FINITE ELEMENT ANALYSIS AND MODELING OF A .38 LEAD ROUND NOSE BALLISTIC GELATIN TEST

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ABSTRACT

Finite Element Analysis and Modeling of a .38 Lead Round Nose

Ballistic Gelatin Test

Danielle Datoc

Firearms are present in two-thirds of United States households. As of 2003, roughly 500,000 projectile wounds occur annually in the United States. This costs an estimated 2.3 billion dollars of medical spending. The best treatment of gunshot wounds relies heavily on experience, but even with experience the unpredictable nature of ballistics can make treatment difficult.

Wound ballistics studies the injury pattern of a particular bullet. Ballistic gelatin tests are used to analyze this pattern. A block of 10 or 20% ballistic gelatin is set and a bullet is fired through the block. Key characteristics of the wound profile seen in this test include: depth penetration, permanent cavity, and temporary cavity. Even with ballistic gelatin tests, there is still confusion and many unknowns throughout wound ballistic literature.

Finite element analysis (FEA) can be used to reproduce the wound profile of a ballistic gelatin test. A .38 lead round nose was chosen to model. The bullet was assigned as an elastic plastic material and the ballistic gelatin block was assigned as an elastic plastic and viscoelastic material. SolidWorks®, TrueGrid®, and LS-DYNA® were used to create the models.

Two elastic plastic and two viscoelastic simulations were developed from these models. Elastic Plastic 2 and Viscoelastic 1 were able to reproduce a depth penetration, temporary cavity, and permanent cavity. Elastic Plastic 1 and Viscoelastic 2 were unable to reproduce the temporary cavity. These simulations provided hopeful results, but further investigation is needed for contribution to the advancement of bullet wound treatment.

Keywords: ballistics, Finite Element Analysis, bullet wound, wound profile

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CHAPTER 1: INTRODUCTION

1.1 Overview

The presence of guns is quite prevalent in today's society. They can be easily seen on television, movies, the internet, videogames, and even in your own neighborhood. It is reported that firearms are present in two-thirds of all households in the United States [1]. The television and internet provide an abundance of information regarding gunshots, whether it is fiction or nonfiction. There are shows such as MythBusters and documentaries dedicated to analyzing the power and effectiveness of guns and bullets. Other shows, like CSI, give some insight, although purely fictional, on using ballistics to solve crime. Many teenagers and some children use a wide variety of weapons and projectiles to kill zombies or enemies on their X-Box. These influences provide readily available information on the destructive power of firearms. Gunshots are the second leading cause of death and injury for youth in the United States [1].

With the increasing presence and knowledge of guns and bullets in society, there needs to be improvement to the trauma system in order to manage gunshot wounds throughout the nation [2]. In addition to trauma systems, emergency room staff needs an understanding of various bullet wound characteristics and improved understanding of ballistics in order to provide proper and more efficient care. Treatment of gunshot wounds still needs to be perfected and the knowledge of treating needs to be spread further throughout the medical society. The literature and educational tools for gunshot wound treatment in civilians is scarce and difficult to practice. "The high prevalence of gunshot injuries in civilians contrasts dramatically with the current paucity of scientific literature pertaining to the diagnosis, classification, and treatment. Most of the literature on gunshot injuries pertains to military weaponry and is difficult to apply to civilians" [3].

In general, bullet wound treatment has not altered significantly since the 18^{th} century [4]. John Hunter, the famous British surgeon and anatomist, discovered that wounds caused by bullet trauma needed to be treated differently than other wounds. Bullet wounds are different because they involve two different cavity formations caused by shockwaves and elastic retentive forces. The damage associated with these cavity formations greatly depend on the type of bullet, the velocity of the bullet upon impact, and the type of tissue disrupted. Low-velocity gunshot wounds, typically from handguns, can be treated nonoperatively with local wound care and outpatient management if no major organs are injured. For medium to high velocity gunshots, aggressive irrigation and debridement are necessary [5]. Effective treatment relies heavily on the surgeon's evaluation and experience. Without experience or good understanding of ballistics, many complications can occur. The surgeon can either excise too much or not enough tissue and either action can cause major damage to the viable tissue surrounding the wounded area. The excessive excision of tissue has become more prominent and a standard method of treatment but has also lead to a higher risk of complications post-surgery [4]. This is increasingly important because as of 2003, roughly 500,000 projectile wounds occur annually in the United States. This costs an estimated 2.3 billion dollars of medical spending, or about $25,000 per hospitalized gunshot victim. 80% of these victims are uninsured [5.6]. Outside of the United States, many soldiers are being treated for bullet wounds due to the War in Iraq and Afghanistan.

In order to improve education and treatment of gunshots, wound ballistics need to be further understood, evaluated, and analyzed in great detail. However, wound ballistics is a difficult subject to fully master and understand. The behaviors of bullets are unpredictable. There are many factors that can contribute to the overall effectiveness of a bullet. There are also are many misconceptions, confusion, and unknowns throughout wound ballistic literature. The effectiveness of the ballistic pressure wave and temporary cavity has inconsistent findings throughout literature. Some researchers believe it is a major factor in tissue disruption and others believe it has little effect.

1.2 Ballistics Background

Ballistics is the study of the firing, flight, and effects of projectiles [7]. It is the science of how a projectile shot from a weapon behaves [8]. Ballistics is categorized into three different areas: internal, external, and terminal. The physics behind ballistics before it enters the body is well understood and can easily be predicted. However, once the bullet enters the body, the understanding and predictability is not as clear and definitive.

The first category, internal ballistics, involves the flight of the projectile within the weapon. The firearm is loaded with a cartridge full of explosive primer, gunpowder, and a bullet. Once the trigger is released, a firing pin is driven into the cartridge, a spark is created which ignites the gunpowder, and propels the bullet down the barrel. Essentially, the pressures within the gun become the force that propels the bullet to leave the barrel [9]. At this point, the mass of the bullet, the amount of gunpowder, the strength of the barrel, the amount of recoil, and the length of the barrel determine exit velocity. Some researchers split internal ballistics into internal and intermediate. Intermediate is the behavior of the projectile as it leaves the barrel.

Once the bullet exits the barrel, it decelerates and faces the effects of atmospheric drag [7]. This area of ballistics is known as external. External ballistics is defined as the flight of the projectile through the atmosphere as it travels towards its target. The bullet is in a state of deceleration due to the atmospheric drag effect. The amount of drag is related to the bullets speed and stabilized by the spin imparted by the grooves machined in the barrel, also known as “rifling of the barrel”. In addition to drag and spin, the bullet also undergoes yaw during external ballistics. Yaw is the angle of the long axis of the bullet with respect to its flight path. This occurs as the bullet rocks back and forth on its center of gravity. Yaw is more significant once the target is struck because it increases the amount of energy transfer thus resulting in more damage to the tissues struck [1].

Once the target is penetrated, the study is categorized as terminal ballistics. Terminal ballistics is the study of the penetration of a medium denser than air. In other words, it is the scientific study of injuries caused by projectiles and the behavior of these projectiles within human biological tissue [10]. This thesis project will solely focus on terminal ballistics.

1.3 Wound Ballistics

Wound ballistics is the area of terminal ballistics that studies the injury pattern of a particular bullet. The characteristics of a bullet wound include the depth penetration, the permanent cavity diameter, temporary cavity diameter, and bullet fragmentation. Wound ballistics analyzes the potential of a bullet to incapacitate and the underlying mechanisms.

1.3.1 Wounding Potential

The Army established “a missile with weight and velocity sufficient to give 58 ft. lb of kinetic energy” as criteria for the effectiveness of a bullet producing casualties. This value was based on experimental data at the time [8]. Today, the potential of the bullet to disrupt tissue is influenced by mass, velocity, and physical characteristics of the projectiles. The construction and shape determines the tendency of the bullet to deform, fragment, or change orientation. For example, a round nose bullet at low velocity has the tendency to create a fairly straight tunnel through the flesh. A flat nose bullet at high velocity tends to move in unpredictable directions and deviates from a straight tunnel through the flesh [8]. However, the actual amount of tissue disruption depends on the efficiency of energy transferred to the location of impact. This energy is derived from the impact velocity, velocity at the time the bullet strikes the body, and residual velocity, the remaining velocity as it passes through the body. For some perspective on energy absorption, a body struck by a bullet absorbs much more energy than a body that is struck during a car accident. This is because a combination of shear, tensile, and compressive forces interact to disrupt tissue and produce the wound when the body is struck by a bullet.

The potential for incapacitation depends on the bullet design and the location of the bullet wound. A bullet that is designed with little fragmentation retains a large portion of its mass and contributes to a deeper penetration depth.

> Optimal use of a bullet's kinetic energy to produce pressure wave incapacitation suggests a bullet design that penetrates the first four inches or so prior to significant expansion of energy loss, and then rapidly expands and transfers a large percentage of its energy and 40% of its mass at penetration depths between four and eight inches before continuing to penetrate to the depth desired for the application [11].

If this bullet was shot through the abdomen and did not exit the body, the energy is transferred to an area containing vital organs that cannot accommodate the pressure and extensive damage can occur.

1.3.2 Wounding Mechanism

The mechanisms of bullet injury include the laceration and crushing of tissues forced apart, shockwaves due to compression of medium in front of the missile, and formation of the wound cavity [12]. Wounding capacity is directly related to kinetic energy and the formation of the temporary and permanent cavity. In order to penetrate skin, the impact velocity must be at least 50 m/s and to penetrate bone it must be at least 65 m/s. Once the bullet penetrates the skin, the tissue damage is caused by kinetic energy absorption, pressure shockwaves, and bullet fragmentation.

Kinetic energy is determined by the formula

$$KE = \frac{1}{2} m v^2 \qquad (1)$$

Here, the m is the mass of the projectile and v is the velocity. The rate of energy conversion into mechanical disruption of tissue can become proportional to the third power of velocity at the speed of sound [5]. The total energy released to the target is determined by the formula

$$\Delta KE = KE_{entry} - KE_{exit} \qquad (2)$$

According to the equation 1, the higher the kinetic energy is at entry, the higher the potential for wounding. However, this is not always the case, if both entry and exit kinetic energy is high, relatively minor tissue damage can result. For example, the body absorbs less of the energy if the bullet passes through the body instead of stopping in the body. Transfer of kinetic energy mainly depends on the impact velocity and the type of tissue struck. It is an important determining factor in a bullets effectiveness to disrupt tissue, but it is not the only determining factor.

Pressure shockwaves also contribute to tissue damage. The first type is the Sonic Pressure Wave. This precedes the projectile following impact and is described as the sound of the projectile striking the surface of the tissue. The second is the temporary cavity (TC) pressure wave which follows the penetrating projectile. This pressure can move tissue and potentially be significant in the overall wounding mechanism. The significance varies greatly and depends on the size, location, and characteristics of the tissue dislodged. Some researchers like to refer to the TC pressure wave as a ballistic pressure wave. The ballistic pressure wave is defined as a force per unit area created by the ballistic impact that could be measured with a high speed pressure transducer [11] Tissue applies a retarding force to the bullet and the bullet applies an equal and opposite force on the tissue. “The pressure exerted by the medium of the bullet is equal to the pressure exerted by the bullet on the medium” [11]. This pressure travels radially outward from the front of the bullet in all directions and causes the formation of the temporary cavity.

The TC is formed when the projectile strikes the tissue and accelerates radially away from entry [12]. TC’s effect will greatly depend on the type of tissue and its elasticity [7]. Higher elastic tissue such as muscle will accommodate stretching. Low elastic tissue like the brain or liver can be seriously damaged. The force of the TC separates tissues that cannot be displaced, and momentarily pushes tissue aside that can be displaced. The location and arrangement of the small blood vessels in this tissue determines which vessels will most likely tear and ultimately help determine the overall bullets effectiveness [12]. The actual clinical effect of the TC is variable and according to some researchers the TC’s effect is overstated. One analysis of the TC produced by high velocity missiles in a gelatin block concluded the TC is an important phenomenon in terminal ballistics and marked tissue disruption can be found in this zone [13]. However, the TC can be prominently seen in ballistic gelatin tests but it is not necessarily as prominent in actual tissue. Gelatin does not model the effect of skin. Skin can decrease bullet velocity equal to about 5 inches of travel in gelatin. Clothing can also contain energy and contribute to the decrease in bullet velocity [14].

The TC's effectiveness is questionable throughout the literature, but the effectiveness of the permanent cavity (PC) is fairly straightforward.

> "Experiment has demonstrated that every foot pound of energy doing work in the wound formation there will be a permanent cavity remaining with a volume of 0.04173 cubic centimeters" [8].

The PC is produced by the bullet entry and consists of the tissue crushed by the bullet. When the projectile strikes the tissue, the stabilization effect of the bullet spin is overcome by the density of the tissue. The bullet yaw can increase in the tissue and the increase is directly related to the yaw upon entry. For example, the yaw of a bullet in air can be 90 degrees and eventually rest in the tissue at a 180 degree angle from its initial path. Depending on the type of bullet, the bullet can yaw at different depths. Tumbling within the tissue can lead to a more significant and destructive bullet wound. In addition to yaw, the ratio of bullet size to velocity, bullet deformation, and bullet fragmentation are other significant contributors the overall PC formation. The severity of the damage to the tissue in the PC can be detrimental and a major factor in the body's response and in treatment.

1.4 Pathophysiology of Bullet Wounds and Treatment

Blood flow in the area of the PC, or bullet damaged tissue, can change dramatically within the first few hours. Tissue disruption causes an increase in blood flow along with migration of leukocytes and fluid to the affected area in order to clean up and destroy bacteria. Inflammation occurs and induces the leukocyte endothelial cell interaction. The leukocytes migrate and adhere to the damaged tissue. This adhesion causes and promotes a persistent pro-inflammatory state [15]. The leukocytes also release reactive oxygen and reactive nitrogen species which contribute to endothelial cell damage and capillary leakage [15]. These contributions along with increased intramuscular pressure and ischemia lead to microvascular dysfunction. Microvascular dysfunction leads to secondary tissue damage. The cellular oxygen deficiency and accumulation of metabolites caused by microvascular dysfunction are ultimately responsible for tissue and cell damage. This is especially problematic if not enough damaged tissue is removed from the bullet wound or the wound is not left open to expel the wastes and heal.

Initially, a ballistic injury is first assessed by checking vitals. Assessing the airways, breathing, circulation, ability or disability of the patient to move, and locations of the exposed wounds can determine the course of action. Pressure must be applied to the areas of impact to help stop the loss of blood. Once the patient is transported to a trauma center, they can be further tested for organ specific damage based on the initial assessment. Excision of the damaged tissue surrounding the entrance and irrigation of the bullet track is the typical treatment for low-risk gunshot wounds with little soft tissue damage due to little bullet fragmentation. For high risk and multiple gunshot wounds with high bullet fragmentation, treatment involves extensive debridement and surgery. A common assessment test for what tissue to excise is the four C’s: color, consistency, capacity to bleed, and contractility measure muscle and tissue viability [16].

Trauma centers are classified by levels. There are four designated levels where Level I is the highest and Level IV is the lowest. Level I functions as a resource center for the other hospitals in that region. Level IV has very limited resources whose main function is to stabilize the patient for transfer to a higher level of care [33]. Based on the level of the trauma center, various protocols are used. Some trauma centers have a more in depth protocol that involve angiographies and CT scans to assess the wound. Others may use sonography and laparoscopy. An even number guide was even developed to communicate and determine if additional imaging is necessary. If a patient has one entry and one exit wound, radiographs are obtained to look for damage along the wound track. If there are an odd number of entry and exit wounds, additional imaging is necessary to locate the other bullet or bullets [17]. There is extensive research being conducted to help determine treatments, assess ballistic wounds , and develop protocols but ultimately the experience of the trauma staff is necessary for the best effective treatment.

According to Fackler, the best treatment with uncomplicated healing is excising the visibly damaged tissue and leaving the wound open for 4-7 days after surgery [12]. This allows the new capillaries to grow without any interruption and allows the bacteria to be expelled naturally without having the body to work overtime. Leaving the wound open decreases the chance of microvascular dysfunction occurring and lessens the possibility of further tissue necrosis. However, “it is seldom possible for even the most experienced surgeon to be able to identify with certainty the line of demarcation between tissue that will survive and which will not” [12]. A better way to analyze and understand bullet wounds could increase the certainty of distinguishing the line of demarcation.

1.5 Analysis of Bullet Wounds

Over the years, bullet wounds have been analyzed a number of different ways. One of the most common and most often seen throughout wound ballistic literature is Fackler's 2D wound profile. His wound profile is a means to predict the wounding pattern of a bullet in living tissue [18]. This profile is created by performing a ballistics gelatin test. A block of either 10 or 20% ordinance gelatin is made and a projectile is shot into the block. Depth penetration, temporary cavity, and permanent cavity are measured to create the wound profile.

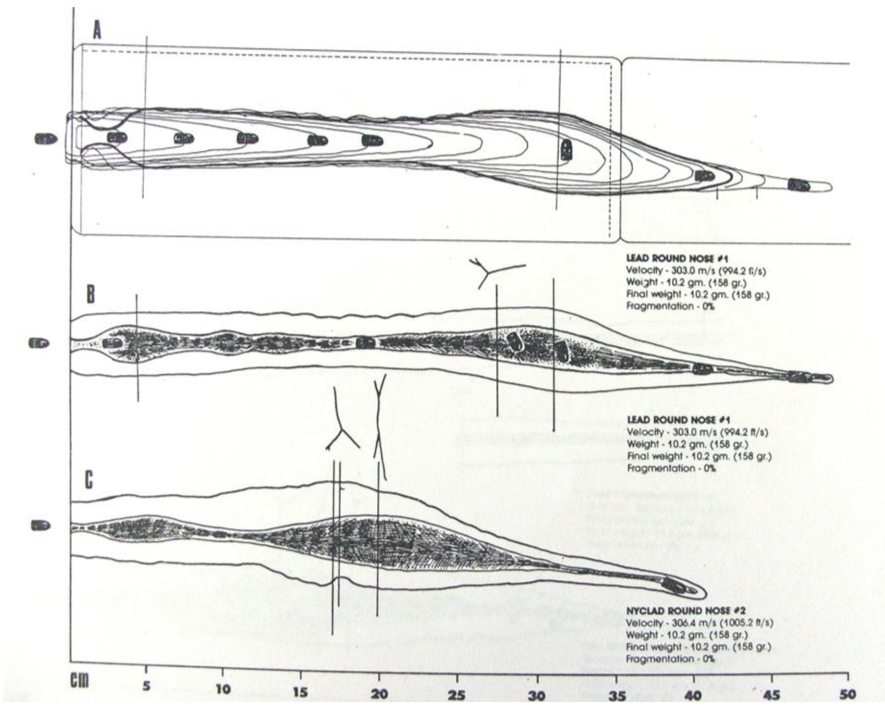


Figure 1: Ballistic Gelatin Wound Profiles [34]

In the 1970's, the U.S. Army created a model called "ComputerMan" to characterize wound ballistics. This model developed the 'Relative Incapacitation Index' which represented the human body in 150,000 segments with properties derived from 20% gelatin tests. Each segment was assigned a numerical value based on how sensitive that area would be to incapacitation and temporary cavity data [19].

The symmetry cavity assignment method (SCAM) was developed by an Arizona State graduate student in 1993 to realistically describe the geometries of bullet wound profiles [15]. This method assigns realistic geometries to the temporary and permanent cavity found in ballistic gelatin test wound profiles to generate a 2D model. This model does not predict wound profiles but allows for another relevant method to be implemented by researchers to obtain quantified data. The goal was for this data to be used as a reference for future applications.

Bullet wounds have also been analyzed with pig tests. One study used a number of live pigs and developed a method for using the regression function to gather tissue destruction data [20]. Another study used pig heads and took CT and 3D face scans before and after being shot. These image data sets were fused and analyzed quantitatively for destruction patterns [21]. Other animal tests include the Strasbourg goat test. This test measured and correlated peak pressure wave magnitudes to incapacitation times [22].

More recently, the Naval Research Lab used finite element analysis to model the behavior of human tissue stimulants under various impact loading conditions [23]. They used a GelMan surrogate human thorax model and ABAQUS to perform the analysis. Each simulation was dynamically loaded with different spherical ball masses and then analyzed.

However, even with all these studies, there is still more that can be contributed to wound ballistics. Most of these studies simply describe and analyze the damage without the potential to predict or simulate other scenarios. The study that implemented FEA only analyzed a certain section of the body and used general spherical ball masses instead of bullets. A finite element model that simulates human tissue in general and analyzes the destruction with specific bullets would be a useful addition to these studies. This type of model and simulation has the potential to accommodate various bullets, various velocities, and eventually use specific modeled body parts for simulations once it is further developed.

CHAPTER 2: SPECIFIC AIMS

2.1 Purpose

The goal of this study is to model the damage response of a bullet by simulating a ballistics gelatin test using Finite Element Analysis (FEA). Ultimately, this thesis can provide a model that will help clear up some confusion about wound ballistics. This model should also be able to contribute knowledge and data that can be applied to gunshot wound treatment with future development.

2.2 Hypotheses and Objectives

FEA can accurately reproduce the behavior of a lead round nose bullet in a ballistic gelatin test. The bullet should enter the block and tumble slightly until coming to a complete stop within the block. Depending on the velocity used, the bullet should fragment accordingly. The impact of the bullet should create the wound track and stop at a depth penetration similar to the Ragsdale ballistic gelatin tests (Appendix C).

FEA can also accurately reproduce the permanent and temporary cavity in the block. The model should simulate the formation of the permanent and temporary cavity as the bullet enters the block representing the formation of a wound track. The size of these properties should be comparable to the Ragsdale ballistic gelatin tests.

The LS-PREPOST software will provide the same data as a ballistic gelatin test. This software will measure the depth penetration, temporary cavity diameter, and permanent cavity diameter. The software will also show the path and final state of the bullet. This software can go one step further and measure the kinetic and internal energies, change in mass of the bullet, and green effective strain of the bullet and block.

CHAPTER 3: MATERIALS AND METHODS

3.1 Materials

3.1.1 Lead Round Nose Bullet

The lead round nose was selected to model because it is and has been one of the most common bullets used. More specifically, the actual bullet modeled is the Hornady® .38 158 grain lead round nose The caliber of this bullet is .38 which means its diameter is 38 hundredths of an inch and weighs 158 grains or 10.2 g. The entire bullet is made of pure lead with a density of 11.34 g/cc. The properties of lead used to model the bullet are shown in Table 1.

Figure 2: Hornady® .38 158 grain lead round nose [31]

Shear modulus is the slope of the linear elastic region of the shear stress-strain curve. It is the ratio of shear stress to shear strain. The yield strength is the stress required to produce a specified amount of plastic strain [32]. Bulk modulus measures the pressure increase needed to cause a given decrease in volume. It is the resistance to uniform compression [33]. These properties are necessary to realistically represent the behavior of the lead round nose bullet.

Table 1: Properties of Lead Used to Model the Bullet

Material Model	Density (g/cc)	G (MBar)	Yield Strength (MBar)	Plastic Hardening Modulus (MBar)	Bulk Modulus (MBar)	Failure Strain
Elastic Plastic	11.34	5.00E-02	1.20E-04	6.00E-04	2.90E-01	0.4

3.1.2 Ordnance Gelatin Block

Ordnance gelatin is created with gelatin and water. A 10 or 20% gelatin concentration is commonly used as a tissue simulant for ballistics testing. This concentration allows for similar properties between the block and actual tissue. Gelatin blocks are ideal for simulating tissue trauma caused by bullets because gelatin's relatively clear nature allows the bullet's wounding capabilities to be visibly tracked and measured.

Two different blocks were used for modeling purposes; one was assigned to an elastic plastic model and the other linear viscoelastic. See Table 2 for properties. Originally the 20% gelatin block was chosen to model but due to insufficient data found in literature, the 10% gelatin block was physically constructed and tested for mechanical properties. Two simulations were run with the same exact process except the gelatin block properties were changed to accommodate each type.

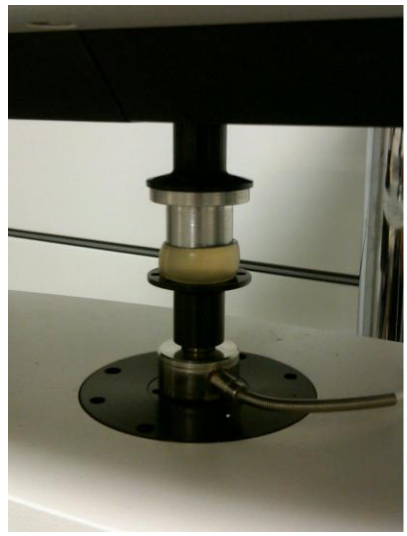
Table 2: Ballistic Gel Properties (Block Size: 12.7 x 12.7 x 35.6 cm)

Material Model	Density (g/cc)	G_o (MBar)	G_∞ (MBar)	Bulk Modulus (MBar)	Failure Strain	Decay Coefficient
Elastic Plastic	1.25	5.357E-3	-	-	.10	-
Viscoelastic	1.20	2.00E-6	1.95E-6	2.90E-4	0.08	0.10

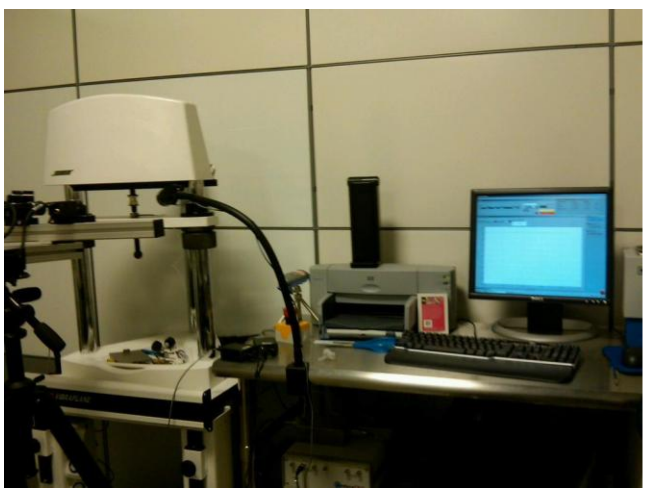
After the block was set, the block needed to be tested for its mechanical properties. The first step of mechanical testing was to determine a way to cut the ballistic gelatin into a measurable area. A blade was used to cut off sections and ¾ in to 1in pipes were used to punch out a given diameter. Next, the pieces were placed in the Bose Smart Test 3200 for a relaxation test. The time set for 5000 seconds and the displacement set at 20% strain. The tested piece shown in the image below is 1.2 cm in height and 2.2 cm in diameter.

(a)

(b)



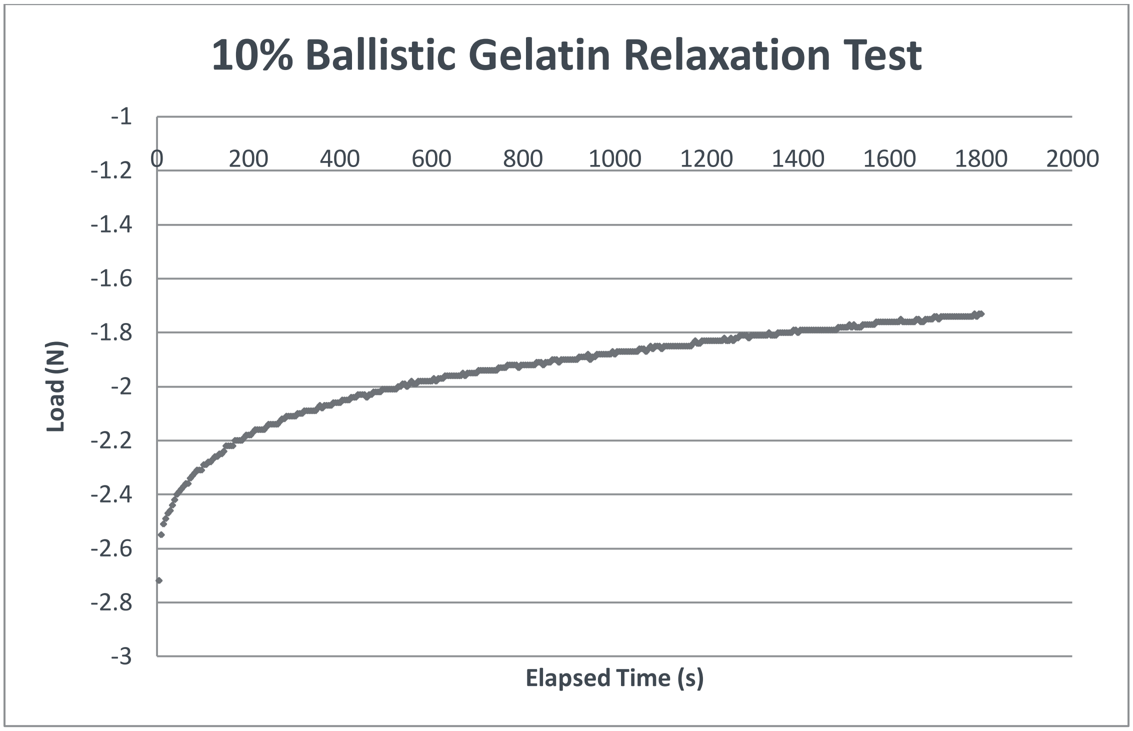
(c)



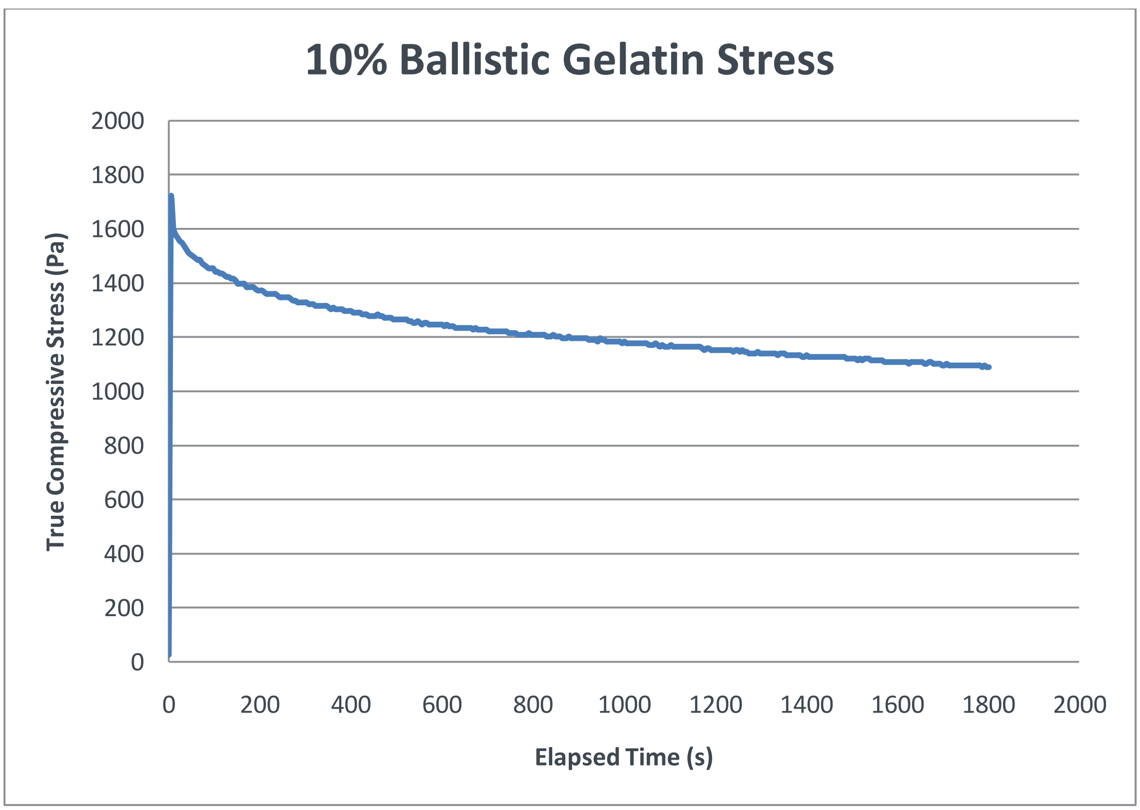
(d)

Figure 3: (a) Cutting ballistic gel with blade **(b)** Punching sectioned pieces with pipe **(c)**Loading test piece onto Smart Bose 3200 **(d)** Smart Bose 3200 System running relaxation test

The results are shown in Figure 4.



(a)



(b)

Figure 4: **(a)** Results from Relaxation Creep Test
(b) Calculated True Compressive Stress

3.2 Finite Element Method and Analysis

The Finite Element Method (FEM) is a numerical analysis technique used to approximate solutions for complex engineering problems. Generally, FEM works by discretizing the continuum, or dividing the solution region into elements, selecting interpolation functions, defining the element properties, assembling the element properties to obtain the system of equations, and solving the system of equations. “The basic premise of the finite element method is that a solution region can be analytically modeled or approximated by replacing it with an assemblage of discrete elements. Since these elements can be put together in a variety of ways, they can used to represent exceedingly complex shapes” [35]. This method was originally used to study stresses in airframe structures, but has been further developed over the years to be implemented as a numerical analysis tool for a broad range of engineering problems. “Finite-element model updating has become a viable approach to increase the correlation between the dynamic response of a structure and the predictions from a model“ [36].

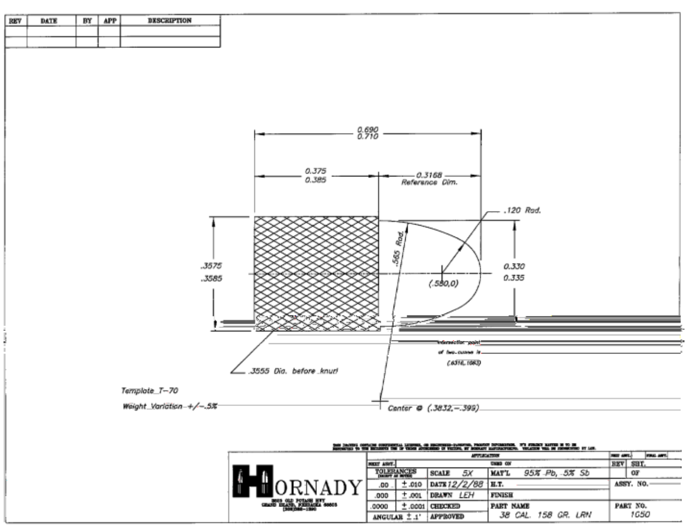
FEM today is more commonly known as Finite Element Analysis (FEA). Currently, FEA is taught using various computer programs as a numerical technique that applies nodes throughout the entire problem. Each node is connected to form an element. Properties are applied to these elements and are analyzed within a given time domain resulting in the final approximation. The solution is developed into a model or simulation that can be further analyzed using the tools within the software. This thesis project uses LS-DYNA to model and simulate the ballistics gelatin test. LS-DYNA is a general purpose explicit code ideally suited to study transient phenomena, such as impact. The newest version of LS-DYNA, LS971 rev.4, was used for the last 3 models.

3.3 Modeling Process

In order to accurately represent and simulate a ballistics gelatin test, both the bullet and the gelatin block were developed using different programs. The bullet's shape is more complicated than the gelatin block and therefore needed to be drawn in a solid modeling program, SolidWorks®. Following SolidWorks®, the bullet was imported into TrueGrid® as an IGES file. This software serves as a preprocessor for finite element analysis and creates a mesh and assigns nodes to the imported bullet. The gelatin block is then created, meshed, and finally merged with the bullet. The final step of this modeling process is to run the output file of the meshed and merged bullet and block through a finite element analysis package, LS-DYNA®. Once the simulation is complete, the data is analyzed.

3.3.1 SolidWorks®

The solid drawing of the lead round nose bullet was created using a schematic contributed by Hornady (Figure 5a). The schematic was used as a guide and the same dimensions were implemented. The bullet was fairly simple to recreate with the computer aided design software, SolidWorks® (Figure 5b).



(a)

(b)

Figure 5: **(a)** Hornady schematic of .38 158 grain Lead Round Nose.
(b) The final SolidWorks drawing of the Hornady bullet.

3.3.2 TrueGrid®

Meshing is essential in order to perform finite element analysis. Meshing applies the nodes and elements throughout the entire problem. In particular, TrueGrid® uses hexahedral meshes for 3D analyses and quadrilateral meshes for 2D analyses.

The solid model of the bullet is imported from SolidWorks® into TrueGrid® as an IGES file. A solid meshed block is drawn around the bullet. This block needs to be fitted within the bullet. Essentially, the IGES file is a stencil or mold that needs to be filled with a mesh. This is done so by adding surface planes through the bullet and block to separate the bullet's surface into different sections. Each surface section is defined and a corresponding curve along each surface edge is also defined. The curve definition of the bullet is attached to an edge of the block (Figure 6). Once that section of the bullet is fully attached to the block, the meshed block is projected onto the surface of the bullet. The end result is a meshed bullet (Figure 7). Nodes can be added to sections of impact and relaxation techniques can be applied for appropriate distribution of the nodes and elements. Once the meshed bullet is satisfactory, the material properties are added.

Since the geometry of the gelatin block is simple, it was created in TrueGrid®. The block developed was already meshed but needed the appropriate number of nodes and element distribution (Figure 7b). The area of impact, where the bullet enters, needed the most nodes to properly analyze the high stress region. The front section of the block also needs more nodes than the back section of the block where the bullet is highly unlikely to affect. Once the meshed block is satisfactory, the material properties are assigned.

Finally, the meshed bullet and the meshed block are merged (Figure 8). The bullet is placed in contact with the block where it will strike at 462 m/s. The boundary and initial conditions are applied and a LS-DYNA keyword output file is generated.

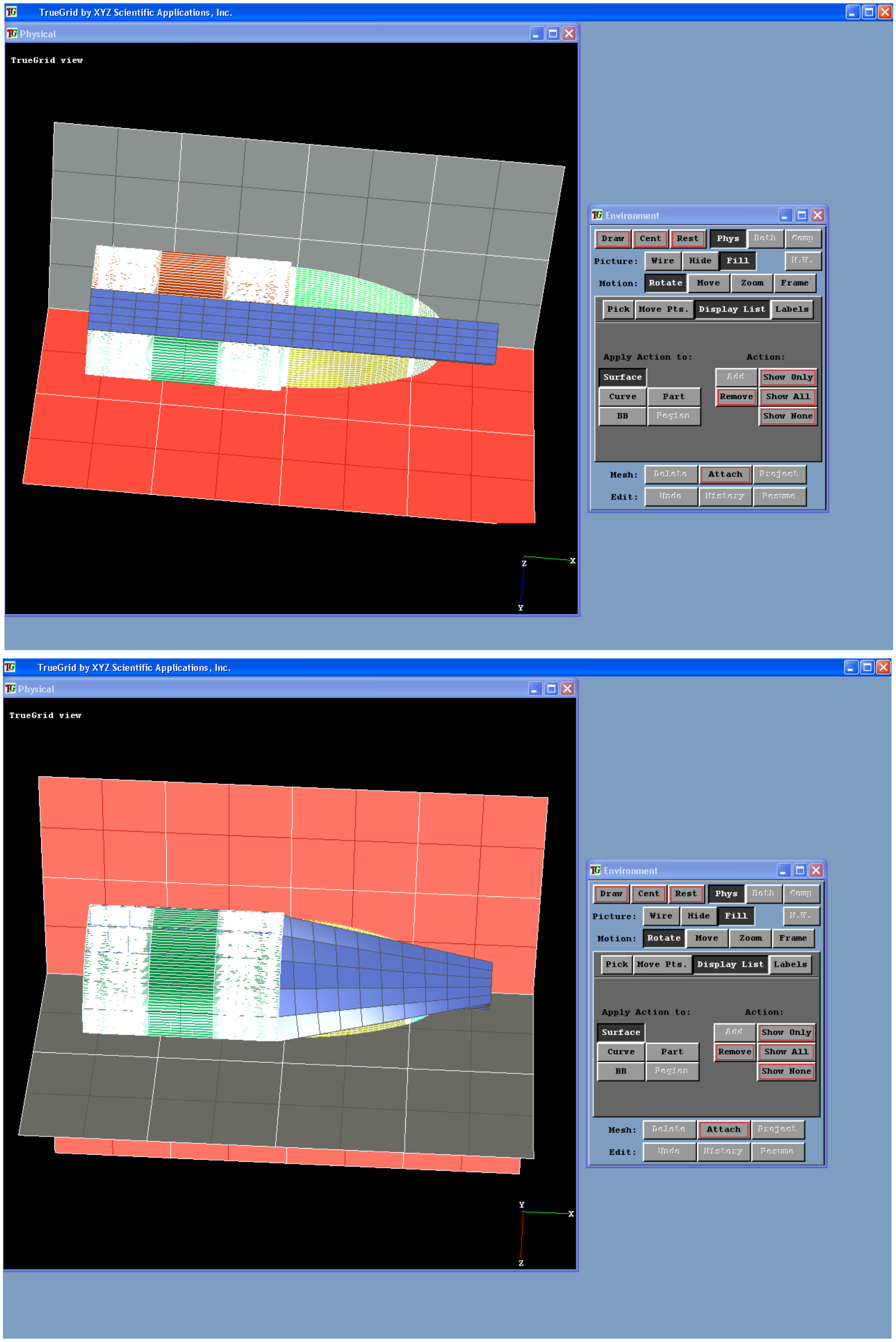
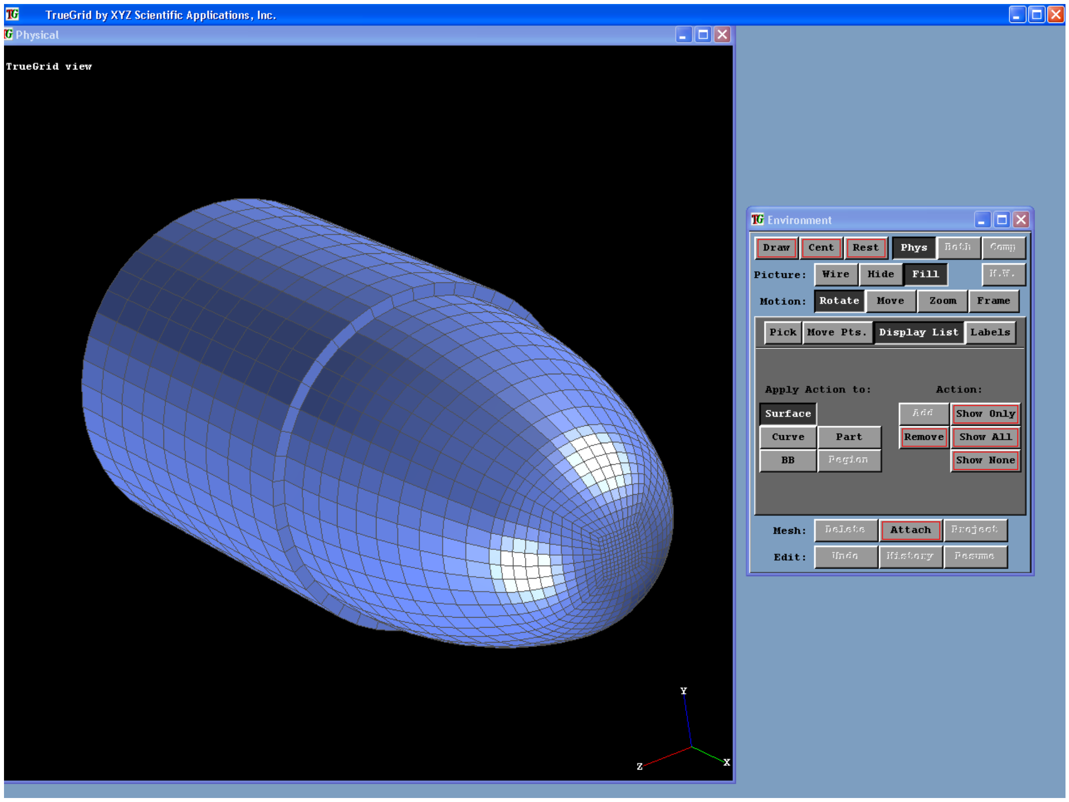
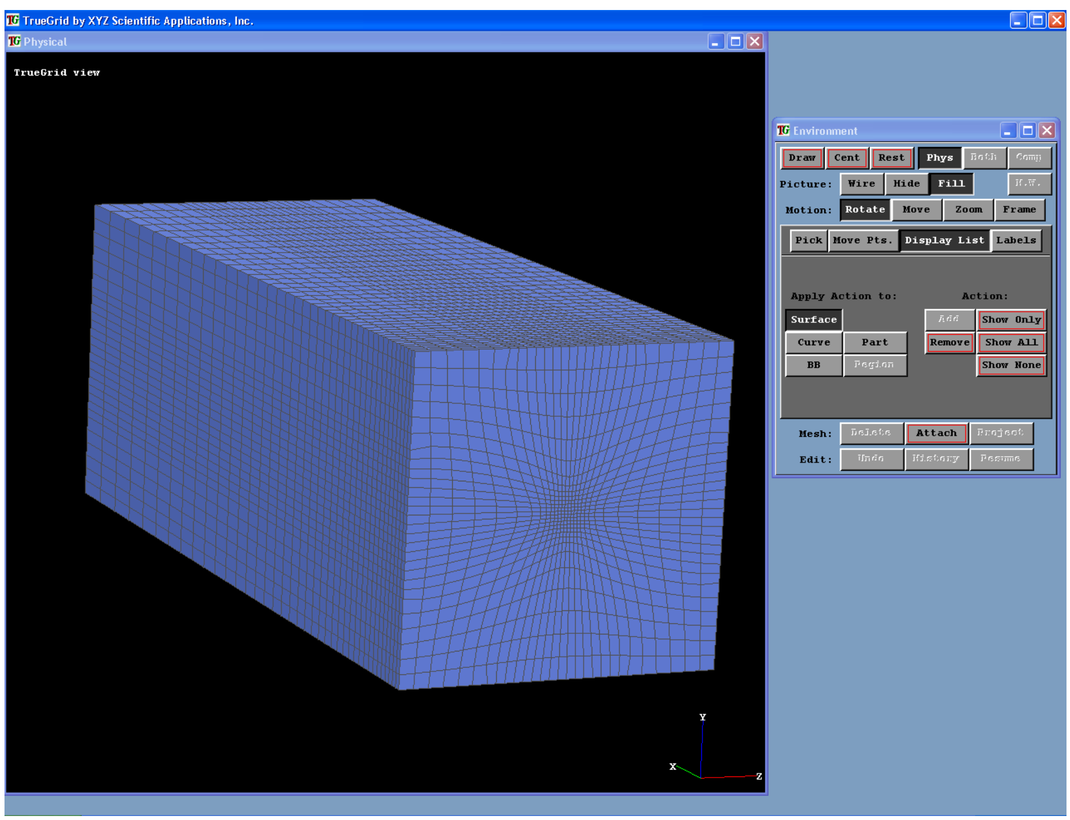


Figure 6: Illustrates the progression of the attachment of curves and projection of mesh onto the bullet.

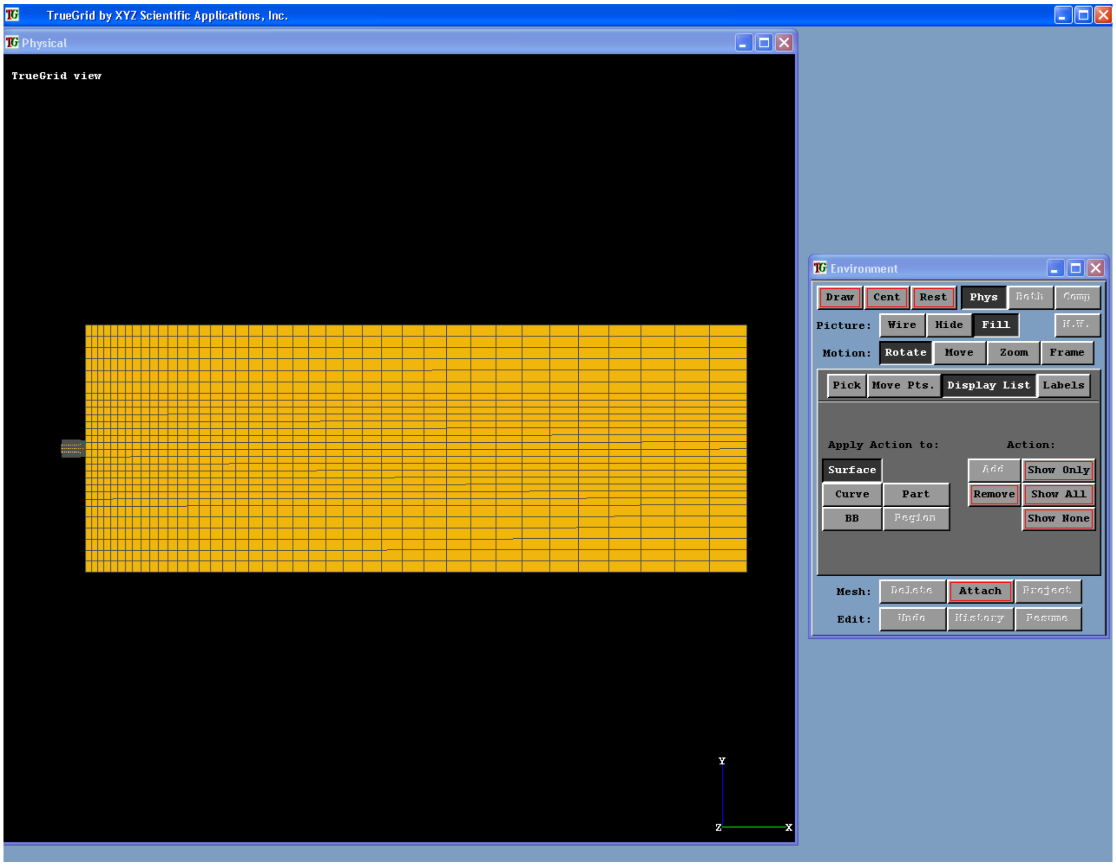


(a)



(b)

Figure 7: **(a)** Final meshed bullet **(b)** Final meshed block



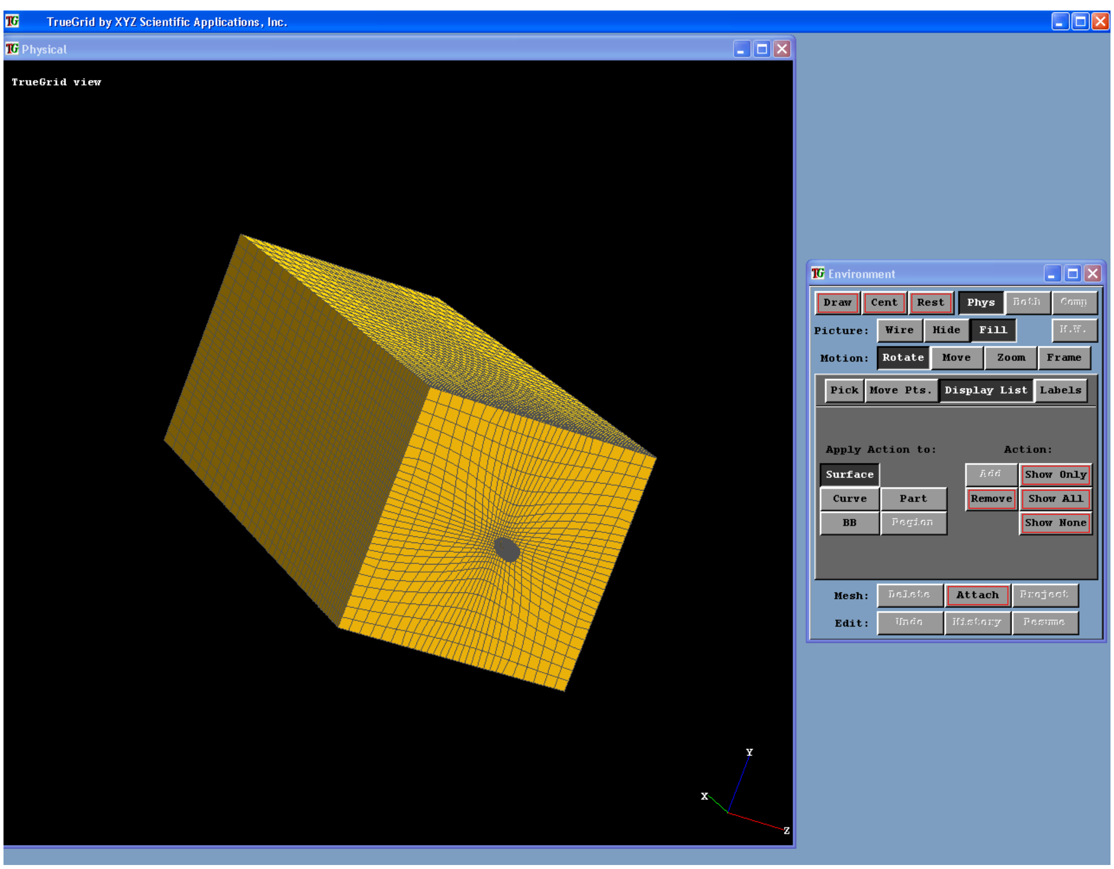


Figure 8: Merged bullet and block

3.3.3 LS-DYNA

The LS-DYNA *KEYWORD format is used to run this analysis. This particular format lets LS-DYNA know that the input deck is a keyword deck instead of a structured format which requires a different defined format to run. The gelatin block was assigned to an isotropic elastic plastic material and a viscoelastic material. Two simulations were run for each material. The bullet was assigned to an elastic plastic material. Both of these materials also included an add erosion material type. Erosion is necessary in order to simulate the cavity formations and degradation of the bullet displayed in a ballistic gelatin test. These materials and their corresponding properties are assigned in TrueGrid before the LS-DYNA Keyword output file is written.

The isotropic elastic plastic material model is known in LS-DYNA as Material Type 12 or *MAT_ISOTROPIC_ELASTIC_PLASTIC (Figure 9). This material model is considered a low cost isotropic plasticity model for three dimensional solids. The viscoelastic plastic material model is known in LS-DYNA as Material Type 6 or *MAT_VISCOELASTIC. This material type allows for modeling of viscoelastic behavior in solids. Each material type has specific cards that indicate the properties needed for application.

Card	1	2	3	4	5	6	7	8
Variable	MID	RO	G	SIGY	ETAN	BULK		
Type	A8	F	F	F	F	F		

VARIABLE	DESCRIPTION
MID	Material identification. A unique number or label not exceeding 8 characters must be specified.
RO	Mass density.
G	Shear modulus.
SIGY	Yield stress.
ETAN	Plastic hardening modulus.
BULK	Bulk modulus, K.

Figure 9: *MAT_ISOTROPIC_ELASTIC_PLASTIC, *MAT_012 [37]

The add erosion model is known in LS-DYNA as *MAT_ADD_EROSION. Most of the models do not allow for failure or erosion to be applied. This material model provides a way to include failure and erosion.

Following the material cards, the contact card is used to apply the properties for the convergence of the bullet into the block. This simulation requires the *CONTACT_ERODING_SURFACE_TO_SURFACE card. This particular contact card allows for the bullet to pass through the gelatin block and create a path or tunnel. This card also allows the bullet to degrade as the gelatin degrades. After the contact card, nodes are assigned throughout the entire problem. This output file is run through LS-DYNA and is analyzed at each point. Once the analysis is complete, a simulation of the results can be animated and processed using LS-PrePost.

CHAPTER 4: RESULTS

4.1 Elastic Plastic 1

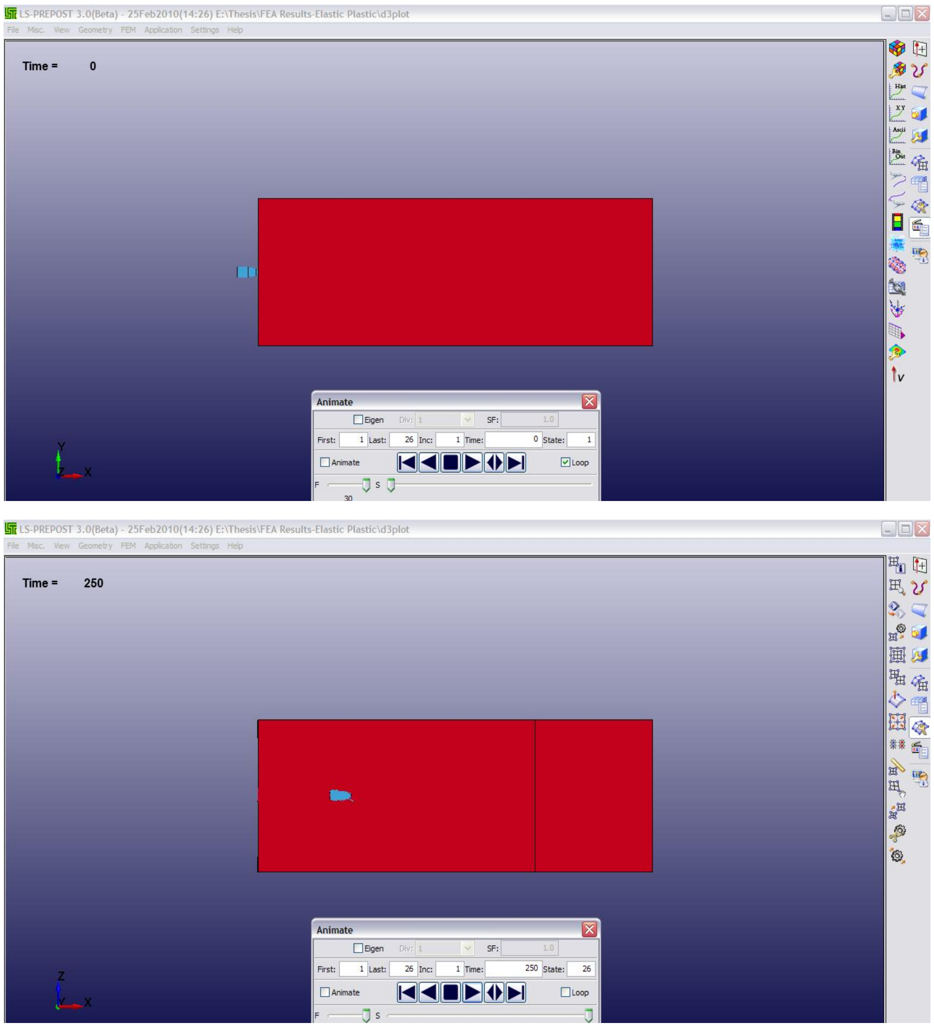


Figure 10: Initial and final state of Elastic Plastic 1.

Elastic Plastic 1 reproduced a visible wound track. The bullet entered the block with the velocity of 304.5 m/s and ended at a depth penetration of 8.1321 cm. The wound track had a relatively straight through path with an entrance diameter of 1.3538 cm, a maximum diameter of 1.3729 cm, and an end diameter of 0.6654 cm. This wound track is strictly the permanent cavity only. No signs of the temporary cavity were visible.

The bullet visibly degraded as it passed through the block. The initial mass of the bullet measured in LS-PREPOST was 10.5378 gm with a final mass of 7.1339 gm resulting in a 32% change. This simulation ran for 250 µs.

Table 3: Elastic Plastic 1 Summary Data

Component	Min Value	State	Part	Item	Max Value	State	Part	Item
X-stress	-4.9235e-001	22	2	H1382	9.7828e-002	4	2	H4256
Y-stress	-4.9545e-001	22	2	H1382	9.5388e-002	4	2	H4157
Z-stress	-4.8747e-001	22	2	H1382	8.4795e-002	4	2	H4157
Effective Plastic Strain	0.0000e+000	1	2	H1	6.0621e+000	24	2	H6705
Effective Stress (v-m)	0.0000e+000	1	2	H1	7.2659e-002	24	2	H6705
Max Shear Stress	0.0000e+000	1	2	H1	3.7280e-002	25	2	H6705
Pressure	-9.2163e-002	4	2	H4526	4.9176e-001	22	2	H1382
Max Principal Stress	-4.8336e-001	22	2	H1382	9.8294e-002	4	2	H4256
2nd Principal Stress	-4.9239e-001	22	2	H1382	9.4149e-002	4	2	H4256
Min Principal Stress	-4.9952e-001	22	2	H1382	8.4046e-002	4	2	H4256
Shell Thickness	0.0000e+000				0.0000e+000			
X-displacement	-2.7539e+000	26	1	N24883	2.0398e+001	26	1	N220
Y-displacement	-2.0080e+000	26	1	N10770	1.8937e+001	26	1	N11736
Z-displacement	-3.2001e+001	26	1	N5207	3.2246e+001	26	1	N11030
Resultant Displacement	-7.5517e-002	1	2	N1	3.7049e+001	26	1	N5207
X-velocity	-1.4404e-001	16	1	N11110	1.0835e-001	21	1	N11733
Y-velocity	-1.4404e-001	16	1	N11356	1.9891e-001	17	1	N11736
Z-velocity	-1.7005e-001	15	1	N10531	2.4078e-001	13	1	N11030
Resultant velocity	0.0000e+000	1	1	N12163	2.6588e-001	13	1	N11030

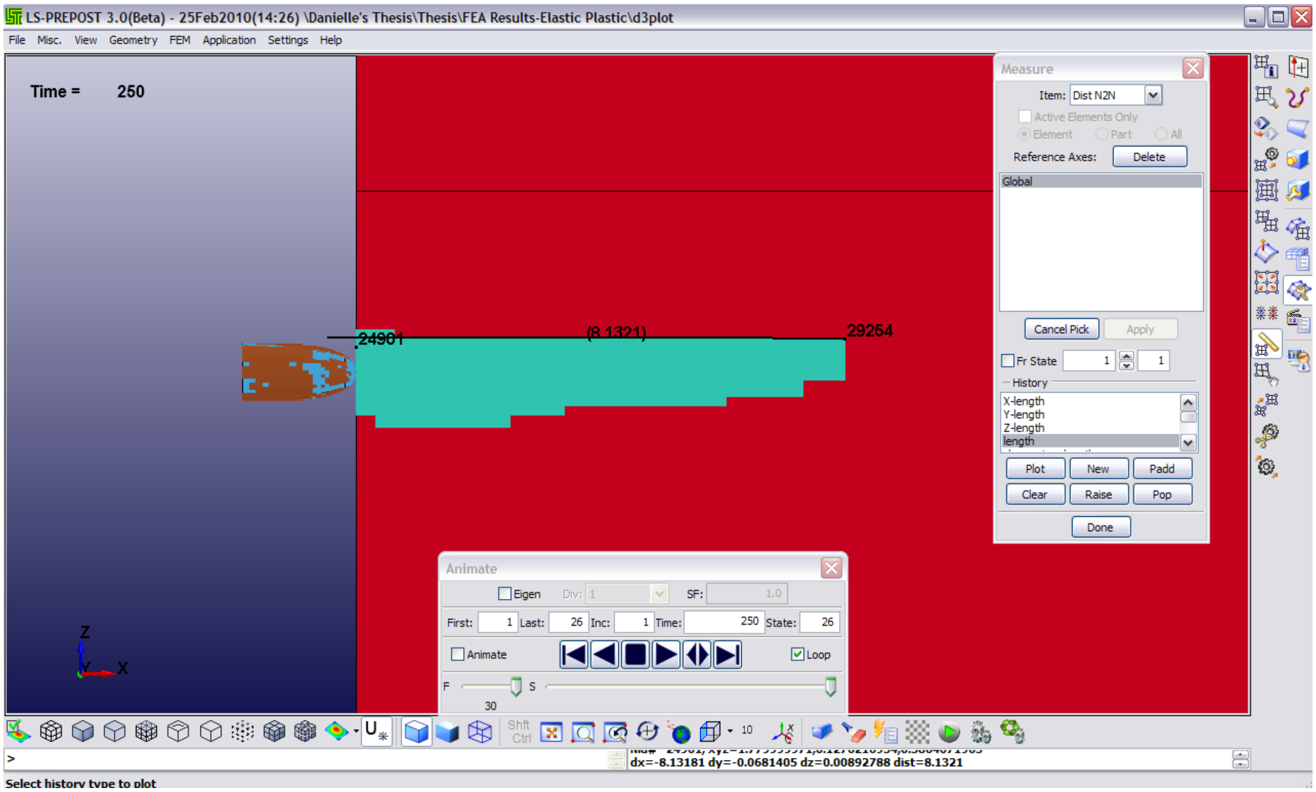


Figure 11: Permanent Cavity and Depth Penetration of Elastic Plastic 1 bullet

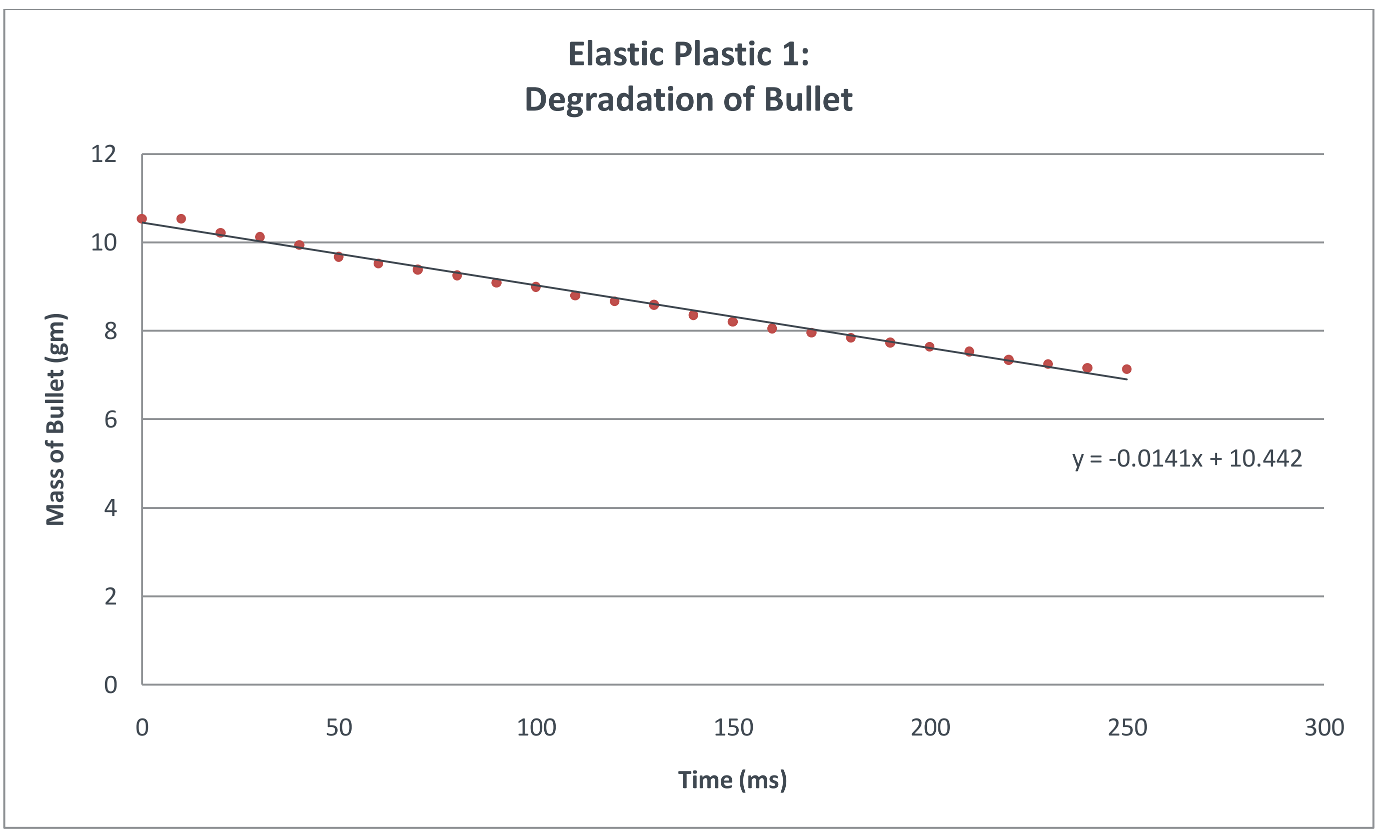


Figure 12: Change in mass of Elastic Plastic 1 bullet

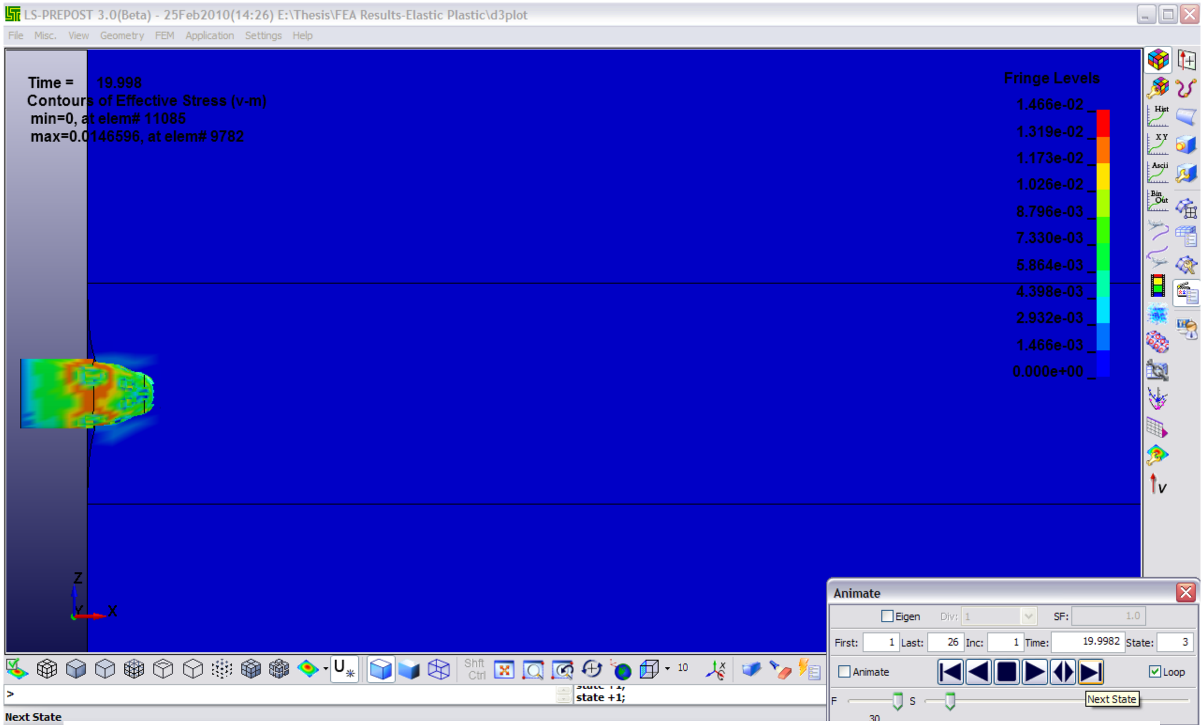


Figure 13: Von-Mises stress applied on Elastic Plastic 1 bullet

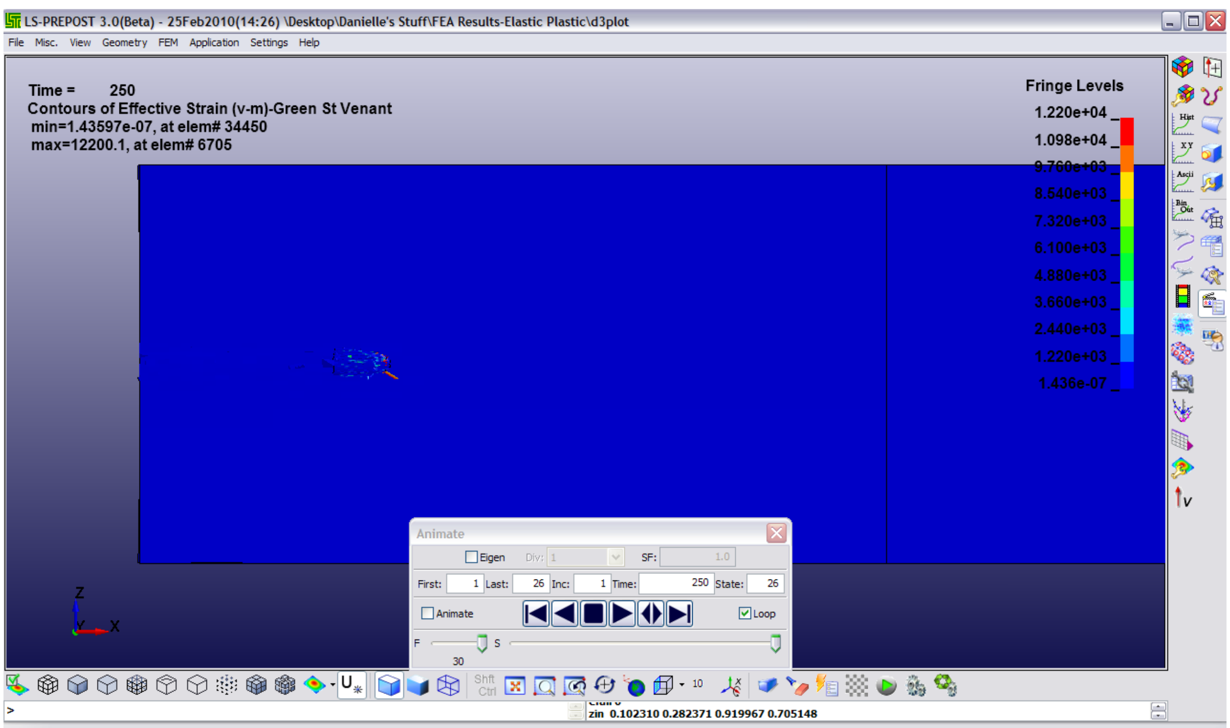


Figure 14: Green Effective Strain at final state of Elastic Plastic 1.

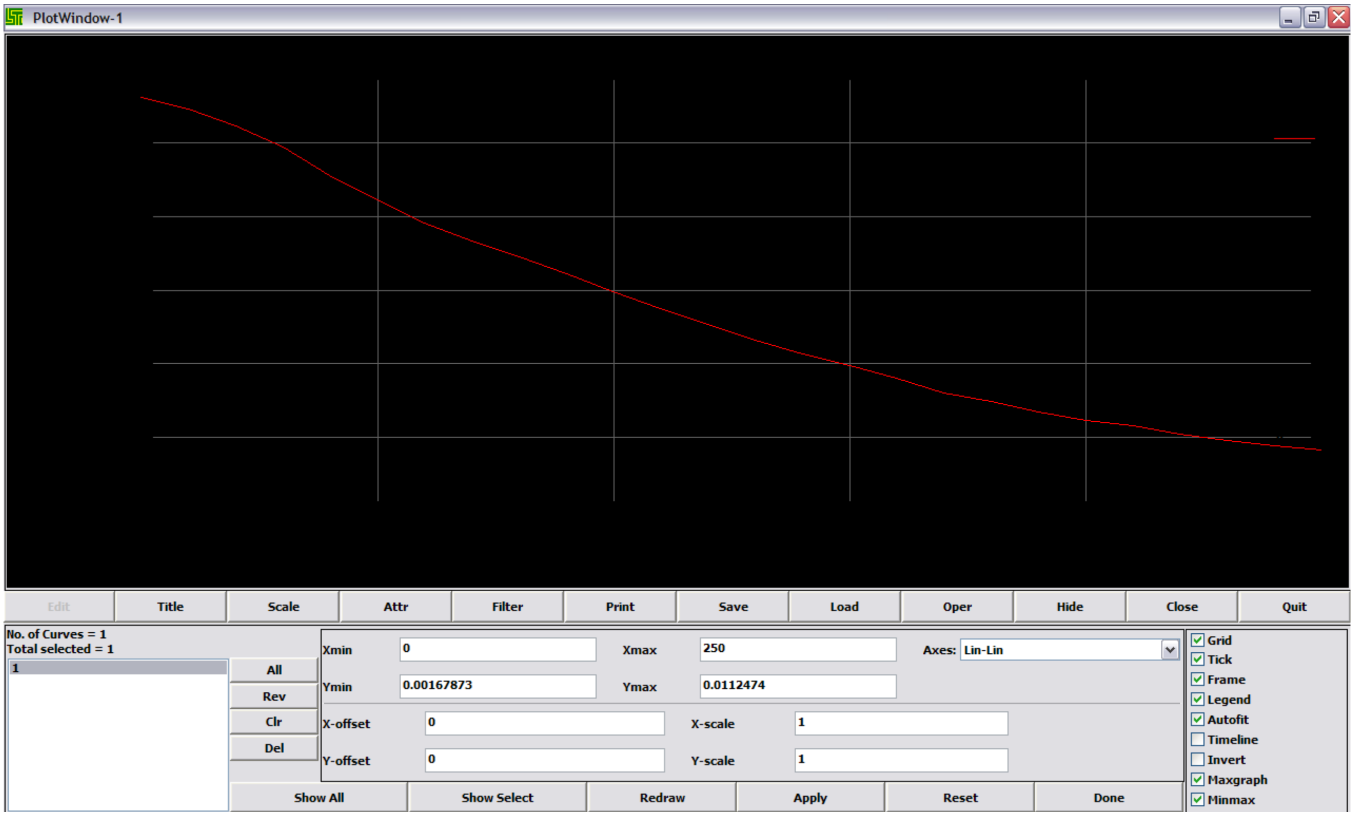


Figure 15: Kinetic Energy throughout Elastic Plastic 1

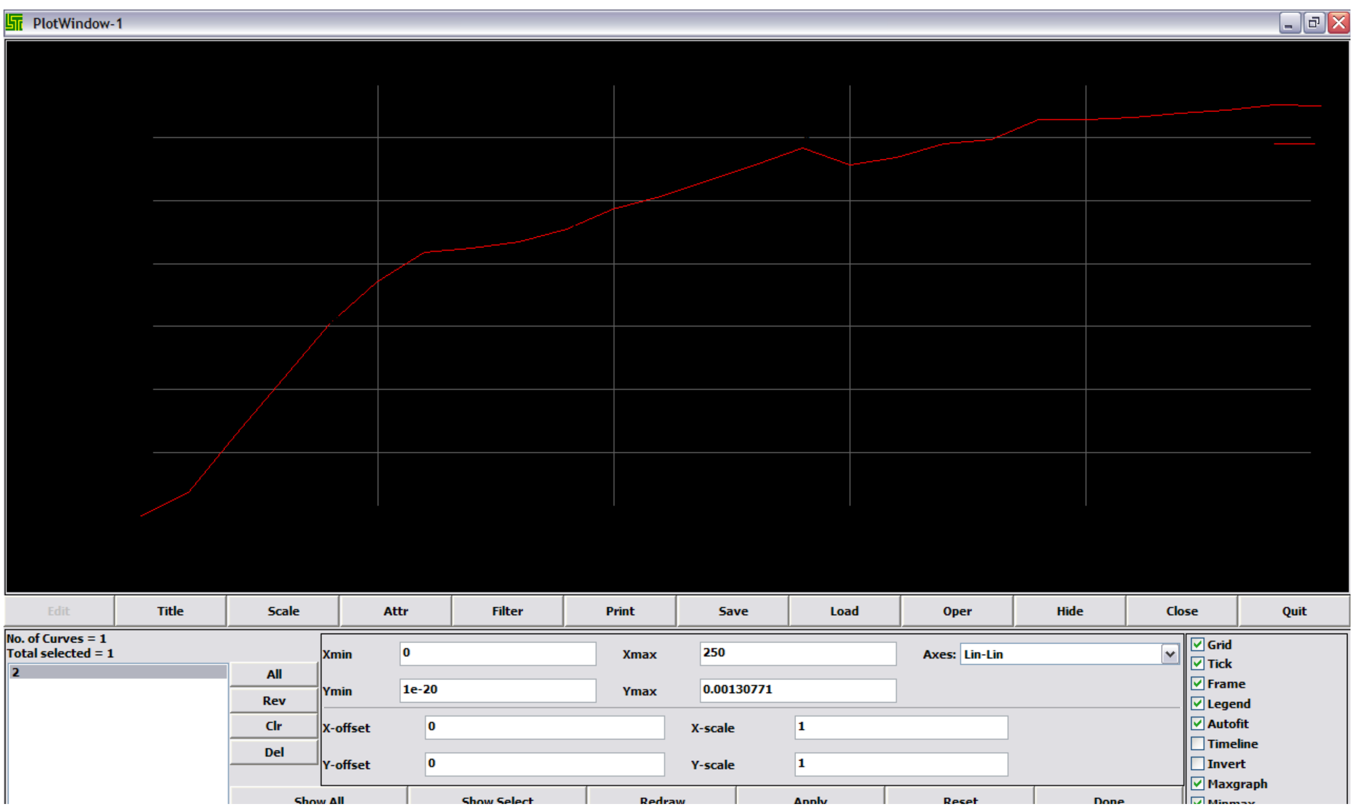


Figure 16: Internal Energy absorbed throughout Elastic Plastic 1

4.2 Elastic Plastic 2

Elastic Plastic 2 also reproduced a visible wound track. The bullet entered the block with the velocity of 304.5 m/s and ended at a depth penetration of 11.8723 cm. The wound track had a relatively straight through path with an entrance diameter of 4.1992 cm, a maximum diameter of 4.1992 cm, and an end diameter of 1.2353 cm. There were signs of a temporary cavity with a maximum diameter of 7.4132 cm (Figure 22). The bullet degraded completely as it passed through the block. A fragment can be seen traveling 5.9547 cm past the end of the permanent cavity without creating a path behind it. This simulation ran for 1000 µs.

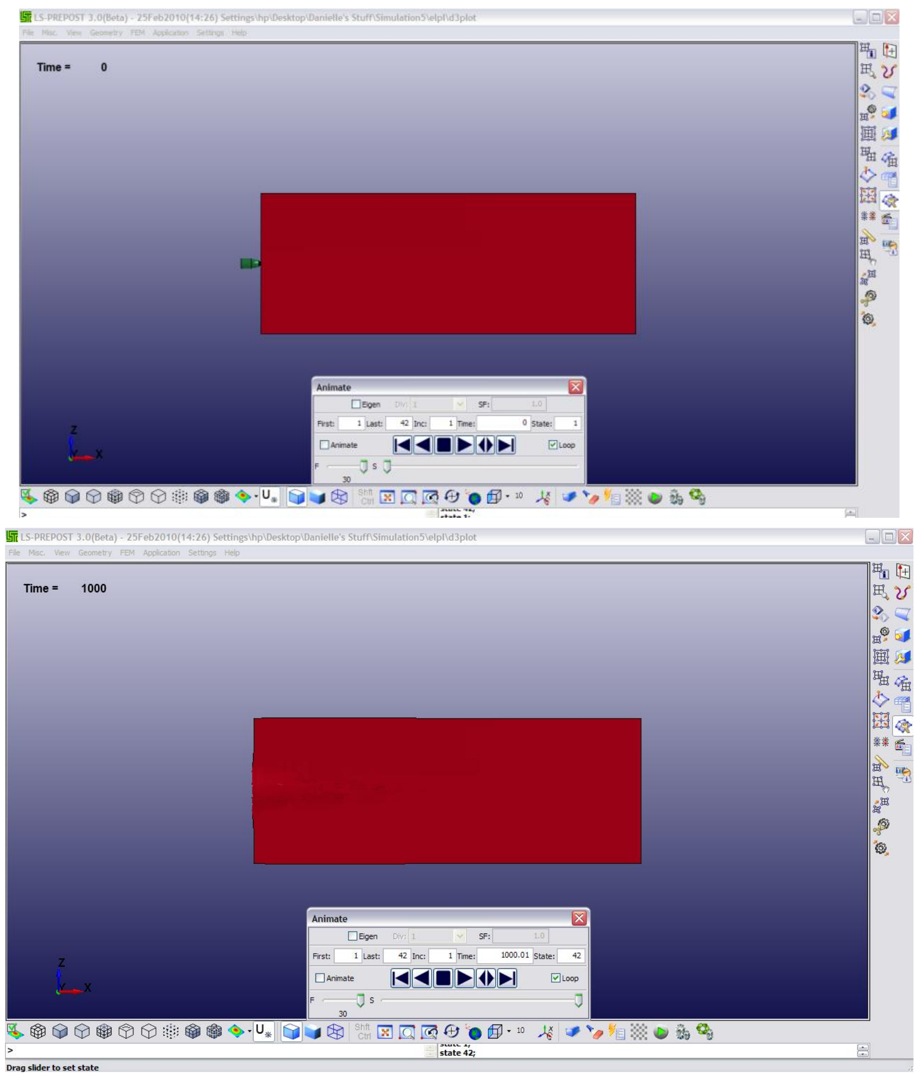


Figure 17: Initial and final state of Elastic Plastic 2

Table 4: Elastic Plastic 2 Summary Data

Component	Min Value	State	Part	Item	Max Value	State	Part	Item
X-stress	-2.7059e-002	2	3	H9046	1.1547e-002	6	3	H3811
Y-stress	-2.7235e-002	2	3	H9046	1.1703e-002	6	3	H3811
Z-stress	-2.7018e-002	2	3	H9046	1.1540e-002	6	3	H3811
Effective Plastic Strain	0.0000e+000	1	3	H1	9.4051e-001	11	3	H3553
Effective Stress (v-m)	0.0000e+000	1	3	H1	6.5451e-004	15	3	H3657
Max Shear Stress	0.0000e+000	1	3	H1	3.7251e-004	15	3	H3657
Pressure	-1.1597e-002	6	3	H3811	2.7104e-002	2	3	H9046
Max Principal Stress	-2.7007e-002	2	3	H9046	1.1734e-002	6	3	H3811
2nd Principal Stress	-2.7020e-002	2	3	H9046	1.1567e-002	6	3	H3811
Min Principal Stress	-2.7278e-002	2	3	H9046	1.1488e-002	6	3	H3811
Shell Thickness	0.0000e+000				0.0000e+000			
X-displacement	-2.3856e+000	42	1	N23494	4.6850e+001	42	1	N8864
Y-displacement	-3.8493e+001	42	1	N10443	2.9472e+001	42	1	N1021
Z-displacement	-3.6319e+001	42	1	N9415	3.0008e+001	42	1	N2505
Resultant Displacement	0.0000e+000	1	3	N1	5.0710e+001	42	1	N9415
X-velocity	-2.4455e-003	3	1	N23494	4.6880e-002	2	1	N8864
Y-velocity	-4.9943e-002	2	3	N10444	3.2674e-002	5	1	N10211
Z-velocity	-3.8088e-002	3	1	N9415	3.5488e-002	8	1	N2505
Resultant velocity	0.0000e+000	1	1	N10821	5.7825e-002	2	3	N10444

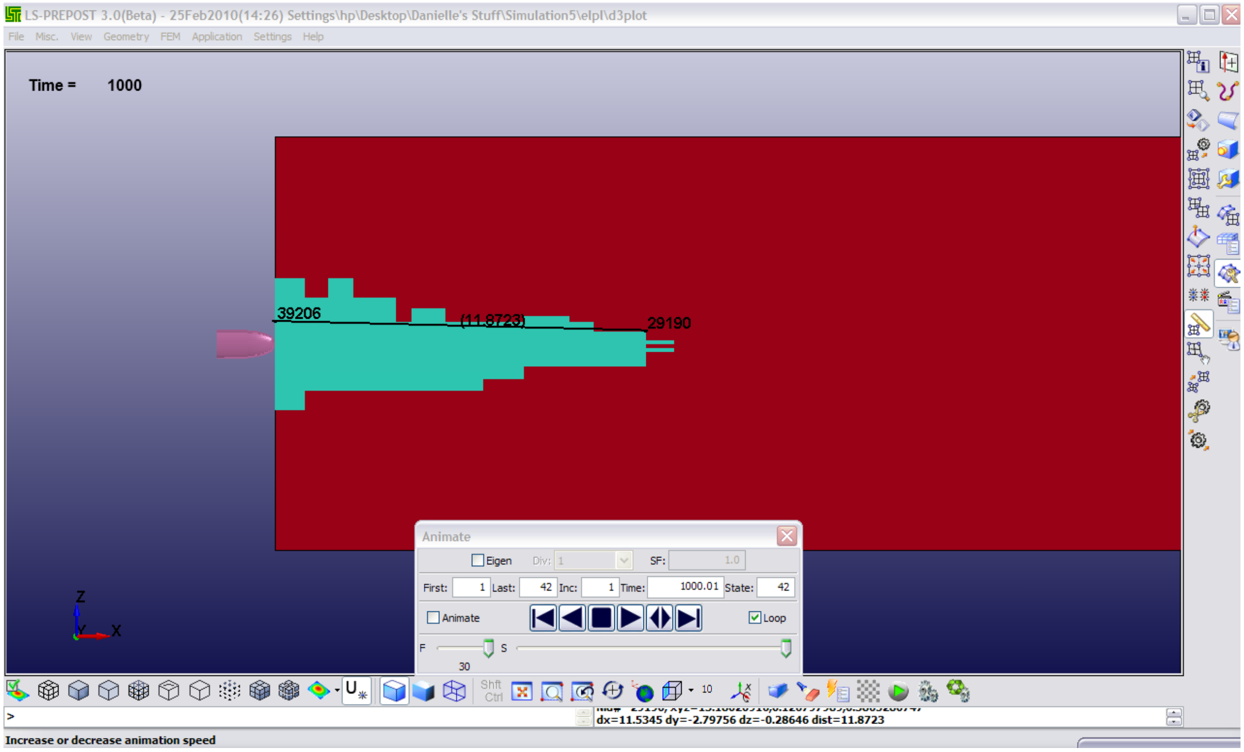


Figure 18: Elastic Plastic 2 Permanent Cavity and Depth Penetration of bullet

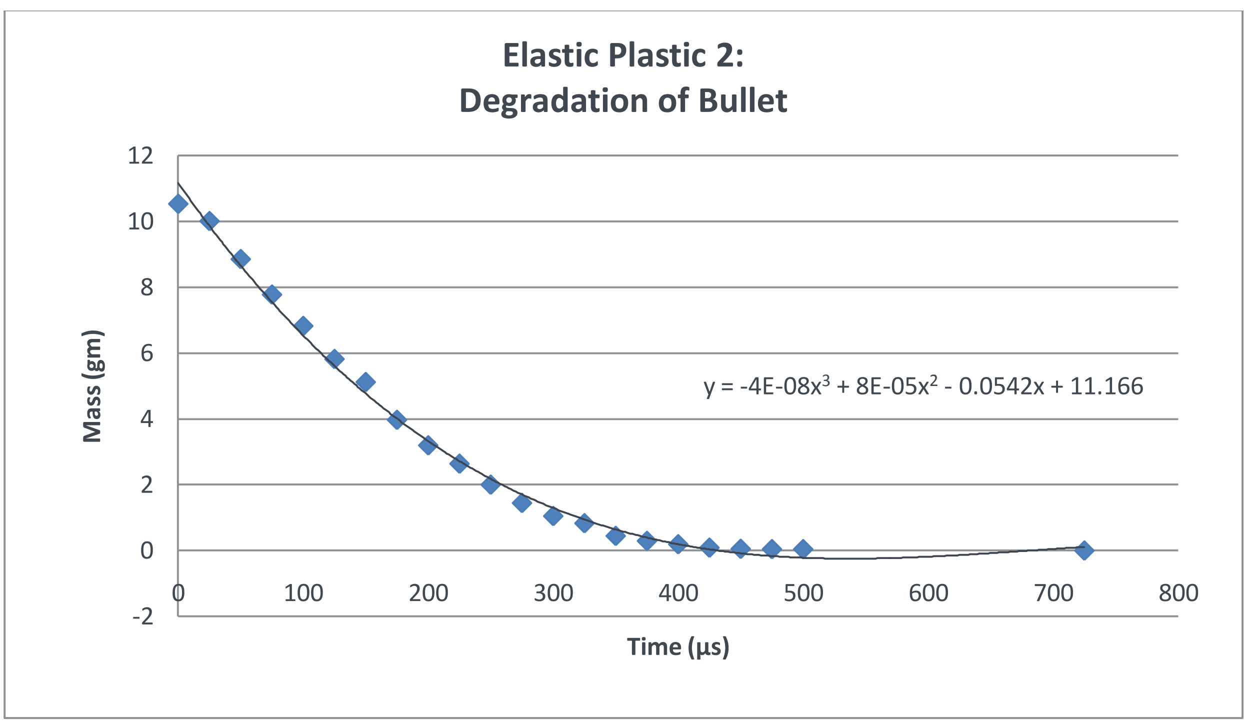


Figure 19: Change in mass of Elastic Plastic 2 bullet. The mass of the bullet after 500 µs could not be measured until it completely disappeared at 700 µs.

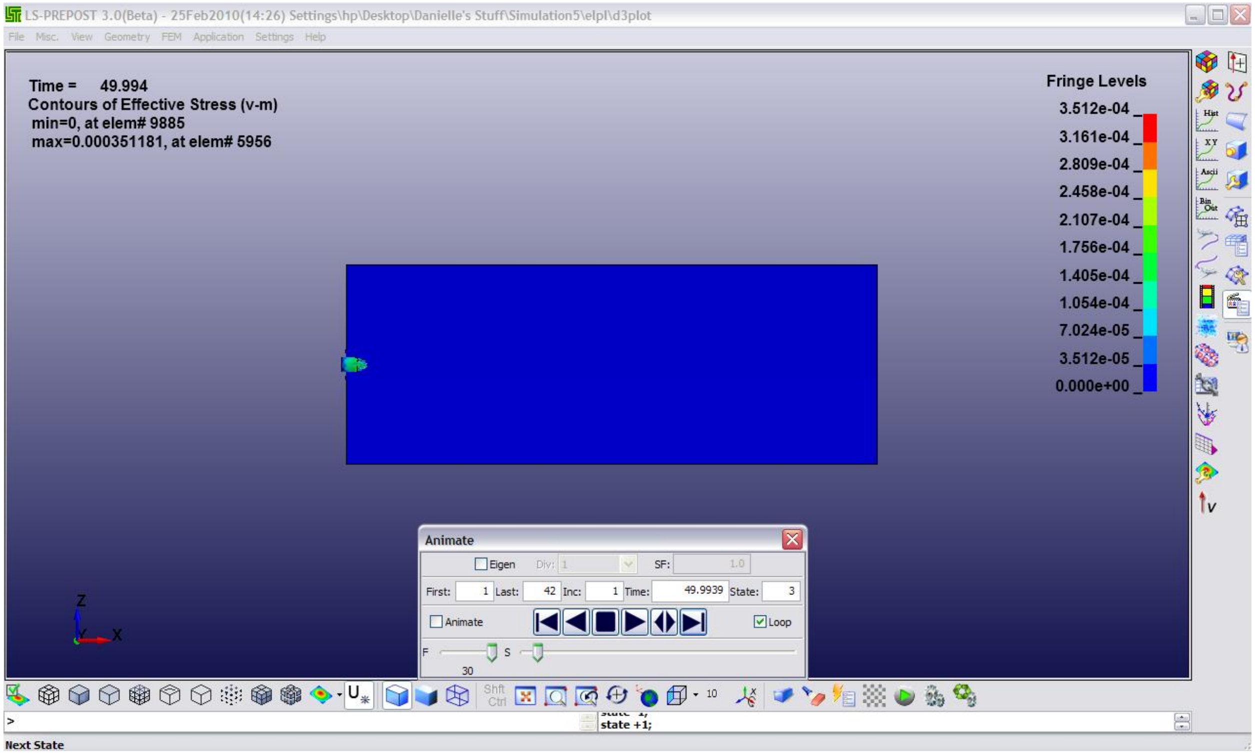


Figure 20: Von-Mises stress applied on bullet of Elastic Plastic 2

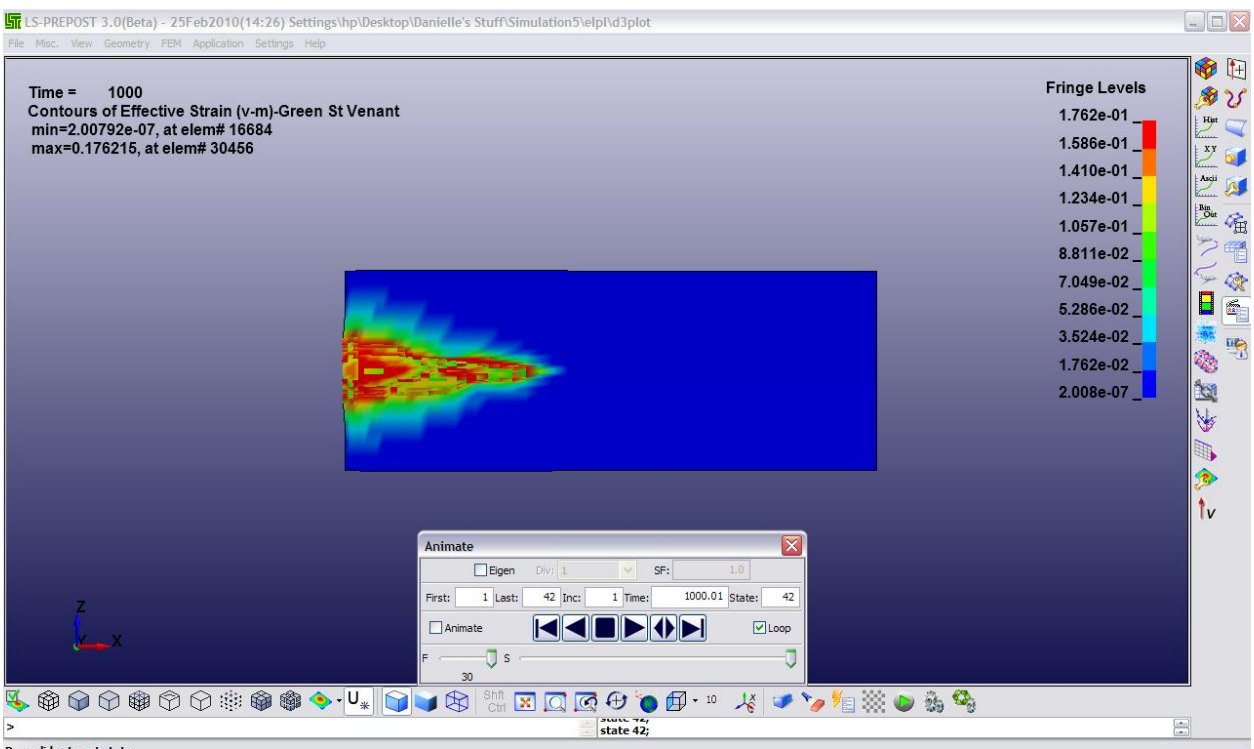
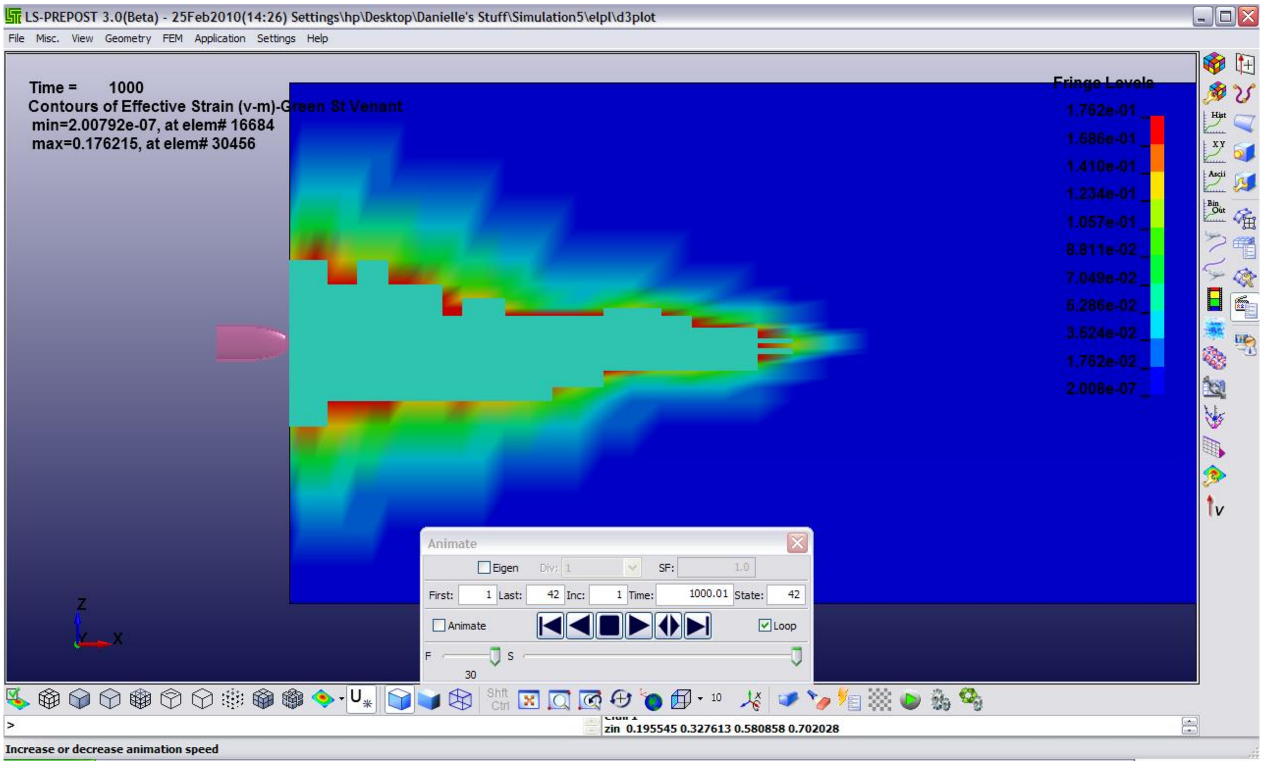
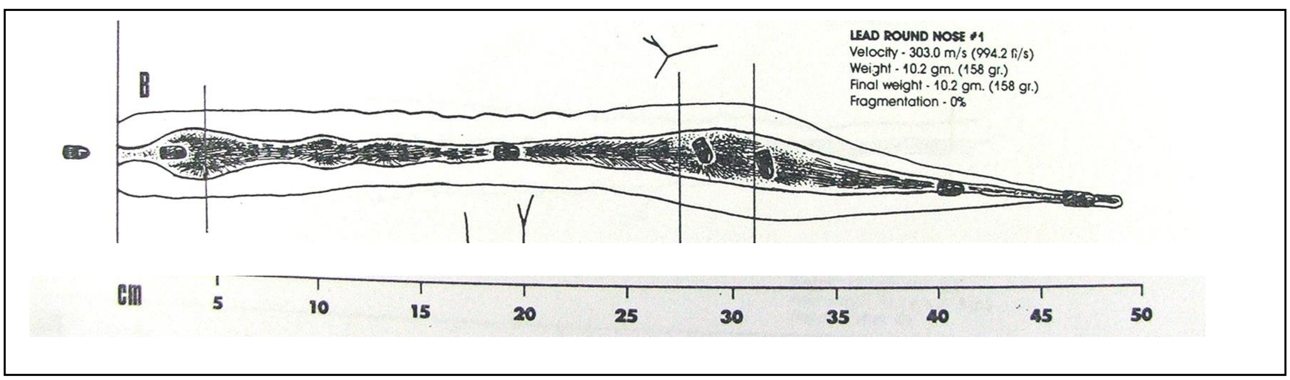


Figure 21: Green Effective Strain at final state of Elastic Plastic 2



(a)



(b)

Figure 22: (a) Elastic Plastic 2 wound profile of Lead Round Nose
(b) Ballistic Gelatin Test wound profile of Lead Round Nose

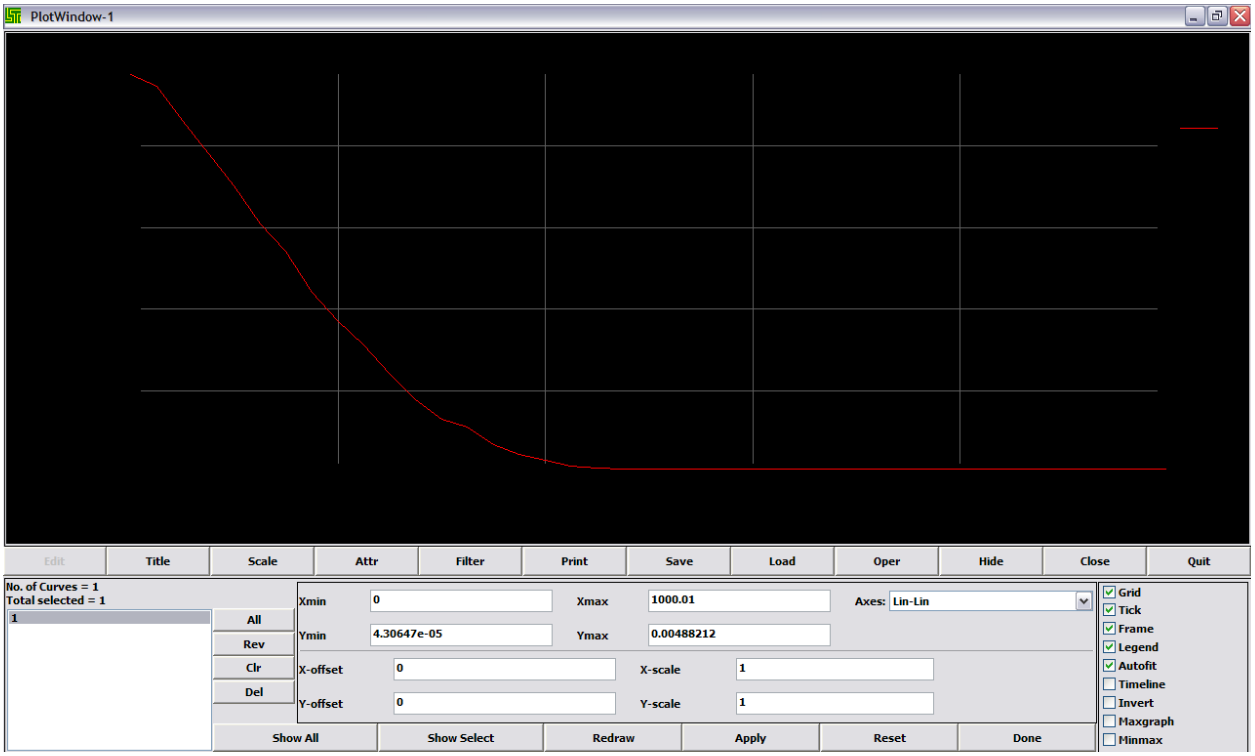


Figure 23: Kinetic energy throughout Elastic Plastic 2

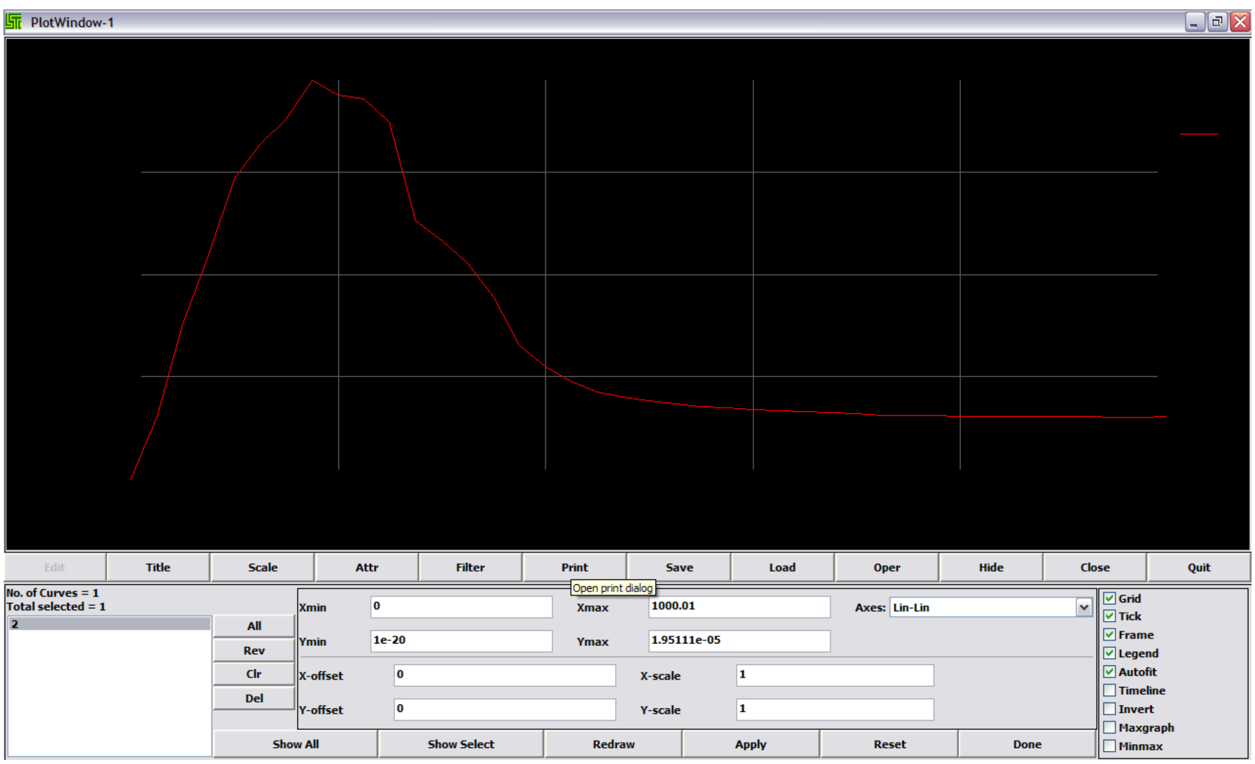


Figure 24: Internal energy absorbed throughout Elastic Plastic 2

4.3 Viscoelastic 1

Viscoelastic 1 reproduced a visible wound track. The bullet entered the block with the velocity of 304.5 m/s and ended at a depth penetration of 20.19cm. This wound track displayed both the permanent and temporary cavity (Figure 28). The permanent cavity had an entrance diameter of 3.4569 cm, a maximum diameter of 3.4569 cm, and a final diameter of 1.1087 cm. The temporary cavity had a maximum diameter of 7.5759 cm. The bullet visibly degraded as it passed through the block. The initial mass of the bullet measured in LS-PREPOST was 10.528 gm with a final mass of 10.2338 gm resulting in a 2.79% change. The bullet also tumbled towards the end of penetration. This simulation ran for 700 µs.

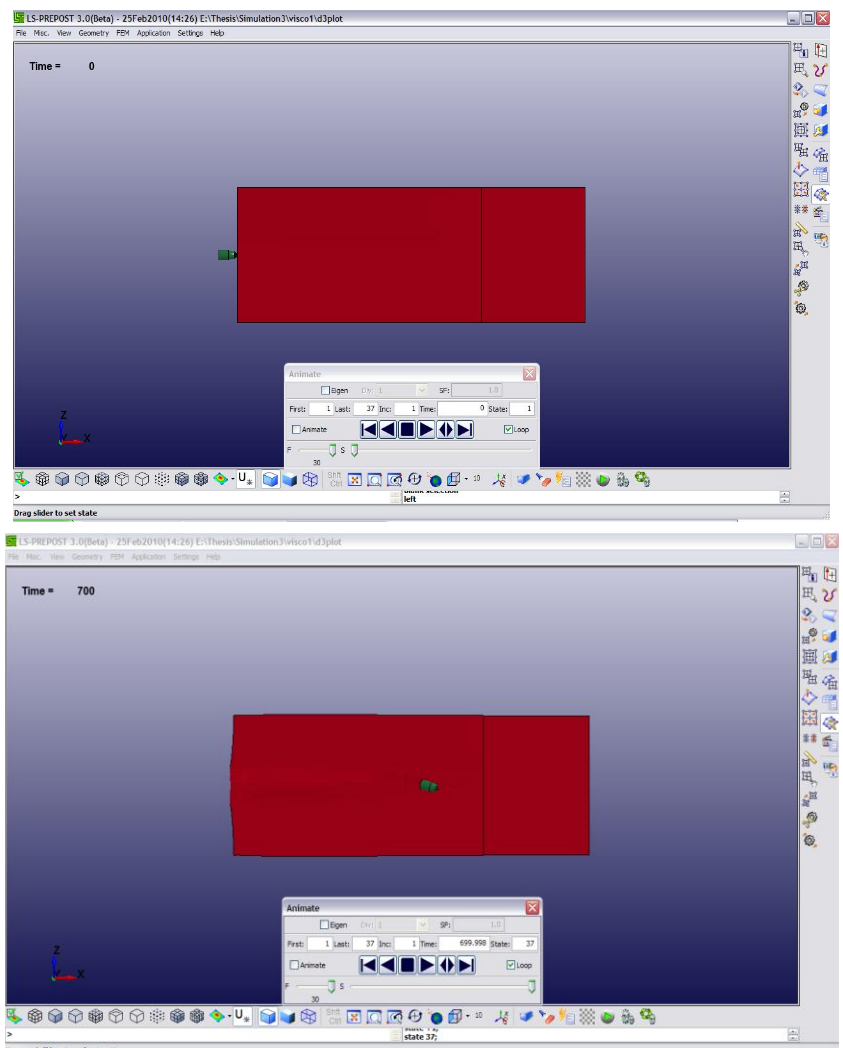


Figure 25: Initial and final state of Viscoelastic 1

Table 5: Viscoelastic 1 Summary Data

Component	Min Value	State	Part	Item	Max Value	State	Part	Item
X-stress	-9.8791e-002	7	3	H5279	4.4736e-002	7	3	H5179
Y-stress	-9.2636e-002	7	3	H5279	4.9244e-002	7	3	H5179
Z-stress	-9.0373e-002	7	3	H5279	4.7145e-002	24	3	H7019
Effective Plastic Strain	0.0000e+000	1	3	H1	6.9811e-001	36	3	H8890
Effective Stress (v-m)	0.0000e+000	1	3	H1	1.8985e-002	36	3	H8890
Max Shear Stress	0.0000e+000	1	3	H1	1.0548e-002	36	3	H8890
Pressure	-4.3476e-002	7	3	H5179	9.3933e-002	7	3	H5279
Max Principal Stress	-8.8317e-002	7	3	H5279	5.0926e-002	7	3	H5179
2^{nd} Principal Stress	-9.0510e-002	7	3	H5279	4.3531e-002	7	3	H5179
Min Principal Stress	-1.0297e-001	7	3	H5279	3.5972e-002	7	3	H5179
Shell Thickness	0.0000e+000				0.0000e+000			
X-displacement	-1.7758e+000	37	1	N23505	3.5869e+001	37	1	N8864
Y-displacement	-1.9175e+001	37	1	N26337	1.9699e+001	37	1	N8846
Z-displacement	-1.7983e+001	37	1	N26337	1.6063e+001	37	1	N26611
Resultant Displacement	0.0000e+000	1	3	N1	3.5869e+001	37	1	N8864
X-velocity	-4.0574e-003	31	1	N30178	5.1235e-002	2	1	N8864
Y-velocity	-4.1278e-002	30	1	N8746	3.9784e-002	13	1	N8846
Z-velocity	-3.4035e-002	11	1	N26337	4.5266e-002	21	1	N28644
Resultant velocity	0.0000e+000	1	1	N10821	5.5388e-002	30	1	N8745

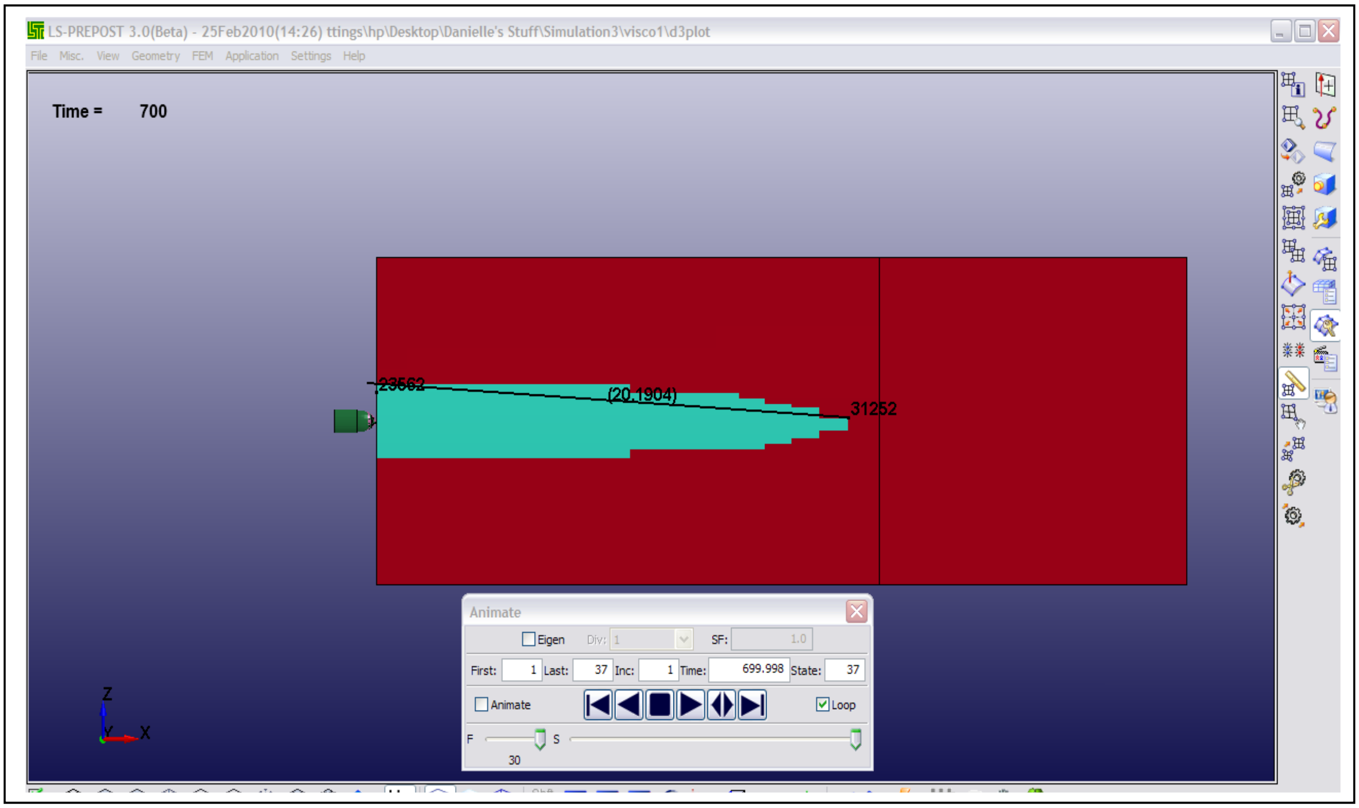


Figure 26: Viscoelastic 1 Permanent Cavity and Depth Penetration of bullet

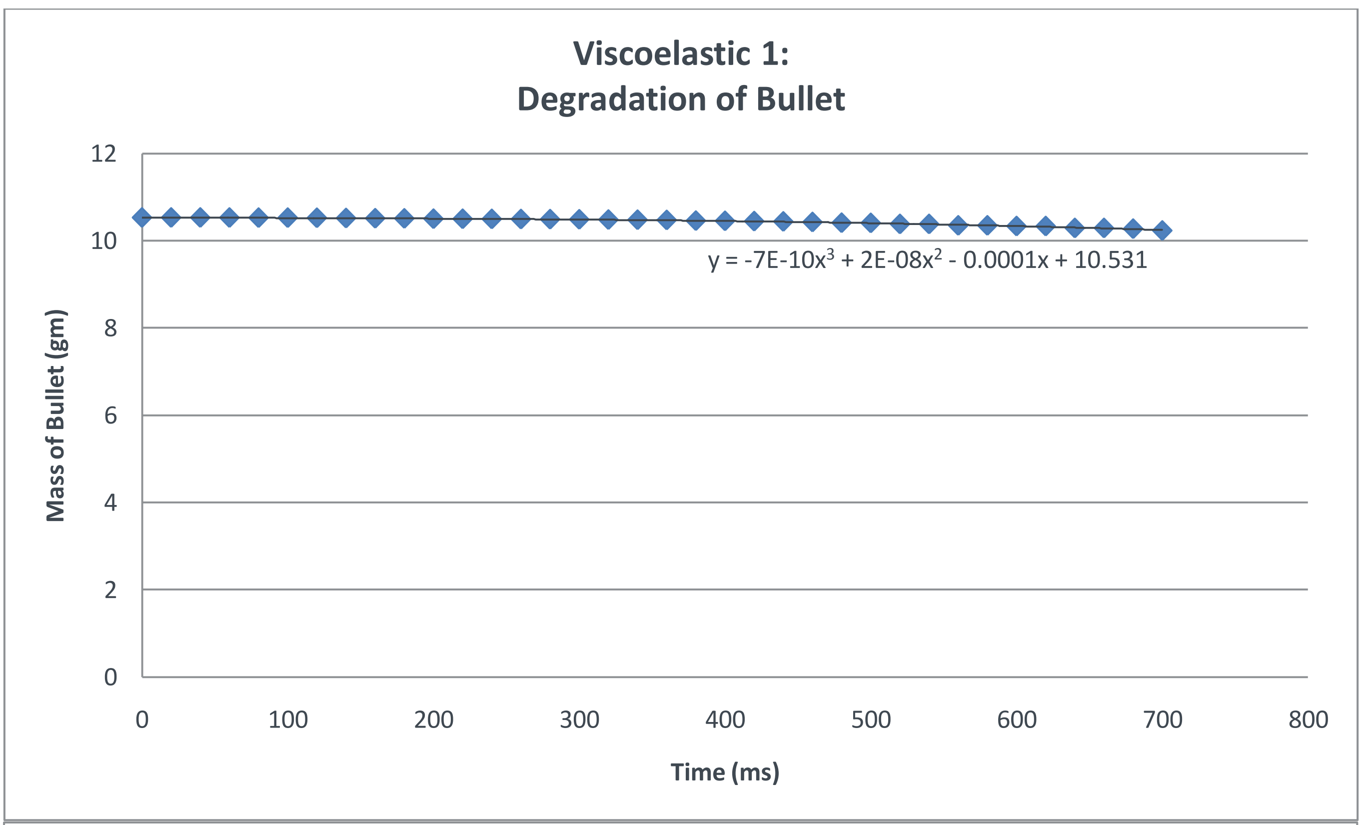
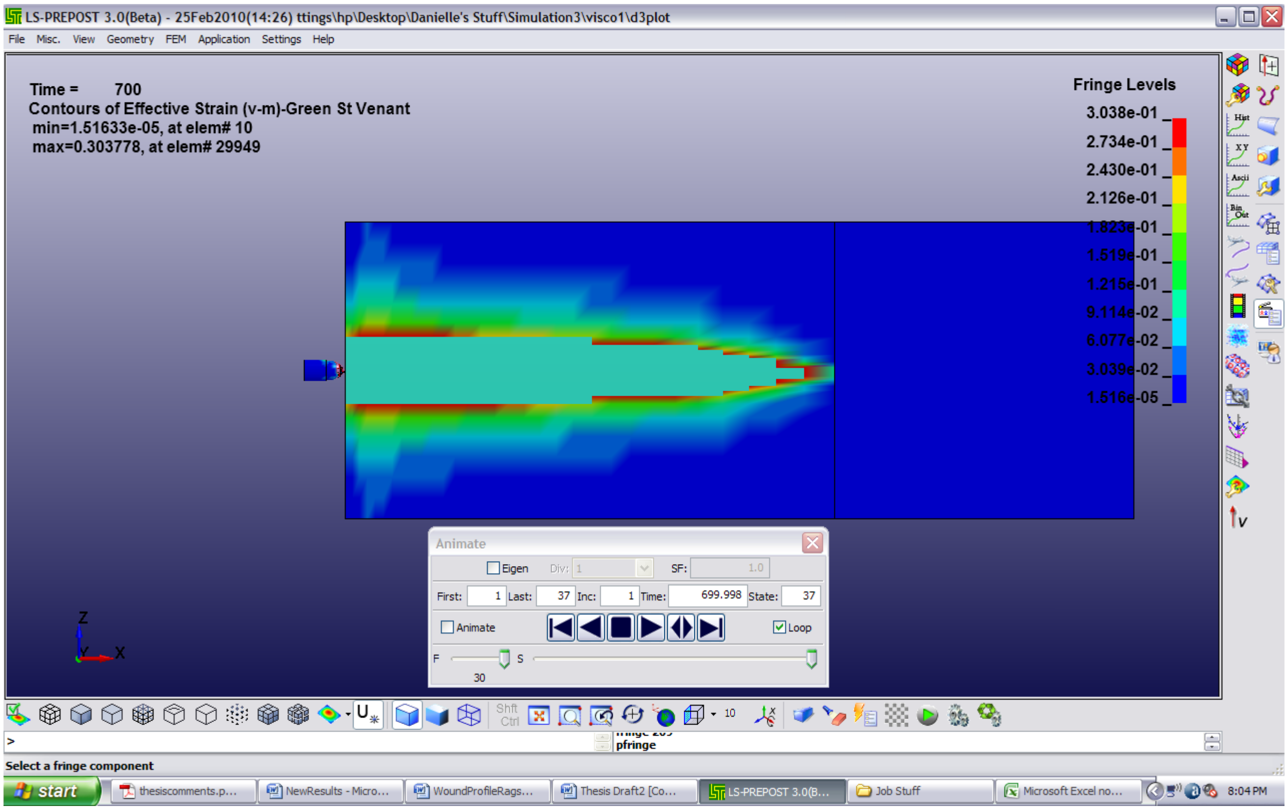
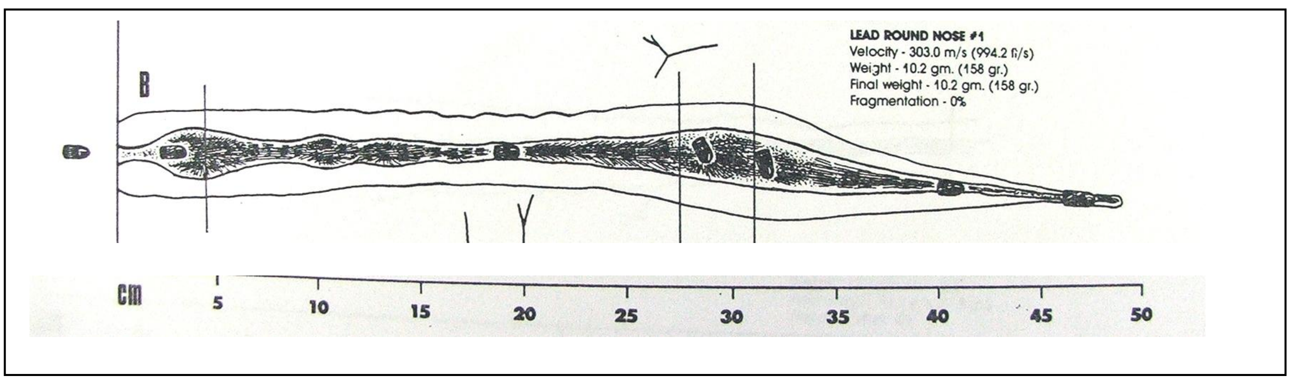


Figure 27: Change in mass of Viscoelastic 1 bullet



(a)



(b)

Figure 28: (a) Viscoelastic 1 wound profile of Lead Round Nose
(b) Ballistic Gelatin Test wound profile of Lead Round Nose

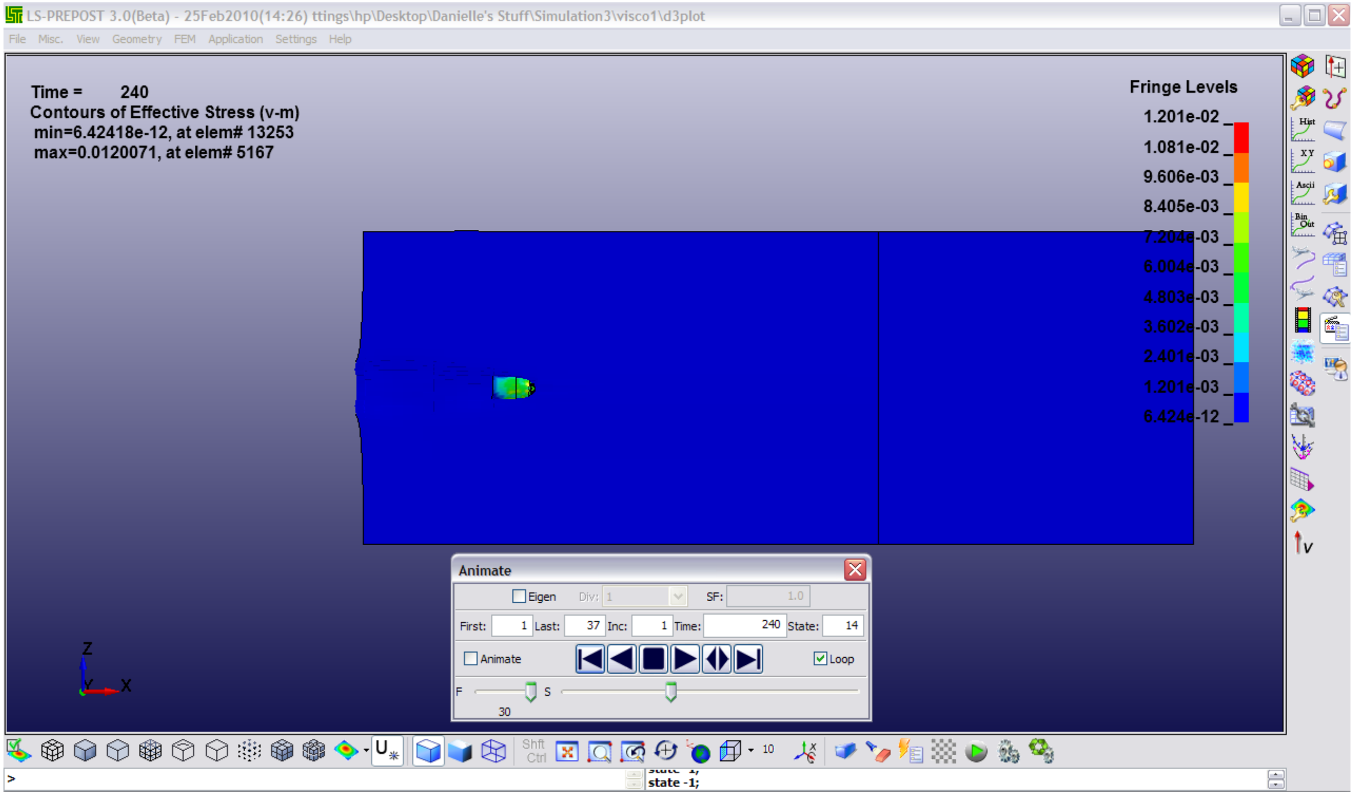


Figure 29: Von-Mises effective stress applied to the Viscoelastic 1 bullet

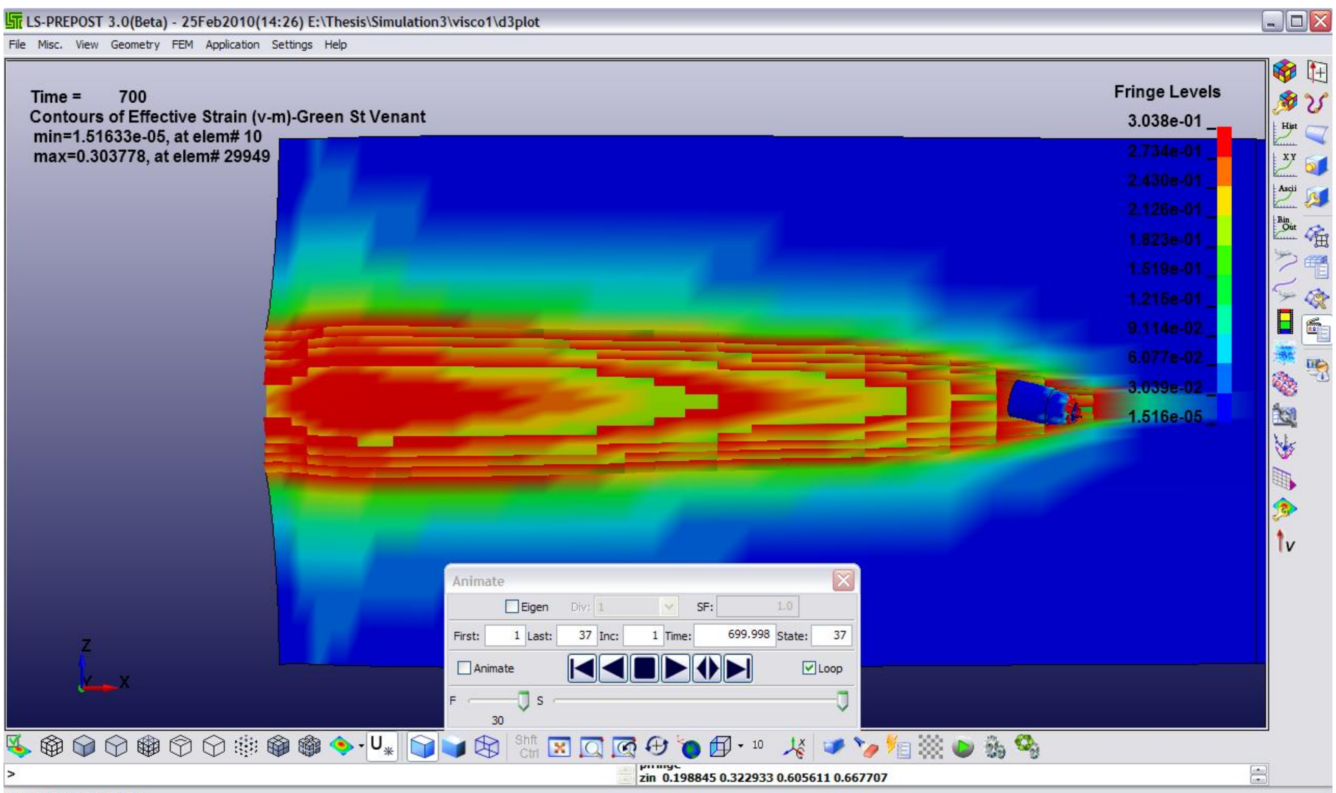


Figure 30: Green effective strain at final state of Viscoelastic 1

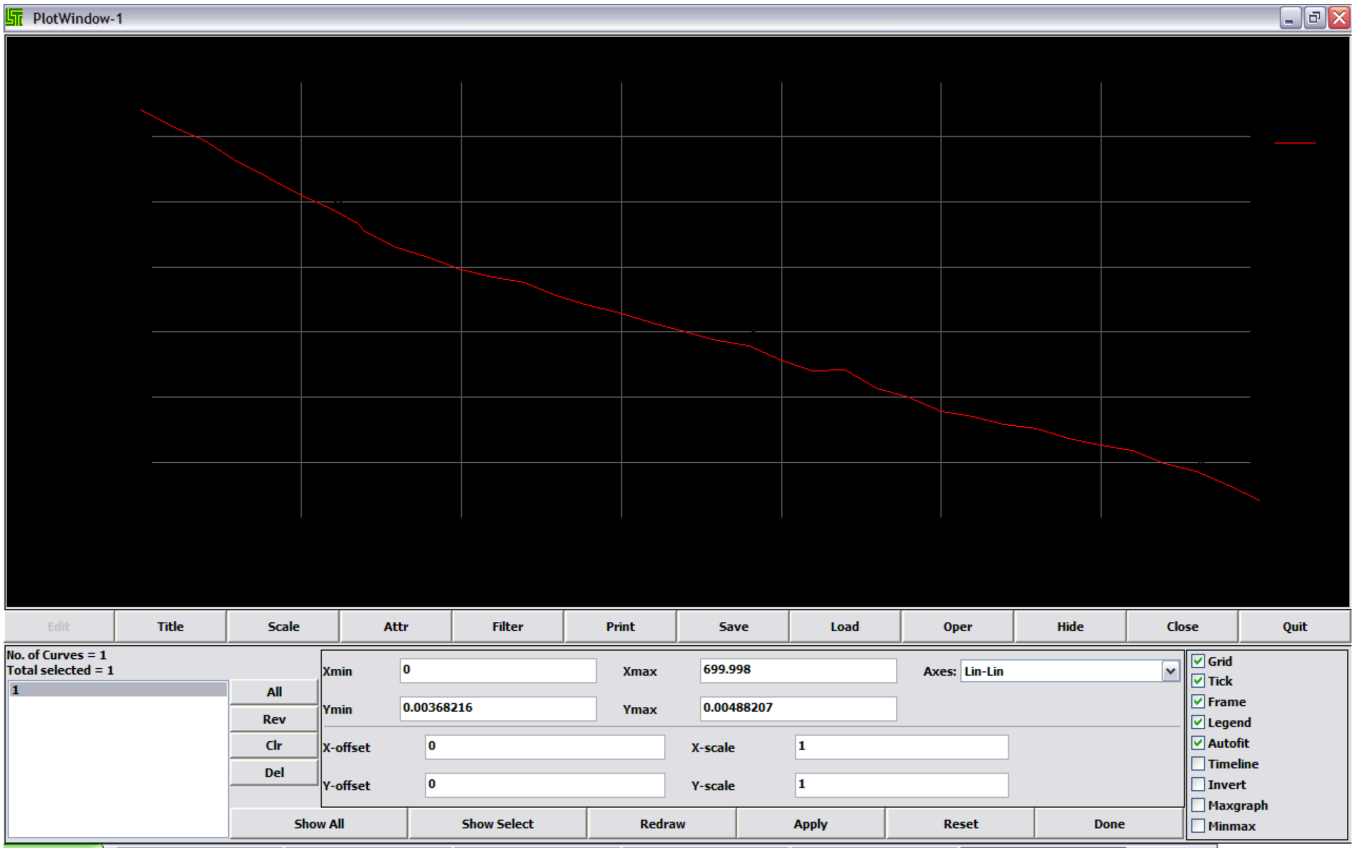


Figure 31: Kinetic energy throughout Viscoelastic 1

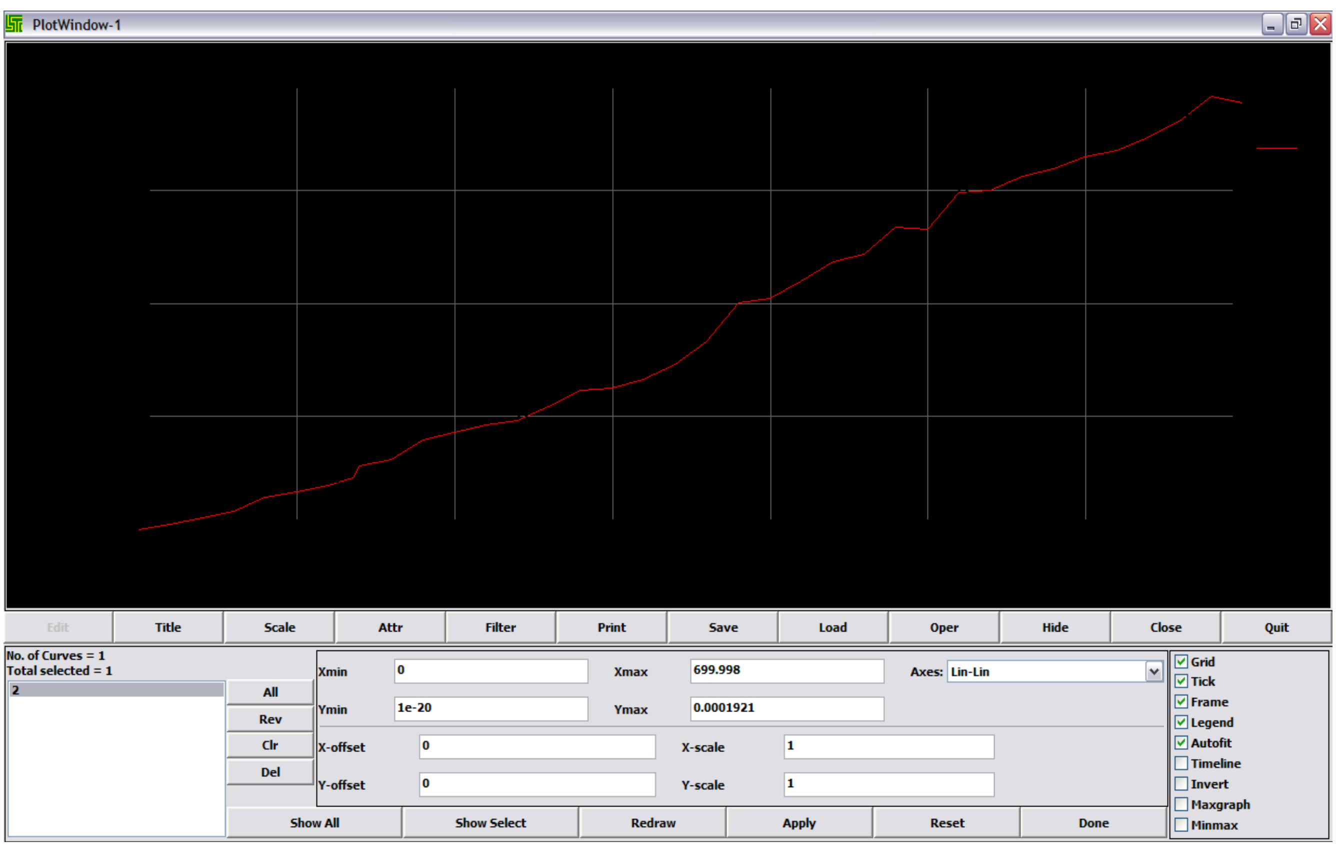


Figure 32: Internal energy absorbed throughout Viscoelastic 1

4.4 Viscoelastic 2

Viscoelastic 2 also reproduced a visible wound track. The bullet entered the block with the velocity of 304.5 m/s and ended at a depth penetration of 33.0362 cm. This wound track displayed a permanent cavity and a questionable temporary cavity (Figure 38). The permanent cavity had an entrance diameter of 4.1229 cm, a maximum diameter of 4.1229 cm, and a final diameter of .9671 cm. The bullet visibly degraded as it passed through the block. The initial mass of the bullet measured in LS-PREPOST was 10.528 gm with a final mass of 7.5968 gm resulting in a 27.8% change. The bullet slightly tumbled towards the end of its path. This simulation ran for 1100 µs.

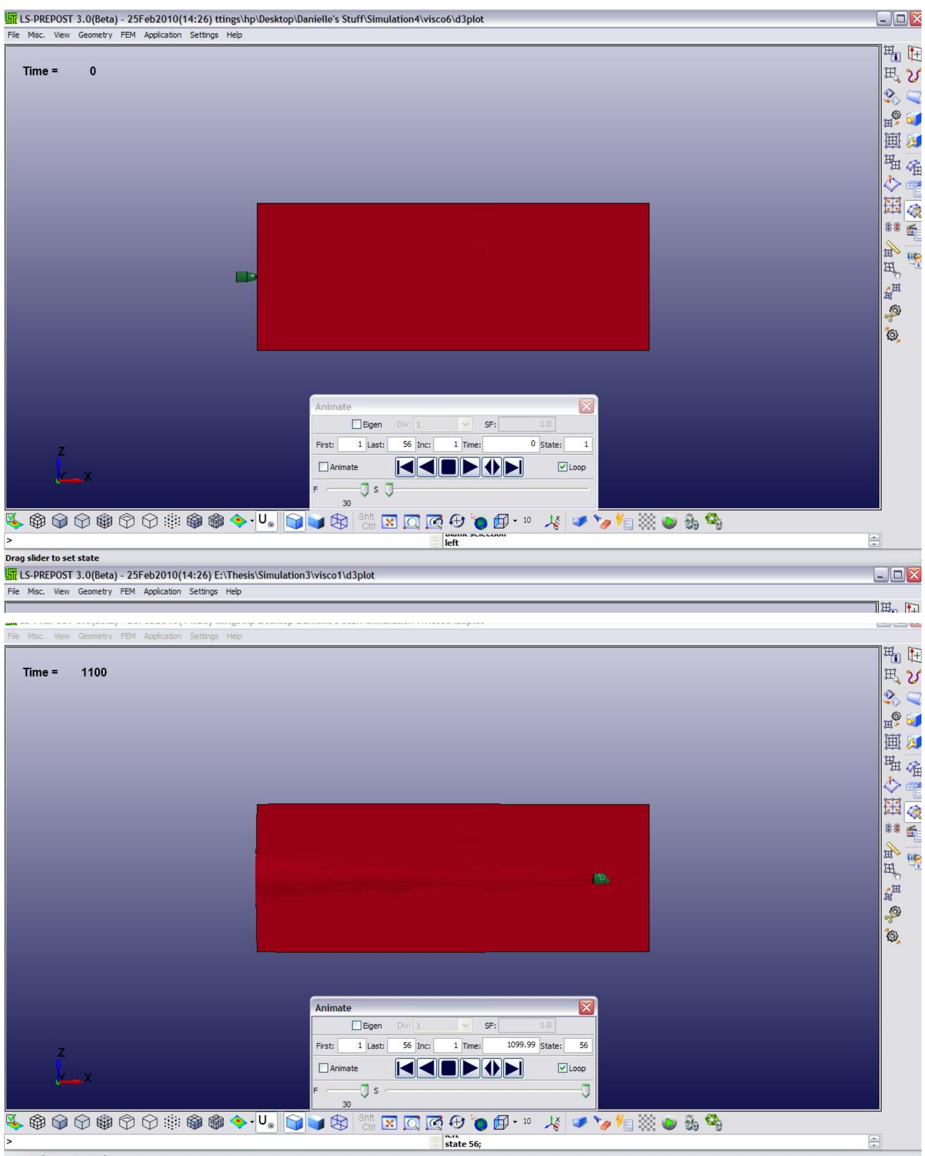


Figure 33: Initial and final state of Viscoelastic 2

Table 6: Viscoelastic 2 Summary Data

Component	Min Value	State	Part	Item	Max Value	State	Part	Item
X-stress	-1-7573e-002	26	3	H5566	1.0789e-002	41	3	H5403
Y-stress	-1.7201e-002	26	3	H5566	1.0487e-002	41	3	H5403
Z-stress	-1.7953e-002	26	3	H5566	1.0763e-002	41	3	H5403
Effective Plastic Strain	0.0000e+000	1	3	H1	4.4871e+000	53	3	H5955
Effective Stress (v-m)	0.0000e+000	1	3	H1	2.4885e-003	39	3	H5955
Max Shear Stress	0.0000e+000	1	3	H1	1.4292e-003	39	3	H5955
Pressure	-1.0680e-002	41	3	H5403	1.7576e-002	26	3	H5566
Max Principal Stress	-1.6896e-002	26	3	H5566	1.1156e-002	41	3	H5403
2nd Principal Stress	-1.7183e-002	26	3	H5566	1.0649e-002	41	3	H5403
Min Principal Stress	-1.8648e-002	26	3	H5566	1.0235e-002	41	3	H5403
Shell Thickness	0.0000e+000				0.0000e+000			
X-displacement	-1.6354e+000	56	1	N24562	5.3136e+001	56	1	N8864
Y-displacement	-4.1220e+001	56	1	N8904	3.1966e+001	56	1	N8827
Z-displacement	-2.0070e+001	56	1	N7628	3.3287e+001	56	1	N7822
Resultant Displacement	0.0000e+000	1	3	N1	5.3136e+001	56	1	N8864
X-velocity	-2.0352e-003	25	1	N29460	4.8322e-002	2	1	N8864
Y-velocity	-4.1806e-002	7	1	N8940	3.4177e-002	10	1	N8827
Z-velocity	-3.2052e-002	26	1	N8525	3.3056e-002	6	1	N7822
Resultant velocity	0.0000e+000	1	1	N10821	4.9902e-002	7	1	N8904

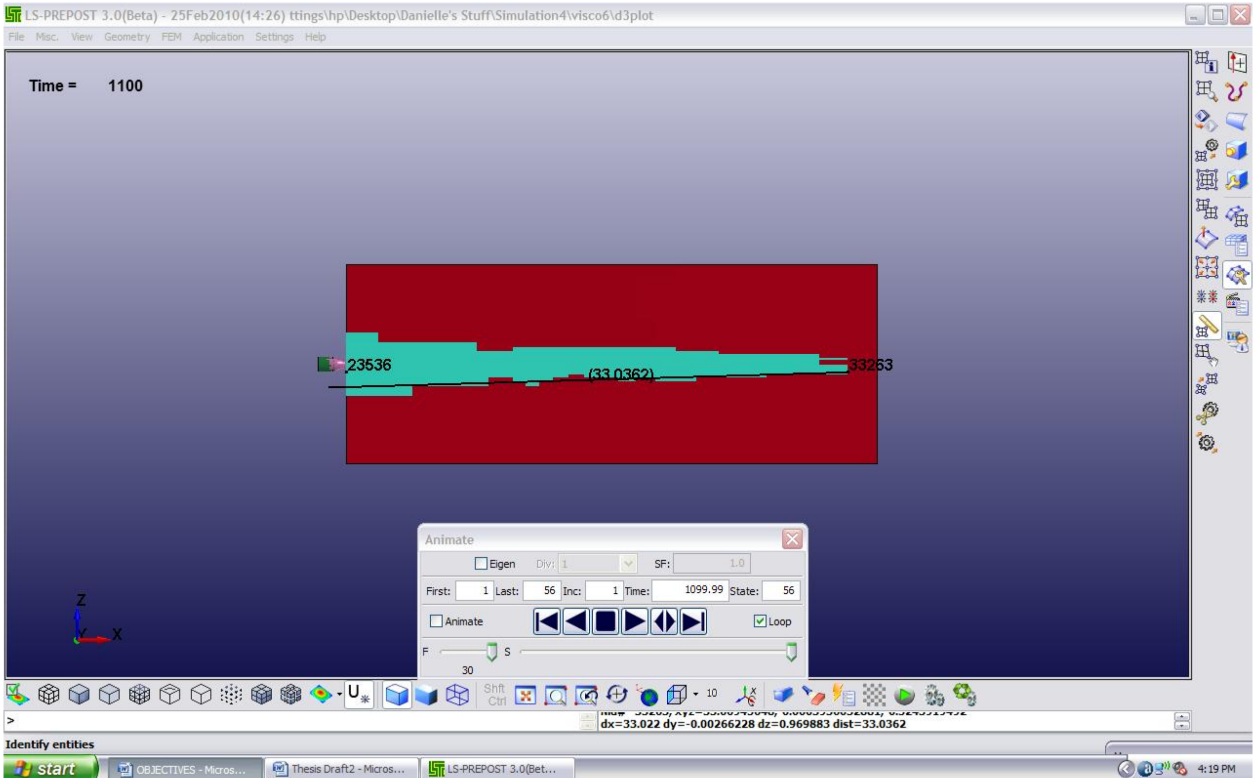


Figure 34: Viscoelastic 2 Permanent Cavity and Depth Penetration of bullet

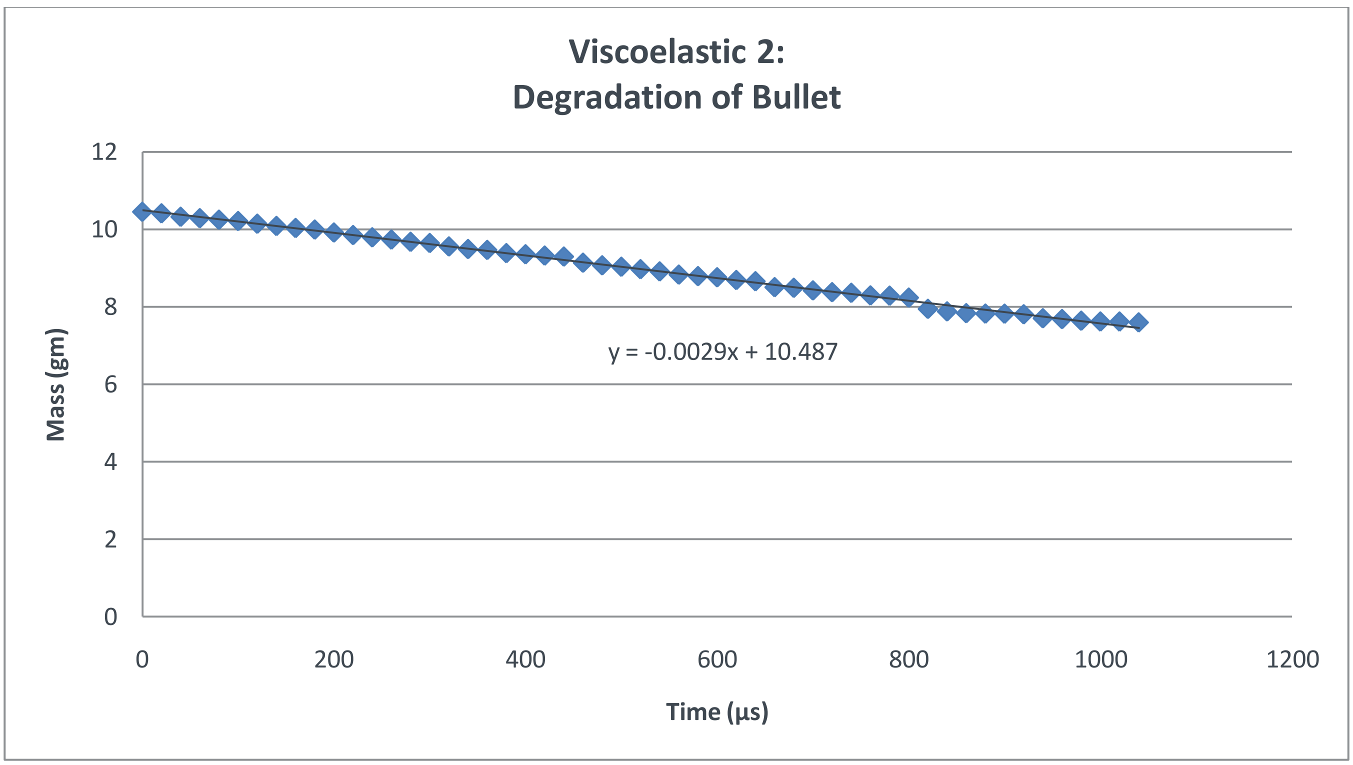


Figure 35: Change in mass of Viscoelastic 2 bullet

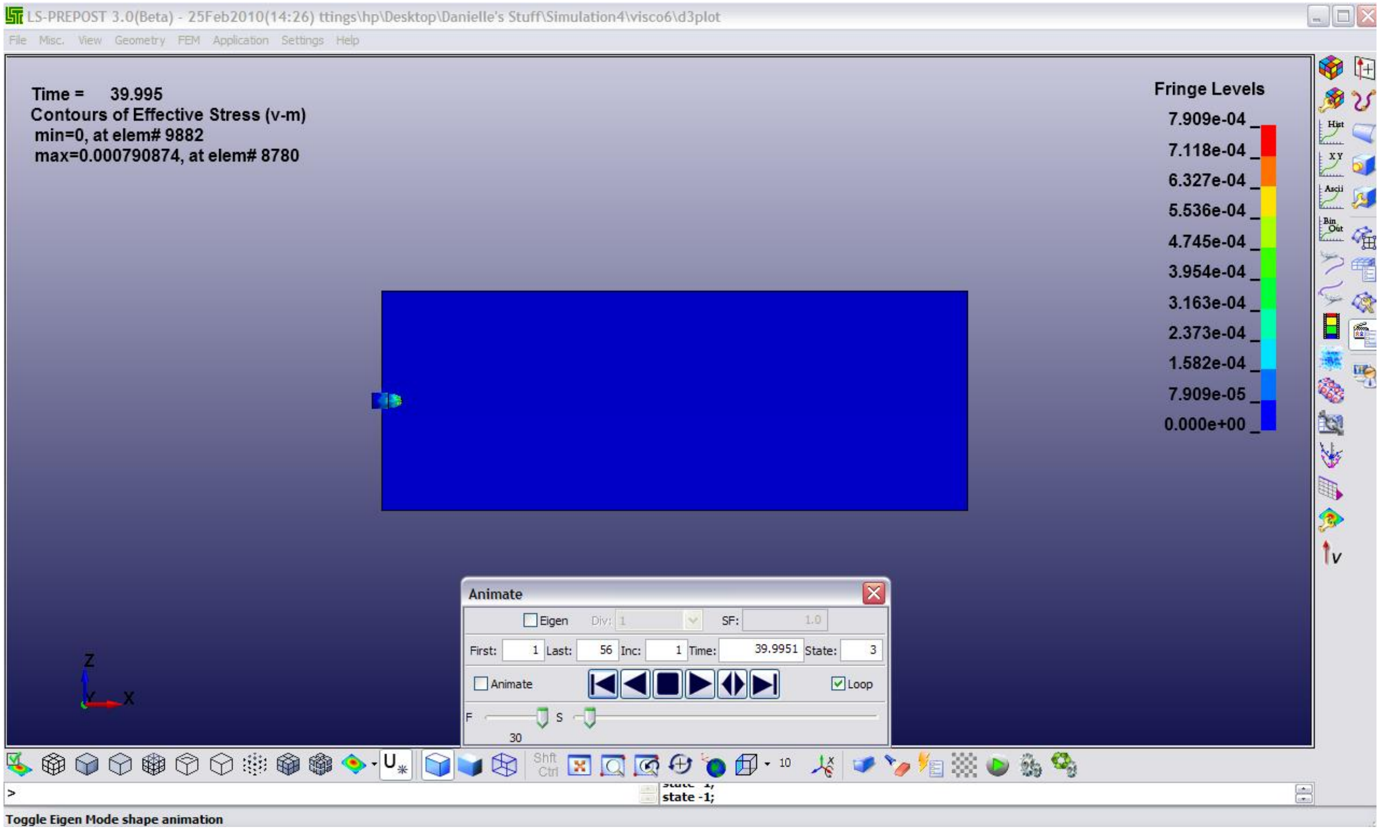


Figure 36: Von-Mises effective stress applied to the Viscoelastic 2 bullet

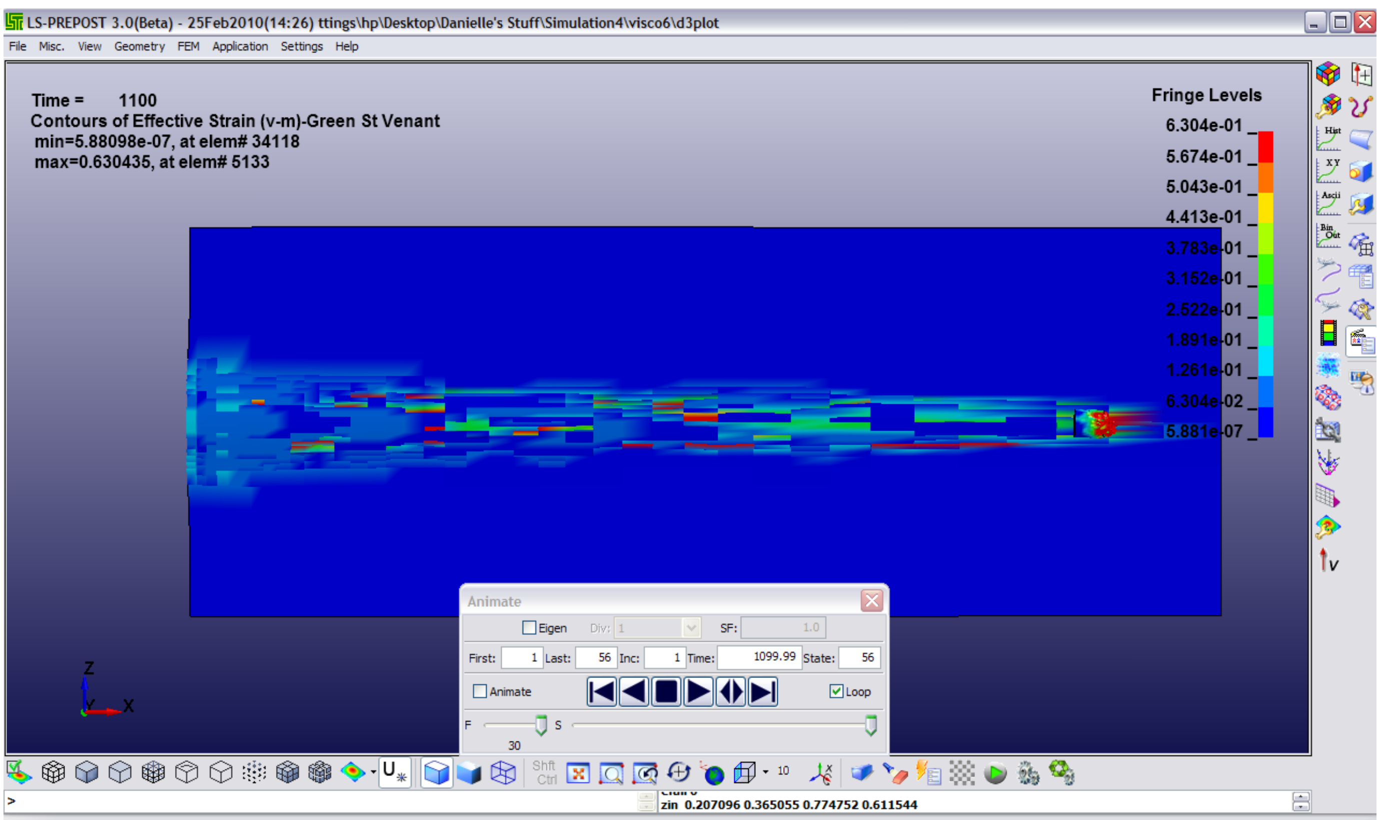
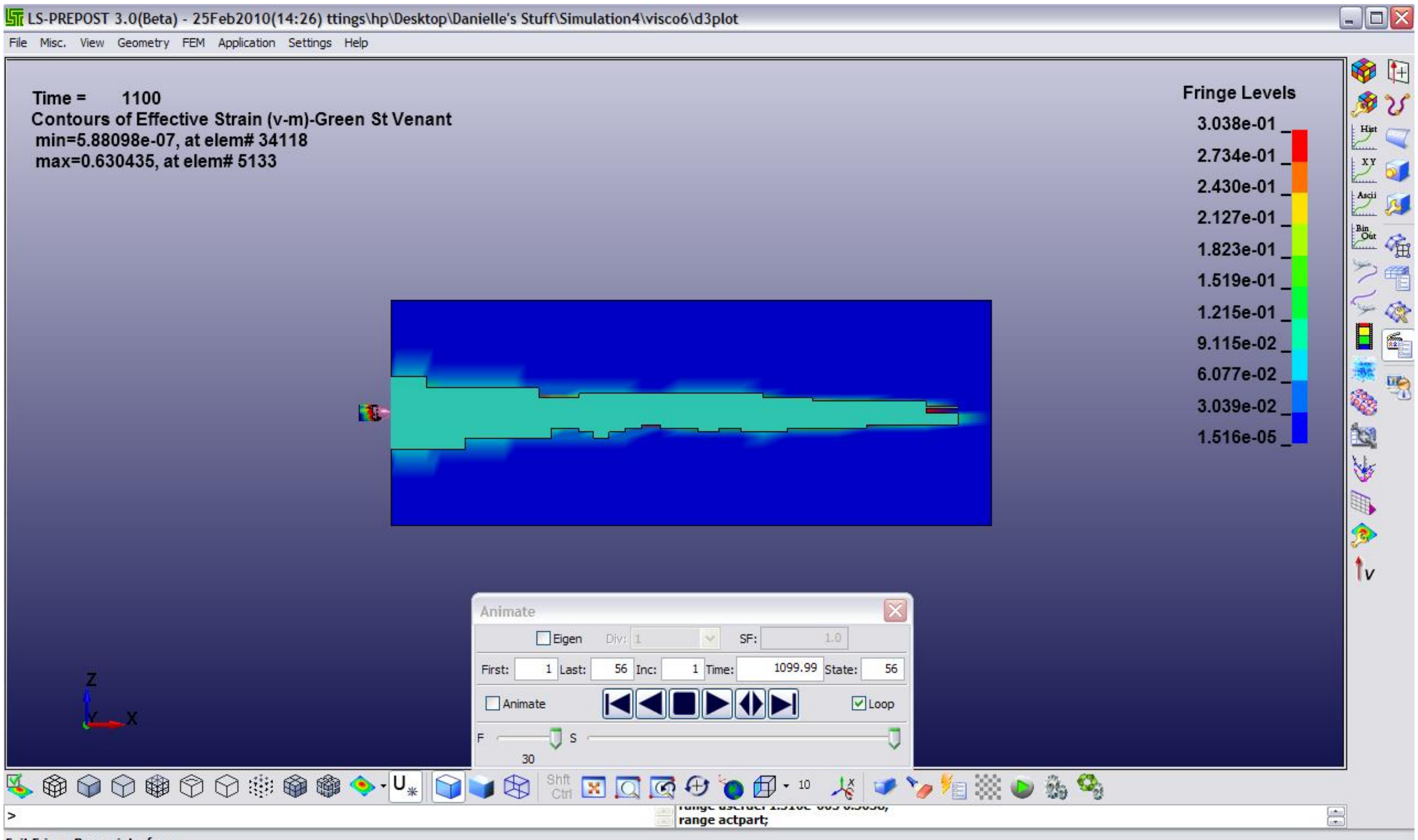
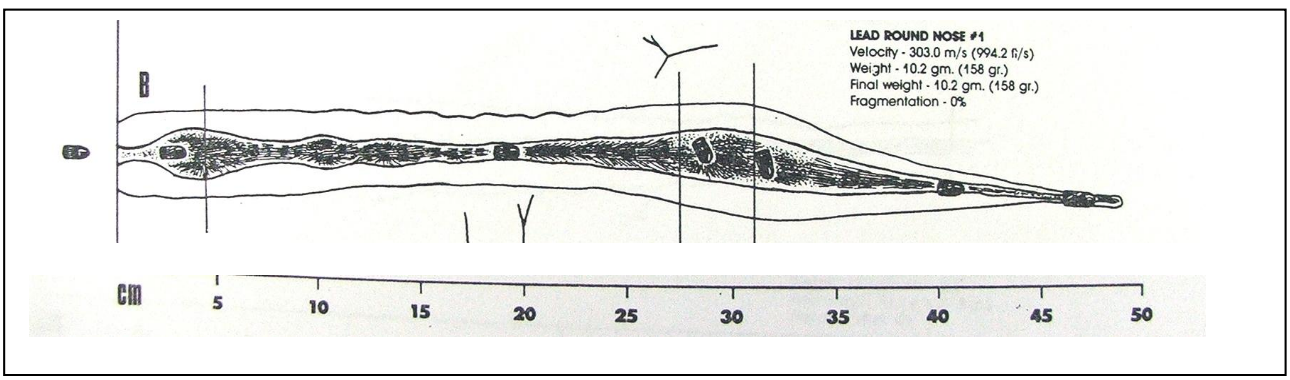


Figure 37: Green effective strain at final state of Viscoelastic 2



(a)



(b)

Figure 38: (a) Viscoelastic 2 wound profile of Lead Round Nose
(b) Ballistic Gelatin Test wound profile of Lead Round Nose

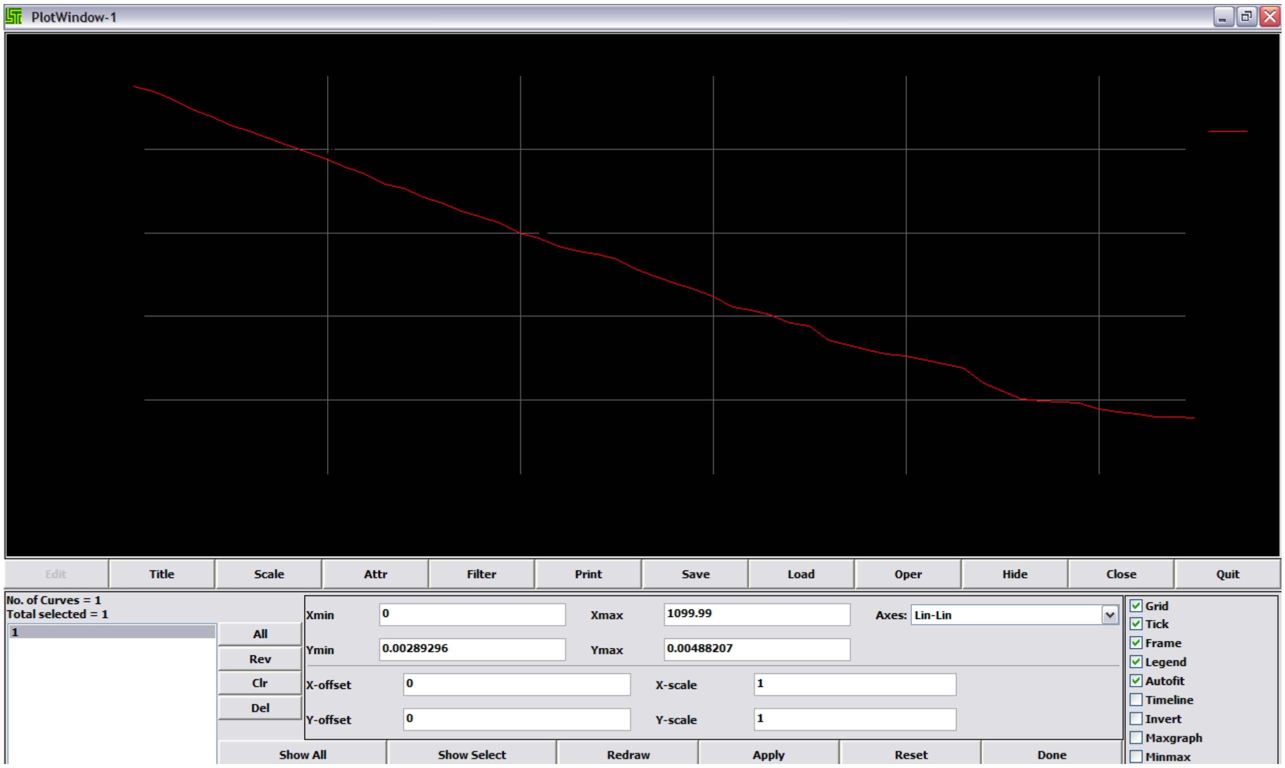


Figure 39: Kinetic energy throughout Viscoelastic 2

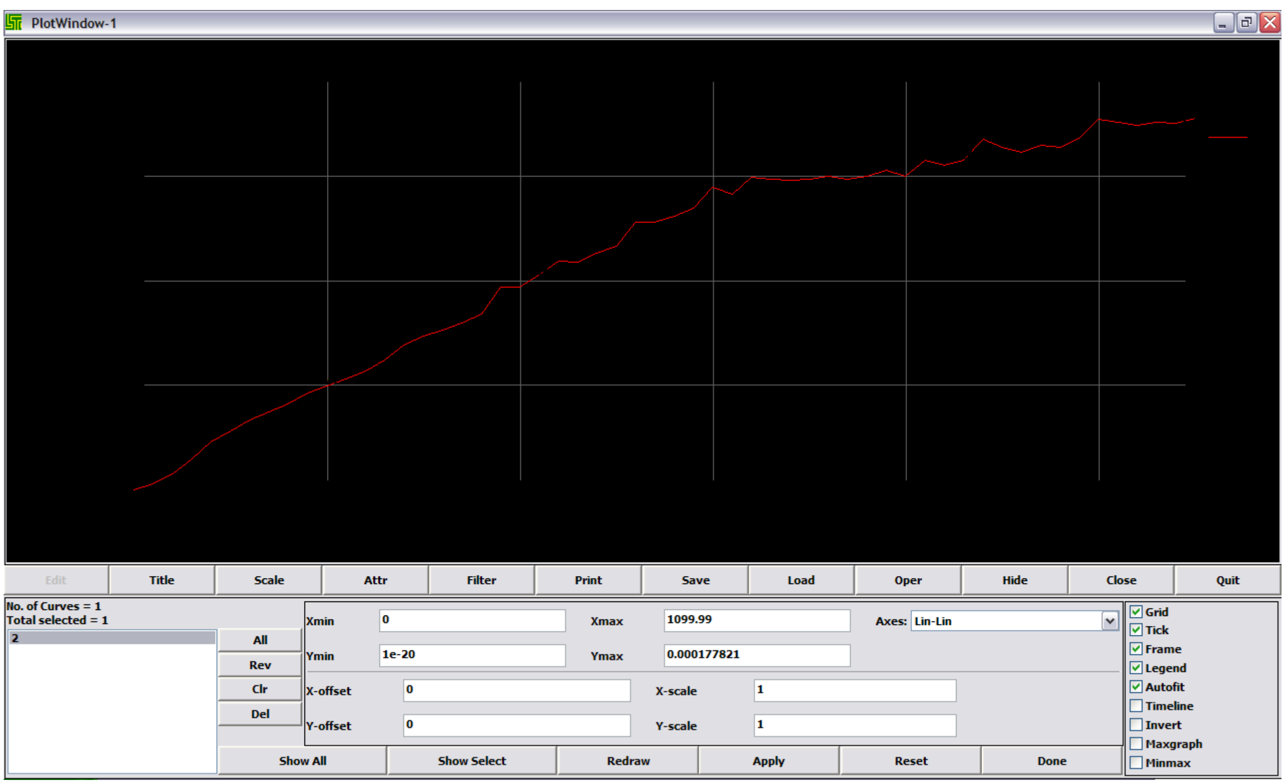


Figure 40: Internal energy absorbed throughout Viscoelastic 2

CHAPTER 5: DISCUSSION

5.1 Interpretation and Limitations of Elastic Plastic 1

Elastic Plastic 1 provided decent results. A visible wound track was demonstrated, but the depth penetration was not as deep as expected. There was no temporary cavity present. These factors are mainly due to the block properties and possible unit discrepancies. The block was modeled as an elastic plastic with properties similar to tissue but not quite as similar as a 10 or 20% gelatin block. In comparison, a ballistic gelatin test conducted by Dr. Ragsdale provided results of a depth penetration of 52.5 cm with a true TC diameter of 4.5 cm. Another factor includes the analysis being stopped before full completion. The analysis continued to run but after a certain time period stopped to provide new data and was terminated. The analysis ran for 250 µs.

The bullet's mass decreased by 32% due to fragmentation. In the Ragsdale test, there was no change in mass of the lead round nose. This could be due to the block properties and the lead properties applied to the bullet. Further investigation needs to be done in this area.

The kinetic and internal energy data trend were expected. Kinetic energy is greatest at the moment of impact. It decreases throughout the simulation because the energy is being absorbed until the bullet stops. The internal energy increases over time and once it reaches its maximum it plateaus. This is due to energy absorption. The greatest amount of energy is absorbed when the forces of the block stops the bullet. This can be contributed to Newton's third law. The block applies a retarding force to the bullet and the bullet applies an equal and opposite force on the block and ultimately transfers energy.

5.2 Interpretation and Limitations of Elastic Plastic 2

Elastic Plastic 2 provided better results than Elastic Plastic 1. A newer version of LS-DYNA was used for this analysis. The simulation ran for 1000μs and produced a depth penetration of 11.8723 cm, larger than Elastic Plastic 1.

This simulation also demonstrated both the permanent and temporary cavity. In the Ragsdale ballistic gelatin tests, the temporary cavity was calculated from radial fissure measurements and compared to the size seen in the high speed footage. The temporary cavity size in Elastic Plastic 2 was calculated by simply measuring the diameter of the cavity seen in the green effective strain contour image. Elastic Plastic 2 provided a temporary cavity size of 7.4132 cm compared to 4.5 cm. This is due to the size of the permanent cavity being 4.1992 cm.

In the wound profile of the Ragsdale ballistic gelatin test, the permanent cavity is generally not much larger than the bullet. The permanent cavity size starts small, and then increases in diameter in pulses throughout the block until it stops. It is largest when the bullet tumbles. At the final spot, there is hardly a permanent cavity. In Elastic Plastic 2, the permanent cavity is largest upon impact and slightly decreases until the end. This difference could be due to the model type. Further investigation needs to be conducted to determine the proper adjustments.

The bullet completely degraded. Typically, the lead round nose does not degrade in the body or a ballistic gelatin test with a low velocity of 304.5 m/s. In this case, it might have degraded because of miscalculation or unit discrepancy. Before the bullet completely degraded, a bullet fragment continued to surpass the permanent cavity without leaving a path. This could be due to the meshing. The mesh needs to be adjusted to detect small fragments. This can be done by making the mesh finer and adding more nodes.

The kinetic energy rapidly decreases until the bullet erodes into a smaller piece. The internal energy rapidly increases and then decreases. The energy is mostly absorbed by the block when the bullet is still fairly whole.

5.3 Interpretation and Limitations of Viscoelastic 1

Viscoelastic 1 met the objectives of reproducing a visible wound track with both the permanent and temporary cavity. Similar to both Elastic Plastic models, the permanent cavity is largest upon entrance and slightly decreases until its final depth. Both the permanent and temporary cavity are larger in diameter in comparison to the Ragsdale ballistic gelatin test. The depth penetration of 20.19 is longer than both Elastic Plastic models but shorter than the Ragsdale ballistic gelatin test.

The bullet’s behavior in this run is most comparable to the bullet’s behavior in the Ragsdale ballistic gelatin test. The bullet hardly degrades. The bullet also tumbles towards the center of block. In the Ragsdale wound profile, the bullet clearly tumbles around 30cm and straightens out towards the end. If Viscoelastic 2 ran longer than 700µs, it could have possibly done the same, but at different depths.

Similar to Elastic Plastic 1, the kinetic energy linearly decreases over time and the internal energy linearly increases. The difference in the minimum and maximum values of energy is much larger in the elastic plastic model versus the viscoelastic model. Elastic Plastic 1 has a minimum of .0017 and maximum of .0112. Viscoelastic 1 has a minimum of .0037 and maximum of .0049. Viscoelastic materials are more fluid like than elastic plastic materials and therefore allow the bullet to travel through the block with less resistance and less energy absorption.

5.4 Interpretation and Limitations of Viscoelastic 2

Viscoelastic 2 demonstrated a visible wound track with the longest depth penetration of 33.0362 cm. The permanent cavity is evident and follows the trend of the other models. The largest diameter is located in the front of the block and slightly decreases until its depth. Unlike the other models, this wound track is fairly narrow and the final permanent cavity area is smaller than the bullet. This wound track is most comparable to the Ragsdale wound profile. This simulation ran longer than Viscoelastic 1 by 400 µs.

Unlike Viscoelastic 1, the temporary cavity is barely present and questionable. The same material properties were used for both viscoelastic models. Further investigation needs to be completed to account for the temporary cavity difference.

The bullets behavior is most similar to Elastic Plastic 1. The bullet travels through the block in a fairly straight manner. The bullet's mass decreased by 27.8%. This difference compared to Viscoelastic1 could be due to the length of the simulation.

5.5 Conclusion

Gun shots occur every day. Deaths from gunshots have decreased, however, the frequency of gunshot wounds seen in emergency rooms has risen. Education and knowledge of gunshot treatment needs to be applied throughout all levels of trauma centers because experience is the best way to provide effective treatment.

Wound ballistics has been thoroughly researched over the years but still remains difficult to fully understand. There are many aspects of wound ballistics that are unpredictable and unknown. The ballistic gelatin test is the most common type of analysis of ballistic trauma. The tissue destruction caused by a bullet can be visibly seen through the gelatin block. The three main elements of the wound profile are the penetration depth, the temporary cavity, and the permanent cavity. There is much controversy over the effectiveness of the temporary cavity and ballistic pressure wave. Some researchers believe it is overstated in a ballistic gelatin test compared to an actual wound. The temporary cavity's effectiveness greatly depends on the area of impact and the type of tissue struck. There needs to be further research and data collected surrounding the temporary cavity to provide better understanding of wound ballistics. Recently, a few studies have used FEA to analyze ballistics but are not specific enough to contribute to the understanding of the temporary cavity. This understanding can contribute to better wound assessment protocols and treatment plans. A model's validation can be determined through comparison of physical ballistic gelatin test data and concurrence of the wound profile properties.

Elastic Plastic 1 provided hopeful results. The change in bullet mass, absorption of energy, permanent cavity, and depth penetration were evident. These findings seemed to fit the general trend of a ballistic gelatin test. Elastic Plastic 2 demonstrated a temporary cavity not seen in Elastic Plastic 1, but the bullet degraded completely. This erosion is uncharacteristic of a lead round nose at 304.5 m/s. Viscoelastic 1 provided better results. A visible wound track with both the temporary and permanent cavity are present. The bullet's behavior is most comparable to Ragsdale ballistic gelatin test. The bullet hardly degraded and tumbled towards the center of the block. Viscoelastic 2 did not reproduce a prominent temporary cavity, but exemplified a permanent cavity most comparable to the Ragsdale wound profile. With further research and development, proper adjustments can be made. A valid simulation can lead to better understanding of wound ballistics and a number of applications.

CHAPTER 6: FUTURE DIRECTIONS

6.1 Next Steps

The next simulation could demonstrate the difference of damage responses between various impact velocities of lead round nose. With a larger data set, validation of the model can be confirmed. Various bullet types can also be simulated to compare different wounding patterns.

Once an established model is validated, specific body parts can be implemented. A limb can be modeled and a gunshot to the area can be simulated and analyzed for specific site wounding patterns. The model can be detailed with bones, muscle, fat, and vasculature. It can even go further and vary the amount and size of the limb corresponding to different ages and body types. There has been progress creating human gelatin models with bones and these models can be used to validate. A ballistic gelatin test can be conducted with these models and the data can be used for validation of a FEA simulation. This would be extremely helpful in education of treating bullet trauma.

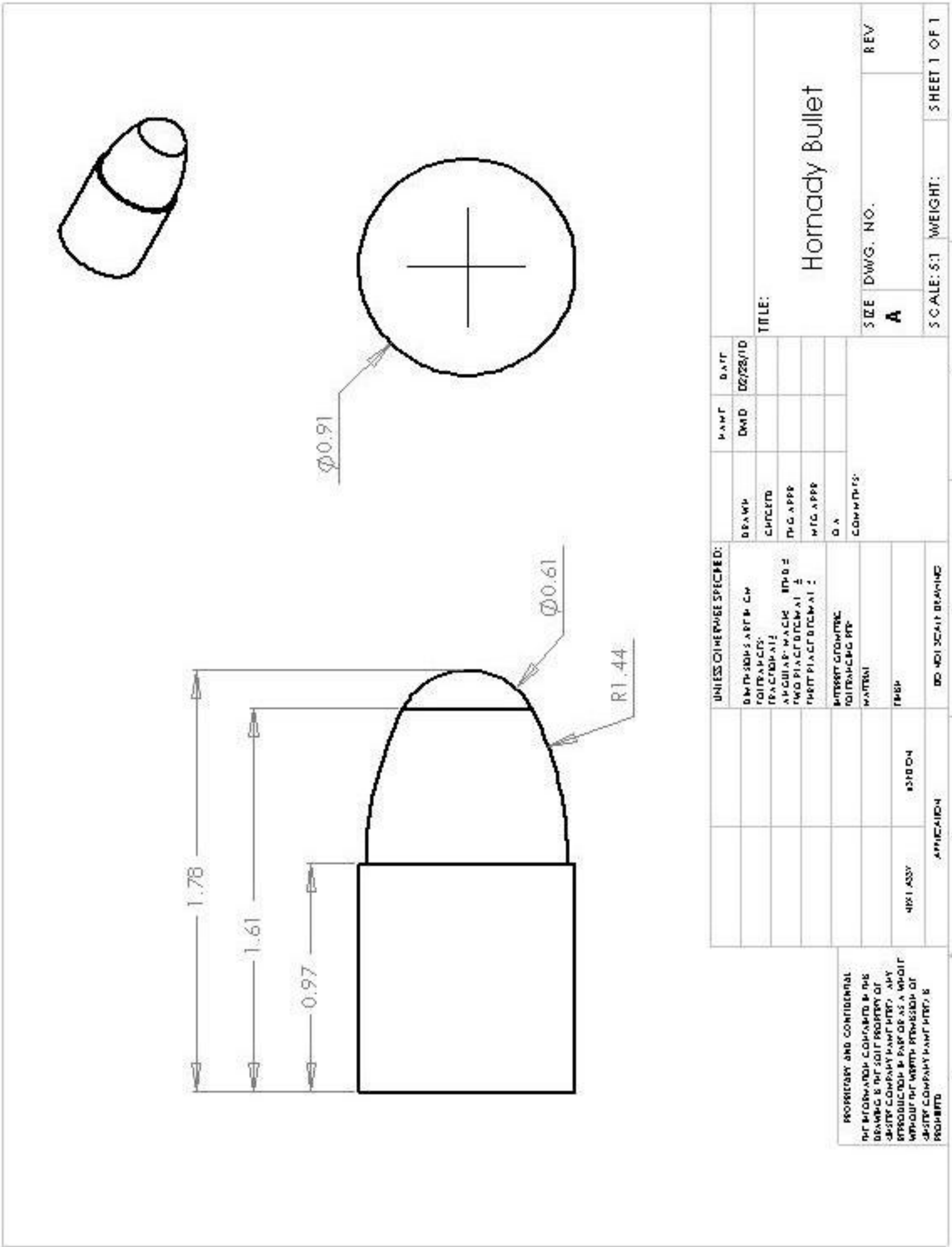
6.2 Future Applications

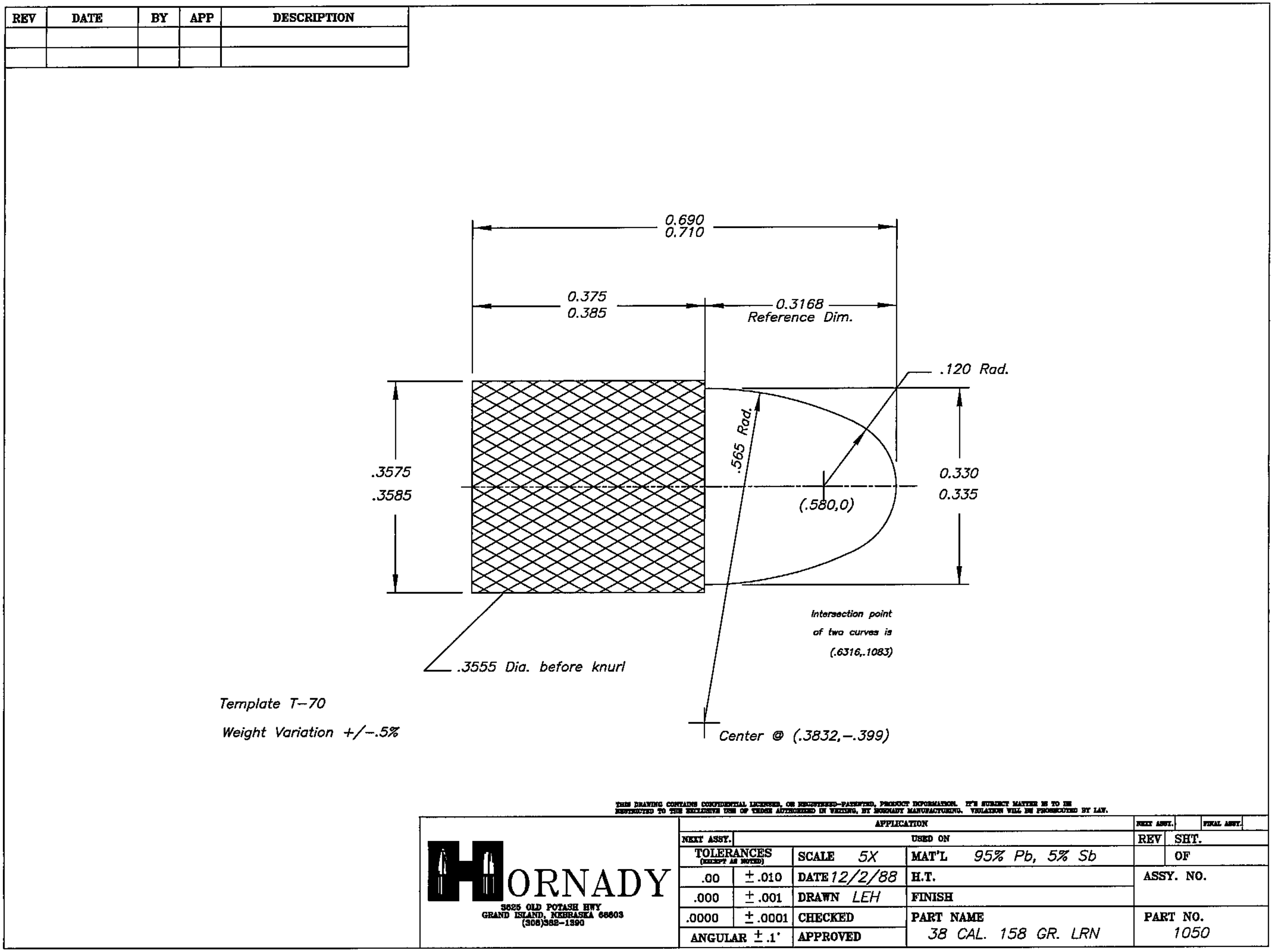
A developed and validated model can be used for educational and assessment purposes. Software can be developed based on the data to demonstrate the various wounding patterns of common bullet types. It can be used as an aide to emergency room staff for better understanding of wound ballistics and ultimately lead to more efficient treatment of gunshot wound victims. The model in conjunction with CT or radiological scans can even be used to help surgeons determine how much tissue to excise and determine bullet fragmentation. The model can also go one step further and be developed into a tool to allow nurses and trauma surgeons practice tissue debridement.

Forensic teams and legal teams can use the model to assess crimes involving gunshots. The model can be developed into a simulation that recreates the crime in question. The trauma surgeon is usually asked to provide a description of the bullet wounds to law enforcement but if they lack experience, they will not be able to accurately describe the pattern. An inaccurate description can lead to mistrials.

The model can also be used for accumulation of data for a database of wounding patterns of various bullets. This can be applied to civilian gunshots and military gunshots. Both can be compared and ultimately lead to better assessment and treatment of bullet wounds. This data would be an excellent addition to wound ballistic literature and contribute to better understanding of wound ballistics overall.

APPENDIX A: SolidWorks Drawings and Schematics of Lead Round Nose Bullet


1.78
1.61
0.97
Ø0.91
Ø0.61
R1.44
UNLESS OTHERWISE SPECIFIED:
DRAWN
DMD
02/28/10
TITLE:
Hornady Bullet
SIZE
A
DWG. NO.
REV
SCALE: 5:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5


REV
DATE
BY
APP
DESCRIPTION
0.690
0.710
0.375
0.385
0.3168
Reference Dim.
.120 Rad.
.565 Rad.
.3575
.3585
0.330
0.335
(.580,0)
Intersection point
of two curves is
(.6316,.1083)
.3555 Dia. before knurl
Template T–70
Weight Variation +/–.5%
Center @ (.3832,–.399)
THIS DRAWING CONTAINS CONFIDENTIAL, LICENSED, OR REGISTERED–PATENTED, PRODUCT INFORMATION. IT'S SUBJECT MATTER IS TO BE RESTRICTED TO THE EXCLUSIVE USE OF THOSE AUTHORIZED IN WRITING, BY HORNADY MANUFACTURING. VIOLATION WILL BE PROSECUTED BY LAW.
HORNADY
3625 OLD POTASH HWY
GRAND ISLAND, NEBRASKA 68803
(308)382-1390
APPLICATION
NEXT ASSY.
USED ON
NEXT ASSY.
FINAL ASSY.
REV
SHT.
OF
TOLERANCES
(EXCEPT AS NOTED)
.00 ±.010
.000 ±.001
.0000 ±.0001
ANGULAR ±.1°
SCALE 5X
DATE 12/2/88
DRAWN LEH
CHECKED
APPROVED
MAT'L 95% Pb, 5% Sb
H.T.
FINISH
PART NAME
38 CAL. 158 GR. LRN
ASSY. NO.
PART NO.
1050

APPENDIX B: Ballistic Gelatin Recipe

Custom Cartridge Inc, "Home-Made" Ballistic Gelatin

Ingredients and Supplies

Knox Unflavored Gelatin (13 oz/ gallon of water for 10% weight mix)
1 gallon of Water
Plastic box for mold (in this case an aluminum deep roaster pan was used)
Thermometer
Non-stick cooking spray (Pam)
Drill with wooden spoon attached
Whisk

Directions

1. Measure water to 105 degrees Fahrenheit, use thermometer to make sure the temperature does not go below 102 or above 108.

2. Spray inside of a clean, empty container very lightly with Pam and wipe off lightly after spraying.

3. Fill the container with 105 degree tap water and have Knox gelatin ready to add.

4. Very slowly sprinkle gelatin, a few ounces at a time, into the water, stirring constantly in order for it to dissolve completely.

5. Continue to stir for another ten minutes after all the gelatin has been added.

6. After the solution is thoroughly mixed/stirred, carefully scoop the foam and bubbles of the top and toss.

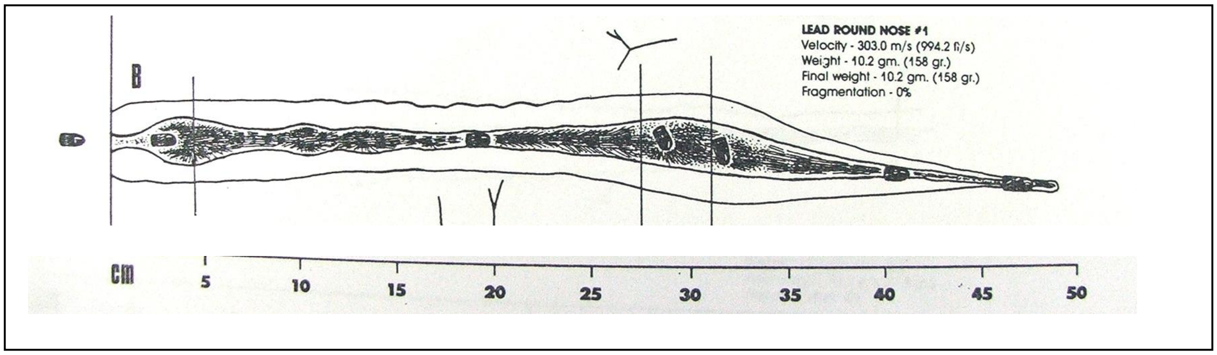
7. Cool the block to about 36 degrees Fahrenheit. Place in refrigerator or garage and let cool overnight for about 8 hours.

8. Once the gel has set up, turn the container over on a large, flat, clean surface and avoid cracking the gel.

9. Carefully wrap the block in plastic wrap covering every surface to maintain the moisture/density balance during transport.

10. Transport to destination in a cooler or anything that will help keep them cool.

APPENDIX C: Ragsdale Ballistic Gelatin Test



Lead round Nose [34]
Test shots: 3
Velocity: 304.5 m/s
Total Penetration: 52.5 cm
Zone of maximal disruption: 29.8-37.1
Plane of maximal disruption: 32.6
Two longest fissures: 3.3 cm
True TC diameter: 4.5 cm

APPENDIX D: Example of TrueGrid Code

```
lsdyopts ncpu 4 endtim 500 d3plot dtcycl 10 ; ;
lsdyna keyword

lsdymats 1 12
head block
rho 1.25 g 0.005357 epsp1 0.1 ;

lsdymats 2 12
head lead bullet
rho 11.34 g 5.6 sigy .012 eh .01 k 46 sigp1 0.1 ;

block
1 10 20; 1 5 10 15 20 25; 1 5 10 15 20 25;
0 1.0 2.0; -.5 -.35 -.1 .1 .35 .5; -.5 -.35 -.1 .1 .35 .5;
iges HornadyBulletCM.IGS 1 1;
dei 1 3; 4 6; 4 6;
dei 1 3; 4 6; 1 3;
dei 1 3; 1 3; 4 6;
dei 1 3; 1 3; 1 3;
sd 20 plan 0 0 0 0 1 1;
sd 21 plan 0 0 0 0 1 -1;
sd 30 sds 13 16;
curd 1
twsurf 30 20
 .14565390e-02 .32500353e+00 -.31729581e+00
 .69851363e-01 .32833688e+00 -.31731482e+00
 .15165272e+00 .32154720e+00 -.31631849e+00
 .27143116e+00 .32189529e+00 -.31583271e+00
 .36034999e+00 .32507751e+00 -.31574855e+00
 .44433584e+00 .32643640e+00 -.31551332e+00
 .52720551e+00 .32773569e+00 -.31527734e+00
 .60916080e+00 .32906215e+00 -.31504784e+00
 .73248873e+00 .33524566e+00 -.31024947e+00
 .78798914e+00 .32436602e+00 -.31382930e+00
 .83544836e+00 .32623942e+00 -.31380093e+00
 .88412981e+00 .32310591e+00 -.31809011e+00
;;;
curs 1 6 3 2 6 3 1
sfi 1 2; -6; 3 4;sd 30
curd 2
twsurf 30 21
 .11249727e-01 .32450902e+00 .32249322e+00
 .51409101e-01 .32357094e+00 .31986265e+00
 .98523521e-01 .32265739e+00 .32263794e+00
 .15895581e+00 .32871943e+00 .32701309e+00
 .21443510e+00 .33028975e+00 .32565603e+00
 .25707874e+00 .32579873e+00 .32285075e+00
 .29072185e+00 .32587571e+00 .32493258e+00
 .33326433e+00 .32162776e+00 .32217681e+00
 .39300129e+00 .32855854e+00 .32666147e+00
 .46360536e+00 .33344934e+00 .33158674e+00
 .47947717e+00 .32249660e+00 .32646654e+00
 .54644485e+00 .33145738e+00 .32681253e+00
 .59713521e+00 .32363377e+00 .31459880e+00
```

```
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 .73451724e+00 .32609539e+00 .32356641e+00
 .80466490e+00 .33337936e+00 .32883999e+00
 .84260559e+00 .32648542e+00 .32568057e+00
 .89844866e+00 .33271742e+00 .32994545e+00
 .92181644e+00 .33080301e+00 .33120744e+00
 .94967031e+00 .33407731e+00 .33335388e+00
 .97748632e+00 .33740988e+00 .33550470e+00
 .99913712e+00 .33396046e+00 .33176048e+00
;;;
curs 1 6 4 2 6 4 2
sfi 1 2; -6; 3 4;sd 30
curs 1 4 6 2 4 6 2
sfi 1 2; 3 4; -6;sd 30
curd 3
twsurf 30 20
 -.15227549e-01 -.33100121e+00 .32674398e+00
 -.30575896e-02 -.32013812e+00 .32872863e+00
 .49934214e-01 -.32561896e+00 .31834743e+00
 .94160008e-01 -.33626149e+00 .33676198e+00
 .12291243e+00 -.32388318e+00 .32077186e+00
 .16212111e+00 -.32354941e+00 .32020330e+00
 .19961503e+00 -.32693825e+00 .32388053e+00
 .23992424e+00 -.32278066e+00 .31876094e+00
 .29001889e+00 -.31587429e+00 .32570820e+00
 .30923855e+00 -.31423519e+00 .32774346e+00
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 .40784745e+00 -.31880555e+00 .32214644e+00
 .47085905e+00 -.33411341e+00 .33475039e+00
 .52653871e+00 -.31708107e+00 .33149962e+00
 .56453247e+00 -.30957942e+00 .32958186e+00
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 .65601859e+00 -.31614990e+00 .32339592e+00
 .68203411e+00 -.31644523e+00 .32452047e+00
 .73238897e+00 -.31904466e+00 .31954200e+00
 .79342356e+00 -.34589012e+00 .34052951e+00
 .84245014e+00 -.34977963e+00 .34614854e+00
 .87549286e+00 -.31703382e+00 .32161705e+00
 .92540283e+00 -.31440556e+00 .32738638e+00
 .97111292e+00 -.30709150e+00 .33222768e+00
;;;
curs 1 3 6 2 3 6 3
sfi 1 2; 3 4; -6;sd 30
curs 1 1 4 2 1 4 3
sfi 1 2; -1; 3 4;sd 30
```

…………………………………………………………………………………………….

```
.96053286  -.3214855   .3214855
   .964995  -.3214855   .3214855 ;
 v .025 0 -.0275;
curd 32 lp3
   0.000005  -.3214855  .32148547
 .11967183 -.32148204  .32148206
 .24556999 -.32148476  .32148476
 .35255964 -.32147527  .32147527
 .47713423 -.32147515  .32147515
 .63887877 -.32147558   .3214756
 .73238893 -.32148001  .32148027
 .84244862 -.32148278  .32148275
 .96053286  -.3214855   .3214855
   .964995  -.3214855   .3214855 ;
 v 0 .025 .025;
curd 32 lp3
   0.000005  -.3214855  .32148547
 .11967183 -.32148204  .32148206
 .24556999 -.32148476  .32148476
 .35255964 -.32147527  .32147527
 .47713423 -.32147515  .32147515
 .63887877 -.32147558   .3214756
 .73238893 -.32148001  .32148027
 .84244862 -.32148278  .32148275
 .96053286  -.3214855   .3214855
   .964995  -.3214855   .3214855 ;

…………………………………………………………………………………………………

c      0 output file(s) written
c  normal termination
sfi -1; 1 6; 3 4;sd 101
sfi -1; 3 4; 1 6;sd 101
velocity .0462 0 0

mate 2
endpart merge stp 0.001


block
1 40; 1 5 10 15; 1 5 10 15;
1.78 35.56; -6.35 -1.0 1.0 6.35; -6.35 -1.0 1.0 6.35;

mseq k 0 5 0
mseq j 0 5 0
mseq k 5 0 0
mseq j 5 0 0
mseq k 0 -2 0
mseq j 0 -2 0
mseq k -3 0 1
mseq j -3 0 1
mseq k 0 5 0
mseq j 0 5 0
```

```
mseq k 0 3 0
mseq j 0 3 0

pb 1 3 1 1 3 1 xyz 1.78000 2.69187 -6.35000
pb 1 2 1 1 2 1 xyz 1.78000 -2.89679 -6.35000
pb 1 3 4 1 3 4 xyz 1.78000 2.83392 6.35000
pb 1 2 4 1 2 4 xyz 1.78000 -2.95821 6.35000
pb 1 4 2 1 4 2 xyz 1.78000 6.35000 -3.61273
pb 1 4 3 1 4 3 xyz 1.78000 6.35000 3.60998
pb 1 1 2 1 1 2 xyz 1.78000 -6.35000 -3.81235
pb 1 1 3 1 1 3 xyz 1.78000 -6.35000 3.61726
pb 2 4 3 2 4 3 xyz 35.5600 6.35000 3.79463
pb 2 4 2 2 4 2 xyz 35.5600 6.35000 -3.62359
pb 2 1 3 2 1 3 xyz 35.5600 -6.35000 3.61579
pb 2 1 2 2 1 2 xyz 35.5600 -6.35000 -3.67903
pb 2 3 1 2 3 1 xyz 35.5600 2.75410 -6.35000
pb 2 2 1 2 2 1 xyz 35.5600 -2.96015 -6.35000
pb 2 3 4 2 3 4 xyz 35.5600 2.85265 6.35000
pb 2 2 4 2 2 4 xyz 35.5600 -2.89349 6.35000

relax 1 1 1 1 4 4 20 .01 1 ;
relax 2 1 1 2 4 4 20 .01 1 ;

res 1 4 1 2 4 1 i 1.05
res 1 3 1 2 3 1 i 1.05
res 1 2 1 2 2 1 i 1.05
res 1 1 1 2 1 1 i 1.05
res 1 1 2 2 1 2 i 1.05
res 1 2 2 2 2 2 i 1.05
res 1 3 2 2 3 2 i 1.05
res 1 4 2 2 4 2 i 1.05
res 1 4 3 2 4 3 i 1.05
res 1 3 3 2 3 3 i 1.05
res 1 2 3 2 2 3 i 1.05
res 1 1 3 2 1 3 i 1.05
res 1 1 4 2 1 4 i 1.05
res 1 2 4 2 2 4 i 1.05
res 1 3 4 2 3 4 i 1.05
res 1 4 4 2 4 4 i 1.05

pb 1 4 2 1 4 2 xyz 1.78000 6.35000 -2.62897
pb 1 4 3 1 4 3 xyz 1.78000 6.35000 2.70829
pb 1 1 2 1 1 2 xyz 1.78000 -6.35000 -2.85950
pb 1 1 3 1 1 3 xyz 1.78000 -6.35000 2.79491
pb 2 4 3 2 4 3 xyz 35.5600 6.35000 2.84975
pb 2 4 2 2 4 2 xyz 35.5600 6.35000 -2.72143
pb 2 1 3 2 1 3 xyz 35.5600 -6.35000 2.68687
pb 2 1 2 2 1 2 xyz 35.5600 -6.35000 -2.87922

bi 1 2;-1;1 4;dx 1 dy 1 dz 1 ;
mate 1
endpart merge
```

APPENDIX E: Example of LS-DYNA Keyword File

```
*KEYWORD
*CONTROL_PARALLEL
4,0,2,0
*CONTROL_TERMINATION
500.0,0,0.0,0.0,0.0
*DATABASE_BINARY_D3PLOT
10.0
$
$ MATERIAL CARDS
$
$
$ DEFINITION OF MATERIAL     1
$
*MAT_ISOTROPIC_ELASTIC_PLASTIC
1,1.25,0.0054,0.001,0.0,0.125
*MAT_ADD_EROSION
1,0.0
0.0,0.0,0.0,0.1,0.0,0.0,0.0
*HOURGLASS
1,0,0.0,0,0.0,0.0
*SECTION_SOLID
1,0
*PART
block
1,1,1,0,1,0,0,0
$
$ DEFINITION OF MATERIAL     2
$
*MAT_PIECEWISE_LINEAR_PLASTICITY
2,11.34,0.14,0.42,0.001,0.01,0.80,0.0
0.0,0.0,0.0,0.0,0.0
0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00
0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00,0.000E+00
*HOURGLASS
2,0,0.0,0,0.0,0.0
*SECTION_SOLID
2,0
*PART
bullet
2,2,2,0,2,0,0,0
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$$$$  Define Contacts
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$...>....1....>....2....>....3....>....4....>....5....>....6....>....7....>....8
$
*CONTACT_ERODING_SURFACE_TO_SURFACE
$     ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
         2         1         3         3
```

```
$
$     fs      fd      dc      vc     vdc   penchk      bt      dt

$
$    sfs     sfm     sst     mst    sfst    sfmt     fsf     vsf

$
$   isym  erosop    iadj
       1       1
$
$ NODES
$
*NODE
1,0.0,-0.3214853,-0.3214857,0,0
2,0.0,-0.3639594,-0.272457,0,0
3,0.0,-0.399031,-0.2178876,0,0
4,0.0,-0.4259812,-0.1588831,0,0
5,0.0,-0.4442515,-0.09664116,0,0
6,0.0,-0.4534866,-0.03243398,0,0
7,0.0,-0.4534866, 0.03243393,0,0
8,0.0,-0.4442515, 0.09664118,0,0
9,0.0,-0.4259811, 0.1588831,0,0
10,0.0,-0.3990309, 0.2178877,0,0
11,0.0,-0.3639592, 0.2724572,0,0
12,0.0,-0.3214851, 0.3214859,0,0
13,0.0,-0.2980191,-0.2980206,0,0
14,0.0,-0.3374048,-0.2525803,0,0
15,0.0,-0.3699391,-0.2020091,0,0
16,0.0,-0.3949009,-0.1473016,0,0
17,0.0,-0.4118358,-0.0896014,0,0
18,0.0,-0.420351,-0.03007624,0,0
19,0.0,-0.4203787, 0.0300543,0,0
20,0.0,-0.4117794, 0.08956803,0,0
21,0.0,-0.3948771, 0.1472764,0,0
22,0.0,-0.3699018, 0.2019754,0,0
23,0.0,-0.3373831, 0.2525547,0,0
24,0.0,-0.2980048, 0.2979972,0,0
25, 0.1055553,-0.3212847,-0.3212878,0,0
26, 0.1055553,-0.3638711,-0.2723689,0,0
27, 0.1055553,-0.398951,-0.2178122,0,0
28, 0.1055553,-0.425988,-0.1588506,0,0
29, 0.1055553,-0.4441187,-0.09656394,0,0
30, 0.1055554,-0.4534918,-0.0323749,0,0
31, 0.1055554,-0.4533135, 0.03247487,0,0
32, 0.1055554,-0.4439289, 0.09662177,0,0
33, 0.1055554,-0.4256679, 0.1588089,0,0
```

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