Available online at www.sciencedirect.com

ScienceDirect

Composites: Part B 39 (2008) 476–489

composites Part B: engineering

www.elsevier.com/locate/compositesb

Effect of frame size, frame type, and clamping pressure on the ballistic performance of soft body armor

G.M. Zhang [a], R.C. Batra [a,*], J. Zheng [b]

[a] Department of Engineering Science and Mechanics, M/C 0219, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States
[b] Program Executive Office – Soldier, US Army, 15395 John Marshall Highway, Haymarket, VA 20169, United States

Received 23 February 2007; accepted 12 April 2007
Available online 10 May 2007

In memory of Professor Kevin Granata who was killed on 16 April 2007 during the massacre in Norris Hall, Virginia Tech.

Abstract

We analyze, with the computer code LS-DYNA, three-dimensional (3D) transient deformations of a 10-layer woven Kevlar armor held in a square steel frame and impacted at normal incidence by a 9 mm FMJ (full metal jacket), 124 grain projectile. The composite armor is discretized into weft and warp yarns to simulate its woven structure. The yarn is modeled as a 3D continuum. We consider failure of the yarn, and friction between adjoining layers and between the armor and the frame bars. For the armor perfectly bonded to the rigid frame bars, the computed residual speed and the residual kinetic energy of the projectile are found to increase with a decrease in the frame size implying thereby that the armor fixed in a smaller frame will have lower V_{50} than that of the same armor clamped in a larger frame. (The V_{50} of an armor equals the speed of a standard projectile that upon normal impact has 50% probability of just perforating the armor). For the armor allowed to slide between the frame bars, we have studied the effect of the pressure applied to the bars of the two- and the four-bar frames on the speed and the kinetic energy of the residual projectile. For both the two- and the four-bar frames, the speed of the residual projectile is found to increase with an increase in the applied pressure. Computed results also show that the armor fixed in the two-bar frame exhibits higher impact resistance than that held in the four-bar frame. The V_{50} is found to be $\sim$270 m/s when the woven armor is held in a four-bar frame with a clamping pressure of 200 MPa. The V_{50} decreases with an increase in the pressure applied to either the two-bar or the four-bar frames.

Keywords: A. Yarn; B. Fracture; B. Impact behavior; C. Finite element analysis (FEA); Ballistic performance

1. Introduction

Composite materials have been widely used in many high-performance structures such as protective clothing, bullet-proof vests and helmets due to their high-specific strength and stiffness. The ballistic performance of soft body armor is characterized by V_{50}, which is usually determined experimentally, and equals the velocity of the projectile that upon normal impact on the armor has 50% probability of penetrating it.

Parameters affecting the ballistic performance of composite armor include material properties of the yarn, woven structure of the armor, projectile geometry, projectile velocity and its material, boundary conditions imposed on the armor, friction between the yarns, and friction between the yarn and the projectile. Duan et al. [1] used LS-DYNA to delineate effects of frictional forces on the ballistic performance of one-layer woven rectangular composite with all four edges either clamped or only two opposite edges clamped. However, they did not consider the failure of the projectile and the composite. A recent review paper [2] has discussed the effect of different material and geometric parameters on the ballistic performance of soft body armor.

* Corresponding author. Tel.: +1 540 231 6051; fax: +1 540 231 4574.
E-mail address: rbatra@vt.edu (R.C. Batra).

1359-8368/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compositesb.2007.04.002

Generally in ballistic experiments the boundary of the armor system is held in a rectangular frame with pressure applied to the frame bars to hold the armor in place. Two different frames, namely, two-bar and four-bar, are employed. Also frame size can be varied by adjusting the distance between the opposite bars of the frame. Shockey et al. [3] experimentally ascertained the effect of boundary conditions on the ballistic performance of the armor and found that for both the 25 g blunt and the 26 g sharp fragment simulating projectile (FSP), the armor fixed on two opposite edges rather than on all four edges was more effective in reducing the kinetic energy of the projectile. Since experiments are very expensive to perform, it will be more economical if one could accurately delineate computationally the effect of the frame size and the pressure applied to its bars on the V_{50}. We note that small values of the applied pressure may not hold the armor well, and when impacted it will slide between the frame bars. However, very large values of this pressure may fracture the armor within the frame bars. Thus the ballistic performance of the armor is likely to depend upon the pressure applied to the frame bars and the frictional force between the yarn and the frame bars. Lee et al. [4] have studied experimentally the effect of the clamping pressure on the penetration resistance of a 5-ply composite laminate and found that the loss of the kinetic energy of the projectile decreased with an increase in the clamping pressure.

Hundreds of parallel high-strength and high-modulus fibers are grouped together to form a yarn and yarns are woven to form a single-ply fabric. It is still not possible to consider each fiber individually because of enormous computational resources required. A possibility is to model woven armor as an assembly of one-dimensional (1D) bar elements [5,6]. Tan and Ching [7] replaced the one-layer composite with a network of viscoelastic bars. For suitable values of material parameters, they found that computed results agreed very well with the ballistic test data. Barauskas and Abraitiene [8] simulated the armor with thin shell elements of thickness equal to that of the yarn. A more realistic discretization of the composite is obtained by using 3D solid elements that can account for orthotropic material properties, inter-yarn and inter-layer friction, material failure and undulations in the woven yarns. Gu [9] considered the actual structure of plain-woven fabrics and developed 3D finite element discretization of the woven composite into weft and warp yarns. The multi-layered woven composite was impacted by a steel projectile and the computed results were compared with the experimental data. However, the failure of the projectile was not considered.

There are three methods to determine the ballistic limit of a soft armor. An accurate but very expensive method is to carry out a large number of ballistic experiments. However, it is tedious to experimentally characterize the effect on V_{50} of each parameter, such as the projectile shape and material, armor material, armor thickness, and armor architecture. An alternative is to employ an approximate model [10] of the armor system, analyze the problem analytically and establish scaling laws. The success in this case depends upon our understanding of the mechanisms involved in the penetration process and how well they can be incorporated in the analytical model. The third possibility is to use a numerical method such as the finite element method that finds an approximate solution of the pertinent initial-boundary-value problem but can incorporate realistic material behavior, complex geometries, friction effects, and material failure. The analysis can be easily modified when additional information on the material response and failure becomes available. After the mathematical model and the computational algorithm have been validated one can perform parametric studies, determine the V_{50}, and also delineate parameters to which it is most sensitive. In this case V_{50} equals the minimum projectile velocity with which the target when impacted at normal incidence is penetrated completely. A few experiments are needed to validate this technique.

Sun and Potti [11] proposed the following relation

$$E_{\mathrm{DP}} = \frac{1}{2} m (V_{\mathrm{s}}^2 - V_{\mathrm{R}}^2)$$

among the initial velocity V_{s}, the residual velocity V_{R} of the projectile of mass m, and the energy E_{DP} required to completely perforate a target. Here E_{DP} is assumed to be constant, and the projectile not to fail during the penetration process. This relation does not account for the energy required to deform the armor, and that dissipated due to friction effects. Lim et al.'s [12] simulation of ballistic impact of fabric armor with LS-DYNA showed that the energy absorbed during the penetration process increased with an increase in the incident speed when it is between the V_{50} and a critical value. For an initial speed greater than the critical value, the energy absorbed decreased suddenly. Zeng et al.'s [13] simulations of ballistic impact of woven fabric armor gave similar results.

Here we have used the commercial software LS-DYNA to numerically simulate 3D deformations of a woven Kevlar armor held in a rectangular frame and impacted at normal incidence by a hemispherical nosed cylindrical lead projectile coated with a thin layer of copper with the goal of finding the effect on the V_{50} of the frame size, the clamping pressure applied to the frame bars, and whether the frame has four-bars or only two opposite bars. We account for the failure of the projectile and the target during the penetration process, simulate the relative movement between the adjacent yarns, assume the Kevlar armor to be an orthotropic material, regard each layer of the woven composite as made of weft and warp yarns, and divide each yarn into 3D solid elements. It is found that the frame type and the pressure applied to its bars influence the ballistic performance of the armor and its V_{50}. This information should be useful to armor designers, and to those involved in certifying acceptable armor performance.