Numerical Modeling of Friction Effects on the Ballistic Impact Response of Single-Ply Tri-Axial Braided Fabric

Daihua Zheng, Wieslaw K. Binienda,
Jingyun Cheng and Marcin Staniszewski
Department of Civil Engineering
The University of Akron
Akron, OH, 44325
E-mail: dz15@uakron.edu

Abstract

It has been shown by experiments that frictional effects play an important role in the energy absorption of fabrics subjected to ballistic impact. However, the specific role of friction is not well understood and established. In this paper, a detailed finite element model was developed, using LS-DYNA®, to parametrically study the frictional effects during the ballistic impact of a square patch of single-ply 2D tri-axially braided fabric. The individual yarns (bias and axial direction) in the fabric were modeled discretely and considered as a continuum by considering the measured properties of the braided fabric (weave architecture, crimp, yarn cross-section etc.). The friction between yarns at their crossovers and the friction between projectile and fabric were taken into account. The damage of a single yarn model were compared with the experimental data and included in the material model of the fabric. It was shown that the friction contributes to decreasing of the residual velocity of the projectile more quickly than the one without friction. Thus the fabric energy absorption capacity can be increased by 18%. The results from the simulation also indicated that the frictional sliding energy starts to play more important role when the fabric begins to get damage and more movements between axial yarns and braider yarns are involved.

Introduction

Lightweight fibrous material systems made from tough, high-strength fibers are often used in flexible protection system, such as body armor for military or law enforcement personnel and turbine engine fragment barriers for airplanes, to resist high-velocity penetration. In the last few decades, several new polymeric fibrous materials have been developed that exhibit greatly improved impact resistance, such as aramids (e.g., Kevlar®, Twaron®, Technora®), highly oriented polyethylene (e.g., Spectra®, Dyneema®) and especially PBO (e.g., Zylon®). Compared to their predecessor Nylon fibers which shows considerable non-linearity in stress-strain relationship with relatively high strains to failure, all those fibers have very high stiffness, high strength to weight ratio and low strain to failure (usually less than 4%). They are essentially elastic in tensile loading. While in transverse compression, unlike common fibers such as carbon or glass fibers, they usually undergo large plastic deformation without considerable reduction in load-carrying capacity. The best one in those fibers can be counted on PBO which has a tensile strength of 5.2 GPA, more than three times of the steel at 20 percent of the density. The strength to weight ratio reaches almost fifteen for these fibers [S. Leigh Phoenix et. al, 2003]. Zylon, a type of PBO fiber, has been used in this research.

Using computational model to predict the ballistic impact behavior of high-strength fibrous material systems has been the subject of considerable research in the past decades. [Roylance and Wang, 1980], [Shim and Tan et. al, 1995] and [Billion and Robinson, 2001] have modeled fabric by an assembly of nodes interconnected by flexible fiber elements. Fabrics have also been analyzed as 2-D either shell or membrane elements numerically by [Tabiei and Ivanov, 2002] and [Lim and Shim et al., 2003], and analytically by [Parga-Landa et al., 1995] and [S. Leigh

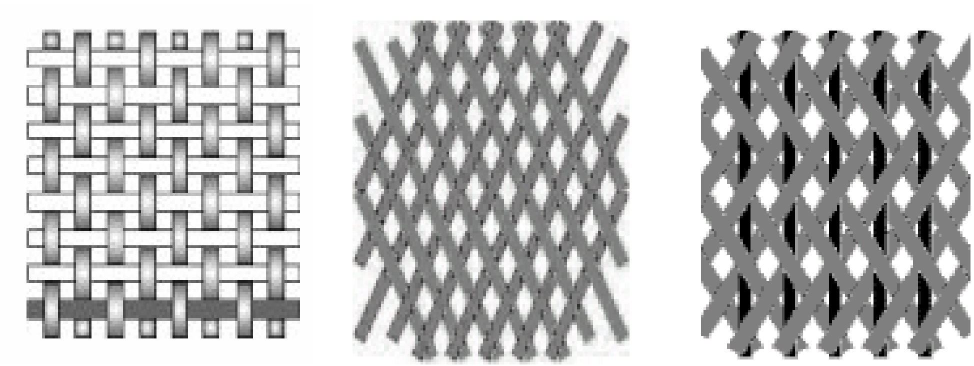
Phoenix et. al, 2003]. However, all those computational models treat yarn crossovers as joints or continuum and ignore the relative motion of the yarns.

It has been shown that the energy absorption characteristics of fibrous material systems are influenced by a number of different factors including the fiber mechanical properties, weaving style, the number of layers, aerial density, projectile properties as well as impact parameters [Cunniff, P.M., 1992]. It has also been experimentally shown that there is strong evidence of frictional effects from abrasion during the impact and perforation of plain-weave fabric [Tan V.B.C. et. al, 2003]. The results from their scanning electron microscopy (SEM) show that the failure mechanisms associated with friction within yarns include flattening of the fibers, fibrillation and rupture of fibers. [Keirkwood K. M. et. al, 2004] studied the yarn pull-out friction as a mechanism for dissipating ballistic impact energy in woven Kevlar® fabric by considering the effects of fabric length, number of yarns pulled, arrangement of yarns and transverse tension on the force-displacement curve during the experiments.

Generally, in ballistic impact experiments, only the initial impact velocity and the residue velocity of the projectile are measured. Because it is very difficult to obtain detailed fabric deformation and failure during ballistic experiments, the role of friction in high-velocity impact is hard to obtain experimentally only. Analytical and numerical models are necessary for a better understanding of frictional effects on the ballistic impact of fabric structures. [Duan Y. et. al, 2005] used numerical analysis to study the role of friction for a rigid sphere impacting on a square patch of woven fabric. In a similar way, in this paper, the frictional effects were studied for braided fabric by explicitly modeling the yarns and incorporating an orthotropic material model with specified failure criterion.

Modeling of Impact of Braided Fabric

Compared to woven fabric, braided fabric has greater strength per weight, but it is more expensive because of its complex manufacturing process. However, manufacturing costs have decreased in these years, thus making braided fabrics more cost-competitive. The strength of braided fabric comes from intertwining three or more yarns without any two yarns being twisted around each other, continuously woven on the bias so that at least one axial yarn is not crimped. This arrangement of yarns distributes the load efficiently throughout the braid. Biaxial braids provide reinforcement in the bias direction only with fiber angles ranging from $\pm 15^o$ to $\pm 95^o$. Tri-axial braids provide reinforcement in the bias direction with fiber angles ranging from $\pm 10^o$ to $\pm 80^o$ and axial (0^o) direction. Figure 1 shows a comparison between woven fabric, biaxial fabric and tri-axial fabric. The efficient distribution of loads makes braided structures very impact resistant. Since all the fibers in the structure are involved in a loading event, braid absorbs a great deal of energy as it fails. This is why braid is becoming more and more popular as fan blade containment in commercial aircraft engine and in energy absorbing crash structures in formula one racing cars.

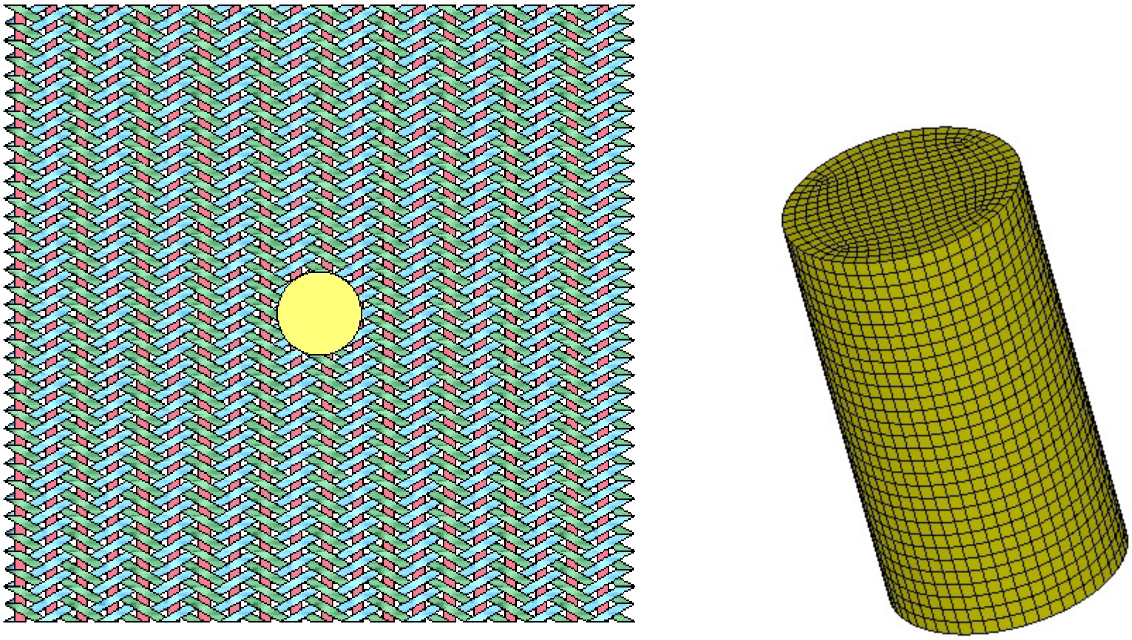


(a) Plain Weave (b) Biaxial Braid (c) Tri-axial Braid

Figure 1. Comparison of Woven and Braided Fabrics

Commercial FEA software, LS-DYNA®, was used to model the impact of a soft projectile on a single-layer braided fabric. Figure 2 shows the geometrical configuration of the ballistic impact event: a cylinder-shaped soft projectile transversely impacts on the center of a square patch of braided fabric. The dimension of the square fabric patch is 20 in x 20 in (Figure 2a). The diameter of the projectile is 2.75 in and the height of the projectile is 5 in (Figure 2b). Four edges clamped boundary conditions are considered. Simple Coulomb frictions are introduced among the yarn crossovers and between the projectile and the fabric. For Twaron® CT 716 plain-weave, single-ply fabric, it was shown from experiments that the static coefficient of friction was between 0.31 in the weft direction and 0.20 in the warp direction [Tan and Lim et al., 2003]. In this study , a friction coefficient 0.5 was used for both the yarn-yarn friction and projectile-fabric friction. In order to study the role of friction during impact, friction coefficient 0.0 was also modeled where all the other condition remained the same.

In this finite element model, the individual yarns were modeled discretely and considered as a continuum. Figure 3 shows a part of the 3-D finite element model. Each braider yarn and axial yarn was modeled as a continuum and combined to form the fabric panel. The thickness of the axial yarns and braider yarns are 0.024 in. Eight node solid elements were used for the projectile and the yarns and surface-to-surface contact was defined among yarns. The mesh of the model was chosen to get a large enough patch of braided fabric with sufficient number of elements and still maintain a reasonable computational time in LS-DYNA®.



(a) Top View of the Transversely Impact Event (b) Soft Projectile

Figure 2. Rigid Titanium Projectile Transversely Impact a Braided Fabric Panel

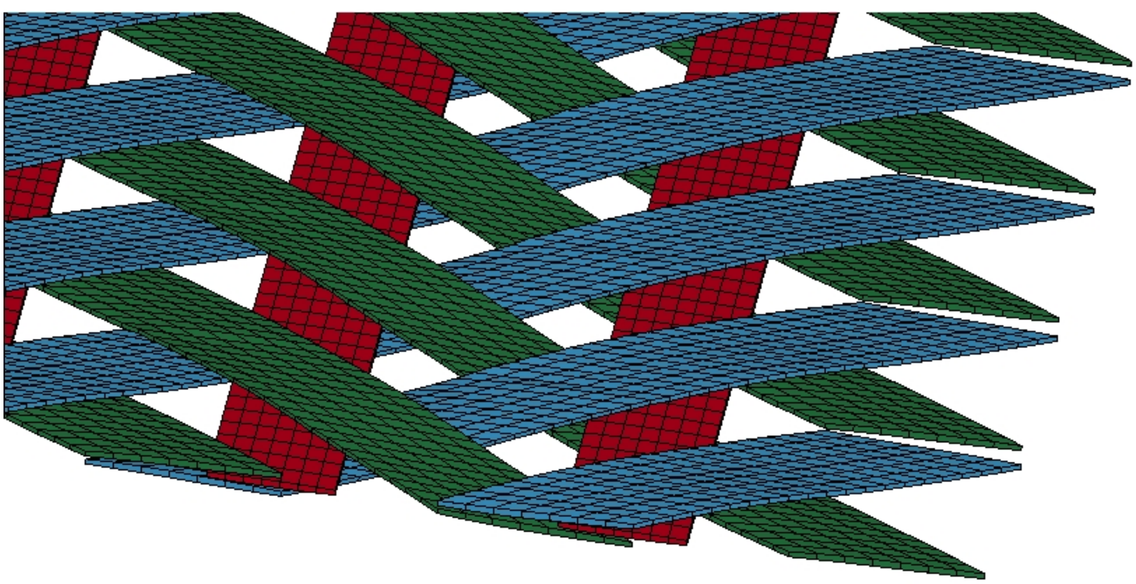


Figure 3. Explicit Modeling of Yarns in Braided Fabric

Material Properties of Yarns

The yarns making up the braided fabric have much less stiffness in all the other directions except for the fiber direction. It was shown that an orthotropic elastic material will have this kind of behavior if the transverse moduli E22 and E33 and shear moduli G12, G13 and G23 are small compared to the longitudinal elastic modulus E11, and the Poisson's ratios ν_{12}, ν_{13} and ν_{23} are very small. Damage growth and failure of the yarn are implemented through using *MAT_ADD_EROSION in LS-DYNA [LS-DYNA, 2003]. There are several different failure criteria in this material model. In our model, we set Von-Mises stress controlled failure criteria.

There are two types of Zylon fibers, Zylon-AS (as spun) and Zylon-HM (high modulus). Zylon-AS was used in this study. The manufacturer's values for the PBO-AS fiber are as follows: modulus of 180 GPa (26 Msi), tensile strength of 5.8 GPa (840 ksi), and strain to failure of 3.5%. Tensile tests were performed by SRI [Shockey and Simons et. al, 1999] using fill fibers that were removed from a 30 x 30 mesh Zylon fabric. The strain rates range over a factor of 200, from 1.6 x 10^{-3} s^{-1} to 3.2 x 10^{-1} s^{-1}. As the strain rate increases, the moduli vary from 164 to 180 GPa (24 to 26 Msi) and the tensile strengths vary from 2.75 to 3.45 GPa (400 to 500 ksi). The strain to failure remains relatively constant at around 2.45%. So the measured modulus for the yarn is similar to that of the fiber, but the measured tensile strength for the yarn is roughly half of that for the fiber, and the strain to failure is about 70%.

In order to define the material constant for the yarns, a single yarn from Zylon-AS with the assigned orthotropic material constants was simulated under simple tension and compared with the experimental data from SRI. Figure 4 shows the finite element mesh for a section of crimped Zylon-AS yarn under simple tension. The left end of the yarn was pulled and the right end was held. Table 1 shows the material constants used in the simulation, where $\bar{\sigma}_{\max}$ is the equivalent maximum stress. Figure 5 shows the comparison of the force versus strain and Figure 6 shows the deformed shape during the simulation. It can be seen that the material model capture the behavior of the crimped yarn under simple tension very well. The load is small initially due to the crimpness of the yarn and increases as the yarn is straighten out. The load reaches a peak value and then the yarn breaks. Figure 6 Shows the deformed shape during the simulation.

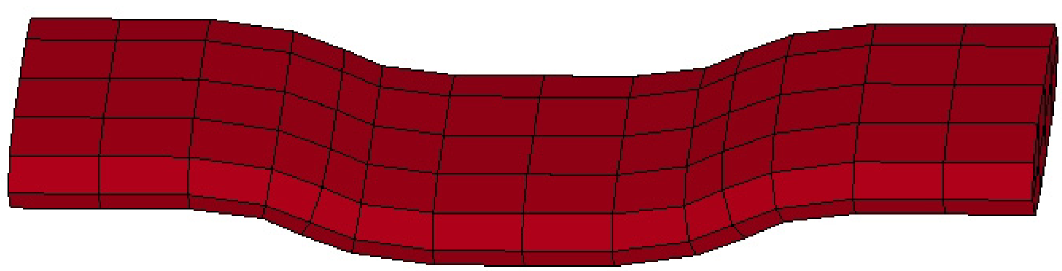


Figure 4. Finite Element of Mesh of A Single Yarn under Simple Tension

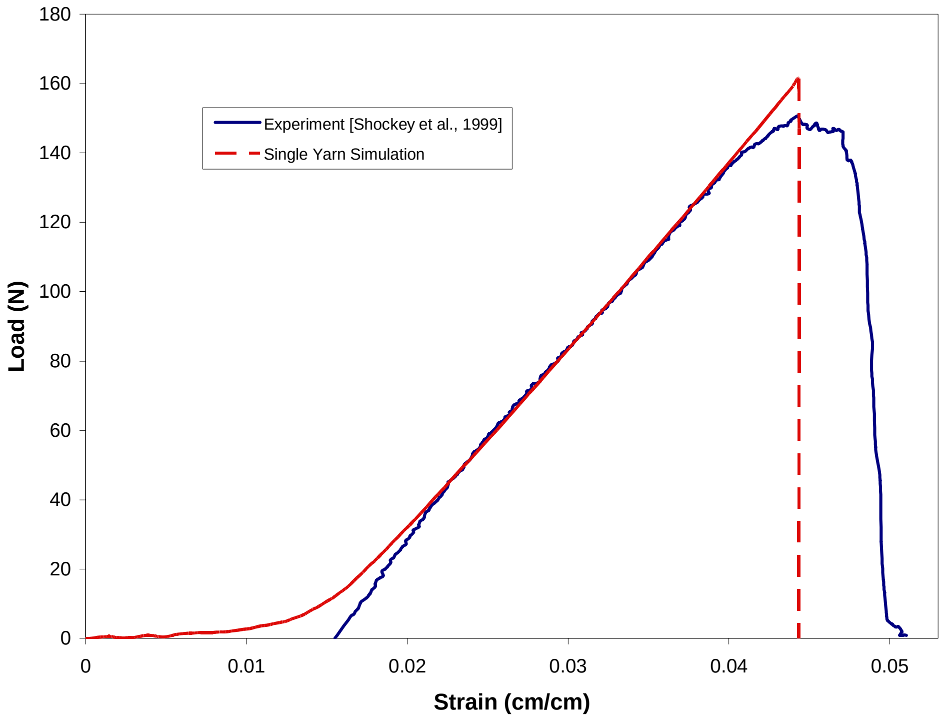
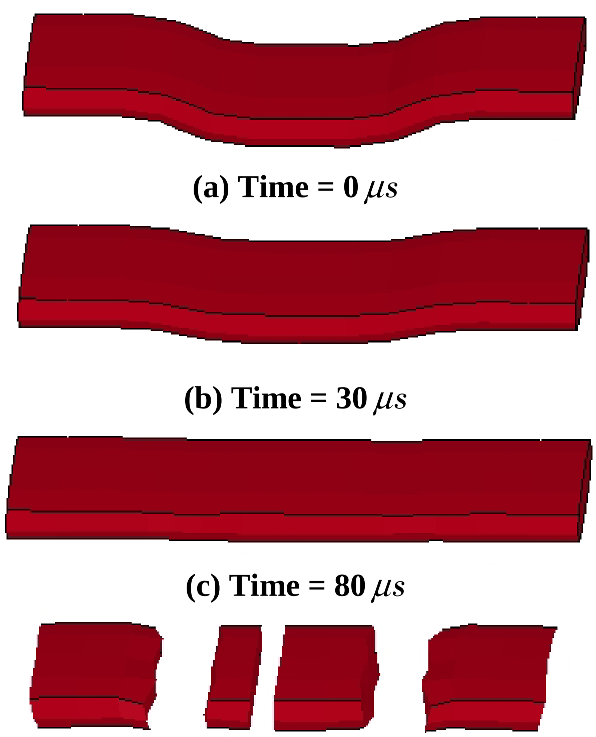


Figure 5. Load versus Strain for the Single Yarn under Simple Tension



(a) Time = 0 μs

(b) Time = 30 μs

(c) Time = 80 μs

(d) Time = 120 μs

Figure 6. Deformed Shaped of the Single Yarn under Simple Tension

Table 1. Orthotropic Material Parameters for Zylon-AS Yarn (Psi)

E_{11}	E_{22}	E33	G12	G13	G23	ν_{12}	ν_{13}	ν_{23}	$\bar{\sigma}_{max}$
26E6	26E4	26E4	26E3	26E3	26E3	0.0	0.0	0.0	4.65E5

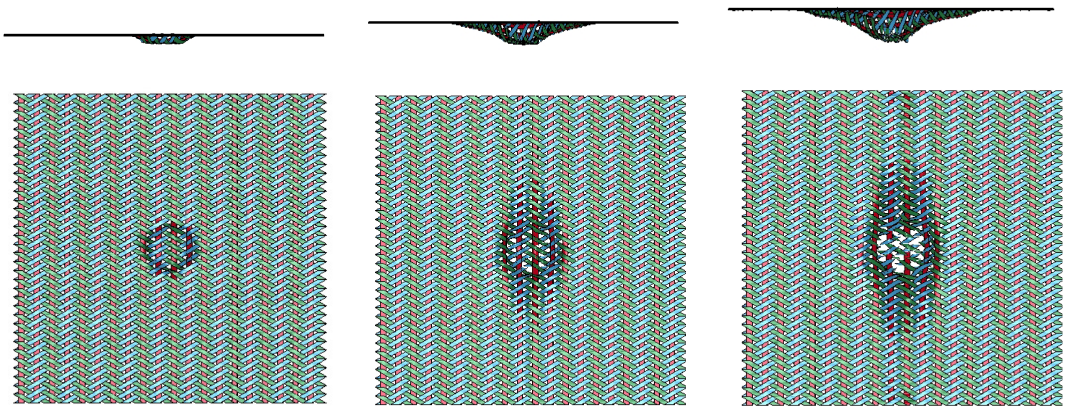
Results and Discussion

Two cases (μ=0.0 and μ=0.5) were modeled for both the yarn-yarn friction and the projectile-fabric friction. Figure 7 shows the top and side view of the fabric deformation at different instant of time. At 50 μs, the transverse deflection coincided with the projectile-fabric contact zone. At 140 μs, the transverse deflection propagated away from the impact region faster in the direction of axial yarns than in the braider yarns. This is due to axial yarns are the principle ones to absorb the energy during this time range. It can also be seen from the deformation history that the braider yarns broke after the axial yarns. At 200 μs, the braider yarns and axial yarns around the impact area had been broken before the transverse deflection wave reached the clamped edges. Figure 7d shows the overall view of the impact event at 200 μs when the projectile perforated the fabric and exited the fabric at a constant residue velocity.

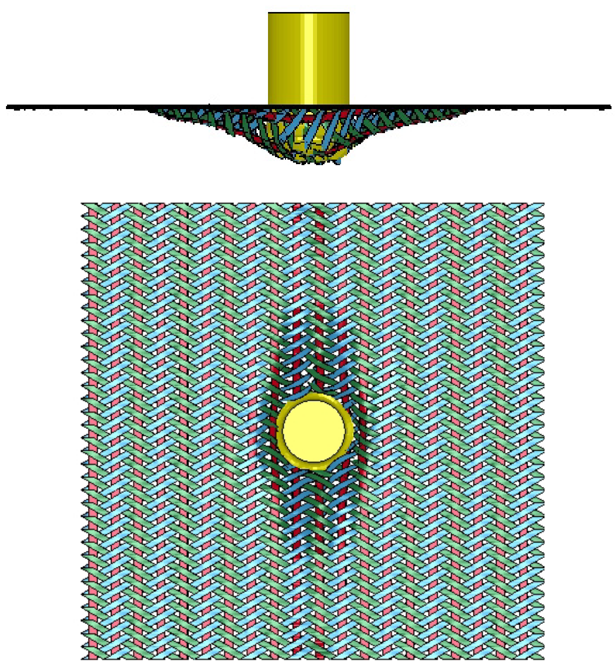
The time history of the projectile velocity for the two cases is shown in Figure 8. It can be seen that the projectile velocity was decreased more quickly when the friction coefficient is 0.5. The residue velocity of the projectile was 775.3 ft/s for the case with μ = 0 while it was 770.8 ft/s for the case with μ = 0.5. The friction contributed to decreasing the residue velocity of the projectile. The energy expanded by the projectile in perforating the braided fabric can be regarded as the energy absorbed by the fabric. It was found by subtracting the residual energy of the projectile from its initial impact energy when the velocity was above the ballistic limit:

$$E_{absorbed} = \frac{1}{2} m_p (v_{impact}^2 - v_{residual}^2) \qquad (1)$$

where $E_{absorbed}$ is the energy absorbed by the fabric, m_p is the mass of the projectile, v_{impact} and $v_{residual}$ are the initial and residue velocity of the projectile respectively. Using the energy absorption of the fabric for case with $\mu = 0$ as a baseline, it can be obtained that the friction increased the fabric energy absorption capacity by 18%.



(a) 50 μs (b) 140 μs (c) 200 μs



(d) 200 μs Overall View

Figure 7. Top and Side View of Fabric Deformation during Soft Projectile Impact

The energy absorbed by the fabric was converted into strain energy from stretching of the yarns and kinetic energy due to transverse deflection of the fabric and inward movement of the yarn material towards the impact region. A portion of the energy was also dissipated through frictional sliding losses. Figure 9 shows the fraction of energy absorption for the case $\mu = 0.5$. It can be seen that the kinetic energy of the fabric plays an important role in the absorption of the impact energy. [Cunniff, 1999] termed this as essentially inelastic impacts and stated that the bulk of absorbed energy depends primarily on the aerial density of the target and the amount of material involved. The dissipation of high-velocity impact energy by mainly kinetic energy of the fabric was also shown in the experimental observations of the ballistic perforation of Twaron woven fabric [Tan and Lim et al., 2003]. From Figure 9, it can also be seen that the frictional sliding energy played more important role after time instant 140 μs when the axial yarns began to damage and there are much more movements between the axial yarns and braider yarns as indicated by the increasing of the kinetic energy of the fabric.

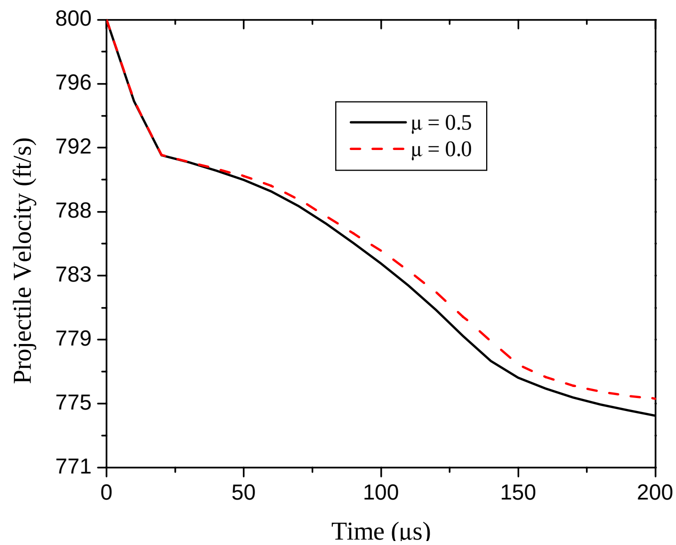


Figure 8. Time History of the Projectile Velocity

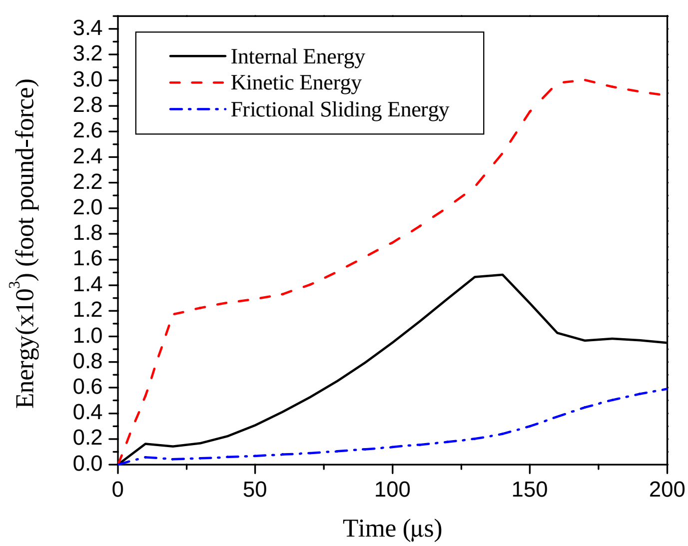


Figure 9. Time History of the Projectile Velocity

Conclusions

By explicitly modeling the yarns of a braided fabric and incorporating the damage and failure growth of a single yarn model, a detailed finite element model using commercially available FEA software, LS-DYNA, was used to analyze the ballistic impact of a soft projectile into a square patch of single-layer Zylon braided fabric. Friction between the projectile and the fabric as well as the friction between yarns themselves during the impact was investigated. It was shown that the fabric can be more efficiently reduce the residue velocity of the projectile and absorb more energy when the frictional effects were accounted for during the impact process.

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