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Modeling the role of friction during ballistic impact of a high-strength plain-weave fabric ☆

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Abstract

In order to examine the role of friction during ballistic impact of high-strength fabric structures, a commercially available finite element analysis code (LS-DYNA) was used to model the ballistic impact of a rigid sphere into a square patch of plain-weave fabric. Two types of boundary conditions were applied on the fabric: four edges clamped and two opposite edges clamped. Simple Coulomb friction was introduced between yarns at crossovers and between the projectile and the fabric. Modeling results show that the friction contributed to delaying fabric failure and increasing impact load. The delay of fabric failure and increase of impact load allowed the fabric to absorb more energy. Results from the modeling effort also indicate that fabric boundary condition is a factor that influenced the effect of friction. The fabric more effectively reduced the projectile residual velocity when only two edges were clamped.

Keywords: Fabric structure; Ballistic impact; Friction; Finite element analysis

1. Introduction

Plain-weave fabrics made from tough, high-strength fibers are often used in flexible protection systems such as bullet resistant vests for soldiers and turbine engine fragment barriers for airplanes. Numerous studies have been conducted on the ballistic impact of high-strength fabric structures [1–13]. Cunniff [1] states that the energy absorption characteristics of fabric systems under ballistic impact are influenced by a number of factors including fiber property, weave style, the number of fabric layers, areal density, projectile parameters, and impact parameters. Additionally, Bazhenov [2], Briscoe and Motamedi [3], and Tan et al. [4] have shown through experiments that interfacial friction within ballistic impact systems is also an important factor that affects fabric energy absorption capacity. Cheeseman and Bogetti [5] recently reviewed numerous studies focusing on improving the ballistic performance of high-strength fabric structures through changing those factors.

Generally, only impact velocity and residual velocity of the projectile are measured in ballistic impact experiments [1,4,6]. Starratt et al. [7] reported that they have developed an efficient method and built an enhanced laser velocity system (ELVS) for continuous measurement of projectile velocity in ballistic impact experiments. The experiment technique greatly improved understanding of fabric ballistic performance. However, the essential physics of the impact problem, such as the role of friction during an impact process, is hard to resolve through experimentation only. This is because it is very difficult or even impossible to obtain detailed information on fabric deformation and failure.

For a better understanding of the ballistic impact of fabric structures, analytical or numerical models are necessary. In previous work of the authors [8,9], a finite element analysis (FEA) model was created to simulate the ballistic impact of a rigid sphere into a square patch of plain-weave fabric. In this paper, a more realistic failure criterion has been added and two types of boundary conditions are applied on the fabric. The role of friction during the ballistic impact is explored by

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comparing the fabric deformation, impact load, and energy absorption capacity at different friction conditions.

2. Modeling the ballistic impact of a plain-weave fabric

A commercially available FEA code, LS-DYNA, was used to model the ballistic impact of a rigid sphere into a single-layer plain-weave fabric. Fig. 1 depicts the initial geometrical configuration of an impact event: a 2.091 g, 4 mm radius rigid sphere struck at normal incidence onto the center of a square patch of fabric. The sphere can only move along the y direction (normal to the *x–z* plane) and its impact velocity was 800 m/s. The fabric edges were perpendicular to the warp/weft yarns. The dimension of the fabric was 32.7 mm × 32.7 mm. Two types of boundary conditions were applied on the fabric: four edges clamped, two opposite edges clamped and the other two edges free. Because the impact system has symmetry with respect to the *x–y* plane and the *y–z* plane, only a quarter of the entire system was modeled. As in the previous paper by the authors [8], the plain-weave fabric was modeled to yarn level resolution. Fig. 2 shows a part of the FEA model for the plain-weave fabric structure. The fabric thickness was 0.23 mm and the yarn crimp wavelength was 1.64 mm. The yarn material density was determined to be 600 kg/m^3.

The orthotropic elastic material data that had been used by Shockey et al. for Zylon yarns was used for yarn material property [10]. Table 1 lists the nine material data. A von Mises stress of 12 GPa was used as a failure

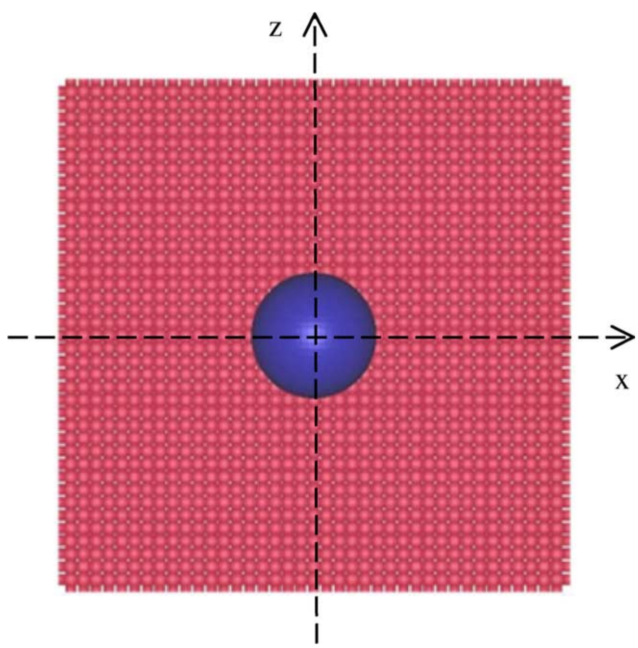

Fig. 1. A rigid sphere impacting transversely onto the center of a square patch of plain-weave fabric.

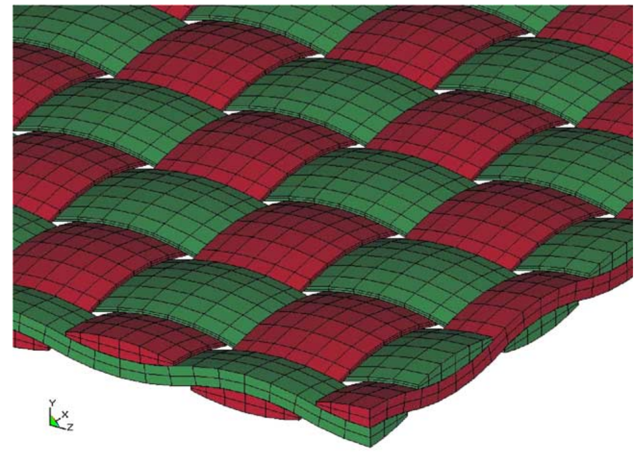

Fig. 2. Finite element analysis model for the plain-weave fabric structure.

criterion for the yarn material. Because the elastic modulus along fiber direction E_{11} is much larger than those along other directions, the von Mises stress at a material point is almost equal to the stress along fiber direction. Therefore, the von Mises stress failure criterion is roughly equivalent to the maximum strain failure criterion used by other researchers for yarn materials [11,12]. For the given material data, the 12 GPa von Mises stress is equivalent to a strain of 7% (along fiber direction).

Simple Coulomb friction was introduced between yarns at crossovers and between the projectile and the fabric. A friction coefficient $\mu = 0.5$ was used for both the yarn–yarn friction and the projectile–fabric friction. The friction coefficient was chosen to represent large friction case. Finally, in order to examine role of the friction, comparative cases were modeled where all the conditions were maintained except that the friction coefficient was 0 instead of 0.5.

3. Results and discussion

As previously stated, two types of boundary conditions were applied on the fabric. The first is all the four edges of the fabric clamped and the second is two opposite edges of the fabric clamped and the other two edges free. Modeling results for both of the boundary conditions are presented and discussed.

3.1. Four edges clamped

A case was modeled where a friction coefficient $\mu = 0.5$ was used for both the yarn–yarn friction and the projectile–fabric friction. Fig. 3 depicts the fabric deformation at different instants of time. At 2 μs, the transverse deflection coincided with the projectile- fabric contact zone; the transverse deflection wave front was