



**Yarn Pull-Out as a Mechanism for Dissipation of Ballistic
Impact Energy in Kevlar KM-2 Fabric, Part II: Prediction
of Ballistic Performance**

**by John E. Kirkwood, Keith M. Kirkwood, Young Sil Lee,
Ronald G. Egres Jr., Eric D. Wetzel, and Norman J. Wagner**

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May 2004

prepared by

**Department of Chemical Engineering
Center for Composite Materials
University of Delaware
Newark, DE**

under contract

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14. ABSTRACT The energy absorbed in ballistic fabrics is modeled by assuming yarn pull-out, including yarn uncrimping and translation, as the primary energy absorption mechanism. Using a semi-empirical model of yarn pull-out based on laboratory tests, predictions for ballistic performance of fabrics are compared to ballistic test results. It is demonstrated that quasi-static pull-out results can be correlated quantitatively with yarn pull-out during ballistic impact.					
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1. Introduction

Woven fabrics made from high-strength fibers, such as Kevlar,^{*} Zylon,[†] Armos,[‡] and Spectra,[§] have been widely used in flexible armors such as ballistic vests and bomb blankets, or within rigid structures such as helmets (Cheeseman and Bogetti, 2003; Billon and Robinson, 2001). These fabrics consist of woven, intersecting yarns, each yarn being composed of several hundred individual fibers.

At high velocities, ballistic damage in fabric armors occurs through localized fabric loading and yarn uncrimping, followed by fiber plastic deformation and fracture (Cheeseman and Bogetti, 2003; Shim et al., 1995; Lim et al., 2002). At lower velocities, however, fabric damage is dominated by yarn uncrimping and translation (Cheeseman and Bogetti, 2003; Shim et al., 1995), which we refer to collectively as yarn pull-out (Kirkwood et al., 2003). The likelihood of yarn pull-out also increases for impacts by blunt projectiles, and for impacts near free edges.

Starrat et al. (1999) observed yarn pull-out during non-perforating impacts of right cylindrical projectiles into Kevlar fabrics with two unclamped edges. Bazhenov (1997) noted both yarn uncrimping and translation in ballistically impacted, unclamped Armos fabrics, with extensive yarn uncrimping zones apparent even for perforating impacts. Shockey et al. (2001) observed yarn pull-out during low velocity (< 300 m/s) impacts of Zylon fabrics, especially when at least two boundaries were unclamped, when impact occurred near the edge of a target, or when a blunt projectile was used. It is also worth noting that yarn pull-out mechanisms will likely dominate material layers near the back face of multilayer targets, even at high impact velocities, if the projectile is successfully defeated by the armor.

Although yarn pull-out has been regularly observed in ballistically impacted fabrics, there is no clear consensus on the precise role of pull-out mechanisms on the energy absorption process. Bazhenov (1997) noted a correlation between the extent of pull-out in a given fabric layer and the amount of energy absorbed by that layer. However, this correlation only indicates that energy absorption increases when more yarns participate in a ballistic defeat process and does not necessarily indicate that pull-out itself is a significant energy absorbing mechanism. Both Bazhenov (1997) and Shockey et al. (2001) performed quasi-static yarn pull-out experiments to quantify energy absorption during yarn pull-out, but did not attempt to quantitatively link these laboratory results to ballistic tests. Starrat et al. (1999) used a combination of continuous

^{*} Kevlar is a registered trademark of DuPont.

[†] Zylon is a registered trademark of Toyobo.

[‡] Armos is a registered trademark of Kamenskvolokno JSC.

[§] Spectra is a registered trademark of Honeywell.

velocity measurements and high-speed photography to conclude that, under nonpenetrating conditions, significant energy was being absorbed during the yarn pull-out process.

The importance of yarn pull-out mechanisms can also be inferred by studies on surface modifications to ballistic fabrics. Briscoe and Motamedi (1992) showed that the ballistic performance of woven Kevlar fabrics with various surface treatments correlated well with measured yarn-yarn frictional coefficients. It is well known that the ballistic resistance of fabrics decreases when they are wet, as demonstrated by Bazhenov (1997). And the addition of frictional agents such as dilatant powders (Dischler et al., 1998) and shear thickening fluids (Lee et al., 2003) has been shown to enhance fabric ballistic performance. These results, however, do not clearly demonstrate whether these frictional effects are most directly influencing filament-filament, yarn-yarn, ply-ply, or fabric-projectile interactions. Furthermore, it is again not clear whether the frictional mechanisms themselves are absorbing significant projectile energy, or whether they simply influence more global fabric response.

Further insight into yarn-yarn interactions can be elucidated by numerical simulations of the ballistic process. Most of these simulations use a simple linear elastic model, or multi-layer membrane model, with damage accumulation (Billon and Robinson, 2001; Johnson et al., 1999; Lim et al., 2003; Roylance et al., 1973), and therefore do not explicitly model yarn-yarn interactions. Some recent efforts have attempted to address the woven fabric architecture directly. Shockey et al. (2001, 2002) modeled a plain-woven Zylon fabric, but assumed frictionless interactions and reported only limited results. Duan et al. (2003) has modeled single-layer woven fabrics with interyarn friction and found that frictional interactions between yarns play a crucial role in determining fabric ballistic performance. Although the specific contributions of yarn pull-out energy absorption have not yet been systematically explored, this modeling approach should be capable of performing such studies in detail.

In this report, ballistic tests are performed to directly determine whether yarn pull-out can act as a significant energy absorption mechanism in woven fabrics. Tests are performed at low velocities on unclamped Kevlar fabrics of small dimensions. Under these conditions, yarn fracture does not occur and is therefore not an operable energy absorption mechanism. Although these ballistic experiments are biased towards producing yarn pull-out behavior, they should also provide practical insight into the behavior near the edges or seams of larger fabric structures such as ballistic vests, or for structures composed of thin strips of fabric, such as ballistic helmets.

The contribution of yarn pull-out to energy absorption will be quantified by measuring the extent of yarn pull-out in the impacted fabrics and then utilizing the quasi-static yarn pull-out model derived in Part I of this series (Kirkwood et al., 2003). Comparing these values with the total ballistic energy dissipated in the fabric provides a measure of the relative importance of the yarn pull-out energy, including yarn uncrimping and translation, to the overall defeat of the projectile.

The model equation developed for yarn pull-out in plain-woven, 180 g/m², 600-denier Kevlar KM-2 fabric, can be summarized as follows (Kirkwood et al., 2003). The energy E_{PO} required to

pull the ends of N yarns a distance x within a fabric of length L , under transverse tension T , is given by

$$E_{PO} = F_p \cdot (x - X_p) - \frac{F_p \cdot (x - X_p)^{K+1}}{(K+1) \cdot (L - X_p)^K} + \frac{F_p \cdot X_p}{M+1} \quad \text{for } X_p \leq x \leq L, \quad (1)$$

where X_p , F_p , K , and M are functions of N , L , and T through the relations

$$F_p = (d_1 + d_2 \cdot N)(a_1 + a_2 \cdot L + a_3 \cdot T + a_4 \cdot L \cdot T), \quad (2)$$

$$X_p = (e_1 + e_2 \cdot N)(b_1 + b_2 \cdot L + b_3 \cdot T + b_4 \cdot L \cdot T), \quad (3)$$

$$K = f_1 + f_2 \cdot L, \quad (4)$$

and

$$M = c_1 + c_2 \cdot L + c_3 \cdot T + c_4 \cdot L \cdot T. \quad (5)$$

The constants a_1 – f_2 , whose values are given in table 1, were found by fitting a series of experimental pull-out curves. F_p represents the maximum force observed during a pull-out experiment, and X_p is the displacement at which F_p is achieved. The peak force is reached as the yarn becomes fully uncrimped along its length, after which the entire yarn begins to translate through the fabric. Significant energy is absorbed during both the yarn uncrimping and yarn translation stages.

To use this model with our ballistic experiments, the fabric length L , number of yarns pulled N , and distance of pull-out x , are directly measured for each layer in the Kevlar targets after impact. The tension T is an unknown parameter and is thought to develop during impact of the unclamped fabrics through momentum effects. The estimation of this tension value will be addressed during the analysis of the ballistic results.

2. Experimental

2.1 Kevlar Fabric

The Kevlar fabric used is plain-woven Hexcel Aramid Style 706 (Kevlar KM-2, 600 denier), a high-performance fabric intended for ballistic protection applications. This fabric has 13.386 yarns per centimeter (warp and weft) and an areal density of 180 g/m².

2.2 Quasi-Static Yarn Pull-Out Experiments

The yarn pull-out observed during ballistic experiments differs from the yarn pull-out experiments performed in Part I (Kirkwood et al., 2003) in two fundamental ways. First, yarn pull-out during ballistic impact originates from the center of the fabric, while the pull-out

Table 1. Fitting constants for pull-out model from Kirkwood et al. (2003).

Constant	Value	Units
a_1	4.399	N
a_2	58.25	$\text{N}\cdot\text{m}^{-1}$
a_3	8.164×10^3	—
a_4	0.3370	m^{-1}
b_1	3.685×10^3	m
b_2	0.0436	—
b_3	-3.951×10^6	$\text{m}\cdot\text{N}^{-1}$
b_4	5.514×10^5	N^{-1}
c_1	0.8783	—
c_2	-1.231	m^{-1}
c_3	5.100×10^4	N^{-1}
c_4	-3.973×10^4	$\text{m}^{-1}\cdot\text{N}^{-1}$
d_1	-1.038	—
d_2	1.978	—
e_1	0.4923	—
e_2	0.4969	—
f_1	0.3252	—
f_2	1.400	m^{-1}

experiments from Part I pulled yarns from the edge of the fabric. To determine the significance of this distinction, quasi-static pull-out experiments are performed using center-pulled yarns, and compared to previous edge-pulled yarns under similar conditions. The second difference is the speed of yarn pull-out because the quasi-static experiments pull yarns at rates much slower than those encountered during ballistic impact. To partly address this effect, pull-out experiments are performed and compared over a range of quasi-static velocities.

To determine the effect of center-pulling vs. edge-pulling, the pull-out apparatus from Part I was modified to pull the yarn from the center of a rectangular target (figure 1). The fabric clamping frame provides transverse tension to the fabric and is mounted perpendicular to the crosshead of the Instron model 4206 universal testing machine. A single yarn is removed from the center of the fabric, along the tension direction, and a wire in the shape of the letter “V” is threaded through this gap under a yarn oriented in the nontensioned direction. The wire is then clamped by the upper grip of the testing machine and pulled. The yarn pulls out from both unclamped edges simultaneously, simulating a projectile pulling the yarns. Center-pulled experiments were performed for a range of sample lengths (3.81–5.08 cm), cross-tension values (250–500 N), and number of yarns pulled (1–8). Only yarn uncrimping energy (up to the peak load value) is

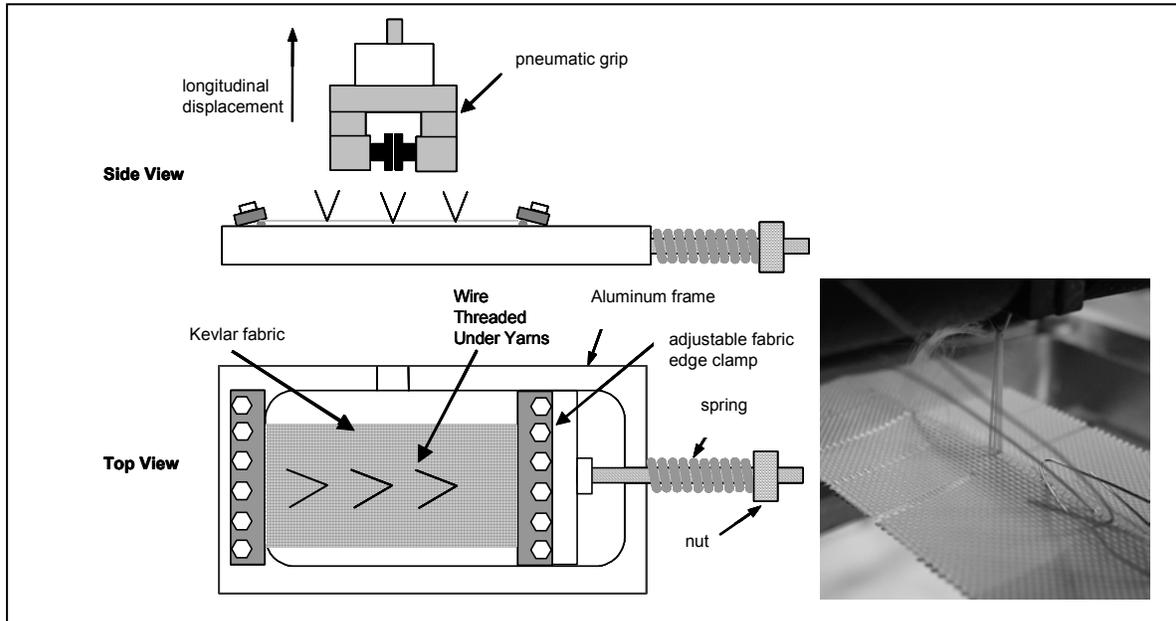


Figure 1. Experimental setup for center pull-out tests.

reported. Pull-out energy during yarn translation (after the peak load value is reached) proved difficult to measure because in most cases one half of the yarn would pull free from the fabric while the other remained in the bulk fabric.

To determine the effect of pull-out velocity, edge-pulled experiments were performed at rates of and 500 mm/min, over a range of sample lengths, cross-tension values, and number of yarns pulled.

2.3 Ballistic Experiments

Ballistic tests were performed according to the procedure described in Lee et al. (2003). Kevlar layers were cut into square pieces 5.08×5.08 cm, and stacked according to the number of layers required for each target. These Kevlar layers were encapsulated in heat-sealed polyethylene film, and further packaged between layers of 50- μ m aluminum foil. The full target stack was then mounted in an aluminum frame and held in place with light pressure from spring clips. Table 2 shows the list of targets, which ranged from 5 to 18 layers of fabric.

Ballistic tests were performed using a smooth-bore helium gas gun at room temperature. The impact velocity V_i of each projectile was measured with a chronograph positioned immediately in front of the target, and ranged between 244 and 265 m/s. The projectile is a standard chisel-nose North Atlantic Treaty Organization fragmentation simulation projectile (FSP) consisting of a metal cylinder with mass m_p of 1.1 g (17 grains), a diameter of 0.56 cm (0.22 cal.), and a presented area A_p of 24.63 mm² (Jacobs and Van Dingenen, 2001). A clay witness was used to determine target ballistic performance, with depth of penetration D used to estimate residual velocity of the projectile V_r through the empirical relation (Lee et al., 2003).

$$V_r = 38.9 + 3720D . \quad (6)$$

Table 2. Summary of ballistic data.

Number of Layers	Mass of Kevlar (g)	Initial Velocity V_i (m/s)	Initial Energy E_i (J)	Depth of Penetration (m)	Residual Velocity V_r (m/s)	Absorbed Energy (J)	Energy Dissipated (%)
5	2.35	246	37.8	0.0184	107.43	26.89	80.9
6	2.82	251	34.6	0.0178	105	28.5	82.4
6	2.82	249	34.1	0.0183	107	27.7	81.5
7	3.29	248	33.9	0.0164	105	33.86	82.1
7	3.29	249	34.2	0.0178	99.87	28.7	84
9	4.23	248	33.9	0.0136	89.5	29.5	87
9	4.23	251	34.6	0.0145	92.8	29.8	86.3
12	5.64	247	33.7	0.0112	80.51	30.04	89.4
12	5.64	265	38.7	0.0123	84.57	34.77	89.8
15	7.05	261	37.5	0.0103	77.29	34.18	91.2
16	7.52	250	34.4	0.0099	75.88	31.21	90.8
18	8.46	244	32.7	0.0087	71.44	29.88	91.4

The dissipated projectile kinetic energy E is then estimated by

$$E = \frac{1}{2} m_p (V_i^2 - V_r^2) . \quad (7)$$

We assume that this energy E is the total energy absorbed by the fabric target during ballistic impact.

Following ballistic testing, each target was inspected to determine the extent of yarn pull-out. Yarn pull-out was evident at the edges of the fabric, with the number of yarns pulled and the distance of translation per yarn recorded. The complete data are catalogued in the appendix. Figure 2 shows a typical post-impact fabric layer, with a close-up of one particular fabric edge. Along this edge, two yarns are pulled a distance of 3 cross-yarns, and four yarns are pulled a distance of 5 cross-yarns (notated as “2:3, 4:5” in the appendix).

Determining the extent of yarn pull-out is not always straightforward because it relies on visual inspection and evaluation of the fabric. In some cases, yarns parallel to an edge are ejected by the ballistic impact (Duan et al., 2003; Shockey et al., 2002), exposing the ends of cross-yarns. These “pull-outs” are neglected because the edge is only lightly constrained and the total absorbed energy by this yarn ejection is insignificant. Also note that the yarns which have translated within the fabric appear different visually than neighboring, unpulled yarns, likely due to localized yarn cross-sectional compression or uncrimping.

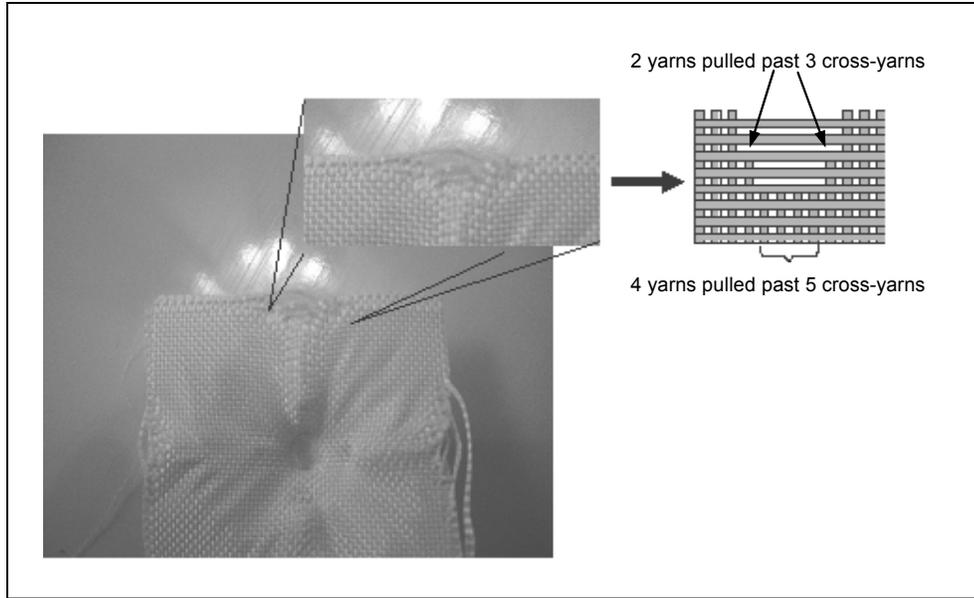


Figure 2. Photograph of yarn pull-out at the edge of a typical fabric layer, and schematic of the yarn pull-out counting methodology.

3. Results

3.1 Quasi-Static Yarn Pull-Out Experiments

Figure 3 shows the pull-out force as a function of crosshead displacement for center pull experiments, for a 5.08-cm-long fabric sample at 500 N of transverse tension and one, two, and four yarns pulled. Also shown are predicted pull-out curves for 2.54-cm-long fabric samples at 250 N, based on the model of Part I (Kirkwood et al., 2003), with the predicted force values multiplied by 2. It should be noted that the larger displacement at peak load (X_p [Kirkwood et al., 2003]) for the center pull-out experiments is the result of out-of-plane stretching of the fabric during the pull-out experiment, but the final displacement is equivalent to model predictions. Figure 4 also compares the yarn uncrimping energy for these cases. For both the force-displacement and uncrimping energy data, the agreement between the experimental and predicted data is reasonable. This agreement implies that each half of a center-pulled yarn acts independently, like an edge-pulled specimen of length $L/2$ and tension $T/2$. Also note that in a center-pull experiment, the crosshead displacement is roughly equal to the translation distance of each half-yarn within the fabric.

Figure 5 shows the effect of pull-out speed on pull-out behavior. At higher pull-out speeds, the uncrimping load curve exhibits more noticeable sublinear growth with displacement and exhibits a higher peak force value. The yarn translation portion of the curve (after peak load) appears smoother at higher pull rates, but we believe that this behavior is an artifact caused by data

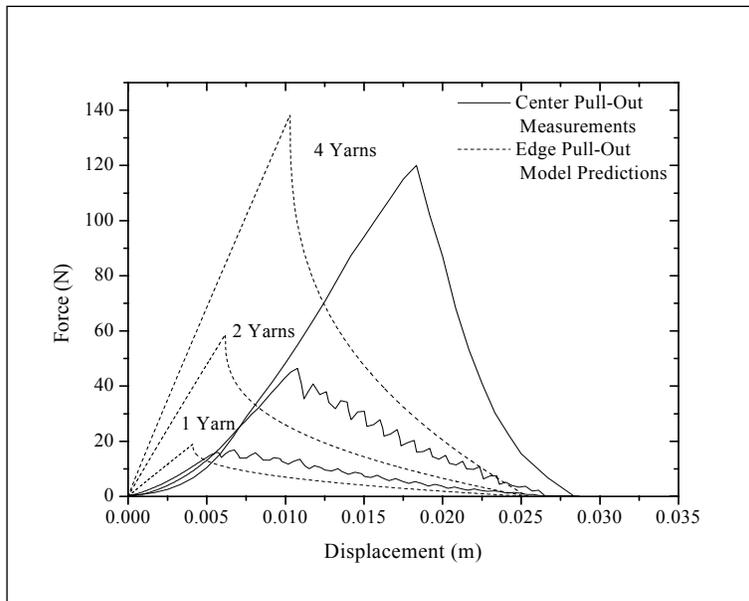


Figure 3. Force-displacement curves for center pull-out and edge pull-out geometries. The center pull-out data are for 5.08-cm samples at a tension of 500 N, and were measured experimentally. The edge pull-out data are for a 2.54-cm sample at a tension of 250 N, generated using the model of (Kirkwood et al., 2003), with the predicted force values multiplied by a factor of 2.

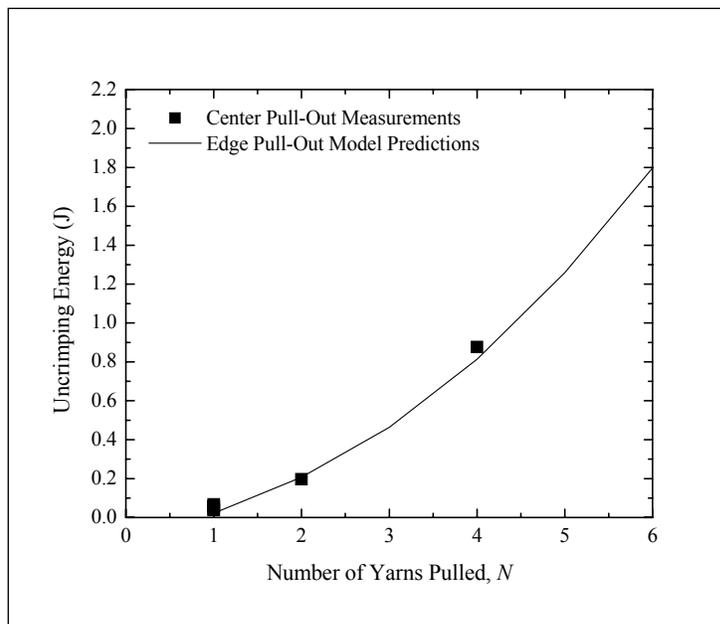


Figure 4. Uncrimping energy values for center pull-out and edge pull-out geometries. The center pull-out data are for 5.08-cm samples at a tension of 500 N, and were measured experimentally. The edge pull-out data are for a 2.54-cm sample at a tension of 250 N, generated using the model from Kirkwood et al. (2003), based on multiplying the predicted force values by a factor of 2.

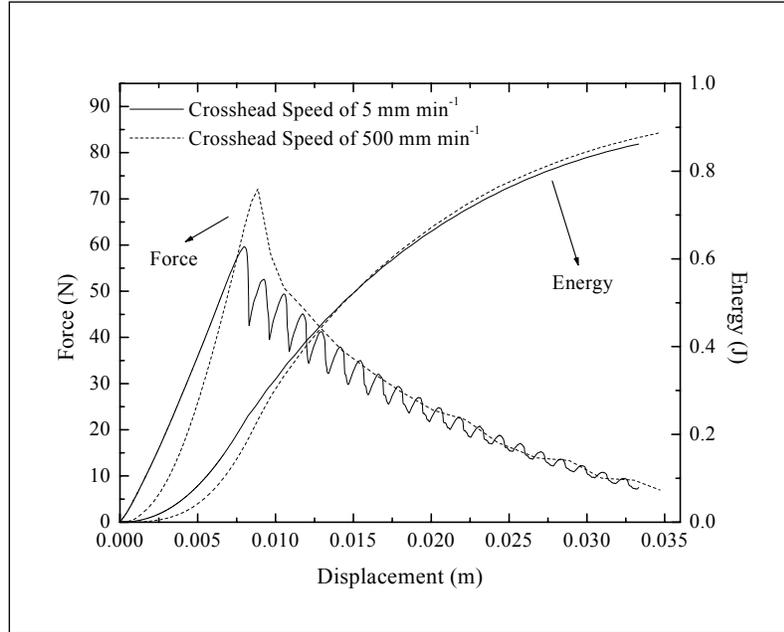


Figure 5. Effect of crosshead speed on the force-displacement and energy-displacement curves during edge pull-out experiments.

sampling rate. In spite of these differences, the energy-displacement curves (figure 5) are relatively insensitive to pull speed. This equivalence was noted for all pull-out speed comparisons, regardless of sample size or tension. Although our maximum pull-out speed (500 mm/min) is well below expected ballistic pull-out speeds ($\sim V_i = 10^6$ mm/min), these results provide some confidence that quasi-static pull-out tests are representative of ballistic pull-out behavior.

3.2 Ballistic Experiments

Table 2 compares the ballistic performance of the various targets. In general, as the number of layers increases, the depth of penetration decreases and the percent of the total energy dissipated increases (figure 6). The total energy dissipated approaches the limiting value of 100% as the number of layers increases. Also shown in figure 6 is the energy absorbed per layer. Because the projectile's initial velocity, and therefore initial kinetic energy, is relatively constant, the energy absorbed per layer necessarily decreases as the number of layers increases.

Post-impact visual inspection of the targets revealed indentations on the Kevlar layers consistent with previously reported findings (Bazhenov, 1997; Dent and Donovan, 1986; Starratt et al., 1999; Walker, 1999), displaying both a pyramid-shaped deformation cone (figure 7) and a cross-shaped pull-out pattern (figure 8) in most layers of each target. The deformation cone results from localized fiber stretching, yarn compaction and uncrimping, and fabric wrinkling, with the pyramidal facets due to the orthogonal nature of a plain-woven fabric. The cross-shaped pull-out pattern is centered on the projectile's impact point, where yarns can be directly grabbed and

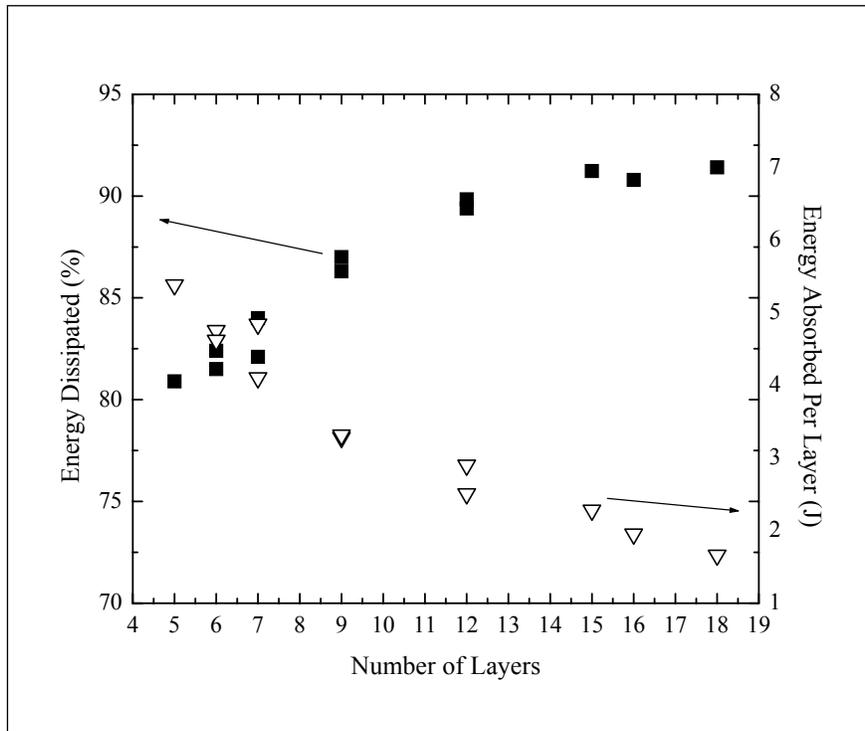


Figure 6. Measured percent energy dissipation, and energy absorbed per fabric layer, for ballistic experiments.

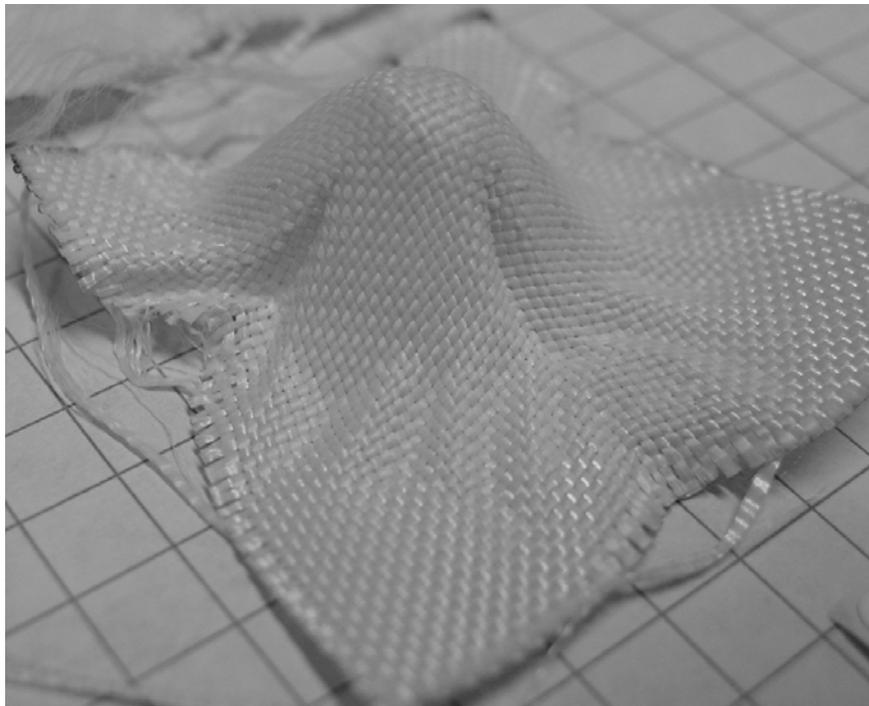


Figure 7. Photograph of typical pyramid deformation cone resulting from ballistic impact.

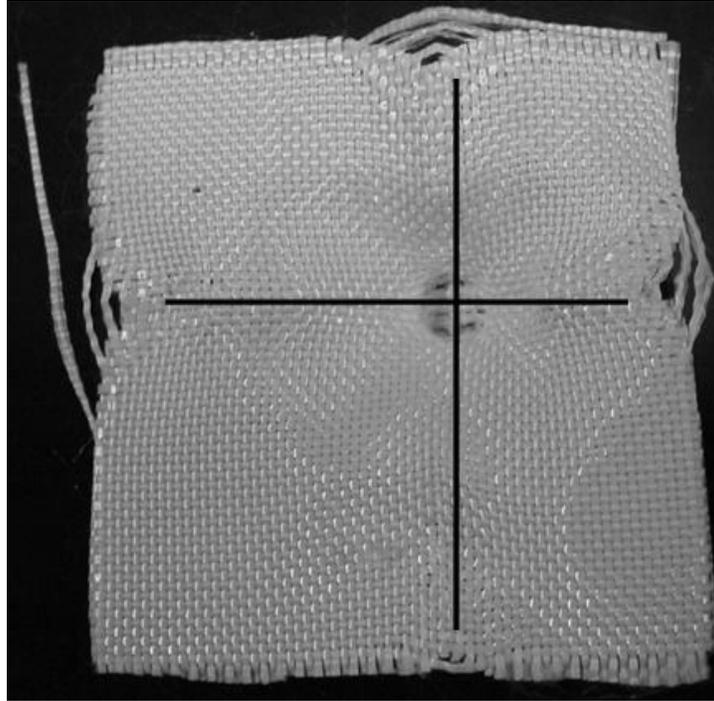


Figure 8. Photograph of yarn pull-out cross pattern resulting from ballistic impact.

pulled by the projectile. Figure 9 shows the first, ninth, and last layers of an 18-layer target, where the impact face is layer 1 of the target. As the layer number increases, the deformation cone widens and the extent of yarn pull-out decreases. These trends also generally hold true for targets with fewer fabric layers. However, as the number of fabric layers decreases, the extent of yarn pull-out and the size of the deformation cone increase.

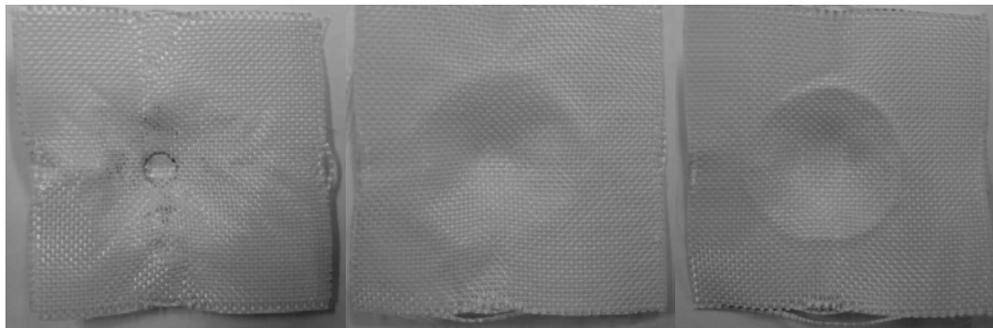


Figure 9. 1st, 9th, and 18th layer of 18-layer target showing variation of fabric deformation through the thickness of the target.

These trends are also evident in the measured extent of yarn pull-out in each layer. Figure 10 shows the average number of yarns pulled per edge, defined as the total number of yarns pulled per layer divided by 4, as a function of layer number for targets of 5, 7, and 18 layers. The data are separated into yarns pulled past at least one cross-yarn and yarns pulled past at least three

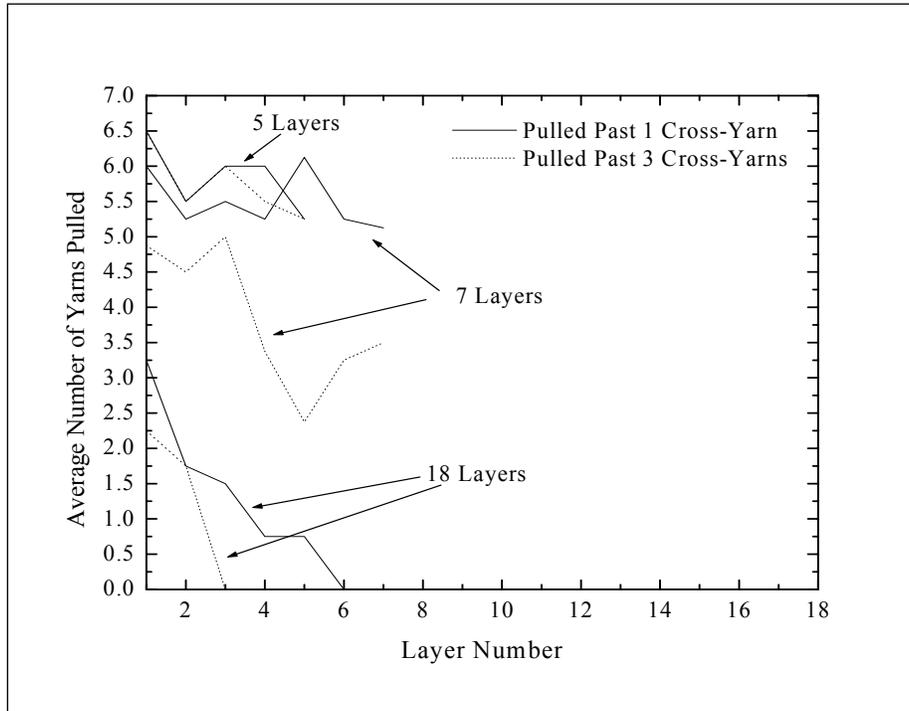


Figure 10. Average number of yarns, per edge, pulled past at least 1 and 3 cross-yarns for 5-, 7-, and 18-layer targets as a function of layer number.

cross-yarns. In general, fewer yarns are pulled per layer as the layer number increases, indicating that pull-out is most likely near the impacted face of the target. The number of pulled yarns also decreases as the total number of layers increases because more layers are able to participate in the energy absorption process. Also note that most of the yarns pulled for the 5-layer specimen were pulled past at least 3 cross-yarns, while for 7- and 18-fabric layers the number of yarns pulled past at least 3 cross-yarns decreases dramatically. This result is a consequence of the decrease in extent of yarn pull-out with increasing total number of layers in the target. In fact, for the 18 layer target, no yarn pull-out was observed for layers 6–18.

4. Analysis

The ballistic energy absorbed by the targets has been estimated in table 2 based on the depth of penetration in clay. In this section, the observed changes to the fabric layers are used to account for this absorbed ballistic energy, through implementation of the model from Part I (Kirkwood et al., 2003).

4.1 Energy Balance

We assume that the fabric absorbs energy through a combination of yarn failure, pull-out, and friction, where yarn failure includes plastic deformation and fracture energies, while yarn pull-out includes yarn uncrimping and yarn translation:

$$E_{absorbed} = E_{yarn\ pull-out} + E_{failure} + E_{friction} = E_{uncrimping} + E_{translation} + E_{plastic} + E_{fracture} + E_{friction} \cdot \quad (8)$$

Frictional energy includes the effect of projectile-fabric friction and interply friction. No yarn fracture was observed in any of the experiments, so we can neglect yarn fracture energy. To determine the possible contribution of yarn plastic deformation, the energy of yarn deformation for Kevlar KM-2 was determined through static load testing using a procedure outlined in Zee and Hsieh (1998). The available yarn deformation energy per length of yarn was measured to be 1 J/m. Since the projectile diameter corresponds to ~ 6 yarn widths, a total of roughly 12 yarns are impacted and pulled per layer. For N layers of 5.08-cm square targets, the total yarn deformation energy available is $N \times 12 \times 5.08 \text{ cm} \times 1 \text{ J/m} = \sim 0.6 \text{ J/layer}$. For the maximum number of layers tested, 18 layers, yarn deformation would therefore only account for $\sim 11 \text{ J}$, only a fraction of the impact ballistic energy of 30 J. More realistically, if yarn deformation is expected to occur only within the impact zone, only 0.45 cm (6-yarn widths) of each yarn could be deformed, which reduces the total yarn deformation energy to $\sim 1 \text{ J}$ for 18 layers. Based on these estimates, yarn deformation is unlikely to account for a majority of the energy absorption during a non-perforating ballistic experiment.

Assuming there is little motion of the projectile relative to the fabric, and the fabric layers relative to each other, we can neglect the effects of friction between the projectile and the fabric and between fabric layers (Billon and Robinson, 2001; Cunniff and Ting, 1999). Therefore, in order to satisfy the energy balance of equation 4, yarn pull-out (both uncrimping and translation) must account for a majority of the absorbed ballistic energy.

4.2 Estimation of Fabric Tension During Ballistic Impact

In order to estimate the yarn pull-out energy for the ballistic targets, we will implement the model of Part I (Kirkwood et al., 2003) using the measured yarn pull-out data from the ballistic experiments (appendix). Implementation of this model requires sample length L , transverse tension T , pull-out distance x , and number of yarns pulled N . Based on the quasi-static yarn center pull-out experiments, we know that it is reasonable to treat the pull-out from each edge independently, assuming a sample length of $L = 2.54 \text{ cm}$ (half of the overall target dimension). The number of yarns pulled is catalogued in the ballistic data (appendix), although some interpretation is necessary. For the example of figure 2, $N = 6$ yarns are treated as pulled a distance of 3 cross-yarns (or $x = 2.24 \text{ mm}$), and $N = 4$ of these yarns are counted as further pulled to 5 cross-yarns (or from $x = 2.24$ to $x = 3.73 \text{ mm}$). The ballistic data also tabulate the total yarn translation distance, which is equal to the model yarn pull-out distance x minus a characteristic

uncrimping distance X_p (Kirkwood et al., 2003). Unfortunately, we are unable to observe yarns, which are partially or fully uncrimped, but do not undergo translation (pull-out distance $x < X_p$).

The remaining model variable is the transverse tension T . The fabric is unclamped, but it is expected that momentum effects result in an effective transverse loading on the fabric. Before attempting to estimate this tension value from first principles, we can calculate the tension required in order for yarn pull-out energy, as estimated by the model, to account for all of the ballistic energy absorbed by the target. These hypothetical tension values were found by iteratively calculating total yarn pull-out energies for each target for different tensions, until the energy predicted by the model matched the measured absorbed ballistic energy for that target. For these calculations, we assume that the tensions in each layer of the target are equal.

Table 3 shows the resulting ideal tension values for each target. Except for the targets with the greatest numbers of layers, the tension values are on the order of ~ 1000 N.

Table 3. Total number of yarns pulled for all edges of the ballistic targets, and theoretical tension values for implementation of yarn pull-out model.

Number of Layers	Total Number of Yarns Pulled	Theoretical Tension Required (N)	Theoretical Tension Required With 20% Uncrimping (N)	Theoretical Tension Required With 40% Uncrimping (N)
5	117	529	529	529
6	142	481	481	481
6	150	309	309	309
7	154	319	306	294
7	154	399	399	399
9	150	754	635	530
9	195	260	234	210
12	169	605	419	268
12	119	953	686	478
15	104	1518	821	410
16	64	2610	1153	503
18	32	6317	1646	558

To demonstrate that these tension values are reasonable, we will assume that fabric tension is due to acceleration forces on fabric (Billon and Robinson, 2001; Roylance et al., 1995). The mass of a single layer of fabric is 0.47 g, and the target is accelerated from rest to the projectile velocity (~ 244 m/s) over some characteristic time scale. We will estimate this time scale to be the diameter of the projectile (0.56 cm) normalized by the projectile velocity, which gives a value of ~ 23 μ s. The acceleration force is then $F_{acc} = ma \approx m\Delta v/\Delta t = (0.47 \text{ g} \cdot 244 \text{ m/s}) / 23 \text{ } \mu\text{s} = \sim 5000$ N. This simple estimate of tension is comparable to the values given in table 3, which verifies that the model provides a reasonable representation of yarn pull-out under ballistic conditions.

Note that the hypothetical tension values increase with increasing number of fabric layers. There are two reasonable explanations for this trend. As the number of fabric layers increases, the effective stiffness of the target increases. This stiffness reduces the acceleration distance of the target, which increases momentum forces, and therefore tension, in the fabric. A second possible explanation for the increase in tension with number of layers is that we are unable to measure yarn uncrimping without translation. This mechanism of energy absorption could be more significant for the thicker targets, which then require less yarn translation per layer than thinner targets. Because this uncrimping energy is not accounted for in our experimental measurements, artificially high tension values are required for the observed translations to account for the total absorbed ballistic energy.

To show the potential significance of this uncrimping effect, we will assume that all fabric edges which did not exhibit pull-out were instead partially uncrimped, with the energy absorbed for these fabric edges corresponding to some fixed percentage of the available yarn uncrimping energy (pull-out energy up to $x = X_p$, see [Kirkwood et al., 2003]). This fixed percentage is called the “uncrimping factor,” and is assumed to act on six yarns on each fabric edge. Table 3 shows the theoretical tension values required for uncrimping factors of 20% and 40%, in order for the total theoretical energy absorption to match the experimentally measured energy absorption. The tension values for the low fabric layer number targets remain unchanged because translation was observed for every edge of each fabric layer. As the number of fabric layers increases, fewer layers exhibited yarn translation, so the uncrimping factor effect becomes more significant. The energy contributions of these uncrimped yarns decrease the required fabric tension for the target. Note that at 40% loading, the amount of tension required is relatively insensitive to the number of fabric layers, and has a value of between ~200 and 500 N.

Taking advantage of this latter result, if we assume a constant tension of 414 N (the average theoretical tension value for all targets) and an uncrimping factor of 40% for all fabric edges without translation, we can estimate the energy absorbed for each target according to the yarn pull-out model. These theoretical ballistic performance values are compared to the experimental values in figure 11. The agreement between the calculated energy dissipation and measured energy dissipation is encouraging and supports the hypothesis that for these ballistic tests the dominant mechanism of energy absorption is yarn pull-out, including both yarn uncrimping and translation. It is also interesting to note that the scatter in the model predictions is relatively high compared to the ballistic experiments, which show highly repeatable results. This scatter reflects that targets of comparable ballistic performance may exhibit significant variations in the nature and extent of pull-out.

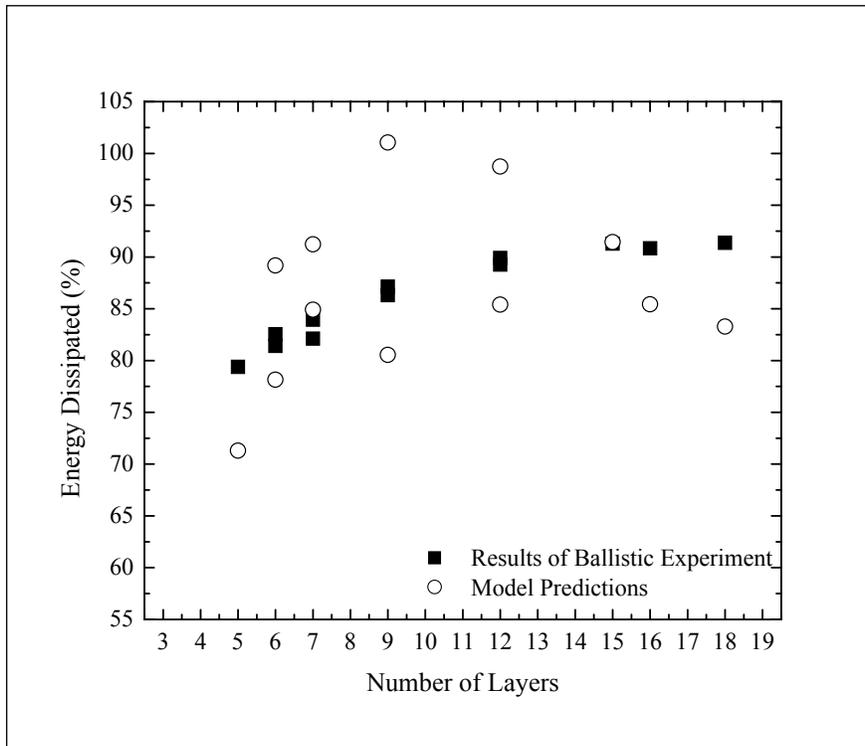


Figure 11. Comparison of experimental ballistic energy dissipation with predicted ballistic energy dissipation based on the model of by Kirkwood et al. (2003), assuming a tension of 414 N and an uncrimping factor of 40%.

5. Conclusions

The ballistic experiments on neat Kevlar fabric show that projectile defeat can be achieved without yarn fracture. This result implies that yarn uncrimping and yarn translation are significant mechanisms of energy absorption for our testing conditions, which include small target sizes (5.08×5.08 cm), relatively low impact velocities (244 m/s), and unclamped fabric edges. Yarn translation is most prevalent for targets with fewer fabric layers, with yarn uncrimping becoming more significant as the number of fabric layers increases. Further testing is required to demonstrate the relative importance of yarn translation and uncrimping for larger target sizes or higher projectile velocities, conditions which tend to increase fabric tension during impact and would likely decrease the probability of yarn translation.

The quasi-static yarn pull-out model from Part I (Kirkwood et al., 2003) is shown to provide physically reasonable values for energy absorption during the ballistic impact of Kevlar fabrics. However, our ability to quantitatively verify the accuracy of this modeling approach is limited by our inability to directly observe yarn uncrimping in impacted targets, restricting our measurements to yarn translation only. Furthermore, the utility of the model for predicting

ballistic performance of fabrics *a priori* is limited by our lack of a rigorous means of calculating impact-induced fabric tension. Further experiments and numerical simulations of ballistic impact of fabrics are required to provide guidance for more accurate estimations of fabric loading and tension effects.

The experimental conditions used in this study resulted in fabric damage dominated by yarn uncrimping and translation. In contrast, conditions of higher velocities, larger targets, and clamped edges will most likely result in extensive yarn plastic deformation and fracture, without significant yarn translation. However, these conditions do often lead to significant zones of yarn uncrimping, which can be effectively modeled using the initial portion of the yarn pull-out model presented here. In fact, this model may be capable of predicting the onset of yarn fracture, when the calculated peak pull-out force value exceeds the fracture strength of the yarn.

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Appendix. Ballistic Yarn Pull-Out Data

Database of observed yarn pull-out for ballistically impacted Kevlar targets. The impact face of the target is the first layer. The data is presented with the notation $n : X$, where n is the number of yarns pulled, and X is the distance, in cross-yarns, the yarns have been pulled through the fabric). The quantitative pull-out distance p can be calculated by multiplying the number X by the yarn width, ~ 0.746 mm. Each edge on each layer is treated individually. Note that n in this table is not directly equivalent to N in the model implementation (see discussion in section 4 of report).

Table A-1. Ballistic yarn pull-out data.

Total No. of Layers in Target	Edge	Layer Number (Impact Face Is 1st Layer of Target)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
5	1	2:3, 4:5	2:3, 5:4	1:3, 4:5	3:3	3:4	—	—	—	—	—	—	—	—	—	—	—	—	—
	2	7:4	4:5	3:4, 4:5	7:3	6:4	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	1:5, 5:6	2:4, 4:5	2:4, 5:5	2:2, 5:3	6:3	—	—	—	—	—	—	—	—	—	—	—	—	—
	4	7:7	5:7	5:6	2:3, 5:4	1:5, 5:6	—	—	—	—	—	—	—	—	—	—	—	—	—
6	1	1:3, 6:4	3:2, 5:4	6:3	1:2, 4:3	6:2	4:2	—	—	—	—	—	—	—	—	—	—	—	—
	2	2:4, 3:6	3:2, 5:4	5:2	5:2	5:1	3:2	—	—	—	—	—	—	—	—	—	—	—	—
	3	2:5, 5:7	3:3, 5:4	2:1, 5:3	6:2	1:1, 5:2	6:1	—	—	—	—	—	—	—	—	—	—	—	—
	4	5:4	2:1, 4:3	1:2, 6:3	6:3	5:1	6:2	—	—	—	—	—	—	—	—	—	—	—	—
6	1	2:4, 5:5	2:3, 2:5, 3:6	2:2, 4:3	5:3	3:1, 4:2	1:1, 5:2	—	—	—	—	—	—	—	—	—	—	—	—
	2	2:3, 2:5, 3:6	2:2, 5:4	5:2	6:2	5:2	1:1, 3:2	—	—	—	—	—	—	—	—	—	—	—	—
	3	1:2, 2:3, 1:4, 4:5	1:1, 5:2	7:3	2:2, 1:3, 1:4, 4:5	7:1	6:3	—	—	—	—	—	—	—	—	—	—	—	—
	4	1:1, 4:3	6:2	1:2, 1:3, 1:4, 1:5, 3:6	6:2	1:4, 3:5, 2:6	2:3, 4:4	—	—	—	—	—	—	—	—	—	—	—	—
7	1	2:6, 3:7	6:2	4:4	1:3, 5:4	4:2, 3:3	8:3	7:3	—	—	—	—	—	—	—	—	—	—	—
	2	7:3	6:4	7:4	6:4	6:3	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	2:2, 4:4	7:5	5:3	3:2	5:2	7:2	6:4	—	—	—	—	—	—	—	—	—	—	—
	4	7:2	3:3	5:3	6:2	8:2	3:3, 2:4	6:2	—	—	—	—	—	—	—	—	—	—	—

Table A-1. Ballistic yarn pull-out data (continued).

Total No. of Layers in Target	Edge	Layer Number (Impact Face Is 1st Layer of Target)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
7	1	6:3	6:3	7:4	5:3	6:3	6:3	5:2	—	—	—	—	—	—	—	—	—	—	—
	2	4:4	5:3	5:3	4:4, 3:5	2:2, 4:3	6:2	6:3	—	—	—	—	—	—	—	—	—	—	—
	3	7:5	1:4, 5:5	3:4, 4:5	3:3	5:2	6:4, 1:5	6:3	—	—	—	—	—	—	—	—	—	—	—
	4	3:3, 3:4	3:4	4:2	6:1	6:2	3:2	2:2, 3:3	—	—	—	—	—	—	—	—	—	—	—
9	1	2:2, 4:3	7:2	5:1	6:1	6:2	7:2	5:2	—	7:2	—	—	—	—	—	—	—	—	—
	2	6:1	5:1	5:1	6:2	5:1	7:2	—	8:1	4:2	—	—	—	—	—	—	—	—	—
	3	1:2, 5:4	5:2	—	—	—	4:1	6:1	6:1	—	—	—	—	—	—	—	—	—	—
	4	5:2	3:2, 4:3	5:1	—	6:1	—	1:1, 4:2	—	—	—	—	—	—	—	—	—	—	—
9	1	2:3, 4:5	7:2	6:2	6:1	6:2	7:2	6:1	—	2:1, 5:2	—	—	—	—	—	—	—	—	—
	2	6:2	3:1	1:1, 5:2	6:2	2:2, 4:3	4:1	4:2, 3:3	6:1	—	—	—	—	—	—	—	—	—	—
	3	1:2, 4:3	7:2	8:2	1:1, 6:2	7:1	6:1	4:1	4:2, 3:4	—	—	—	—	—	—	—	—	—	—
	4	6:2	3:2, 4:3	5:2	—	4:1	7:3	6:1	7:1	7:2	—	—	—	—	—	—	—	—	—
12	1	5:4	4:4	5:3	5:4	6:4	6:4	6:4	4:4	—	—	—	—	—	—	—	—	—	—
	2	2:3, 4:5	7:3	6:4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	4:4	4:3	3:3, 4:5	—	—	6:4	6:5	—	—	—	—	—	—	—	—	—	—	—
	4	2:2, 4:4	6:3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table A-1. Ballistic yarn pull-out data (continued).

Total No. of Layers in Target	Edge	Layer Number (Impact Face Is 1st Layer of Target)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
12	1	4:2	5:1	4:2	6:1	—	—	—	—	—	—	7:1	8:2	—	—	—	—	—	—
	2	6:2	7:2	7:1	—	—	6:2	5:2	8:1	6:2	6:1	—	—	—	—	—	—	—	—
	3	—	2:1, 3:2	5:2	4:1	7:1	—	—	—	—	—	6:1	4:1	—	—	—	—	—	—
	4	7:1	5:1	7:2	6:1	6:1	7:1	7:2	5:1	—	—	—	—	—	—	—	—	—	—
15	1	7:2	—	7:3	7:1	7:1	6:2	8:1	—	—	6:3	7:1	—	—	—	—	—	—	—
	2	—	7:3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	7:3	—	7:2	6:3	6:2	—	—	—	—	5:1	—	—	—	—	—	—	—	—
	4	4:2	7:2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
16	1	4:4, 2:5	2:3, 4:4	—	—	—	7:2	—	8:3	6:3	—	—	—	—	—	—	—	—	—
	2	—	—	4:3	5:2	—	—	—	5:1	—	—	—	—	—	—	—	—	—	—
	3	3:2, 3:3	4:2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	4	—	—	4:3	3:1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18	1	—	—	—	3:2	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2	3:4	3:3	—	—	3:2	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	4:2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	4	1:4, 5:5	4:3	6:2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

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