

NUMERICAL CHARACTERIZATION OF THE EFFECTS OF TRANSVERSE YARN INTERACTION ON TEXTILE BALLISTIC RESPONSE

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June 11, 1998

ABSTRACT

Textile construction is well known for having a significant effect on the ballistic response of fabrics. One possible mechanism for this effect is the change in yarn-yarn interaction with changes in weave geometry. During an impact event, strain waves propagate through both fill and warp yarns. Energy transfer from warp to fill yarns and fill to warp yarns is a phenomenon that has been largely neglected in the field of ballistic modeling. Efforts to date have assumed that yarns are rigidly coupled and have the same stiffness characteristics in the through-thickness direction as they do in the axial direction. A newly developed computer program simulates transverse yarn interaction using an empirically derived model of crossed yarn stiffness. This program also models the complex, out-of-plane geometry of yarns woven into a fabric. These new features allow detailed analysis of fabric behavior including decrimping, a phenomenon that occurs when woven yarns straighten. Results to date indicate that the initial amount of crimping, decrimping, and yarn-yarn interaction has a significant effect on ballistic response models.

KEY WORDS: Modeling, Fabrics, Armor

1. INTRODUCTION

Textiles consisting of materials such as Kevlar and Spectra are used by the military to provide lightweight and flexible personnel armor against ballistic threats. There is an on-going effort to improve these systems, to provide greater protection to personnel as well as to lighten the considerable load that each soldier must carry in the field [Laible, R.C., 1980].

Computer modeling of these systems has shown itself to be a valuable tool in the understanding of how textile armors work and in their improved design. Compared to experimental studies, computer modeling is inexpensive and easy to use to obtain performance predictions of proposed designs. Nevertheless, current techniques of modeling of textiles subjected to ballistic impact are far from providing perfect agreement with experimental studies. The simplicity of these early models has placed limits on their accuracy since they lack sufficient detail to fully model important mechanisms that may affect a system's performance.

A new simulation program has been developed to predict the behavior of multi-layer fabric panels. These programs model the physics of several parameters, which were previously unaccounted for or only partially accounted for. The programs incorporate analytical models developed at the U.S. Army Natick RD&E Center and Vision R.E. of various physical parameters including:

- the interaction and coupling of warp and fill fibers at the cross-over points (crimp)
- the interaction and coupling of multiple layers
- yarn bending
- clamp imperfections
- multiple projectile geometries

Each of these models was tested before being implemented into the full fabric codes with a series of simple programs simulating the behavior of single yarns or pairs of yarns. The results from these simple codes are of some interest in themselves since they provide some insight into the physics of wave propagation in crimped yarns.

This paper describes the full fabric code and several of the individual models focusing on the components accounting for transverse yarn interaction. A number of illustrative examples are also presented and discussed to illustrate the mechanics of both the fabric code and the individual single yarn codes. Because of limitations of space, this discussion is limited to the effects of decrimping and warp/fill coupling on the fabric models.

2. BACKGROUND

2.1 Description of Fabric Code

The code discretizes a quarter fabric panel as a collection of weighted nodes connected by mass-less fiber elements and coupled with springs. A sketch of the modeled system is shown in Figure 1. Each set of elements represents one physical pair of warp and fill fibers. The projectile collision is modeled as an inelastic impact with the mass elements distributed over the cross sectional area of the projectile. The response of each set of fibers and nodes is found by applying simple expressions of impulse-momentum and by adding the contributions from each fiber element to compute the motion of the nodes. The new positions are then used to compute the effective fiber strain and then tension. The time step, Δt , is computed from the time required for a longitudinal wave to travel from one node to the next.

This approach was previously applied to fabric modeling by Roylance [Roylance and Wang, 1981] and is described in detail in a number of papers. A number of sources with further information are listed in the reference list at the end of this paper.

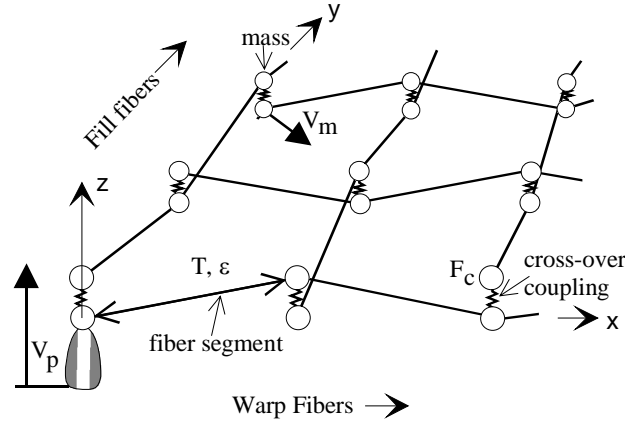


Figure 1: Sketch of model illustrating the breakdown and geometries of the warp and fill fibers. V_p represents the velocity of the projectile. T , ϵ , and F represent the tensions, strains, and forces in each fiber/spring element.

Fiber strains are monitored throughout the entire panel. If the strain anywhere in a panel exceeds the breaking value set in the input file, the associated fiber is flagged as broken and the tensile force in the broken fiber element is set to zero. Adjacent fibers are then forced to carry additional load as the broken fiber unloads. Panel failure is defined as the point at which all of the fibers in contact with the projectile have failed and provide no resisting force against the projectile.

2.2 Decrimping Model

Fiber elements are allowed to be oriented at an angle from the plane of the panel to model the crimped nature of a woven fabric. Warp/fill cross-over points are represented by two nodes, one attached to the warp fiber, and the other attached to the fill fiber. The nodes are coupled using transverse spring elements. The introduction of the non-planar geometry introduces significant changes into the propagation of a wave – depending on the relative orientation of the fiber elements, some elements near the projectile are automatically forced into compression. Previous fabric models treated each cross-over point as a simple pin joint [Roylance, 1995]. This new model, based on a concept developed by Cunniff [1996] at the U.S. Army Natick RD&E Center, allows the codes to take into account the bending and the orthotropic properties of a yarn.

Any fabric consists of a system of inter-woven warp and fill fibers. As a fabric is pulled tight, the fibers tend to flatten out and press together. We refer to this phenomenon as decrimping. Previous work at the U.S. Army Natick RD&E Center indicates that the process of decrimping is responsible for significant differences in the mechanical behavior of fabrics in comparison to the behavior of single yarns. A sample stress-strain curve illustrating the non-linear nature of the compressive stiffness measured from a panel of Kevlar 29 is shown in Figure 2 [Cunniff, 1997]. Note that at small strains, the effective stiffness of the fabric panel is very small, but that as the strain increases, the stiffness approaches that of a yarn.

The experimentally measured stress-strain curves can be fit with non-linear expressions of the form:

$$\sigma_c = A(\exp(B\varepsilon_c^C) - 1)$$

where σ_c and ε_c represent the compressive stress and strain, and A, B, and C are constants.

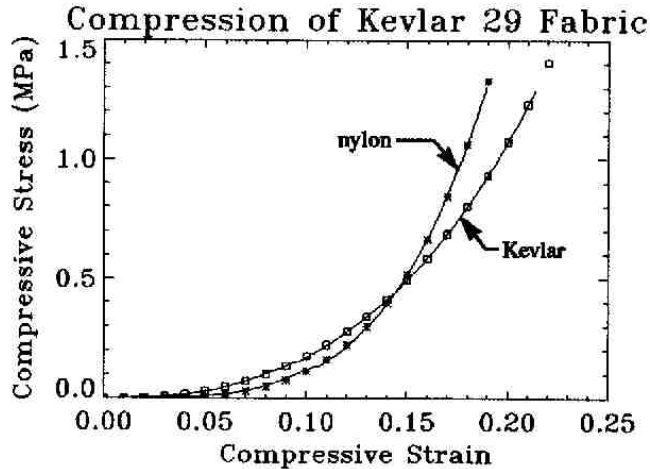


Figure 2: Compressive stress-strain curve measured in the transverse direction [Cunniff, 1997]

The codes model the essential physics of the interaction of each pair of warp and fill node with a number of options. Each pair of warp and fill nodes can be coupled rigidly or with a linear or a non-linear spring with the form above. Both types of springs can carry a compressive load only -- when two fibers lose contact, there is no coupling force pulling them back together. The codes also prevent fibers from passing through one another. When the distance between a warp node and a fill node becomes negative, the codes call a non-linear impact sub-routine to compute the new position of the nodes as they travel together.

The addition of the spring allows detailed analysis of the cooperative nature of wave propagation in fabrics. As a transverse wave propagates through a fabric, crossing fibers, which are orthogonal to the fibers passing under a projectile are picked up and so the energy from the impact is spread out and dissipated. The interaction between fibers has a significant effect on the longitudinal wave speed, causing a deviation from the theoretical speed in a single yarn [Cunniff, 1992].

2.3 Fiber Bending Model

The bending stiffness of the fibers at each cross-over is currently accounted for by using simple torsion springs. The sketch in Figure 3 shows how a continuous fiber is broken up and how the torsion springs are attached. Note that this model does not account for the stresses and strains associated with bending.

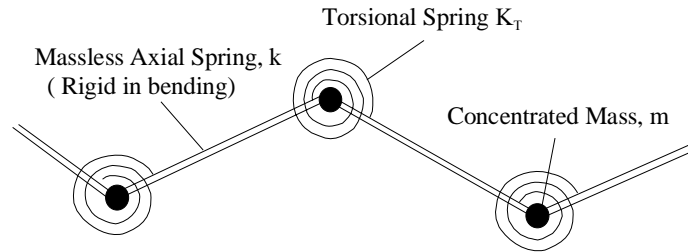


Figure 3: Sketch of torsional springs at each node providing fiber bending stiffness

The torsion springs produce a moment, M which is proportional to the change in the angle between two fiber elements. If the initial angle between the two elements is Θ_0 and the new angle is Θ , then $M = K_T(\Theta - \Theta_0)$. Each fiber element is modeled as a straight Euler beam. The torsional spring constant, K_T , is computed using the expression $K_T = EI/L_0$, where E is the tensile modulus of the fiber, I is the moment of inertia of the fiber in the bending plane and L_0 is the initial length of a fiber. The fabric codes calculate the moment of inertia using an expression developed at the U.S. Army Natick RD&E Center, $I = \pi\sqrt{N}D_f^2D_y^2/64$, where N is the number of filaments in the fiber, D_f is the diameter of a single filament and D_y is the diameter of the fiber [Cunniff, 1997].

2.4 Fiber Buckling

The existence of a finite bending stiffness in the fibers as described in the previous implies that there is also a finite buckling load. The code models takes into account the possibility of buckling by providing three choices: 1) allow the fiber elements to carry any compressive load, 2) don't allow the fiber elements to carry any compressive load, or 3) limit the maximum compressive load to the critical load computed for a pinned column, $P_{crit} = \pi^2 EI/L_0^2$, where E , I and L_0 are the same quantities described in the earlier section on bending stiffness.

2.5 Fabric Panel Boundary

Ballistic test data is often obtained from panels clamped in metal frames. Data has shown that predicted performance is often sensitive to both the size and shape of the frame. In contrast, fabric panels are often actually used in a nearly free condition, with no constraints on the edges of the panels. The code incorporate boundary models for both cases.

2.6 Projectile Geometry

Both the size and the shape of the projectile can be varied in the program input file. Currently, the codes allow normal impact of both circular and rectangular projectiles. Future versions of the codes will allow oblique trajectories and greater control over the rotation of the projectile.

2.7 Multiple Layer Fabric Panel

The codes model multiple layer fabrics with the same approach used for warp-fill coupling – each layer of the panel is coupled with the next using a series of compression elements.

Currently, the codes provide a choice of a rigid element, a linear spring, and a non-linear spring with a stiffness of the form:

$$\sigma_c = A(\exp(B\varepsilon_c^C) - 1)$$

The codes assume that the plies are laterally uncoupled, although future versions may incorporate slipping and friction. Also, for simplicity, the codes do not check for contact of consecutive layers.

3. NUMERICAL RESULTS FROM FABRIC CODES

Numerical studies have been performed to demonstrate how well the analytical models work in the full fabric codes. Some of these results are presented here to illustrate the mechanics of the model and to provide some insight into impact mechanics.

3.1 Single Fiber Response

Results from a model of a single fiber illustrate some important aspects of the physics of yarn response. A sketch of the single fiber model is shown below in Figure 4. Figures 5 through 8 show the strain profile of one half of a single yarn of Kevlar 29 struck by a 1 g projectile at $x = 0$ m at times 5 and 10 μ sec. The analytical results shown in Figure 5 represent the response of a completely flat yarn with no modeled bending stiffness and no fiber element compression allowed. The results shown in Figure 6 show the response of a crimped yarn pulled from a panel constructed with a Kevlar 29 plain weave with no modeled bending stiffness and allowable fiber compression with no limits. Note that the strain profile for the crimped fiber with a zero buckling force is sharply uneven, has amplitudes an order of magnitude higher than that of the flat fiber, and indicates an extremely slow strain wave speed.

Figure 7 shows the strain response of crimped fiber with no bending stiffness but with the allowable fiber compression set to the critical load for a pinned column. The strain wave profile shows a wave that is more irregular and slower than the results for the straight fiber shown in Figure 5.

The results shown in Figures 5 through 7 shows the varying effects that compression and bending have on the analytical fiber behavior. The amount of compression that a fiber element can carry affects both strain wave speed and shape. Increasing amounts of compression increases both the apparent wave speed and the smoothness of the profile. In comparison, fiber bending appears to have a relatively small effect. A quick look at the model geometry in Figure 4 helps explain these results.

As the projectile strikes the yarn, a number of the elements close to the impact point are forced into a state of compression. Force cannot be transmitted effectively until the elements have *decrimped*, allowing them to carry load in tension. This phenomenon occurs for every other fiber element, reducing the effective wave speed and disrupting the strain profile.

In the case in which absolutely no fiber compression is allowed, this phenomenon is even more extreme. Figure 8 shows the strain wave profile of a crimped fiber with allowable

compression and bending stiffness included via torsional springs. Note that bending stiffness in itself plays a role in wave transmission that is typically very small.

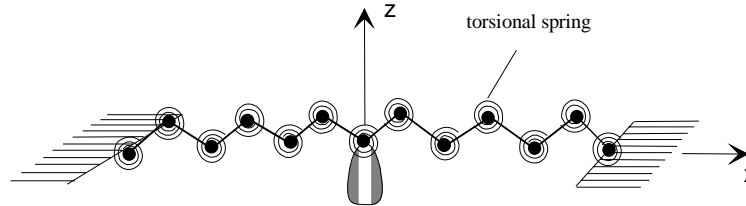


Figure 4: Sketch of single fiber model with bending.

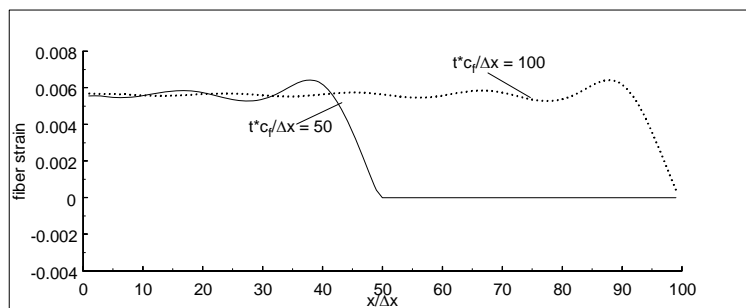


Figure 5: Strain wave profile of a single uncrimped yarn of Kevlar at times 5 and 10 μ sec. No fiber compression allowed and no bending stiffness included.

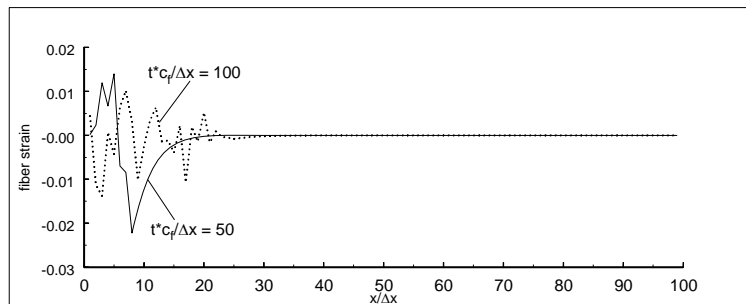


Figure 6: Strain wave profile of a single crimped yarn (consistent with a Kevlar 29 plain weave). No fiber compression allowed and no bending stiffness included.

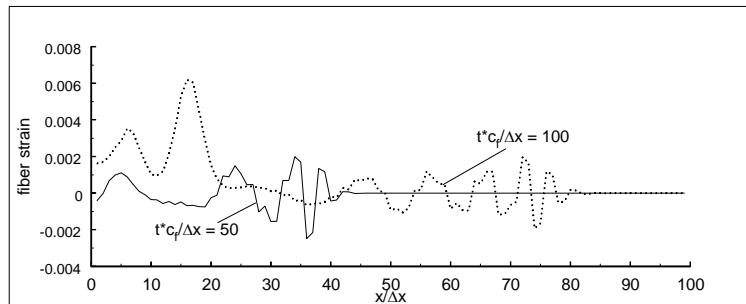


Figure 7: Strain wave profile from a model of a single crimped yarn of Kevlar 29 consistent with a plain weave. Fiber element compression limited to analytical buckling load, no bending torsional stiffness included. Output shown at times 5 and 10 μ sec.

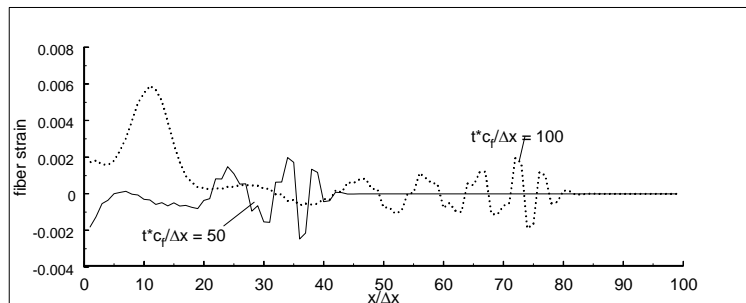


Figure 8: Strain wave profile from a model of a single crimped yarn of Kevlar 29 consistent with a plain weave. Fiber element compression limited to analytical buckling load, bending torsional stiffness included. Output shown at times 5 and 10 μ sec.

3.2 Fabric Ballistic Resistance of Single Ply of Fabric

Ballistic resistance is probably the most important measure of the effects of the various fabric construction parameters on fabric performance. The code was used to simulate the behavior of a panel of 1500 denier Kevlar 29 to generate curves of residual velocity, V_r vs. striking velocity, V_s comparing:

- crimped model fabric construction vs. flat model fabric construction
- rigid warp-fill coupling vs. coupling with a linear elastic spring vs. coupling with a non-linear elastic spring

The baseline model consisted of a square panel, 20 cm on a side. The model fabric was struck in the center of the panel with a generic circular 17 grain projectile. Unless otherwise noted, the model fabric panels were perfectly clamped at the edges and fibers are allowed to take compression to fiber buckling. The analytical results from these models are shown in Figure 9

and are compared with equivalent experimental results obtained at the U.S. Army Natick RD&E Center.

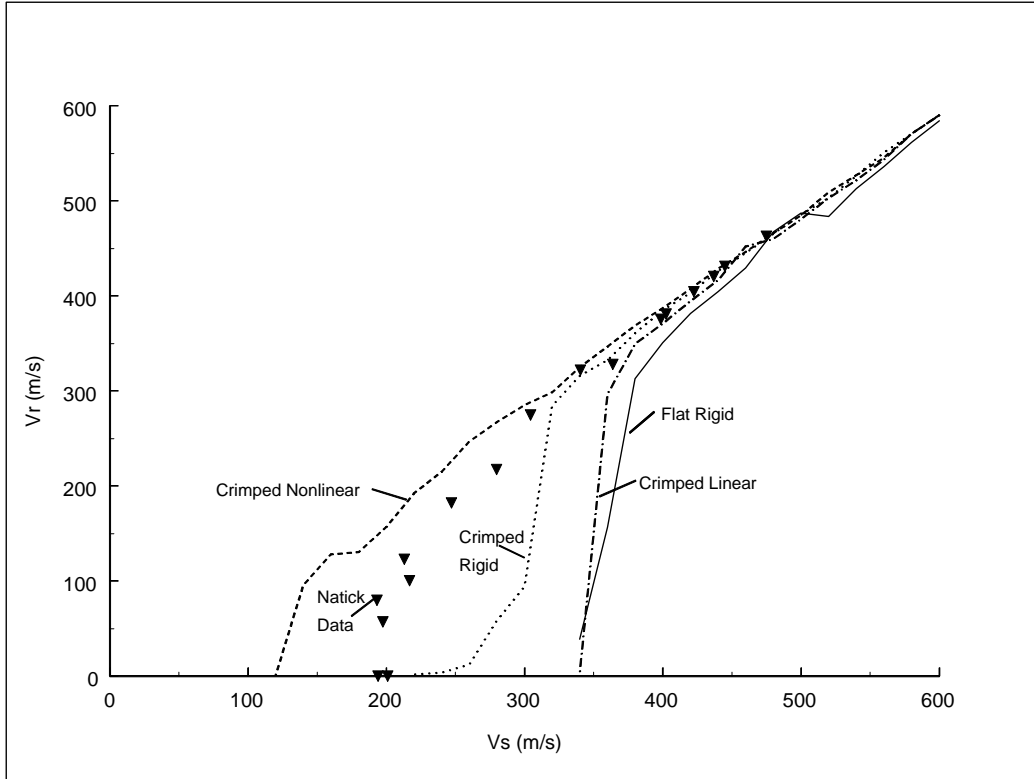


Figure 9: VrVs curves illustrating the effect of crossed fiber coupling on the ballistic response of the model fabric using flat rigid elements, crimped rigid coupling elements, linear elastic coupling elements, and non-linear elastic coupling elements. Experimental data from a panel with approximately the same physical properties is shown for comparison. Model fabric panels were perfectly clamped at edges.

3.2.1 Effect of Crimped Geometry

Figure 9 demonstrates some of the changes in behavior caused by the introduction of crimped fiber elements compared to the behavior of a panel with pin jointed, flat or planar fiber elements used in a number of older models. The VrVs curves for the flat rigid model versus the crimped rigid models shows that the geometry of the model fabric elements has a significant effect on ballistic performance. Both the flat pin-jointed model and the crimped profiles appear nearly linear for high initial velocities, Vs, but break downward with decreasing Vs. This break usually signifies that a fabric is close to reaching its ballistic limit, the point at which it is capable of stopping a projectile. The point at which the residual velocity goes to zero is often referred to as the V₅₀ value, the velocity at which a projectile has a 50% probability of penetrating a panel. The ballistic limit predicted by the models of the crimped fabric appears to be much lower than the limit predicted for the flat fabric, a difference of nearly 100 m/sec.

Complete modeled fabric panels show this same phenomenon. Figures 9 and 10 show the fiber strains caused by a projectile impact of 200 m/s at 15 μ sec for the flat rigid and crimped nonlinear models. The strains from the warp and fill fibers were averaged at each cross-over. These profiles show the same general trend shown in the single fiber model results – the addition of the crimped geometry lowers the effective strain wave velocity.

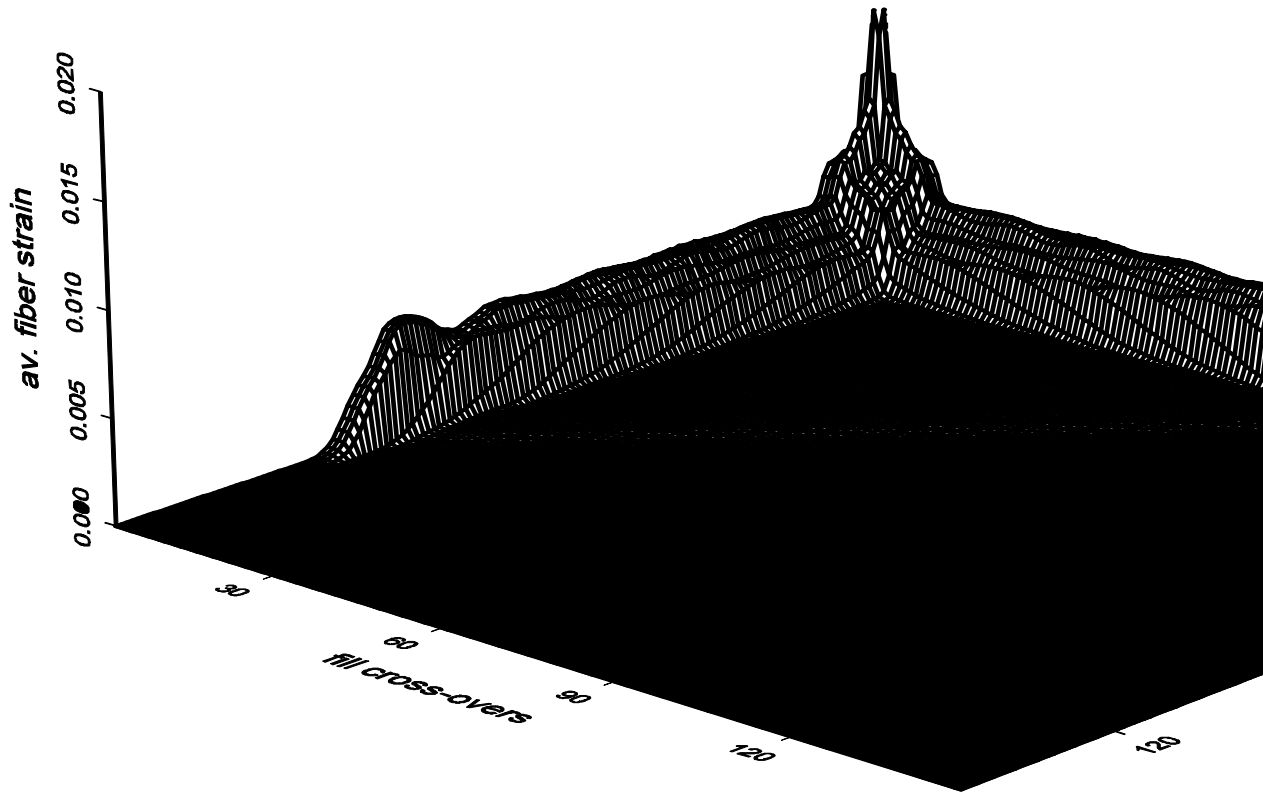


Figure 10: Average fiber strains of warp and fill fibers in one quarter of a model with flat fiber elements, no crimping, struck by 200 m/s projectile at time 15 μ sec.

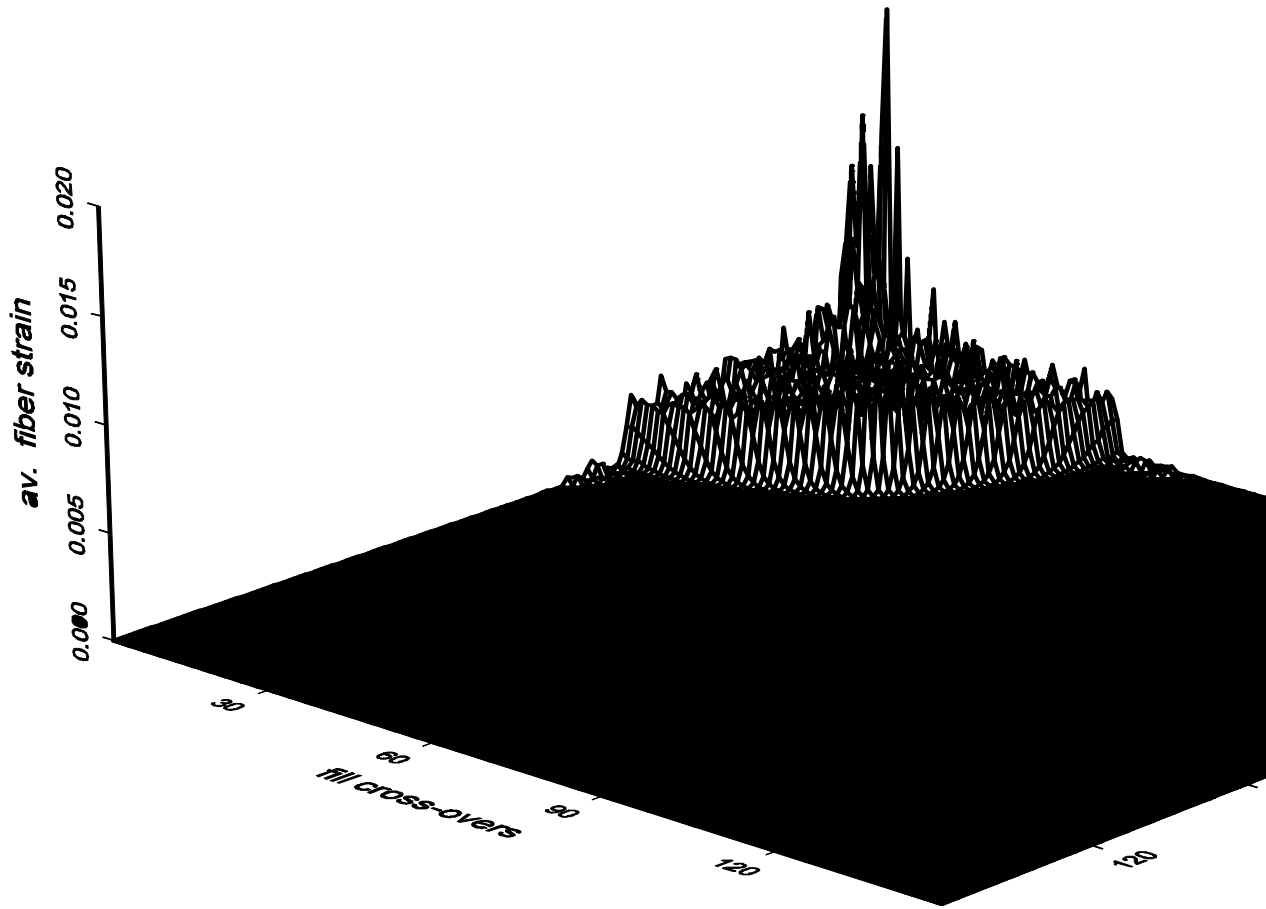


Figure 11: Average fiber strains of warp and fill fibers in one quarter of a model with crimped elements, non-linear warp-fill coupling elements, struck by 200 m/s projectile at time 15 μ sec

3.2.2 Warp-Fill Coupling

The effect of the warp-fill coupling elements on ballistic performance is also illustrated in Figure 9. Three panels were modeled with identical material properties and geometries, but with different warp-fill coupling elements: rigid, linear elastic, and non-linear elastic. The linear elastic element stiffness was set using the conventional tensile modulus measured axially from a yarn. The non-linear elastic stiffness element was set using experimentally derived constants obtained by measuring the transverse stiffness of a multi-layer panel of Kevlar 29. It is important to note that the linear elastic stiffness was significantly higher than the effective non-linear elastic stiffness at small strains. At 10% strain, the linear model produced over 300 times more force than the non-linear model. The two stiffness models do not produce equivalent stiffness values until approximately 53% [Cunniff, 1997].

The results show a dramatic difference in the response of the modeled fabric panel with the three different warp-fill coupling elements. The model using the linear coupling element produced the most conservative results of the three models, providing a value for V_{50} , 340

m/sec, that was much higher than the experimental value for V_{50} , ~ 190 m/sec. The model using the rigid coupling element provided a value for V_{50} of 220 m/sec, close to the experimental results, but the shape of the VrVs curve was very different from the shape of the experimentally derived VrVs curve. In comparison, the model using the non-linear coupling element with the experimentally derived coefficients provided a reasonably conservative value for V_{50} , 120 m/sec, and a realistically shaped VrVs curve. Of the three models, the one using the non-linear coupling elements appeared to provide the best overall match to the experimental data.

4. SUMMARY AND CONCLUSIONS

The ballistic simulation program breaks up a fabric panel into a series of simple elements, capturing the essential physics of a number of parameters including:

- non-planar or crimped fiber geometry
- variations in projectile geometry
- orthogonal nature of crossed fibers – different stiffness behavior in different directions
- compression coupling between multiple plies in a fabric panel
- non-idealities of fabric panel clamping and differences between experimental panel measurement and behavior in actual soft armor

The programs appear to produce reasonable behavior compared to limited experimental observations. Numerical results indicate that:

- Introduction of the crimped fiber geometry has a significant effect on the modeled behavior of a fabric. One major reason is the reduction in the effective strain and transverse wave speeds.
- Modeled fabric ballistic response varies with projectile geometry
- Modeled fabric ballistic response is extremely sensitive to boundary condition
- Transverse coupling springs have a significant effect on modeled fabric behavior. The empirically based non-linear modeled appears to produce ballistic behavior closest to available data.

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