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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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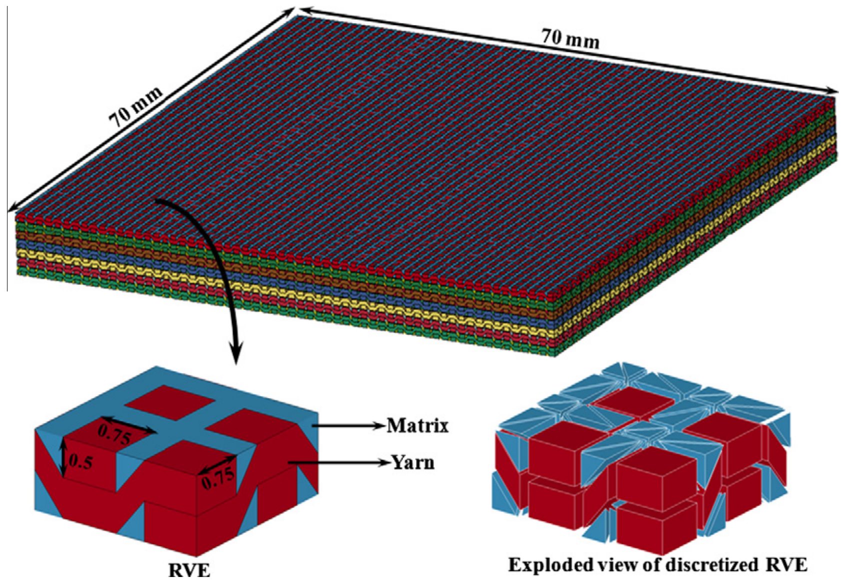

Fig. 1. Sketch of the woven fabric composite, and its discretization into finite elements (lengths depicted in the RVE are in mm).

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 $\times$ 70 mm composite laminates

Table 1
Values of material parameters of Kevlar yarn fabric.

E_a	$E_b = E_c$	$G_{ab} = G_{bc} = G_{ca}$	$\mu_a = \mu_b = \mu_c$	ρ	
164.0 GPa	3.28 GPa	3.28 GPa	0	1440 kg/m^3	
S_{ab}	X_a	X_b (X_b)	X_c	S_{cb}	S_{ca}
1.886 GPa	2.886 GPa	1.486 GPa (1.7 GPa)	1.486 GPa	1.886 GPa	1.586 GPa

Table 2
Values of material parameters for soft and stiff matrix.

E_{soft} (E_{stiff})	μ_{soft} (μ_{stiff})	$\sigma_{yield\text{-}soft}$ ($\sigma_{yield\text{-}stiff}$)	ρ_{soft} (ρ_{stiff})
0.5 (3.5) GPa	0.35 (0.35)	20 (50) MPa	900 (900) kg/m^3

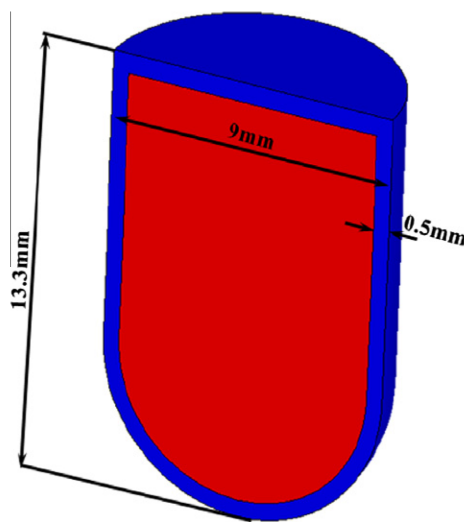

Fig. 2. Cross section of projectile, Remington FMJ.

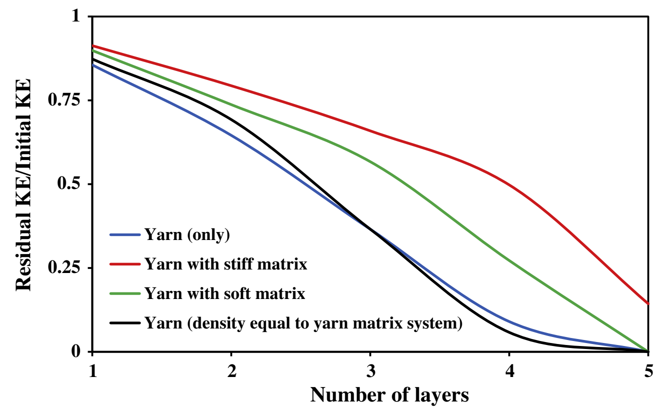

Fig. 3. Normalized residual kinetic energy of the projectile vs. the number of laminate layers. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

with 0.1 mm gap between adjacent layers and having a total thickness of approximately 7.6 mm were used in the simulations. All edges of the laminate were rigidly clamped; thus the three displacement components of all nodes on the laminate edges were set equal to zero. The strain rate dependence, if any, of material properties of the yarn has been neglected. The material model MAT_COMPOSITE_DAMAGE and the contact algorithm ERODING SINGLE SURFACE available in LSDYNA [12] are used to simulate the mechanical response of the yarn and the contact between different layers. We assume that the static and the dynamic coefficients of friction between the contacting surfaces equal 0.2 and 0.15, respectively. Values of material properties of the yarn, taken from [10], are listed in Table 1.

Here *a*-axis is aligned along the yarn direction, the *b*-axis is the transverse direction in the plane of the layer, the *c*-axis is along the normal to the *ab*-plane, '*S*' represents the shear strength, '*X*' represents the tensile strength, E_a is Young's modulus in the *a*-direction, μ_a is major Poisson's ratio, G_{ab} is shear modulus for deformations in the *ab*-plane, and ρ is the mass density. We note that X_a/E_a equals 0.018 giving approximately 1.8% axial strain to failure. Zhou et al. [35] have reported that the failure strain of Kevlar fiber depends upon the strain rate and used the value of 0.023 in their work. Here, a yarn element is assumed to fail when the maximum principal strain in it equals 0.02 and the MAT_ADD_EROSION option in LSDYNA is used to delete failed elements from the analysis. This enables one to use a reasonable time step size while computing the solution. The element deletion algorithm affects the time step size used for computing a stable solution.

The polymer matrix is modeled using MAT_PIECEWISE_LINEAR_PLASTICITY material model in LSDYNA that accounts for strain rate effects. We have used a bilinear effective stress-effective strain curve, specified the yield stress and the hardening modulus, and employed the Cowper–Symonds relation to consider strain-rate effects. To delineate effects of the matrix stiffness upon the ballistic performance we have considered two

Table 3
Values of parameters for the projectile materials.

Values of material parameters for copper in the Johnson–Cook relation					
A	B	C	n	m	T_m
0.09 GPa	0.292 GPa	0.025	0.31	1.09	1356 K
Values of material parameters for elastic deformations of copper					
ρ	G	K			
8950 kg/m^3	47.27 GPa	102.4 GPa			
Values of material parameters for copper in the Johnson–Cook damage relation					
D_1	D_2	D_3	D_4	D_5	σ_{spall}
1	0	0	0	0	1.9 GPa
Values of material parameters for elastic–plastic deformations of lead					
ρ	E	μ	σ_{yield}	Failure strain	
11,340 kg/m^3	16 GPa	0.44 GPa	0.383 GPa	0.3	

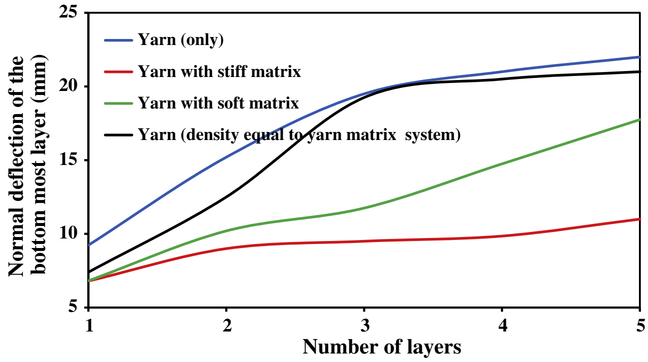

Fig. 4. Deflection of the bottom most layer vs. the number of laminate layers. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

sets of data listed in Table 2 – one mimicking a soft polymer and the other a stiff polymer; these need not correspond to values of parameters for a real material.

For each polymer, the failure was assumed to occur at the effective plastic strain of 0.05, the hardening modulus was set equal to one-half the elastic modulus, and the two parameters in the Cowper–Symonds relation to have values [13]: $C = 4000$ s, $P = 0.182$. To study the effect of the matrix adhesion with the yarn we have considered two extreme cases. Tie constraints are imposed between the yarn and the matrix to represent perfect adhesion and no constraints between them to represent no adhesion.

The projectile considered in our analysis is a 13.3 mm long Remington 9 mm full metal jacket (FMJ). The projectile, shown in Fig. 2, is comprised of 0.5 mm thick outer copper cap with a solid lead shot filling. The geometric and the material parameters are identical to those used by Zhang et al. [10] and are briefly summarized here for completeness. The Johnson–Cook (JC) relation is used to simulate the thermo–elasto–viscoplastic response of copper, and lead is modeled as an elastic perfectly plastic material; each material is assumed to be isotropic. The JC damage model is used to characterize damage induced in copper. Values of material parameters appearing in these relations are listed in Table 3.

3. Results and discussion

3.1. Projectile impact on composite layer system

In order to delineate the effect of the matrix in a composite on the impact performance we have considered four cases, namely, yarn without matrix, woven yarn surrounded by soft and stiff matrix, and yarn without matrix but with density equal to that of the yarn matrix composite system. Inertia effects for the final case should be nearly the same as those for the second and the third cases but the yarn-matrix constraining effects will be different. For all cases considered the initial impact velocity of the projectile was taken to be 250 m/s, and the matrix, if present, is assumed to be perfectly bonded to the yarns. In Figs. 3 and 4 we have plotted the residual kinetic energy (normalized with respect to its initial kinetic energy) of the projectile and the normal displacement of the bottom most layer of the composite as a function of the number of layers (or the thickness) of the composite system.

From results displayed in Fig. 3 we conclude that the residual kinetic energy of the projectile for the composite system made of only yarns is less than that when the composite system contains matrix. It is also seen that the composite containing the soft matrix is more effective in slowing down the impactor than a composite having the stiff matrix. In the absence of the matrix, lighter yarns

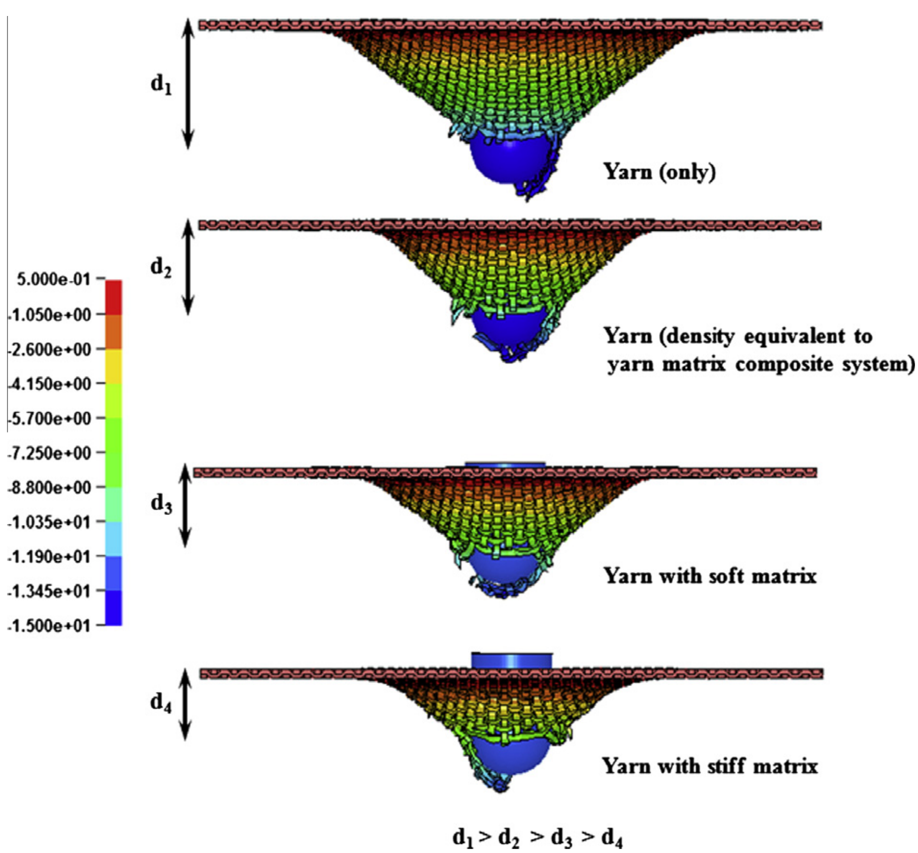

Fig. 5. Effect of matrix on the depth of the cone formed in a lamina. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

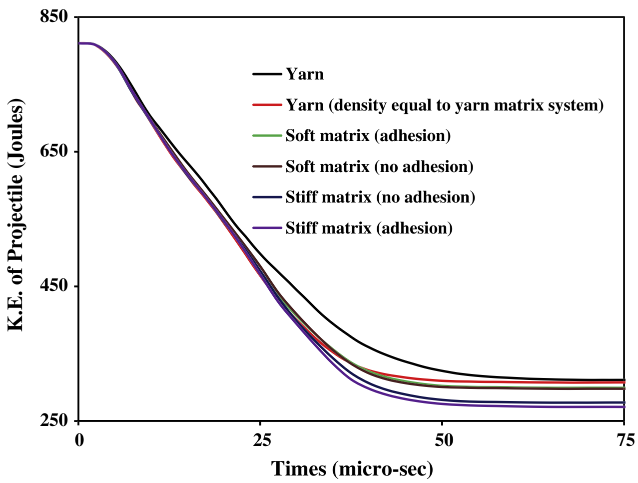

Fig. 6. Time histories of the kinetic energy of the projectile impacting the 7-layer composite laminate for impact speeds above the ballistic limit. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

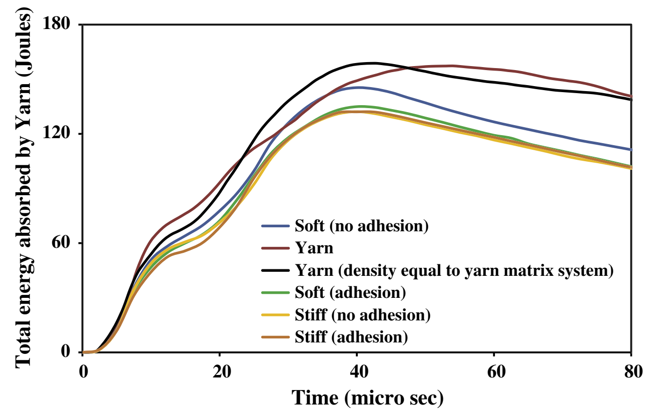

Fig. 7. Time histories of energies absorbed by the yarn. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

perform better for 1- and 2-layer laminate systems, but heavier yarns slow down the impactor more when the laminate has 3 and 4 layers. The residual kinetic energy of the projectile reveals that the projectile perforates laminates of layers 1, 2, 3, and 4 but not of layer 5. Also, it is evident that the ballistic limits for the 4 laminates are different since the 5-layer laminate having stiff matrix is perforated but the other 5-layer laminates are not perforated as indicated by the zero kinetic energy of the penetrator.

In Fig. 4 we have plotted the maximum normal displacement of the composite system as a function of the number of layers. For the composite system containing the stiff matrix the maximum displacement is least while for the composite systems containing light yarns it is the maximum. For the laminates studied, clearly there is a direct correlation between the impact performance and the flexibility/stretch-ability of the composite systems, i.e., more the normal displacement lower is the residual kinetic energy of the projectile. With an increase in the number of layers composite systems containing matrix tend to perform better than those with only yarn. This is evident from slopes of the curves; for the composite systems containing only yarn these curves tend to flatten as compared to those containing matrix. This will be further explored in the next section when we consider a 7 layer composite system. Fig. 5 illustrates this view point for a single layer composite system. We note that even though the flexibility of the laminate made of only yarn has allowed it to absorb more energy the cone formed is far too deep to be effective in protecting personnel from injuries.

3.2. Projectile impact on multi-layer composite systems

We next analyze a 7-layer composite system and additionally consider the effect of adhesion between the yarn and the matrix. To model adhesion between the matrix and the yarn we employ tie constraints between contacting surfaces, this represents a case of strong or perfect adhesion. In the extreme case of weak adhesion no constraints are imposed. Fig. 6 represents the time history of the kinetic energy (KE) of the projectile impacting the composite system at a velocity of 450 m/s, which is above the ballistic limit of the laminate systems. In the figures legend adhesion refers to the case when tie-constraints have been imposed between the matrix and the yarn.

Results depicted in Fig. 6 indicate that, out of the six cases studied, the composite laminate with the stiffer matrix (no matrix) perfectly bonded to the yarn is most (least) effective in reducing the KE of the projectile. For impact speed above the ballistic limit, the system with the stiffer matrix perfectly bonded to the yarn decreases the KE of the projectile by about 45 J more than that for the case of no matrix. To further analyze this problem and see how the yarn-matrix interaction plays a role in interacting with the projectile we have displayed in Figs. 7 and 8 the total energy (= KE + strain energy) absorbed by the matrix and the yarn separately (accounting only for the active elements in the simulation). It is observed that the total energy of yarns is the maximum when

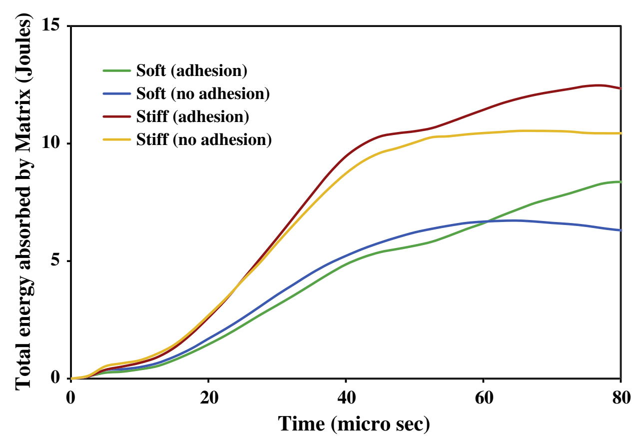

Fig. 8. Time histories of energies absorbed by the matrix. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

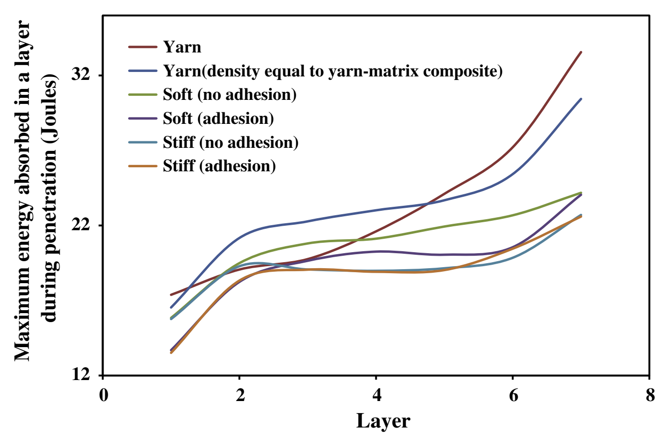

Fig. 9. Maximum energy (strain energy + kinetic energy) absorbed in each layer of the 7-layer composite. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

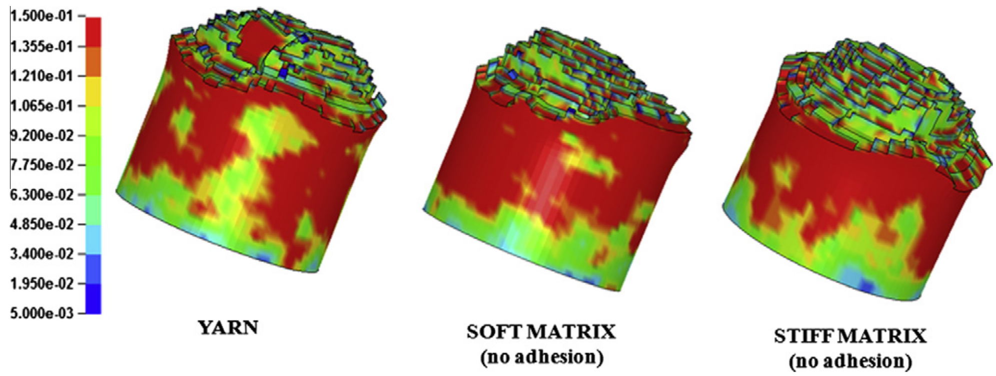

Fig. 10. Fringe plots of the von Mises stress (GPa) in the projectile at 100 μs for initial projectile velocity of 450 m/s. (For interpretation to colours in this figure, the reader is referred to the web version of this paper.)

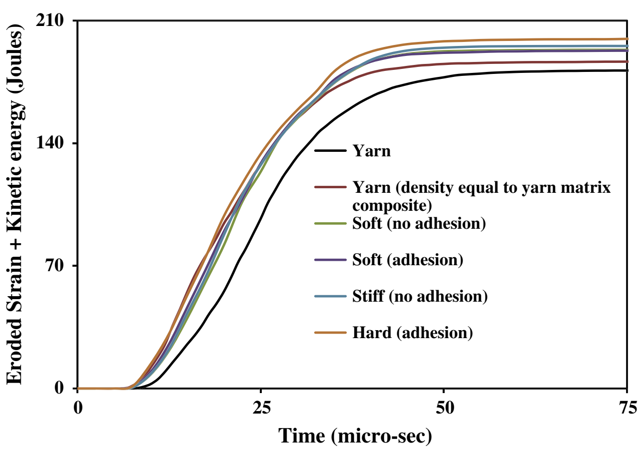

Fig. 11. Time history of eroded energy and the kinetic energy of the projectile for the six composite systems.

they are loose and the least when they are perfectly bonded to the stiffer matrix. However, the total energy of the stiffer matrix perfectly bonded to the yarns is the maximum and that of the soft matrix not sticking with the yarns the minimum. These results suggest that the matrix not only restricts the motion of yarns during penetration into the composite but also prevents the yarns from fully stretching to their ultimate values before breakage. This view point is further supported by results displayed in Fig. 9 where we have plotted the maximum energy (strain energy + kinetic energy) absorbed during penetration for each layer of the 7-layer composite system.

Clearly the yarn fibers are stretched more at a particular instant during penetration for each of the 7 layers in the absence of matrix and are stretched the least when the matrix is bonded to the yarn. The curves remain essentially flat for composite systems containing matrix as compared to yarn systems without matrix. This essentially implies that very few yarns have been engaged and damaged for the composite system made up of only yarn as compared to composite systems containing the yarn and the matrix.

In Fig. 10 we have exhibited fringe plots of the von Mises yield stress in the projectile at $t = 100$ μs for an initial impact velocity of 450 m/s. It is clear that the projectile impacting the composite system containing the stiffer matrix experiences the most damage while the projectile impacting only yarns the least. When the projectile impacts the composite system made of only yarns, there is a possibility of the yarns to slide and not fully engage with the projectile thereby facilitating the passage of the penetrator into the target. The matrix perfectly bonded to the yarns constrains their sliding, forcing more yarns to engage with the projectile and deforming the projectile. Severe deformations of the projectile consume some of its KE thus less of it is available for deforming the target. In order to quantify this damage we have plotted in Fig. 11 the sum of the internal energy and the kinetic energy of elements deleted from the analysis. These results evince that the KE of the projectile used to erode the penetrator material is the most for the composite containing stiff matrix and the least for the composite system containing only yarn.

4. Conclusions

We have studied deformations of a clamped woven fabric rectangular laminate impacted at normal incidence by a full metal jacket projectile and considered the effect of the matrix strength and the bonding of the matrix to the yarn on the impact response of the plate; it is a surrogate model of the body armor. It is found that the presence of matrix significantly influences the ballistic performance of body armors. The addition of polymer perfectly bonding yarns prevents their full stretching to the limiting value before failure. The weaker the adhesion between the matrix and the yarn the more the yarns can stretch before failure. However, the coupling and constraining effect the matrix has on yarns outweighs the loss in flexibility for the two cases considered and improves the performance of the body armor by reducing the maximum deflection. The comparison of results for stiff and soft polymers suggests that the stiffer polymer enables the system to absorb more of the kinetic energy of the projectile. Results presented herein also suggest that the size of the deformed area is not a good indicator of the energy absorbed during impact.

Here the matrix was assumed to be either perfectly bonded or not bonded at all to the yarns and effects of debonding between the two have not been studied. The consideration of debonding and the consequent redistribution of stresses will provide a more realistic analysis of the problem.

We have assumed that the matrix and the fiber instantaneously fail once the pertinent failure criteria have been satisfied. A more realistic approach is to assume that the damage initiates when a failure criterion has been met and then progressively degrade material properties till failure. Several researchers including [36–39] and works cited therein have followed this approach.

Acknowledgments

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