The role of friction in cylindrical projectile impact on fabric structure

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Abstract. A three-dimensional finite element analysis model for plain weave fabric was created. Impact of a rigid cylindrical projectile on a square fabric clamped along its four edges were simulated using commercially available software LS-DYNA. To reveal the role of friction in ballistic impact, comparative study was conducted in which projectile velocity, boundary condition, and material property are kept the same but friction between projectile and fabric and between yarns themselves are varied systematically. Results from the study show that the friction between projectile and fabric has little effect on fabric energy absorption but the friction between yarns themselves has apparent effect. Fabric has larger impact energy absorption capacity when friction coefficient between yarns are smaller. Smaller friction between yarns delays initiation of yarn failure, increases the duration of interaction between projectile and fabric and thus increases impact energy absorption capacity of fabric structure.

1. Introduction
Para-aramid fibers such as Kevlar, Twaron, and Technora et al. are a class of high-modulus, high-strength synthetic fibers. Fabrics made from para-aramid fibers are widely used in flexible ballistic impact protection system. Examples of the application are bullet proof vest and aircraft jet engine small fragments shield belt.

Cheeseman & Bogetti (2003) reviewed the studies on ballistic impact of fabric structures and summarized the factors that affect impact energy absorption capability of high-strength fabric structures. The factors include shape of projectile, impact velocity, yarn material property, plies of fabric, boundary condition, and interfacial friction of the impact system. Bazhenov (1997) showed that friction between yarns has significant effect on fabric energy absorption through ballistic impact test on dry and wet fabrics, in which different inter-yarn friction characteristics exist. Briscoe & Motamedi (1992) prepared aramid fabrics that have different friction characteristics through adding or removing surface lubricant. Quasi-static tests and ballistic tests were conducted on a single layer of aramid fabric. Test results show that friction is an important factor that influences fabric energy absorption capacity. Duan et al. (2005) created a three-dimensional finite element model for plain weave fabric and modeled effects of interfacial friction during ballistic impact of a rigid, spherical projectile on a single-ply high-strength fabric. Tabiei & Nilakantan (2008) reviewed research work on ballistic impact of dry woven fabric and pointed out that interfacial friction between fibers in a yarn, between yarns themselves, and between projectile and fabric are important factors in impact mechanics of fabric structures and need further investigation.
This paper focuses on examining the role of friction in rigid cylindrical projectile impact on plain weave fabric structure. A three-dimensional finite element analysis model for plain weave fabric was created. Transverse impact of a rigid cylindrical projectile on a square fabric clamped along its four edges were simulated using commercially available software LS-DYNA. To reveal the role of friction in impact, comparative study was conducted in which projectile velocity, boundary condition, and material property are kept the same but interfacial friction between projectile and fabric and between yarns themselves are varied systematically.

2. Finite element analysis model

2.1. Finite element model for crimped yarn

A yarn is composed of quasi-parallel fibers and is in a crimped state in plain weave fabric. The three-dimensional finite element model created in this paper is to the yarn level resolution. Fibers are not modeled explicitly. Figure 1 shows cross section of a single ply plain weave fabric structure and the geometrical parameters used for creating the three-dimensional finite element analysis model.

For a plain weave fabric with thickness H of 0.226 mm and yarn wave length L of 1.634 mm, radius of the arc r is calculated to be 1.48 mm and angle of the arc θ is determined to be 16°. A three-dimensional finite element model for the crimped yarn in the plain weave fabric is created using the calculated parameters r and θ, and is shown in Figure 2.
2.2. Yarn material property
As stated in Section 2.1, a yarn in a plain weave fabric is made of hundreds of quasi-parallel fibers. Elastic modulus along fiber direction is large while the moduli in all other directions are very small. Therefore, yarn is modeled as orthotropic material in the three-dimensional finite element analysis. Table 1 shows the nine orthotropic material parameters for solid yarn examined in this paper, where $E_{11}$ is for elastic modulus along fiber direction.

| $E_{11}$ | $E_{22}$ | $E_{13}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ | $\nu_{12}$ | $\nu_{13}$ | $\nu_{23}$ |
|----------|----------|----------|----------|----------|----------|------------|------------|------------|
| 75       | 0.75     | 0.75     | 0.148    | 0.148    | 0.148    | 0          | 0          | 0          |

In a plain weave fabric, yarn is crimped and the fiber direction varies periodically along yarn length. In addition, a yarn subjects to transverse deflection during impact and the fiber direction changes with deflection of the fabric structure. In order to describe the mechanical behavior of yarn material, local coordinate system is defined for each and all of the solid elements with one axis along the fiber direction. The local coordinate system is used as reference coordinate system for the orthotropic material property defined in Table 1. Yarn failure criteria is determined to be 2.5 GPa for maximum principal stress according to the reference (Das et al. 2015).

2.3. Finite element model for fabric structure
Figure 3 shows the three-dimensional finite element analysis model created for plain weave fabric structure using the parameters defined in Section 2.1. As shown in the figure, warp yarns and weft yarns are woven together. Frictional contact is defined between warp yarns and weft yarns and between warp or weft yarns themselves.
Figure 3. Three-dimensional finite element analysis model for the plain weave fabric with a thickness of 0.226 mm and yarn wave length of 1.634 mm

3. The role of friction in ballistic impact on fabric structure

3.1. Impact of a rigid cylindrical projectile on fabric

Figure 4 shows a finite element analysis model for transverse impact of a rigid cylindrical projectile on a plain weave fabric. Size of the fabric is 49 mm × 49 mm and mesh of the fabric structure is shown in Figure 3. Yarn material property of the fabric is discussed in Section 2.2. The orthotropic material parameters used in the finite element analysis are listed in Table 1. All the sides of the fabric are clamped. Diameter of the cylindrical projectile is 8 mm and its mass is 2.0 gram. The cylindrical projectile is located at center of the fabric structure and initial impact velocity is 200 m/s. Due to symmetry of the impact system, only a quarter of the system need be modeled, as shown in the figure. This greatly reduces computing resources and computing time.

Figure 4. Three-dimensional finite element analysis model for transverse impact of a rigid cylindrical projectile on a square plain weave fabric
During impact, the loss of projectile kinetic energy $\Delta E_{pk}$ is completely converted to yarn strain energy $E_{ys}$, yarn kinetic energy $E_{yk}$, and friction dissipated energy $E_f$. Energy balance of the impact system is given by Equation 3.

$$\Delta E_{pk} = E_{ys} + E_{yk} + E_f$$  \hspace{1cm} (3)

Let mass of the rigid projectile be $m$, initial impact velocity be $v_i$ and residual velocity of the projectile after it completely penetrates the fabric be $v_r$, the loss of the rigid projectile kinetic energy may be obtained from Equation 4.

$$\Delta E_{pk} = \frac{1}{2} m (v_i^2 - v_r^2)$$  \hspace{1cm} (4)

The commercially available finite element analysis software LS-DYNA was used to model the ballistic impact. Friction coefficient between projectile and fabric and between yarns themselves was set as 0.5. Figure 5 shows time history of the normalized yarn strain energy, yarn kinetic energy, friction dissipated energy and loss of projectile kinetic energy. It can be seen that at initial stage of the impact there exists a sudden loss of projectile kinetic energy. Large portion of the loss of projectile kinetic energy was converted to yarn kinetic energy. At 11.3 $\mu$s when yarn strain energy reaches the peak, yarn kinetic energy and yarn strain energy account for 41% and 36% of the total absorbed energy, respectively. The fabric structure starts to fail at the moment and after that yarn kinetic energy and friction dissipated energy have a clear upward trend while the yarn strain decline. When the fabric is completely penetrated, yarn kinetic energy accounts for 62% of the total absorbed energy while yarn strain energy and friction dissipated energy account for 24% and 14%, respectively. Yarn kinetic energy and yarn strain energy are the primary energy absorption mechanism.

![Figure 5](image)

**Figure 5.** Time history of normalized energy for the ballistic impact case with a friction coefficient of 0.5 for both the projectile-fabric interface and yarn-yarn interface.

### 3.2. Effect of friction on fabric energy absorption

To explore the role of interfacial friction in the ballistic impact, comparative study was conducted in which projectile velocity, boundary condition and material property are kept the same while friction coefficient between projectile and fabric and between yarns themselves was set as 0.1, 0.2, 0.3, 0.4 and 0.5, respectively. Figure 6 shows time history of the projectile velocity at various friction conditions. It can be seen that there is no much difference for time history of the projectile velocity up to about 13 micro seconds. After that, the projectile velocities show apparent difference for different friction conditions.
conditions. The projectile velocity drops the most for the case with $\mu=0.1$ while it drops the least for the case with $\mu=0.5$. Equations 3 and 4 provide the relationship between fabric energy absorption capacity and the projectile velocity. Therefore, for friction coefficient within the range from 0.1 to 0.5, the plain weave fabric structure has larger impact energy absorption capacity for smaller friction.

![Graph showing projectile velocity over time](image)

**Figure 6.** Time history of projectile velocity at various friction conditions. The friction coefficient between projectile and fabric and the friction coefficient between yarns themselves are set as the same $\mu$ value.

For the results shown in Figure 6, there exist two types of interfacial friction: the friction between projectile and fabric, and the friction between yarns. To differentiate effect of the two types of friction,more cases were simulated where the friction coefficient between yarns was set to 0.0 while the friction coefficient between projectile and fabric varied. Table 2 shows modeling results of the projectile residual velocity. It can be seen that the friction between projectile and fabric has little effect on projectile residual velocity or fabric energy absorption capacity.

| Friction coefficient between projectile and fabric | Projectile residual velocity (m/s) |
|--------------------------------------------------|-----------------------------------|
| 0.1                                              | 192.65                            |
| 0.2                                              | 192.60                            |
| 0.3                                              | 192.30                            |
| 0.4                                              | 192.62                            |
| 0.5                                              | 192.70                            |

**Table 2.** Effect of friction between projectile and fabric on projectile residual velocity

4. Conclusion
A three-dimensional finite element analysis model for plain weave fabric was created. Impact of a rigid cylindrical projectile on a square fabric clamped along its four edges were simulated with various interfacial friction conditions. Comparative study was conducted in which projectile velocity, boundary condition, and material property are kept the same but friction coefficients between projectile and fabric and between yarns themselves are varied. Results from the study show that the friction between projectile and fabric has little effect on fabric energy absorption but the friction between yarns themselves has apparent effect. Fabric has larger impact energy absorption capacity when friction between yarns are smaller. Smaller friction between yarns delays initiation of yarn failure, increases
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