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Effect of matrix on ballistic performance of soft body armor

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ABSTRACT

We analyze three-dimensional (3-D) deformations of soft body armor in the form of a clamped rectangular plate impacted at normal incidence by a projectile. Results have been computed by the finite element method, using the commercial software LSDYNA, for the armor with and without a matrix, and in the former case with either perfect or no bonding between the matrix and the yarn. Also, two impact speeds and two polymers, one stiffer than the other, have been considered. Significant contributions of the work include studying 3-D elastoplastic deformations, and delineating the effect of the matrix on the ballistic performance of the armor. It is found that the matrix reduces the maximum deflection of the armor, increases the size of the deformed area, and enhances the reduction in the kinetic energy of the projectile. However, the size of the deformed area is not a good indicator of the energy absorbed during impact. These results are useful for armor designers since the reduction in the maximum deflection should reduce the intensity of injuries to persons wearing the armor. On the other hand the larger deformed area of the armor can increase the possibility of injuries.

1. Introduction

Body armors made of woven fabric composites are extensively being used by the military and other law enforcement agencies to protect personnel. Apart from preventing the projectile from penetrating, the vest must also be designed so that an impact does not induce significant bulge at the back face as this would lead to severe injuries even if the projectile does not completely penetrate the armor. The bulge height can be reduced by incorporating a layer of soft fibrous material [1] inside the armor. During penetration yarns which engage the projectile directly are called the principal or primary yarns. These yarns absorb most of the energy during impact and hence are the first to fail. Fibers having high tensile strength and failure strain can absorb more energy per unit volume before failing and hence are ideal candidates for use in body armor. The energy absorbed by secondary yarns which do not directly contact the projectile is limited. Thus the ballistic performance of a body armor should be improved if not only more yarns engage the projectile during penetration but also disperse stress waves away from the point of contact. Roylance [2], through numerical simulations, showed that enhancing friction between yarns increases dispersion of stress waves. This was also shown experimentally by Briscoe and Motamedi [3] and through finite element simulations by Duan et al. [9].

Lee et al. [4] have studied the effect of matrix resin on the performance of fabric composites. Though the amount of matrix present in such composites is small (typically in the range of 20–25% by volume) it can significantly influence the performance of the body armor. The presence of matrix has two important consequences; it not only restrains yarns from moving but also holds different yarns together. Evidence for the above phenomena was given by Lee et al. through a series of load deflection experiments and postmortem inspections of deformed specimens. Load deflection curves indicated that during penetration of the composite laminates there was a sudden drop in the load after the failure whereas for armors made of only yarn fabric the load gradually dropped. The gradual decrease was attributed to yarn slippage and successive breakage of individual yarns. Photographic evidence of the damaged area showed that more yarns were engaged for composites when compared to laminates made of only yarns. Also, smaller penetration radius was observed for body armors made of only yarns than that for composite laminates. Another consequence of having the matrix is that the effect of taper/curvature of the projectile on penetration is greatly reduced. We note that the amount of energy absorbed by the resin material during penetration is only marginal. The above discussion suggests that the presence of matrix improves the ballistic performance, but this is not always the case as the matrix tends to make the body armor less flexible and hence reduce the depth of the cone formed during penetration leading to a lesser amount of energy absorbed. Also, the loss in flexibility can lead to reduced interaction between different layers of the fabric composite. It has been observed that laminates that have either

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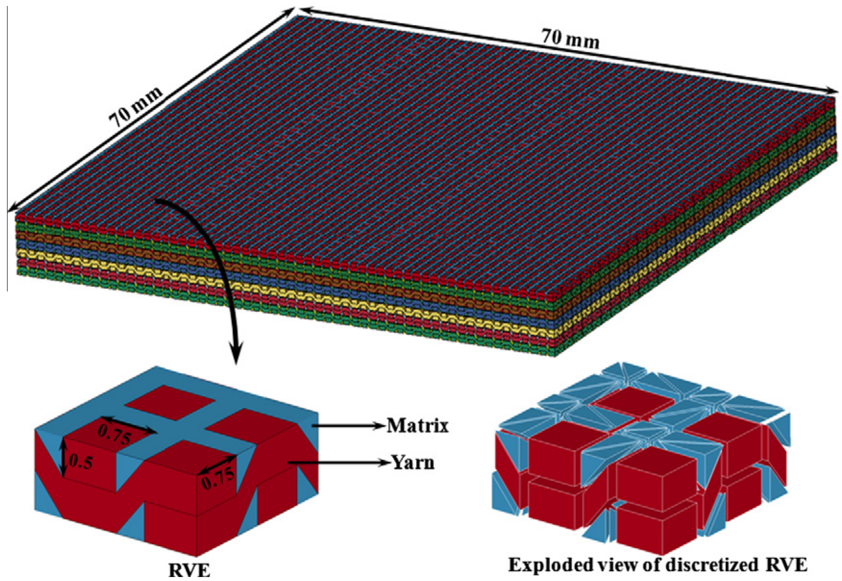

Fig. 1. Sketch of the woven fabric composite, and its discretization into finite elements (lengths depicted in the RVE are in mm).

weak or no interaction between constituents generally tend to absorb less energy than those that interact with each other [5–7]. Cheeseman and Bogetti in their review article [8] have suggested that weak interaction between the matrix and the yarn is preferable as this facilitates delamination between the matrix and the yarn allowing fibers to extend to failure.

The ballistic impact behavior of woven fabric composites can be analyzed using analytical, numerical and experimental methods. Analytical techniques would be very desirable since they are based on energy transfer between the projectile and the target [16–18], and help quantify the importance of various parameters through non-dimensional numbers. Failure mechanisms considered include tensile failure of the primary yarns, energy absorbed by secondary yarns, delamination and matrix cracking. Though such models predict reasonably well the residual velocity of the projectile, they only give a global picture and do not account for intricate interactions between the projectile and the target. Details of such interactions will help design better and lighter armors.

A sophisticated two-dimensional (2-D) membrane model has been proposed by Phoenix and Prowal [34] in which a blunt nosed projectile impacting a membrane was analyzed. A common approach for analyzing the impact behavior of woven fabric structure is to use the finite element method (FEM); software such as DYNA3D [19], LSDYNA [20–22], AUTODYN [23,24] and ABAQUS explicit [25,26] have been used for this purpose. Armors made of yarns have been modeled with varying degree of sophistication, e.g., as shells [19], beams [27] and solid structures [10]. Micro/meso mechanics approaches have been used to derive constitutive equations for the fabric [28–31] and simulate it as a deformable continuum rather than consider details of the woven architecture. A multi-scale approach to model fabrics [32,33] has also been employed.

Woven fabric composites generally have matrix bonding the yarns and its effect on the ballistic performance of the soft body armor has not been studied in the literature; conclusions are based on results of a few experimental investigations such as those of Lee et al. [4]. The presence of matrix has two competing influences; on one hand it engages more yarns and prevents their relative sliding thereby increasing the ballistic performance of the body armor, on the other hand, it reduces the flexibility and interaction among various layers thereby reducing the ballistic performance. We investigate here how the matrix influences the impact performance by looking at flexibility of the composite and the engagement of primary yarns with the projectile due to presence of the matrix. We numerically analyze the problem as it is easy to assess results based on controlled parameters. The problem studied involves the impact of a Remington 9 mm full metal jacket (FMJ) projectile on a woven composite made of Kevlar fabric and resin matrix. The effect of the matrix on the ballistic performance is studied by considering two polymers. The effect of bond strength between the resin matrix and the yarn fabric is also examined. A unique feature of this work is the consideration of how matrix influences deformations of yarns in a 3-D setting, which should provide a more realistic consideration of friction and failure mechanisms [10,11,15]. Our analysis of the problem has revealed that (i) the matrix surrounding the yarn, and the interaction between the matrix and the yarn significantly influence the overall performance of the body armor, and (ii) the size of the deformed area is not a good indicator of the energy absorbed during the impact. We note that strategies to simulate 3-D deformations of woven composites have been reviewed by Ansar et al. [14].

The rest of the paper is organized as follows. Section 2 describes the material and the geometric parameters of the armor and the projectile, constitutive relations and failure criteria, and values assigned to different parameters. Results from simulations delineating the effect of the resin properties on the deformation and failure of the body armor are presented in Section 3. Conclusions of the work are summarized in Section 4.

2. Material and geometric parameters

Commercial packages ABAQUS, ETA-VPG and LS-PREPOST have been used to construct the complex geometric configuration of the yarn matrix network. Fig. 1 shows the woven composite with matrix resin and a representative volume element (RVE) of the composite laminate. Kevlar yarn bundle is modeled as a 3-D continuum and meshed with 8-node brick elements. The width and the thickness of the yarn bundle equal 0.75 mm and 0.5 mm, respectively, and no gap is assumed at yarn crossovers to simplify the geometric structure of the resin matrix and its discretization into a FE mesh.

The volume fraction of the polymer calculated from the RVE equaled 21%. The polymer matrix was meshed with tetrahedral elements, and seven layers of 70 mm × 70 mm composite laminates