silicone gel was mixed with another gel from Dow Corning® (called “200 fluid”) with less thickness. This mixing was performed in two different ratios to understand the effect of the “200 fluid” and the new gels were tested for DMA analysis to find the storage and loss modulus values. Both of these new gels showed modulus values close to those of human brain tissue. Especially in shear, the modulus values were much lower than those in compression, and these values were promising for simulating human brain.

![Comparison of Storage and Loss Modulus for Brain Simulants](image)

Fig. 3.26 Comparison of the storage and shear modulus values for different brain simulant materials as obtained from final DMA analysis. All the values are for the frequency of 90 Hz. Human brain data obtained from [52].

### 3.2 Ultrasonic Vibration Analysis

To test the response of the brain simulant materials at even higher frequency, it was decided to use ultrasonic vibration and analyze the data accordingly. The principle was to send ultrasonic vibration through the material and find out the material properties by analyzing the wave
propagation properties through that specific material. As the materials were soft, it was not possible to test these materials like other solids. The placement of the probes on the surface of these soft materials could result in non parallel surfaces for the probes, which is not desired. So a test setup was designed and prepared to solve this problem. This consisted of two aluminum blocks with a sandwiched layer of soft brain simulant material inside them. The lengths of the blocks were such that there would be a minimum of noise due to reflections of the ultrasonic waves on the surfaces of the blocks. The widths were also sufficient to reduce noise by allowing enough space to hold the probes. The blocks were first placed on a polycarbonate plate, and then the two sides of the gap were covered using adhesive tape. A release agent was sprayed and placed thoroughly on the inner surfaces so that the setup can be reused after each experiment. The uncured liquid gel solution was poured inside the gap. The gel was cured for one week. Then the tape was removed and the setup was ready to be used in the experiments. Fig. 3.27 shows the experimental setup for these tests.

![Fig. 3.27 Test setup for ultrasonic vibration analysis of brain simulant materials.](image)

The working principle of this setup was such that for either the pulse-receiver or pulse-echo technique, it would be possible to collect data with the two aluminum blocks having the gel layer
inside. Then the data would be collected for only one aluminum block to get the ultrasonic wave propagation properties in the aluminum. The first data would contain information for both the two aluminum blocks and the gel, from which the aluminum’s portion would be deducted to find material properties of the silicone gel brain simulant material, which is the desired outcome of this experiment. Data were collected for this experiment using different frequencies, and also for transverse and shear cases. However, the experiment needs more improvements to acquire meaningful results. This is because even it is possible to see the clear peaks in these plots, it is hard to discern one peak from another to find which peak belongs to which material interface. The limitation was in the experimental set up that had several material interfaces. Due to these interfaces, reflection of ultrasonic waves occurred and they contaminated the actual data. However, we can interpret the results from the peaks and their distances to some extent. The procedure of finding the material properties is discussed below. Sample plots from the tests are provided in Figs. 3.28 and 3.29.
Fig. 3.28 (a) Ultrasonic vibration plot for pulse-echo technique for gel 527 at 10 MHz; and (b) a closer view of the waveforms.
Fig. 3.29 Ultrasonic vibration plot for pulse-receiver technique for gel 527 at 10 MHz; and (b) a closer view of the waveforms.

Fig. 3.30 Peak identification for pulse echo technique.
For the pulse echo technique, signal #1 refers to the first peak reflecting back from the first aluminum-gel interface. Signal #2 refers to the signal reflected back from the second interface and signal #3 refers to the reflection from the end of the aluminum block. Knowing this from the chart, we can read meaningful data out of the plots. The formula for finding wave speed propagation speed through the materials is:

\[
\text{Wave speed} = \frac{2 \times \text{material thickness}}{\text{time}}
\]

Using this and the data for Fig. 3.28, we can interpret that for the first peak, approximate wave speed is:

\[
\text{Wave speed (aluminum)} = \frac{2 \times (101.6 \times 10^{-3})}{(53.72 \times 10^{-6})} \text{ m/s} = 3782 \text{ m/s}
\]

which is much lower than the speed of sound in aluminum, that is, 4877 m/s.

The second peak (a smaller peak because of damping of the signal in soft material) could possibly represent signal #2. In such a case, as we know that time taken to travel through twice the length of the aluminum block is: \(53.72 \times 10^{-6}\) sec. Deducting that time from the time for signal #2, we get the time for the ultrasonic wave to travel through the thickness of the gel twice, which is in this case \((61.35 - 53.72) \times 10^{-6}\) sec. or \(7.63 \times 10^{-6}\) sec. Using this, the wave speed through gel can be found as

\[
\text{Wave speed (gel)} = \frac{2 \times (9.8 \times 10^{-3})}{(7.63 \times 10^{-6})} \text{ m/s} = 2568.81 \text{ m/s}.
\]

This result is between the range of the wave propagation speed of aluminum (4877 m/s) and water (1433 m/s) which is possible. However, the uncertainty in this test procedure should be reduced so that we can obtain a dependable value for the wave propagation speed through the gel.
The pulse echo data obtained so far has some problems related to time synchronization of the pulser and receiver. But the working principle is explained by Fig. 3.31 as follows.

![Diagram of Fig. 3.31](image)

**Fig. 3.31 Peak identification for pulser-receiver technique.**

### 3.3 Summary

In this chapter, the high frequency tests were performed using DMA (up to 3 kHz) and ultrasonic vibration (up to 10 MHz). The DMA results were compared to available literature and the silicone gels’ properties were controlled to a level to match this value. In the case of gel 3-4190, both the room temperature cured and high temperature cured gels showed closeness to this literature value. By mixing the thinner gel, this value was even closer for shear. Thus, it can be decided that gel 16.67 and gel 25 are the best gels to be used in the RED Head at this moment. So far, these thinner gels were prepared using only gel 527, but it is possible to prepare such gels using gel 3-4190 too, and this would be a time saving process as this gel cures much faster than gel 527.
Both the storage and loss modulus values went to the negative region as seen from some of the DMA plots. This indicates that this DMA data was not dependable in those cases. It was hypothesized that the DMA software could not handle the calculation for higher values of frequency. Another possible explanation is that because the models assumed within the DMA software do not take mass into account, the resonances resulting from mass in the system lead to the erroneous modulus values at certain values or ranges of frequency. This seems to make sense in terms of the physics of the experiment. In any case, a more dependable solution could be found by analyzing the raw data from the experiment rather than depending on the software to calculate and plot modulus values directly.

The modulus values were much higher in the cases for compression than that for shear. This was also true for the DMA analysis of pig brain performed by Thomas Boulet of the Engineering Mechanics Department at the University of Nebraska-Lincoln as a part of this collaborative research. But all these tests were performed only once, which poses uncertainty in the test data. More tests should be performed to validate the repeatability of this analysis and to establish confidence intervals for the modulus values.

Another conclusion is that, as the literature values for modulus vary to a great extent, it is not wise to take any one of them as being absolutely valid. Rather, one should remain aware that in the case of real brain, these values could be anywhere in this range. For the time being, it is acceptable to perform all the tests taking one set of modulus value for human brain matter as a target value. In this sense, the relative magnitudes of loss and storage modulus for each material are of interest rather than the value of the two parameters separately.

From the ultrasonic tests, it is impossible to come to a decision of choosing a best gel. This portion of this thesis should motivate additional research - firstly, to establish a better and
dependable experimental process, and then perform tests on different gels to finally choose a better gel for simulating human brain matter at high frequencies.
4 DEVELOPMENT OF THE INSTRUMENTED HEAD MODEL

4.1 Skull Development

Choosing the right material and geometry was the main challenge in developing a skull that would be used as an important component of the RED Head. The skull should not only represent a real human skull properly, but also its geometry should allow the artificial brain to be inserted along with the sensors array. For the first version of the headform, a skull was used which lacked some of the desired features. However, for the final version, more care was taken by considering the necessary material properties and geometry.

4.1.1 THE INITIAL VERSION OF THE SKULL

The available literature suggests that target skull material properties are: 1.4 gm / cm$^3$ density, Young’s modulus of 3.2 – 4.5 GPa and bulk modulus of 4.8 GPa [53]. The initial version of the head model was prepared from dense urethane foam having two pieces of skull approximately symmetric about the sagittal plane. The skull material properties were not very close to the desired values. But the geometry was like a real human skull which was one of the reasons of using this for the headform. Fig. 4.1 shows the two-piece skull.
Fig. 4.1 The two piece dense foam skull: (a) the two-pieces of the skull; and (b) side view of the skull with bolts and clamp attached at the back.

The comparison of the target and actual properties can be found in Table 4.1:

Table 4.1 Comparison of material properties of a real human skull and dense foam skull model.

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cc)</th>
<th>Young's Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired</td>
<td>1.4</td>
<td>3.2-4.5</td>
</tr>
<tr>
<td>Actual</td>
<td>0.8</td>
<td>2.9</td>
</tr>
</tbody>
</table>

It is obvious from the table that the dense foam skull had limitations of not being accurate in its material properties. Moreover, it was a two-piece skull which is not good enough to be tested under blast loading because the different materials and interfaces involved could change how the shock waves propagate. This could lead to error in the results. Also, the skull could be clamped from behind which is not identical to a human head that is supported by means of the neck. Due to such limitations, a new skull model was prepared to be used in the final version of the RED Head.
4.1.2 THE FINAL VERSION OF THE SKULL

The final version of the RED Head consisted of a molded polyurethane one piece skull. This skull was not as detailed as the previous version in its geometry, but it was expected to have better material properties, being a one-piece skull, it could offer more consistency in the propagation of shock waves through it into the brain model. This skull had a stainless steel base plate which could be bolted into the bottom of the skull. The plate contained silicone rubber gasket to offer resistance against fluid leakage. This is an advantage, as now it would be possible to insert cerebrospinal fluid simulant inside to offer the head model with more similarity to a real human head. Another feature of the base plate was that it could be connected to a flexible neck structure which is generally used for crash test dummies. Incorporation of such a neck structure would give the head a flexible movement in front of a shock wave.

![One piece polyurethane skull](a) ![Bottom view of the skull](b)

Fig. 4.2 (a) One piece polyurethane skull; (b) the bottom view of the skull.

4.1.3 DMA TESTS ON FINAL VERSION SKULL MATERIAL

Dynamic mechanical analysis was performed on the polyurethane skull simulant material.
4.1.3.1 Compression Tests

For the compression tests, pre-load values were varied as 0.5, 1, 2 and 5 N. From overall results, it can be seen that the storage modulus slowly increases with frequency until about 80-100 Hz, and then it goes up suddenly, which may be because of mass-resonance effects or software error at higher frequencies as discussed in section 3.3. Loss modulus values remain more or less constant throughout the entire range of frequency. But the pre-load increment increases both the modulus values.

![Storage Modulus for Polyurethane Skull Material in Compression](image)

Fig. 4.3 DMA analysis in compression: storage modulus for polyurethane skull material.
4.1.3.2 Shear Tests

In case of shear modulus, the storage modulus increases gradually with frequency while the loss modulus remains more or less constant. From around 90 Hz, the erroneous results (the cause of this is as discussed in section 3.3) start to show up.
Fig. 4.5 DMA analysis in shear: Storage shear modulus for polyurethane skull material.

Fig. 4.6 DMA analysis in shear: Loss shear modulus for polyurethane skull material.
4.2 Skin Development

The initial head model did not have any skin, but the final one had a two-piece skin made of polydimethylsiloxane (PDMS) – a silicon-based organic polymer. The larger part of the skin covered the cranium, face and neck, and it was attachable-detachable over the one-piece skull. The smaller part of the skin was glued at the back of the skull covering mostly the occipital bone area. The average thickness of the skin was 7 mm, which is consistent with the 5-7 mm scalp thickness as of section 1.2.1. Fig. 4.7 shows the PDMS skin.

The skin was painted with white spray paint, and then black dots were painted on it. The reason for doing so was to enable three dimensional displacement measurement of the head by means of a high-speed and high-resolution video system known as ARAMIS®. The skull could be inserted into the skin through the opening at the back side as seen in fig. 4.3 (c). The holes provided under each of the ears facilitate insertion of the pin that would attach the skull with the neck. Its eyes
were open i.e., two holes were provided in place of the eyes but there was no ear cavity, mouth opening or nasal cavity.

4.2.1 DMA ANALYSIS ON SKIN MATERIAL

The DMA analysis for skin material was performed for both compression and shear.

4.2.1.1 Compression Tests

In these tests, pre-load was kept as 0.1, 0.2, 0.5, 1 and 2 N. For both storage and loss modulus, the trend was gradual increment with frequency. This material showed much more consistent values even in higher frequencies. Both the modulus values increased significantly with increasing pre-load.

Fig. 4.8 DMA analysis of PDMS skin simulant: storage modulus plot for compression.
4.2.1.2 Shear Tests

To find the shear modulus, displacement of oscillation was varied as 1, 3, 10, 30 and 100 µm. Both moduli showed gradual increase with frequency, with the storage modulus showing higher increase than the loss modulus. After about 80 Hz, both the moduli displayed sudden rise in their values – probably because of effects of higher frequencies on the material. Similar phenomena to those described in section 3.3 with respect to negative modulus may be noted.
Fig. 4.10 DMA analysis of PDMS skin simulant: storage modulus plot for shear.

Fig. 4.11 DMA analysis of PDMS skin simulant: loss modulus plot for shear.
4.3 Brain Mold Preparation

For the initial headform, gelatin brain was prepared by curing the gel inside a plastic bag which was placed inside the skull. The two pieces of the skull were joined together using the bolts, and then the bag was placed inside the skull through the hole where normally the medulla oblangata of the brainstem would rest. Then the liquid gel was poured inside the bag through that hole. The fluidity of the gel helped the bag to take the shape of the inner cavity of the skull, which was close to the brain’s dimensions. Fig. 4.12 illustrates the opened skull after the tests were done with cured gel brain inside it.

![Cured gelatin brain after opening the initial skull model.](image)

Later for the final headform, a similar approach was chosen to prepare brain inside the skull cavity. In this case the silicone gel solution was poured inside the bag that was kept inside the one piece skull. As the opening at the bottom of the skull was much bigger for this case, it was much easier to insert sensors before the curing of the gel. Fig. 4.13 shows the silicone gel brain prepared inside the one piece skull model.
Both the brain models developed lacked the detailed size and shape of a real human brain. These were of plane surface lacking the sulci or the fissures on the real brain’s surface. Keeping these shortcomings in mind, a brain mold was prepared so that it would be possible to cure the brain with detailed geometry inside the mold and then put it inside the skull cavity as it cures. A brain model for medical demonstration purposes was used as a negative to prepare the mold. This brain model had the dimensions of a real human brain including the sulci or fissures.
The brain mold was prepared in the laboratory of the sculpture facility of the Department of Fine Arts of University of Nebraska-Lincoln. First, wooden blocks were placed and clamped in such a way as to hold the liquid silicone rubber. The chamber was made liquid tight by putting on walls of molding clay. Half of the model brain was placed inside this chamber. The silicone rubber solution was prepared by mixing the liquid rubber with the catalyst in a 10:1 weight ratio. This solution was then poured inside the chamber. After 24 hours of curing, the chamber was turned upside down and the other half of the mold was prepared in a similar way. The mother mold or the rectangular shaped mold was prepared from plaster by arranging the wooden blocks in a way to make a larger chamber. Finally, the silicone rubber molds were placed inside the mother molds so that they could not get damaged. Pegs and holes were provided on both the molds to facilitate precise geometry while opening and closing them.
4.4 The Instrumentation in the Headforms

The initial version of the headform was instrumented with two polyvinylidene fluoride (PVDF) pressure gages. The gages were placed inside the uncured gel solution that was poured inside the skull cavity. Insertion of sensors after gel curing would damage the gel and may create local stress (or air-gap interface) which is not desired. For this reason, they were placed before gel curing. The PVDF gages were made liquid resistant by means of hot glue. Care was taken to perform this process fast so that the heat could not damage the thin polymer film of the gage. Fig. 4.15 shows the gages with glue deposited on them and the gages placed inside the head model.

For the final version of RED Head, sensors were placed in a much more organized way so as to offer possibilities for comparing one sensor response to another and measuring attenuation of waves. Eight small (2 mm diameter) holes were prepared on the stainless steel bottom plate of
the skull for inserting eight fiber optic gages. At the beginning, two of the holes were used – one for a fiber optic gage, the other one for a PVDF gage. At the front portion, three holes were placed in line so that comparison could be made for the pressure profiles of the in-coming pressure waves propagating through the brain simulant. Two more holes were prepared at the front right and left side and the final two holes at the back right and left sides of the plate. A 3-mm hole was prepared in the front portion of the plate to insert a strain gage which could be attached to the inner surface of the skull. The sensors were still liquid tight, as they were inserted through the layer of silicone rubber attached to the inner side of the base plate that worked as a liquid tight gasket for them. Fig 4.16 shows instrumentation in the final head model.

![Fig. 4.16 Instrumentation for final version of RED Head: (a) curing the gel brain while holding the PVDF gage inside it using a clamp; (b) the fiber optic sensor inserted in the brain through the stainless steel bottom plate of the final head model; and (c) position of the gages inside the gel brain (CAD model).]
4.5 The Complete Experimental Model

Three head models were developed – the first one with the two-piece skull, the second one with a simple geometry model with a polycarbonate cylinder, and the final one with the one piece skull. The tests were performed on the last two models, and these are presented in chapter 5. These three complete head models are described below.

4.5.1 INITIAL HEAD MODEL

The initial version of the head model with the two-piece skull contained gelatin brain and two PVDF gages inserted in it. The gages were connected to the data acquisition system by wires via an amplifier. The sensor responses were displayed by a LabVIEW® front panel display. This instrumented head with the data acquisition system is illustrated in Fig. 4.17.

Fig. 4.17 First version of the RED Head with data acquisition system.
4.5.2 SIMPLE GEOMETRY MODEL

As the human head has a very complex geometry, it was decided to perform the initial blast tests with a simple geometry (cylindrical in this case) skull surrogate filled in with gel and instrumented with sensors. This model would supply blast response inside the polycarbonate cylinder (that is, in the gel) and this would be helpful to understand how the pressure wave behaves in case of such a known geometry. The polycarbonate cylinder, replicating skull, was first filled in with the uncured gel solution. Then one PVDF and one fiber optic sensor were inserted through the two openings. The openings were then sealed with polycarbonate caps and hot glue. The whole model was clamped for a week to cure the gel. After a week, the model was ready to be tested with blast loading.

![Instrumented simple geometry model clamped for curing the inner gel.](image)

4.5.3 FINAL HEAD MODEL

The final version of the RED Head was prepared from the polyurethane one piece skull and silicone gel brain simulant cured inside the skull cavity. The head was supported by a flexible neck (generally used for crash test dummies) which was secured to a slotted holder designed specially to hold the head in the desired position. It was possible to change the position of the
head in all X, Y and Z directions. The holder could be connected to the front of the 9” X 9” square cross section shock tube where the head was intended to be tested. Fig. 4.11 (a) shows the CAD drawing for this holder, which illustrates the holes and slots provided to control the desired position of the head model.

For the initial tests on this head model, one PVDF gage and one fiber optic sensor were inserted into the gel brain. The PVDF gage output was connected to a signal conditioner via a charge amplifier, and the fiber optic sensor’s output was connected to its signal conditioning unit as well. All the inputs were connected to a PXI® Express high speed data acquisition system with a real-time operating system which acquired and recorded the data through a LabVIEW® program loaded in the PXI® system. Fig. 4.19 (b) shows the head model secured in front of the shock tube ready to be used under blast loading. The black and white stripes at the background were provided for convenience to watch the passing of shock waves in the captured video. The skin was not included in order to capture data without the effect of the skin. Fig. 4.19 (c) shows the head model with its skin on.

![Fig. 4.19](image1.jpg)  
(a) The steel holder prepared to hold the RED Head in front of shock tube; (b) the head model instrumented and ready for blast loading; and (c) the RED Head with the skin on.
The test procedures for all three head models developed will be discussed in chapter 5. This can elucidate the answers to many questions about blast loading response on these headforms and can help decide what changes should be made to replicate a human head even more accurately for such loading conditions.
5 **BLAST TESTS AND OUTCOMES**

5.1 **Tests with the First Version of the RED Head**

The first version was not tested under blast loading. It was a preliminary model to test small impact loading rather than blast loading. The reason behind this was to ensure that the sensors worked inside the brain simulant material that was placed into the two piece skull. The head model was given impulse-type stimuli on the surface, and the result was investigated in plots acquired using an oscilloscope and a LabVIEW® data acquisition system. Fig. 5.1 shows the oscilloscope outcome for tapping the head model several times.

![Oscilloscope showing spikes generated by tapping the head model.](image)

After each tapping on the skull surface, the output was a spike of voltage in the plot. Due to this model’s unsuitability to be used with blast loading, especially because it had a two-piece skull and was supported from the back side, it was used only for such tests. For further tests using the
shock tube, the simple (as in section 5.2) and improved (as in section 5.3) versions of the head model were used.

5.2 The Shock Tube in Brief

The shock tube in the University of Nebraska-Lincoln’s high-pressure shock wave generation facility consists of a pressurized breech (driver) and barrel (driven section). The driver section is compressed with inert gases like nitrogen or helium. In between the driven and driver sections, Mylar sheets are used as the pressure barrier for the two sections. The Mylar sheets are rated to fail or rupture at a certain pressure, and the overall burst pressure can be controlled by increasing the number of layers of these sheets. The driven section includes a test section where a sample can be placed and investigation can be performed though transparent windows located in the sides of the barrel. The tube can generate up to 1200-psi pressure waves. The reason for testing the sample inside the shock tube was to get rid of the jet flow that generally follows a shock wave as the driven gas emerges from the end of the barrel and expands. Fig. 5.2 illustrates the shock tube’s CAD model.

Fig. 5.2 The 9” X 9” cross-section shock tube for creating blast loading [CAD diagram by Aaron Holmberg and Nick Kleinschmit, Engineering Mechanics Department, University of Nebraska-Lincoln].
5.3 Basics of Blast Loading

A shock wave is generated in compressive flow systems when the flow speed increment in the supersonic region intensifies the wave front by building up pressure at that region. The shock develops to resolve a forced pressure mismatch in such a compressible flow [54]. Such high-speed fluid flow is developed in free-field explosions. Without any wall or obstacle, this pressure wave expands uniformly outwards in a spherical shape from the center of the explosion, and the dimensionality and directionality of blast-generated pressure waves within a bi-directionally open-ended tube are similar to those observed in free-field explosions [8]. The general plot for the pressure spike generation due to a blast wave is illustrated in Fig. 5.3. This is a pure shock wave that will interact with the head model and will change the flow conditions temporally and spatially over the surfaces [54]. The goal of this research was to record the pressure wave patterns inside the head model, that is, the changed patterns inside the brain after the shock wave interacted with the head.

![Diagram of blast wave](image)

**Fig. 5.3** An ideal blast wave created by detonation of moderate charge [8].
5.4 Tests with the Simple Geometry Model

The polycarbonate cylinder filled with silicone gel and fitted with sensors was bolted inside the shock tube test section. The body of the cylinder was painted with white spray paint, and then black dots were added to provide visible markers for measuring displacement of the cylinder due to shock wave propagation using the ARAMIS video system. Fig. 5.4 shows the ARAMIS-captured image of the cylinder inside the shock tube’s test section.

![Image](image.png)

Fig. 5.4 The simple geometry cylindrical head model inside the shock tube (ARAMIS® image).

The PVDF gauge and fiber optic pressure sensor placed inside the cylinder delivered voltage outputs into the data acquisition system. Then the voltage was converted to pressure values according to the prior calibration of the sensors. The pressure vs. time plot for the fiber optic sensor is presented below.
5.5 Tests with the Final Version of RED Head

The final version of RED Head with one PVDF sensor and one fiber optic pressure sensor was fitted in front of the shock tube for finding the pressure profiles inside the brain of the head model. The brain in this case was made of silicone gel cured in place within the skull, so there was a relatively uniform interface between the skull and brain simulants. The first tests were performed with the PDMS skin on, and it was found from the ARAMIS video that without gluing the skin onto the skull surface, there were pressure wave ripples inside the skin (flapping of the skin against the skull), which is not consistent with blast wave propagation through a real human head. So it was decided to perform tests without the skin. The head still had the small piece of skin glued at the back of the skull, but that would not affect the data as it was downstream of the
shock wave. Fig. 5.6 shows the ARAMIS®-captured images of the test with the skin on. We can understand the movement of the head with the shock wave and the rippling effect of the skin being due to passage of the wave through the skin and the skull, and the associated energy transfer.

Fig. 5.6 Movement of the RED Head with the skin observed by ARAMIS®.

The pressure vs. time plot for the fiber optic sensor recorded from these tests is presented below.
The illustration of the movement of the head model without skin is presented below. The head model moved back and forth several times and came to a steady position after 13.26 seconds. It should be noted here that this type of movement was true for the head model without skin as well.

Fig. 5.7 Blast loading plot for the RED Head with skin.

Fig. 5.8 Back and forth movement of the head model (without skin) as captured by ARAMIS® video system.
The pressure vs. time plot for the fiber optic sensor obtained from these tests is presented below.

![Blast Loading Plot for the RED Head Without Skin](image)

**Fig. 5.9** Blast loading plot for the RED Head without skin.

From these blast tests, it is obvious that a fair amount of pressure is transferred to points deep inside the gel brain. In case of the RED Head experiments, peak pressure for the ‘with skin’ condition was more than 7 psi, whereas for the ‘without skin’ condition, it was just above 6 psi. It is unclear from this result whether pressure is intensified by the skin being present. In these cases, input peak pressure was approximately 60 psi. So roughly 10% of the input peak pressure was propagated inside the head. To develop a firmer understanding of the amount of pressure propagation and the factors which may affect this, more tests should be performed to validate the repeatability.
6 CONCLUSION AND FUTURE WORKS

6.1 Materials for the RED Head

As discussed in the previous chapters, the RED Head was built considering materials for three parts of the human head – the skin, skull and brain. The principal objective of this thesis was to choose the correct materials for developing the head model as close as possible to a real human head in terms of its response to blast waves. Out of numerous other properties (e.g., biological, chemical, neurological etc.) of these tissues, only the material properties relevant to the dynamic response to blast loading were of specific interest. Analyses were performed to find synthetic materials whose properties match closely to those of the tissues.

Examining the work flow of the thesis, in Chapter 1, a rigorous literature survey was performed to acquire knowledge about the material properties obtained so far by other researchers. These properties were used as targets to match the properties of the synthetic materials.

In Chapter 2, several brain simulant materials were tested with low-frequency excitation so as to understand their responses; this helped to eliminate many of the materials under consideration due to their properties being dissimilar from those of human brain matter. The initial DMA analysis results showed some counterintuitive outcomes related to negative modulus, but in addition to providing some useful data, they elucidated the requirements for the tests to be performed with more control of the operator rather than depending almost entirely on “canned” software calculations. The initial stress relaxation tests implied the necessity of maintaining low strain in the samples so that they would not leave the linear region. Although the blast loading
may create nonlinear strain in the brain matter, it is wise to develop an understanding about the linear region first, as the study of nonlinear strain in such viscoelastic materials is much more complex. The temperature degradation tests on water-based gelatin samples indicated an important requirement for the brain simulant material – its stability at room temperature. The custom-made gelatins showed some of the best material properties for simulating brain matter, but they displayed very fast property degradation at room temperature which actually eliminated them from consideration for use in the RED Head for blast loading. The initial tests also indicated that other water-based colloids are not stable enough to be used for our purposes. This outcome was important to steer us towards alternatives such as oil-based mixtures and finally to silicone-based gels. The step response tests and especially the rheometry analysis helped to eliminate the oil-based mixtures, as the silicone gels showed more promising results in terms of shear properties. However, in the step response analysis, the developed mathematical model for the brain material containing a standard linear solid model with an attached mass displayed some results where the mass effect did not appear to accurately reflect the physics of the system. That is, the mass, as determined through optimization fitting the measured data to the model, was not close to the actual applied mass of the system.

Chapter 3 presented the DMA analysis and ultrasonic tests, which were the next meaningful step of analysis on these brain simulant materials following the low-frequency tests. The DMA analysis was performed much more carefully this time compared to the previous tests. For the tests under compressive loading, various preloads were applied, and for shear loading, the amplitude of displacement was varied. Performing such variations in these values, it was possible to get sets of data which could be confirmed as authentic outcomes. Most of the DMA plots implied that at high frequencies, the silicone gels show large variations in the storage and shear modulus values; this may have happened because of material damage at high frequencies. This
led to testing the materials with ultrasonic waves, which could offer material response data at much higher frequencies and, most importantly, without damaging the material. The ultrasonic tests done so far are difficult to analyze because even though the peaks and troughs could be easily seen in the plots, they were not easy to identify with physical aspects of the setup. That is, it was hard to find which peak belonged to which material interface because of the reflection of the ultrasonic waves at the material interfaces. This implied that a setup is required to be designed having fewer interfaces or else interface-related wave features which are easier to analyze.

The overall results suggested to use silicone-based gels for their temperature and time stability and the similarity of their values for storage and loss shear modulus to human brain matter as found in the literature. The PDMS skin shows promising outcomes too, as we can compare the value of dynamic modulus of 1.54 MPa mentioned in section 1.2.1 to dynamic modulus values found through DMA analysis presented in section 4.2.1. As a whole, the RED Head was well designed for serving as a human head surrogate from the material properties point of view.

6.2 Blast TBI and the Head Model

The entire RED Head exhibits similarity to a real human head in terms of geometry too. Both the matching of material properties and geometry were important for testing the head model in a shock tube environment. The flexible neck added even more similarity of the model to the dynamics of a real human head under such loading. The head holder was also designed in such a way that that it would be possible to test different parts of the head by keeping the region of interest aligned with the mid-axis of the cross section of the shock tube. The holder was made from ¼” steel to make it rigid enough so that it contributes no additional vibration component to the measured response.
The cylindrical experimental model showed movements which appear to be rigid-body movements related to the cylinder/bolt interfaces as observed from the ARAMIS® video. The PVDF gauge did not give sufficiently authentic pressure data, as it captured some unwanted signals such as the 60-Hz supply signal. It also seemed oversensitive to minute movements and vibrations. In a later experiment, the PVDF gauge was replaced by another fiber optic sensor to compare the data from the two fiber optic sensors placed inside the silicone gel.

The blast loading on the head model with the skin generated some ripples on the skin, created from the passage of the shock waves through the interface of the skin and the skull. In reality, there is no delamination of the skin from the skull, as they are strongly attached together. So, to avoid the effects of pressure concentration because of this, the skin was removed and blast loading was applied. (Alternatively, the skin can be applied with an adhesive.) For these tests, the original blast pressure generated by the shock wave was attenuated to a great extent as the pressure propagated inside the head. This outcome is important to understand blast TBI, as it leads toward an idea of the pressure magnitude generated inside the head due to various pressure levels of the source blast wave.

### 6.3 Future Modifications

The RED Head model went through several changes which can be observed by comparing the two versions developed so far. The final version still has several things to be considered to make it more like a real human head. The PDMS skin material’s thickness can be varied according to actual skin thickness values. It is also important to attach the skin to the skull so that delamination does not occur when subjected to shock waves. From the blast tests, it was also obvious that the shock waves propagate through the eye-holes of the surrogate skin. In future versions, there should be consistency between skull and skin in terms of orifices of this type. Propagation of
shock waves through natural orifices such as the nasal and auditory fissures may be an interesting area of future study.

The skull material was upgraded from dense foam to polyurethane and from a two-piece skull to a one-piece skull. Real skull is made of spongy bones that contain numerous void spaces. But the polyurethane skull was a uniform solid material. To make the simulated skull more like human skull, research is in progress to develop polycarbonate (or other) skull material containing channeled structures in it, representing sinuses (voids) and other microstructure properties. This skull material would be rapid-prototyped to give it the shape of a human skull. Research is at present going on in the Engineering Mechanics Department of the University of Nebraska-Lincoln to make this model possible. Another idea that was also proposed was to keep a real (cadaver) skull hydrated to achieve high-fidelity head model properties.

The brain matter was simulated so far as a single uniform material. The gray matter, white matter and cerebellum can be simulated in the future separately to differentiate each part from the other. This could be helpful to find the blast loading responses in different parts of the brain, which is important to understand blast TBI affecting different parts of the brain individually. The silicone gel was cured inside a polyethylene bag which simulated the meninges. But the polyethylene material did not go through any load test or DMA analysis. Performing such tests on more materials, it will be possible to find a material that can effectively simulate the meninges. Cerebrospinal fluid (CSF) is another important consideration for such blast loading which was not included to a great level of detail in the current RED Head model. The skull was prepared liquid tight for providing a CSF simulant material, and water is the default choice. So there is good potential to include such a fluid in the current head model and to make incremental improvements in the specific choice of fluid. Also, it can be a good consideration to include the
vessels which carry and circulate CSF in and around the brain. Simulating the anisotropic behavior of human brain can be another challenge for development of such a realistic head model.

The mathematical model developed in the step response analysis can be analyzed in more detail to make the model more effective to simulate step response of brain simulant materials. A more complex model could offer more accuracy, although it is more difficult to optimize the parameters for such a model. The standard linear solid model could be made more accurate by converting it into a generalized higher-order model. There was indication of the mass effect not converging as expected in this model probably because of the quasi-static behavior of the tests.

The RED Head was placed in front of the shock tube for the tests performed so far. For shock waves generated in such a tube, the collision of rarefactions at the lip of the tube produces a pocket of sub-atmospheric pressure but very high flow velocity at the aperture. For this reason, high shear and pressure differential is created which generates a toroidal vortex accompanied by a jet of venting shock tube gas [53]. So, to generate clean results, the head model should be placed inside the tube rather than in front of it. To make this possible, a 28” X 28” cross-section shock tube was designed, and this will be used in future tests to get more authentic results from the blast loadings.

It was also proposed to perform blast loading tests on animals and compare the data with the data obtained from loading on the head model. This may offer better understanding of the comparison of in vivo results with those of the simulated experimental model.

Since skull flexure may be an important issue for blast TBI as described in section 1.2.2, it is planned to attach strain gauges on the surface of the skull to investigate this phenomenon. By placing the strain gauges in a well planned orientation, it will be possible to compare the strain
induced on the skull at different points. It is also planned to place accelerometers in the head model to obtain information about the movement of the brain relative to the skull.

The ongoing research on this collaborative project also includes development of mathematical models for simulating the blast response of the head. These simulation models must include characterization of the skin, skull and the brain materials and their geometries. The material characterizations carried out and described in this thesis provide a foundation with which to build computational models of the experimental headform. The obtained data from the physical head model could be verified by comparing to the mathematical model to offer cross-validation of both research approaches. This may in the future lead to accurate computational modeling based on exact geometries and dynamic properties of human tissues.

6.4 Summary

This project of blast headform development offers immense importance in the field of traumatic brain injury. For understanding the injury mechanics, it is required to perform blast loading tests for numerous times as this is a very complex phenomenon. It is very expensive to use animals for such experiments. Using animals like swine and rats has problems of accuracy in head geometry. Moreover, it is very difficult to perform instrumentation in vivo. In such a condition, the RED Head offers solutions to most of these problems.

This type of head development was attempted before, most of which is available in literature as discussed in Chapter 1. Many of these headforms were made for testing impact responses. Among the very few research works focused on blast loading, not all performed rigorous research to simulate brain, skin and skull materials properties and their geometry to such an extent as RED Head. The research performed so far on this topic has enlightened more on what to do in the future to make this head model a very realistic one in every relevant aspect. The mysteries of
blast-induced traumatic brain injury will be clarified to a great extent upon successful completion of the long-term goals of this project.
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