State of the Art in the Deterministic and Probabilistic Ballistic Impact Modeling of Soft Body Armor: Filaments to Fabrics

G. NILAKANTAN and S. NUTT

ABSTRACT

The ballistic impact and penetration of soft body armor, comprised of dozens of plies of high-strength woven fabric, is an extremely complex physical event given the very short time scales, high strain rates, range of structural length scales, and multiple mechanisms involved. For example, the hierarchical structure of Kevlar spans the nanometer to the meter length scales (fibril→filament→yarn→fabric→armor). During ballistic impact, large magnitudes of projectile kinetic energy need to be dissipated in very short time scales (~tens to hundreds of microseconds). This process occurs through several mechanisms of deformation, energy dissipation, and failure across the various time and length scales. A strategic tailoring of these mechanisms can lead to improved and lightweight body armor designs, which first requires a detailed understanding of the mechanisms. These are accomplished using a materials-by-design approach and advanced computational techniques as outlined in this paper.

In this paper, we review and present the state of the art in the finite element (FE) modeling of woven fabric structures, including filament-level, homogenized yarn-level, and membrane-level architectures as well as a multiscale hybrid element analysis (HEA) model that uses impedance matched interfaces to combine various structural length scales with various element formulations to balance accuracy of predictions with computational efficiency. The sources of statistical variability that affect the probabilistic penetration response of woven fabrics are outlined along with experimental efforts to characterize them. A recently developed probabilistic computational framework that can predict the complete V0-V100 curve or probabilistic velocity response (PVR) curve of soft body armor is presented, which includes mapping in the sources of variability into the fabric FE model. Image-based modeling techniques are used to develop realistic filament-level FE models that capture all the geometric variability. Realistic sized ballistic fabric targets are simulated using a supercomputer, including the largest fabric FE model to date.

Gaurav Nilakantan, Steven Nutt
M.C. Gill Composites Center, Department of Chemical Engineering and Materials Science, University of Southern California, 3651 Watt Way, VHE-602, Los Angeles, CA 90089, USA

INTRODUCTION

In this paper, we present an overview of the state of the art in the ballistic impact modeling of woven aramid fabrics used in soft armor, and in particular, focus on the current and previous work of Nilakantan et al. [1-14] in this area over the past several years.

Kevlar is commonly used for torso and extremity protection in law enforcement and military body armor, providing protection against stab and ballistic threats. Soft armor usually comprises of dozens of layers of woven Kevlar fabric stitched together, and is used with a ceramic backing plate when providing torso protection. Kevlar is a para aramid material that is transversely isotropic (also considered to be cylindrically orthotropic) with its longitudinal tensile stiffness between one to two orders of magnitude larger than the transverse stiffness. This behavior arises from a radially pleated structure with highly aligned chains providing high tensile stiffness.

There are two challenges when modeling the high strain rate or ballistic impact response of woven Kevlar fabrics. They arise from the highly multiscale structure of Kevlar fabrics and the statistical variability inherent in the geometric and material properties that leads to a probabilistic penetration response.

Figure (1) displays the various structural length scales in Kevlar fabric armor. They range from nanometers (individual fibrils) to microns (filament diameter) to millimeters (yarn cross-section and fabric unit cell) to centimeters (woven fabric patch) to meters (body armor).

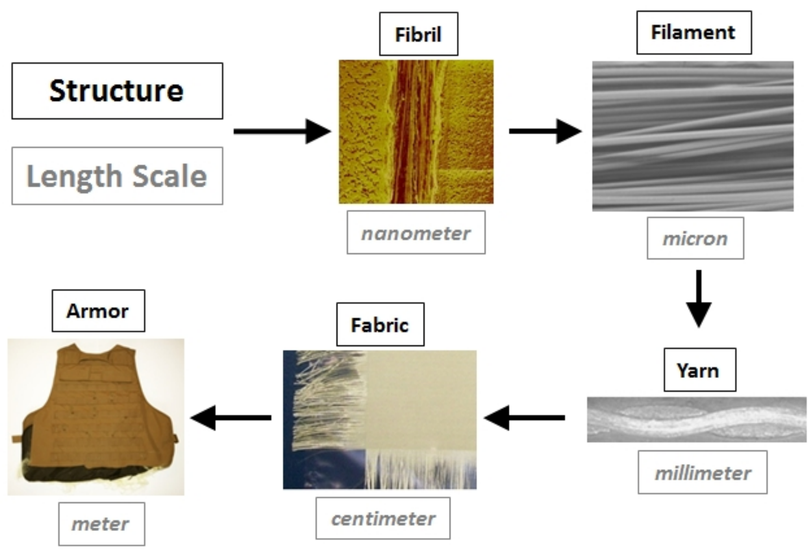


Figure 1. Structural length scales in Kevlar fabric armor

Figure (2) displays the library of FE models developed by Nilakantan et al. that span the continuum structural length scales from the filament level to the woven fabric level that were shown in Figure (1). 1D, 2D, and 3D finite element formulations are used at the various length scales. The computational expense in terms of both processing power and memory requirements drastically increases as the degree of modeling resolution increases.

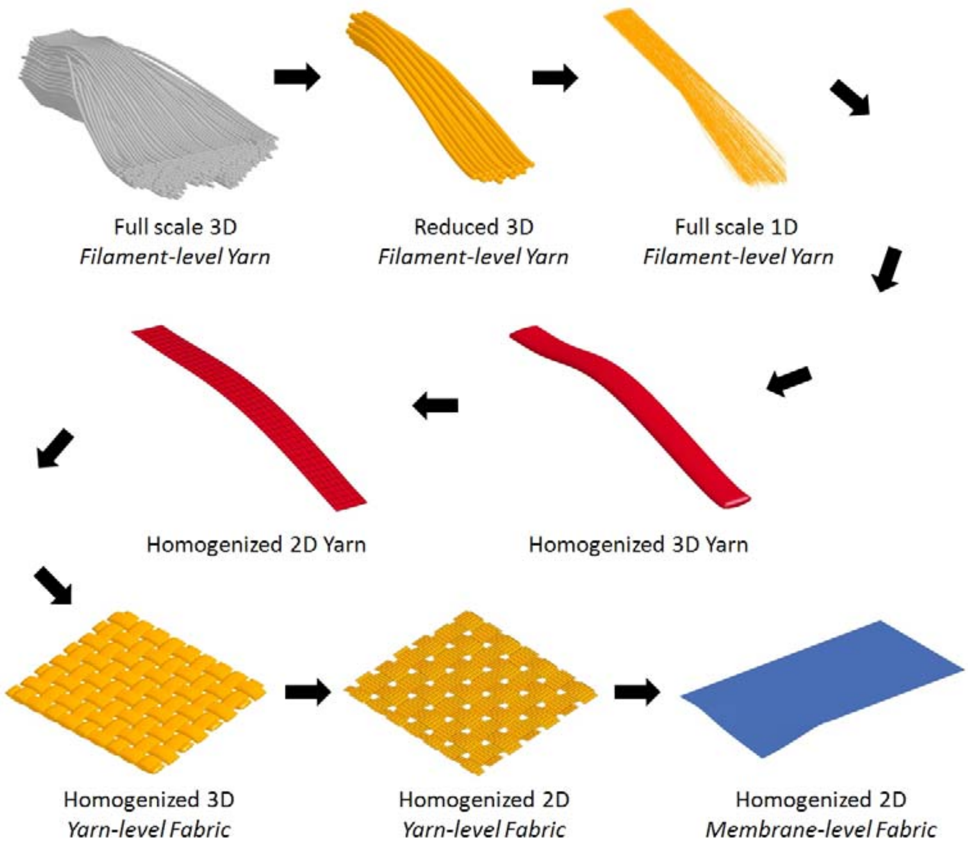


Figure 2.Filament, yarn, and fabric FE models discretized using 1D, 2D, and 3D elements

The ballistic impact and penetration behavior of woven fabric based armor is probabilistic in nature which arises from several sources of variability. The complete probabilistic penetration response can be described by the V_0-V_{100} curve or probabilistic velocity response (PVR) curve that describes the probability of complete fabric penetration (X%) for a given projectile impact velocity (V). Commonly used V_X parameters include the V_0 and V_{50} velocities. There is a unique PVR curve for each combination of fabric material, target configuration, and threat. Figure (3) displays a typical PVR curve. The zone of mixed results (ZMR) comprises the region between the lowest penetrating velocity (V_P) and highest non-penetrating velocity (V_{NP}). From a deterministic perspective, the relation $|V_P| > |V_{NP}|$ always holds true. However from a probabilistic perspective, the relation $|V_P| \leqslant |V_{NP}|$ can hold true because of the aforementioned sources of variability.Intrinsic sources of variability refer to sources within the fabric target, typically related to the geometry and material, which can be described by a statistical distribution or occur totally randomly. Examples include such as the filament (fiber) and yarn tensile strengths, filament cross-sectional shapes, filament packing patterns, filament misalignment, inter-filament and inter-yarn friction. Extrinsic sources of variability refer to all other sources, typically related to the experimental testing conditions and projectile. Examples include the precise projectile impact location relative to the principal yarns and relative to the fabric dead center, projectile trajectory, mass and impacting velocity, backing material properties, and clamped fabric boundary slippage.

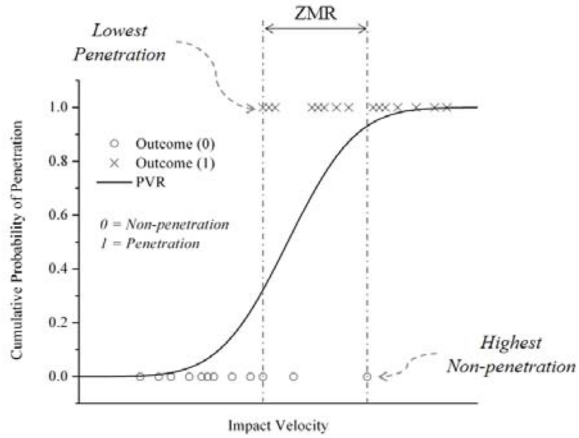


Figure 3.Fabric PVR curve showing the ZMR

CHALLENGES AND OPPORTUNITIES

The Army has a constant need to design improved lightweight armor, to provide enhanced protection against emerging threats as well as to enhance soldier performance and endurance. There is an increasing emphasis on using a materials-by-design approach to meet this need. The materials-by-design approach is one of the underlying philosophies of the materials genome initiative, and includes bridging the length scales together with controlled and focused experiments and modeling efforts at each length scale. During ballistic impact of woven fabrics, there are several interactions and mechanisms of deformation, failure, and energy dissipation that are simultaneously at play across the length scales. It is important to understand how these mechanisms translate across the length scales, as well as the short time scales that are associated with ballistic events (tens to hundreds of microseconds). Developing such an understanding is key to assessing whether observed performance improvements at one length scale actually translate into measurable performance improvements at higher length scales, which in turn can help guide a systematic and strategic tailoring of geometry, architecture, material, and interface to optimize the ballistic impact performance of novel lightweight armor.

Deterministic bridging of length scales requires developing predictive FE models at each length scale starting with the lowest level. We consider the lowest length scale to be the continuum filament level as we are neglecting the atomistic and molecular length scales that is beyond the scope of FEA and requires techniques/codes such as molecular dynamics (MD) and peridynamics. The behavior at each length scale (e.g. response to deformations and loadings of various magnitudes and strain rates) is used to develop the constitutive behavior at the next length scale(that includes both geometric and material effects), thereby allowing a progressive homogenization of the material/structure that in turn allows the modeling of realistic sized structures with available computational infrastructure.For example it is currently impossible to model a realistic sized ballistic fabric target with an entirely 3D filament-level resolution even using the latest available supercomputers. However in certain cases, in lieu of developing micromechanical models and direct feeding of load curves to the next length scale (i.e. implicit multiscaling), it becomes necessary to explicitly model at a lower length scale. In such cases, multiscale models are required that explicitly combine multiple length scales into a single model (i.e. explicit multiscaling) wherein the finer modeling resolutions are typically used in regions that experience the most severe loadings and deformations, e.g. underneath the projectile. The challenge with these multiscale models lies in how information (e.g. stress wave propagation) is able to flow continuously and uninterrupted across the model interfaces (e.g. no spurious wave reflections at the interfaces).

While a deterministic bridging of the continuum length scales is itself a challenging task, additional complications arise when trying to accomplish a probabilistic bridging of the length scales that is necessary to understand how the sources of intrinsic and extrinsic statistical variability at one length scale translate into variability at higher length scales as well as to understand how sources of statistical variability (i.e. input) affect the probabilistic system performance (output). One example, discussed in subsequent sections, is understanding how observed statistical filament tensile strengths affect the observed statistical yarn tensile strengths, and in turn how they affect the probabilistic fabric impact response.

Another important challenge lies in reducing the dependence on and overcoming the shortcomings of experimental testing, mostly to do with fabric ballistic impact testing. The V_{50} velocity is still used as a primary measure of fabric armor ballistic impact performance because it is relatively easy to experimentally measure with only a few to a dozen test shots. However it is of little practical relevance. Parameters such as the $V_{0.1}$ or V_1 velocities are significant because they provide a large measure of confidence that an impacting threat will always be stopped. However these parameters require many dozens of tests to estimate, making the experimental testing process highly labor intensive, time consuming, and expensive. Moreover experimental testing can only be conducted with already available materials and weaves. However predictive models and simulation techniquescan be used to explore conceptual materials, interfaces, and weave architectures at a fraction of the time and cost. Moreover unwanted sources of experimental variability and error, that can bias the PVR curve, can be eliminated. Examples include fabric boundary slippage from the clamps and variability in backing material properties.

The field of view and image resolution during experimental ballistic impact testing is limited, with resolution often decreasing as the scanned area increases in size. Even with the most advanced high speed imaging equipment, it is impossible to monitor filament-level deformations and mechanisms at the impact site. Even tracking the deformation and failure of individual yarns at the impact site is extremely challenging. Thus it is very difficult to closely monitor high strain rate deformation events, especially to capture important phenomena at the lower length scales which are vital to developing an understanding of the various mechanisms and interactions. However all this can be accomplished through predictive FE simulations by modeling the yarn or fabric structure at the required length scale.

The next section identifies some of the key research areas that are vital to the materials-by-design approach for ballistic woven fabrics, and reviews the corresponding experimental and numerical work that has been conducted as well as ongoing by Nilakantan et al. The woven fabric under consideration is Kevlar Style

706(JPS Composites), a plain weave fabric with an areal density of 180 g/m^2 and a yarn span of 0.747 mm. The warp and fill yarns are comprised of 600 denier continuous-filament Kevlar KM2 yarns. The Kevlar KM2 filaments are approximately circular with a manufacturer reported diameter of 12 microns and a density of 1.44 g/cm^3.

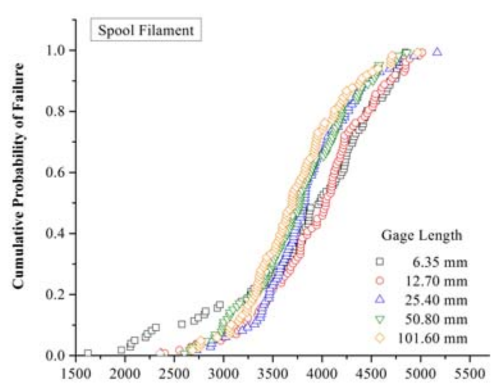
THRUST AREAS

Experimental Testing and Statistical Characterization of Geometry and Material Properties

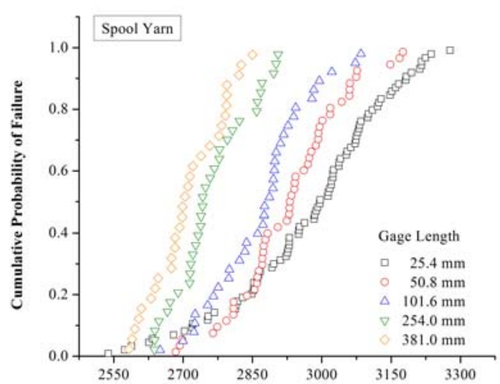
Our current database of experimental testing and statistical characterization of the Kevlar S706 fabric and its constituents comprises of the following studies:

1. Filament geometry and packing (microscopy)
2. Yarn cross-sections and undulations (microscopy)
3. Filament and yarn tensile strengths (mechanical testing)
4. Inter-yarn friction (mechanical testing)
5. Ballistic impact of woven fabrics (mechanical testing)

Tensile strengths of single Kevlar KM2 filaments and 600 denier Kevlar KM2 yarns were experimentally determined and statistically characterized [11]. Single filaments of varying gage lengths (6.35 mm - 101.60 mm) were carefully extracted from a spool yarn as well as from the warp and fill yarns in both greige and scoured Kevlar S706 fabrics. Similarly, yarns of varying gage lengths (25.4 mm – 381.0 mm) were cut from a spool and from the warp and fill yarns of greige and scoured fabrics. Between 30 to a 100 samples were tested for each configuration to generate the median ranks and cumulative distribution function (CDF) that describes the probability of failure as a function of tensile strength. Both 3-parameter Weibull and generalized Gamma distributions were used to generate the CDFs.



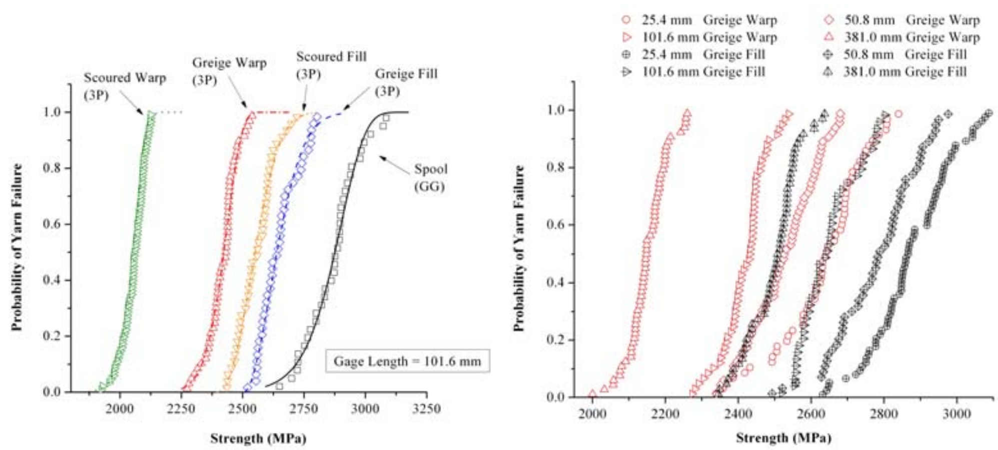
(a)



(b)

Figure 4.Statistical tensile strengths at varying gage lengths for spool-extracted (a) single Kevlar KM2 filaments (b) 600 denier Kevlar KM2 yarns

The tensile strengths of Kevlar KM2 filaments are statistical in nature as seen in Figure (4a). There doesn't appear to be any sensitivity to gage length within the range of lengths studied, and the degree of variability in strengths remains similar. The tensile strengths of 600 denier Kevlar KM2 spool yarns, comprised of these same filaments is also statistical in nature as seen in Figure (4b) however a gage length scale effect is clearly visible wherein the tensile strengths as well as the associated variability in strengths decreases with increasing gage lengths. Obviously the defect distribution in the filaments alone cannot explain this relationship between statistical filament and yarn tensile strengths of the same gage length. Other potential factors include the filament centerline misalignment, filament packing patterns, and inter-filament friction, all of which affect load sharing and progressive failure during the quasi-static tensile loading of yarns.

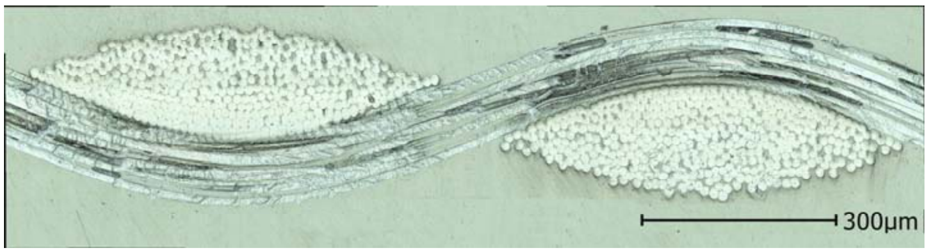


(a) (b)

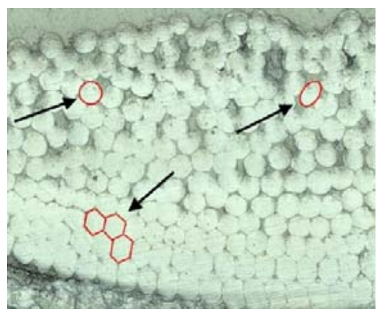
Figure 5.(a) Strength distributions for 101.6 mm gage length yarn samples (b) Strength distributions for greige fabric yarns of varying gage lengths

Figure (5a) displays yarn tensile strength distributions for spool and fabric-extracted yarns with a constant gage length. Figure (5b) displays yarn tensile strength distributions for the warp and fill yarns of a greige fabric at various gage lengths. The weaving process degrades yarn strengths with warp yarns showing greater degradation levels than fill yarns and scoured fabrics showing greater degradation levels than greige fabrics. The fabric probabilistic penetration response is expected to be dependent on the statistical tensile strengths of the constituent yarns. Thus knowledge of the weaving effects is important and can help guide the development of optimal weaving processes and design of new weave architectures that minimize weaving degradations.

Another source of intrinsic variability at the filament-level arises from the variability in both filament cross-sectional shape and size. While Kevlar KM2 filaments were widely assumed to be circular in shape with a diameter of 12 microns, our studies revealed two important findings. Firstly, the filaments showed variability in diameters (or the major dimension of the cross-sectional shape) not just from one filament to another but also along the length of a single filament. Secondly, the filaments exhibited varying cross-sectional shapes ranging from circles to ellipses to hexagons. This range of cross-sectional shapes is apparent from Figure (6) which displays a cross-sectional micrograph of the warp yarns in a greige Kevlar S706 fabric. Perhaps due to transverse yarn compression induced during the weaving process coupled with the low transverse stiffness of the filaments, some filaments have assumed hexagonal cross-sections and are packed in a hexagonal close packing configuration, whereas other filaments near the free surface of the fabric (i.e. away from the interlacing orthogonal yarn) exhibit a much looser packing configuration with somewhat circular and oblong cross-sections. The residual strains in some filaments and varying shapes and packing configurations are important parameters that can affect the yarn and fabric response to high strain rate loading.



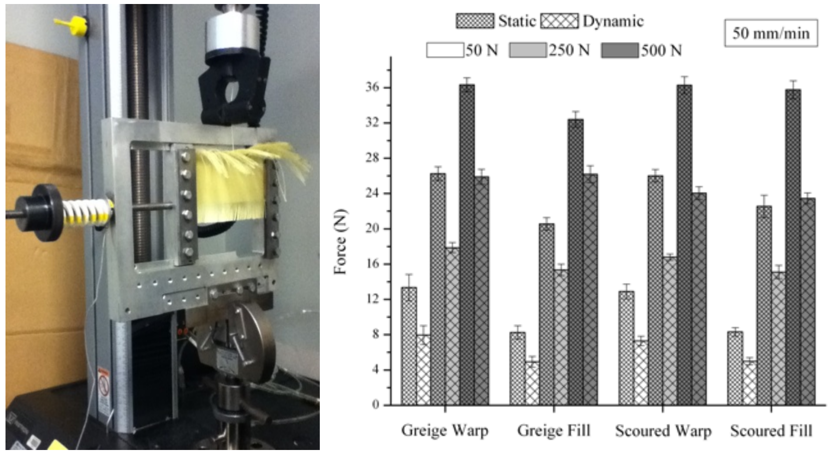
(a)



(b)

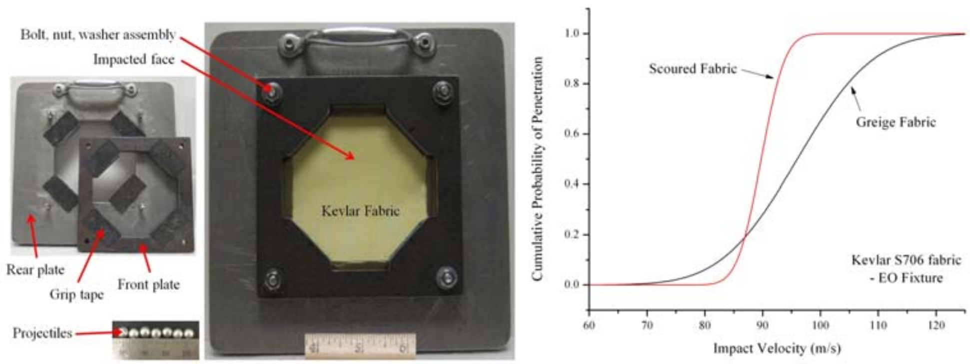
Figure 6.Greige Kevlar S706 fabric microstructure (a) warp yarn cross-sections (b) close-up of the cross-section showing filament shapes and packing patterns

Controlled yarn pullout experiments [4]were conducted in order to study the variability in inter-yarn friction, by pulling out individual yarns at varying speeds from a woven fabric patches held at varying transverse preloads. Figure (7a) displays the experimental setup for the yarn pullout test.



(a) (b)

Figure 7.(a) Experimental test setup for yarn pullout (b) Average greige and scoured yarn pullout forces for a constant pullout speed



(a) (b)

Figure 8.(a) EO frame (b) Greige and scoured Kevlar S706 fabric PVR curves

Figure (7b) displays the static and dynamic yarn pullout forces for the warp and fill yarns of both greige and scoured Kevlar S706 fabrics held at three levels of transverse preload (50 N, 250 N, 500 N) and with a yarn pullout speed of 50 mm/min.Some of the overarching trends observed from the pullout studies were as follows. Static pullout forces were higher than dynamic pullout forces, warp yarn pullout forces were higher than the fill yarn pullout forces partly due the increased crimp or undulations of the warp yarns, and pullout forces increase with increasing fabric preload levels. Also, the degree of variability in yarn pullout forces is larger for the greige yarns, larger for the dynamic pullout forces, and larger at lower pullout speeds. Yarn friction levels and associated variability affect the fabric probabilistic penetration behavior, especially for partially clamped and unclamped fabrics.

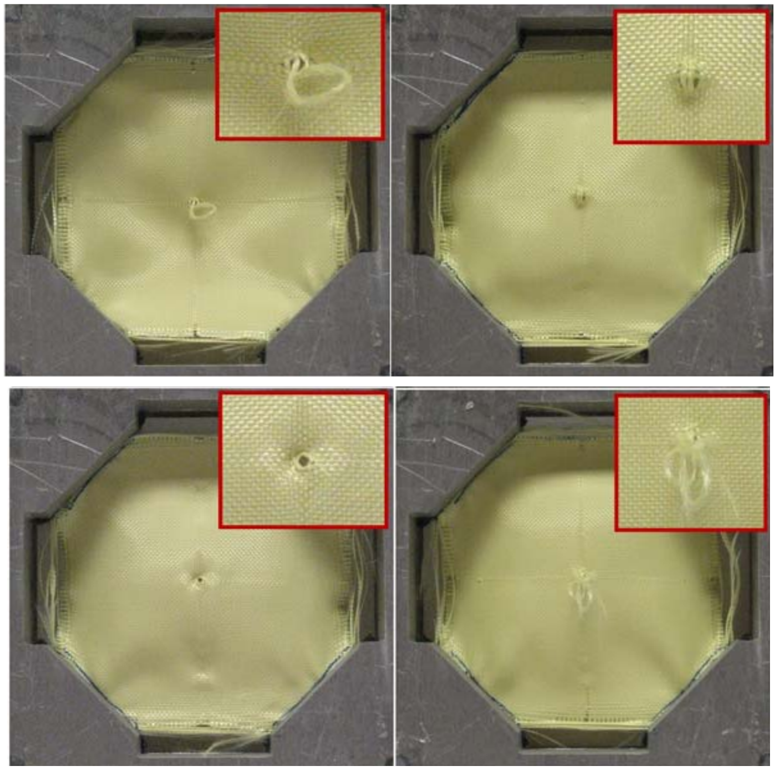


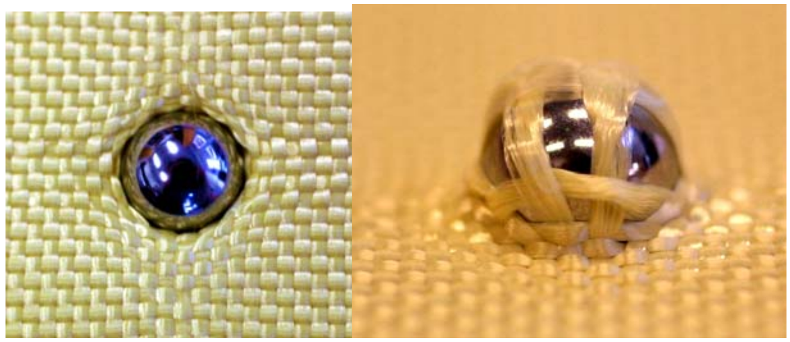
Figure 9.Post impacted greige Kevlar S706 fabrics (rear face)

Friction has both a primary affect that results in direct energy dissipation due to yarn sliding and pullout as well as a secondary affect that controls inter-yarn load sharing and correspondingly the yarn stress levels. Thus knowledge of yarn friction is important and can help guide the development of new yarn and fabric treatments and interfaces.

A series of fabric impact experiments was conducted to assess the role of clamping on the impact response and in particular to mitigate boundary slippage. Combined with numerical modeling efforts, this resulted in the development of an equilateral octagon (EO) fixture, shown in Figure (8a). The EO fixture was then used to compare the PVR curves of greige and scoured Kevlar S706 fabrics, shown in Figure (8b). The EO fixture resulted in a yarn pullout dominated fabric impact response and a windowing mode of fabric penetration. Figure (9) displays exemplary post impacted greige Kevlar S706 fabrics showing both principal yarn pullout and windowing penetrations. Trends in the experimental fabric PVR curves agreed well with the trends in the single yarn pullout experiments, demonstrating the relationship between statistical material properties (yarn friction) and probabilistic system performance (fabric PVR curve).

Filament-level Modeling of Yarns and Woven Fabrics

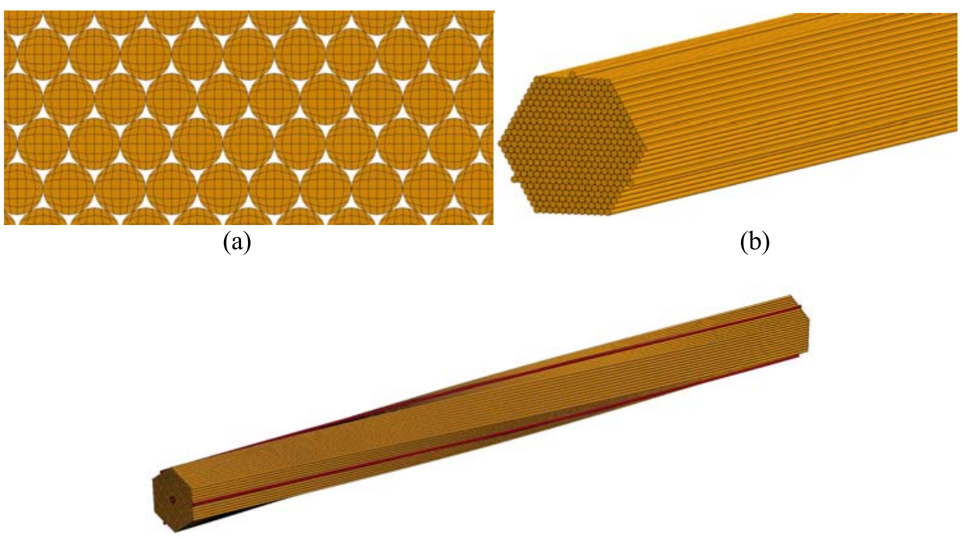
Existing homogenized yarn-level fabric FE models cannot explicitly capture many filament-level or sub-yarn interactions and mechanisms, thereby limiting the predictability of these models. There is a lack of understanding of the mechanisms at the filament length scale. Figure (10) displays an interesting impact scenario where a 0.22 caliber spherical steel projectile has been caught within the Kevlar S706 fabric weave, inside a basket-like structure created by principal yarn pullout and yarn spreading at the impact site. Out studies have shown that such phenomenon can only be captured by filament-level yarn FE models.



(a) (b)

Figure 10.Yarn spreading and pullout at the impact site (a) fabric strike face (b) fabric rear face

There are several approaches to modeling a yarn at the filamentlevel. All the filaments within the yarn, 400 filaments for the case of a 600 denier Kevlar KM2 yarn, can be explicitly modeled (full scale model) or only a fraction of the filaments (reduced resolution). The filaments can be discretized using 1D rod and beam elements or 3D solid elements. Obviously a full scale model with 3D elements will be the most computationally intensive model; however such models provide an unparalleled level of insight into the complex interactions and mechanisms at the filament length scale. Figure (11a) displays the cross-section of such a yarn model, wherein all filaments are assumed to be perfectly circular and arranged in a HCP packing configuration. The filament centerlines can be perfectly straight and parallel (see Figure 11b) or twisted in a helical pattern (see Figure 11c).



(a) (b)

(c)

Figure 11. Filament-level yarn model of 600 denier Kevlar KM2 yarns discretized with 3D solid elements (a) circular filaments in HCP packing configuration (b) straight centerlines with zero yarn twist (c) helical centerlines with non-zero yarn twist

Single yarn transverse impact studies [3] were conducted on these 3D filament-level yarns to assess the effect of filament transverse (E_t) and shear material (G_{ij}) properties, and inter-filament and projectile-yarn friction on the impact response. The effect of filament mobility and redistribution during impact was studied by either leaving the edges of the yarn free or by constraining the yarn from sideward spreading by modeling two frictionless walls at each side. Figure (12) displays exemplary filament-level yarn deformation and failure states during transverse impact. Figure (13) displays the yarn cross-section directly underneath the projectile for the unconstrained and wall-constrained yarns at the same time instant during the impact event. Filaments within each layer of the HCP packing are color-coded to visualize their redistribution. Such filament-level yarn models help calibrate homogenized yarn-level models through the incorporation of user defined material models.

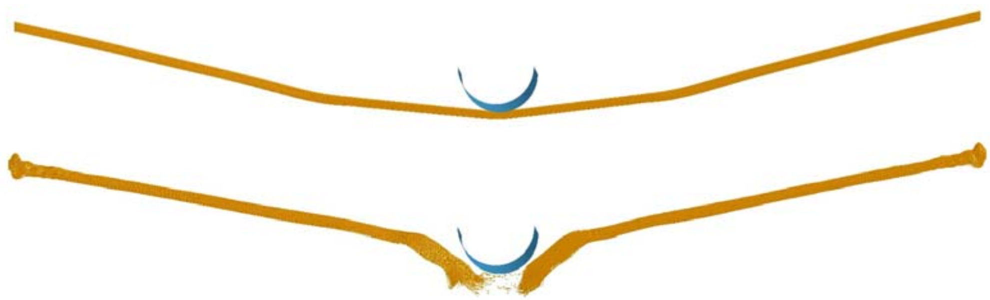


Figure 12. Filament-level yarn deformation and failure states during transverse impact

(a) (b)

Figure 13.Instantaneous yarn cross-sections at the impact site for the
(a) unconstrained yarn (b) wall-constrained yarn

The next step is incorporating these filament-level yarn models into a woven fabric FE model. The computational expense however limits the size of the fabric patch and the number of filaments that can be explicitly modeled. This problem can be partly overcome by using filament-level yarns at the impact site and homogenized yarns elsewhere. Figure (14) displays two such multiscale models wherein all the filaments (in yellow and green color) have been explicitly modeled using 1D elements (see Figure 14a) and only a fraction of the filaments (19 of the 400 total) have been explicitly modeled using 3D elements (see Figure 14b), while the remaining yarns in the fabric model are homogenized (in red color).

(a) (b)

Figure 14.Multiscale fabric models with homogenized yarns and filament-level yarns (a) full scale with 1D elements (b) reduced resolution with 3D elements

Image Based Modeling at the Filament-level

The filament-level yarn models in the previous section utilized deterministic representations of the filament geometry, packing, and centerlines. In reality however, the filament cross-sections vary in size and shape, the packing order varies within the yarn cross-section, and the centerlines show misalignment or non-parallel trajectories even in untwisted yarns. Figure (15) displays a micro-CT image of a Kevlar S706 fabric patch taken at a 2 micron resolution. We have begun to develop high-fidelity, image-based FE models of yarns that capture all of the geometric variability inherent in the textile structure. Such models, when combined with the previously experimentally characterized statistical filament material properties will provide the most realistic and robust representation of the actual yarn structure and comprise the building block for the most advanced probabilistic fabric FE model.

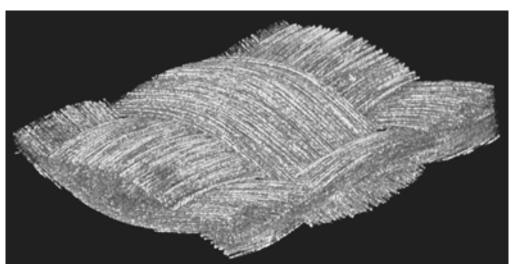


Figure 15.Micro-CT scan of a greige Kevlar S706 fabric

The framework to develop image-based FE models involves creating high resolution yarn cross-sectional micrographs, then extracting geometric features from the image to create a CAD model, and finally meshing the CAD model to create the FE model. Figure (16) displays the imaging-CAD-FE framework applied to a 600-denier Kevlar KM2 twisted spool yarn.

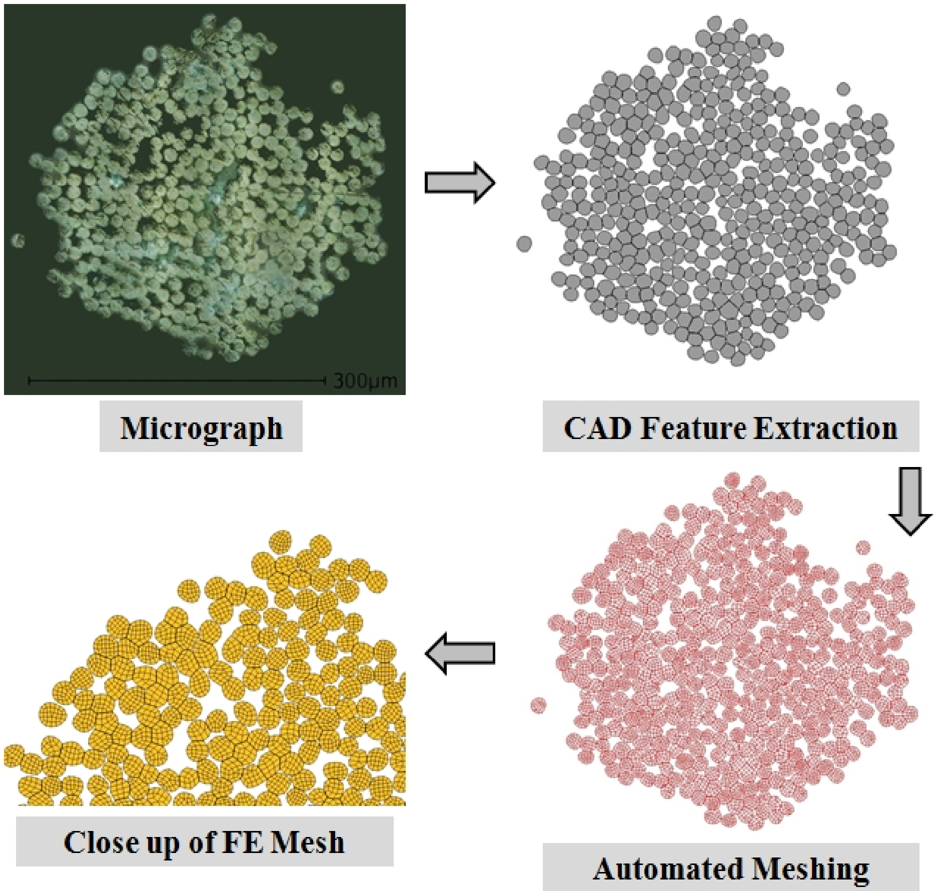


Figure 16.Imaging-CAD-FE framework applied to a twisted spool yarn

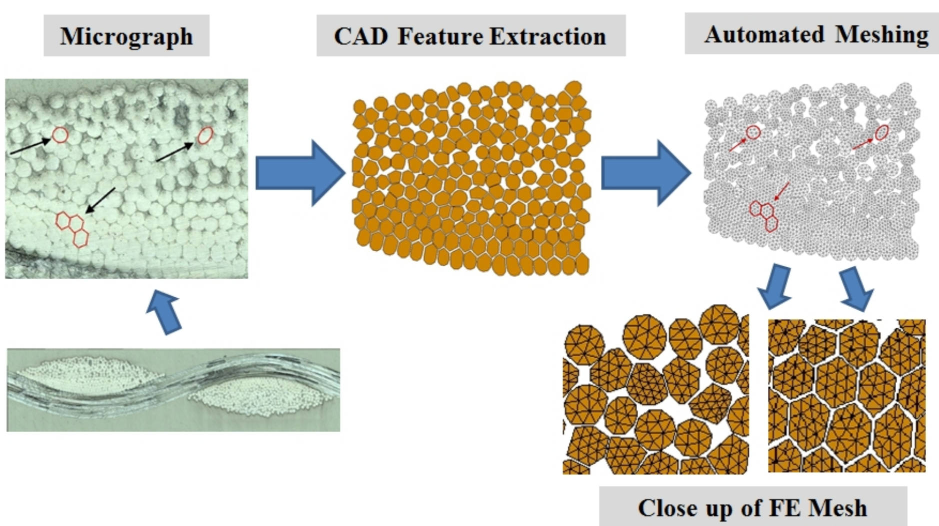


Figure 17.Imaging-CAD-FE framework applied to a woven fabric

Figure (17) displays the imaging-CAD-FE framework applied to a greige Kevlar S706 fabric. All of the inherent geometric variability has been captured in these models. These 2D FE models can then be converted into 3D models by incorporating the filament centerline trajectories obtained from the micro-CT scans.

Multiscale Modeling of Woven Fabrics

Computational expense is always an important consideration, which limits the degree of modeling resolution and the size of the model that can be simulated within a reasonable amount of time using available computing infrastructure. Even with the most advanced supercomputing infrastructure, it is intractable to model a realistic sized ballistic fabric target with an entirely 3D filament-level resolution. These issues can be partly addressed with multiscale models. However predictive multiscale models first require a successful bridging of the length scales such that the mechanisms at one length scale can be accurately captured using a model homogenized at the subsequently higher length scale. It then becomes possible to use a higher degree of modeling resolution only wherever necessary. For example, the hybrid element analysis (HEA) developed by Nilakantan et al. [12,13] combined a homogenized yarn-level resolution at the impact site and a homogenized membrane-level resolution at far field regions. Another unique feature of the HEA approach involved modeling one length scale using a combination of multiple FE formulations within the same model, for example the yarn was modeled using 3D solid elements directly underneath the projectile which transitioned to 2D shell elements after a finite distance from the impact site. These 2D yarns eventually transitioned to a 2D membrane at the far-field fabric regions. An important feature of the HEA models was the impedance matching technique used to ensure there were no spurious reflections of the longitudinal strain wave or transverse displacement wave at the various model interfaces. The impedance matching technique also allowed a-priori estimation of the global region material properties without the need for a trial-and-error estimation. Various HEA configurations were developed for various impact scenarios and included the single-scale configuration (entirely yarn-level with 2D and 3D elements) and multi-scale configurations based on the location and shape of the yarn-level region (central-patch, center-cross, center-strip), as shown in Figure (18).

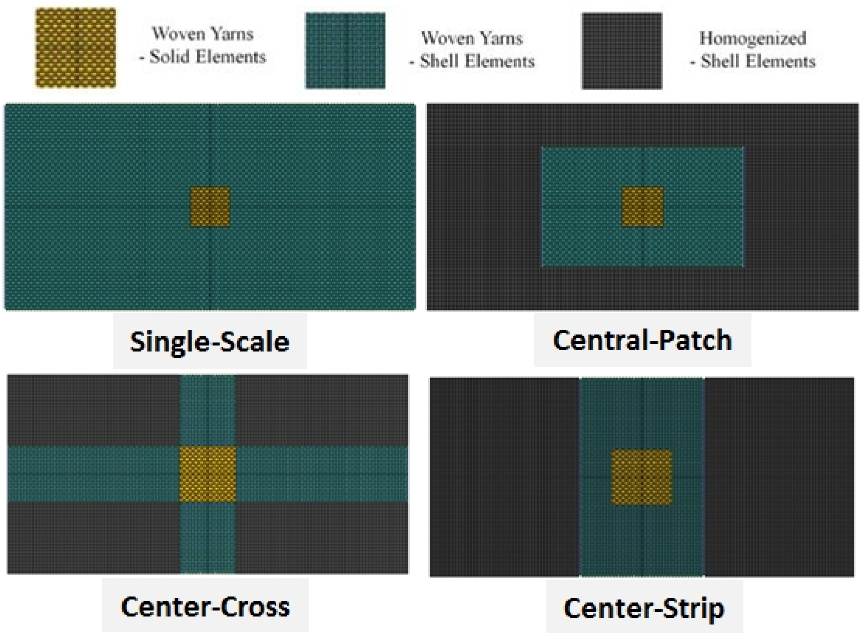


Figure 18.HEA fabric models

The HEA multiscale models were validated against a baseline fabric model comprising entirely of 3D homogenized yarns for both non-penetrating and penetrating impact scenarios. The HEA models were able to accurately capture the fabric impact response at only a fraction of the computational expense. The faster run times and reduced memory requirements provide a pathway towards the modeling of realistic sized fabric targets using only a desktop computer. Ultimately, the filament-level yarn models will be incorporated into these HEA fabric models providing the capability to capture filament-level mechanisms in a large-scale fabric simulation. Another important advantage of the HEA multiscale models becomes apparent when dealing with probabilistic simulations to estimate the fabric PVR curve, which is discussed in a later section. Such an approach requires the running of dozens of fabric impact simulations (usually 30-40), which can benefit from fabric models with reduced computational requirements.

Modeling of Realistic Sized Fabric Targets using Supercomputing

Supercomputing infrastructure, if available, provides the capability to tremendously scale up the size of the ballistic fabric target simulated. For example, with our supercomputing cluster (USC HPCC), we have recently modeled perhaps the world's largest fabric impact simulation, a multi-hit oblique impact of a multi-layer Kevlar S706 fabric target. The FE model comprised of 32.5 million elements and 81.5 million nodes. Special computational nodes were used with 128 GB of memory available per node. Figure (19) displays a close-up of this multi-layer multi-hit fabric impact scenario. Figure (20) displays a multi-layer Kevlar fabric target with various projectile threats. Obviously such models provide the US Army and scientific community with a tremendous capability to rapidly assess the role of material and architecture on the fabric armor impact response for a plethora of impact scenarios and threats, before any prototypes are made. In addition to the execution of the simulations, special infrastructure (e.g. graphics hardware) is also required to render and visualize the simulation results (e.g. deformation states).

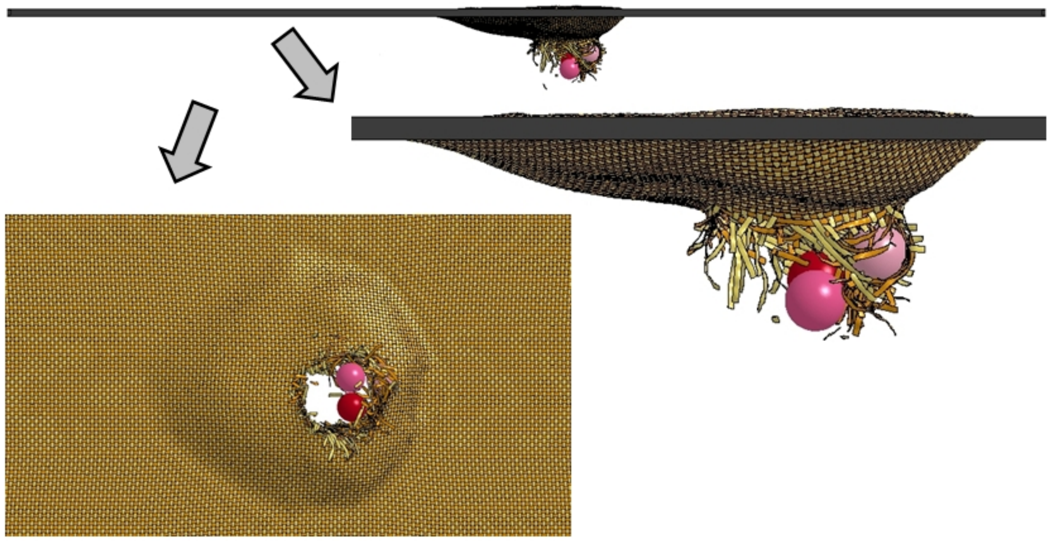


Figure 19.Deformation and failure states during the oblique multi-hit impact of a multi-layer Kevlar S706 fabric target simulated using a supercomputer

Supercomputing infrastructure is also required to model full-scale 3D filament-level yarns such as those shown in Figure (11). As the degree of modeling resolution increases (i.e. modeling lower length scales), the number of contact pairs dramatically increases. The handling of such large 'contact' in the FE model, in addition to the number of elements drives up the memory requirements of the model, requiring nodes with large amounts of memory and fast interconnects to ensure high-speed inter-nodal communication. Beyond a certain point, the use of additional nodes and processors results in diminishing returns, i.e. the common plateau effect observed in high performance computing.

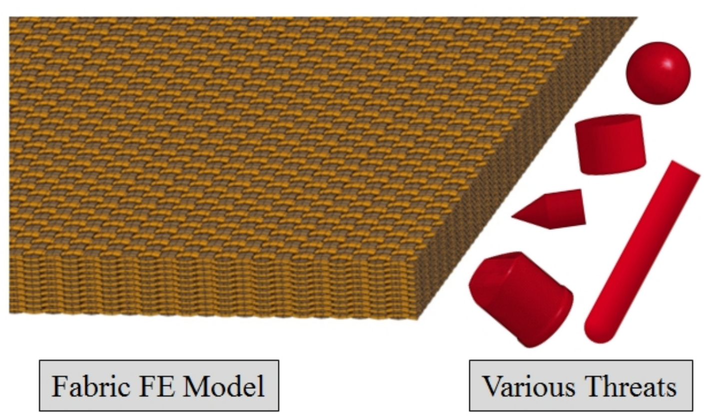
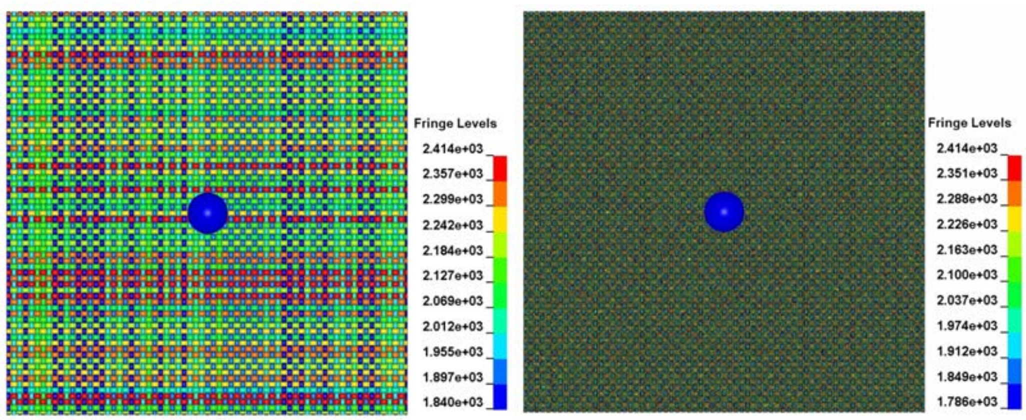


Figure 20.Multi-layer Kevlar S706 fabric target with various projectile threats

Probabilistic Modeling of Fabric Ballistic Impact and Numerical Prediction of the V_0-V_{100} Curve

The entire body of work dealing with the modeling of fabric impact in the literature is deterministic in nature and can neither account for the inherent statistical variability in geometry and material nor model the probabilistic penetration response of woven fabric. While deterministic simulations are very useful to gain insight and assess simple trends in the fabric impact response and quickly explore the role of material and architecture, they cannot be used to assess the actual, real-world fabric penetration response which is probabilistic in nature. Hence deterministic models cannot be used to design fabric armor or compare the performance of different armors, wherein knowledge of parameters such as the V_1 and $V_{0.1}$ velocitiesis critical.

Nilakantan et al. [6,7,9]overcame this problem by developing a probabilistic computational framework. First the experimentally characterized sources of variability are mapped into the FE model using various mapping techniques. For example statistical yarn strengths can be mapped into the fabric FE model by assigning each yarn to a different tensile strength such that the histogram of mapped strengths corresponds to the experimental strength distribution. A sample yarn-level strength mapping is shown in Figure (21a). The mapping of strengths can also be done at an element-level as shown in Figure (21b).



(a) (b)

Figure 21.Mapping of statistical yarn tensile strengths into the homogenized yarn-level fabric FE model using (a) yarn-level mapping (b) element-level mapping

Next, a series of impact simulations are run at varying impact velocities and the outcome (penetration or non-penetration) is recorded. The choice of projectile impact velocity for each simulation can be obtained using statistical shot selection strategies (e.g. Langlie or Neyer-D) or by operator intuition. Each impact simulation uses a different mapping. Finally, statistical analysis techniques are used to determine the V_0-V_{100} or PVR curve, which involves the fitting of a curve (usually the Normal distribution) to the test shot data. Other sources of intrinsic and extrinsic variability can also be considered, such as inter-yarn friction wherein each yarn-yarn contact pair has a differently assigned static and dynamic friction coefficient based on observed experimental results [4]. Another example is the precise projectile impact location relative to the principal yarns because it is experimentally difficult to control the precise impact location around the fabric dead center, which varies between hitting a yarn cross-over location and the gap between two yarns. Figure (22) displays twenty five possible projectile impact locations considered during one such implementation of the probabilistic computational framework. Each impact simulation randomly utilizes one of the possible impact locations.

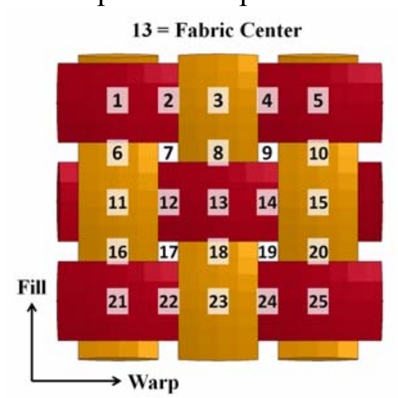


Figure 22. Projectile impact locations

Figure (23) provides exemplary results from a study [8]that sought to relate variability in tensile yarn strengths with the fabric PVR curve for a given impact scenario and excluding all other sources of variability. Different variants of the original 600 denier Kevlar KM2 spool yarn tensile strength distribution were considered, that differed either in the mean strength or degree of variability, and for each distribution a fabric PVR curve was generated. Such an exercise cannot be conducted experimentally because it is neither possible to isolate the various sources of variability nor to decouple them from each other. This demonstrates the usefulness of the probabilistic computational framework, in systematically studying the effect of isolated and coupled sources of intrinsic and extrinsic variability for a plethora of impact scenarios.

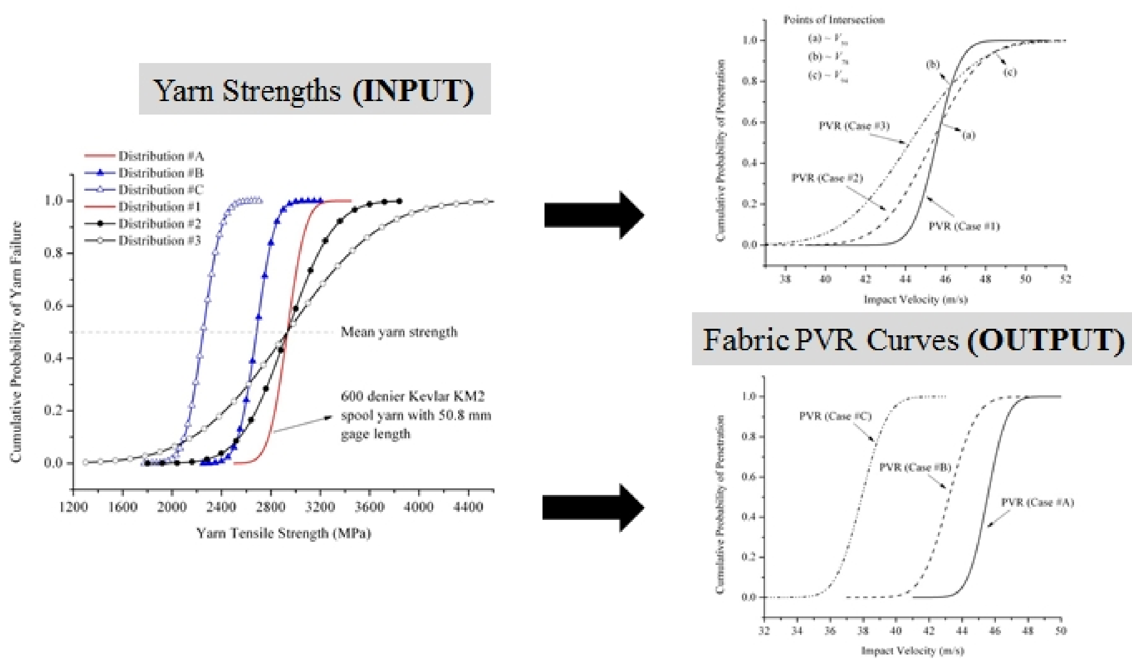


Figure 23.Relationship between statistical yarn tensile strengths and probabilistic fabric impact response obtained through FEA simulations

CONCLUSIONS

Predictive numerical modeling of the ballistic impact of woven fabric targets is an extremely challenging problem. There is an increasing need to reduce the weight of fabric armor while improving its penetration resistance to enhance soldier performance and protection. Understanding the various interactions and mechanisms at every length scale and bridging these length scales together will enable the systematic and strategic tailoring of geometry, material, interface, and architecture to optimize the performance of fabric armor. This forms the basis of a materials-by-design approach, consisting of focused experimental testing and numerical modeling at every length scale. Our ongoing work (Nilakantan et al.) over the past several years has addressed various components of the materials-by-design approach and contributed significantly to the advancement of the state of the art in ballistic impact modeling of woven fabrics. The statistical experimental characterization of the geometry and material of the woven fabric and its constituents, as well as the development of the probabilistic computational framework has led to the first time that the entire fabric V_0-V_{100} curve can be predictively estimated numerically. When coupled with advancements in image-based filament-level modeling that will improve the predictability of homogenized yarn-level fabric models, and the modeling of realistic sized fabric targets using supercomputing infrastructure, our research work will provide the capability to predictively model the probabilistic ballistic impact response of fabric targets and begin to reduce the dependence on experimental impact testing at ballistic gun ranges. More importantly, our work will ultimately provide a virtual environment to test conceptual architectures, interfaces, and materials and help engineers design new, improved, and lightweight fabric armor.

While this paper has primarily focused on summarizing the body of work by Nilakantan et al. [1-14]that is relevant to the state of the art in woven fabric ballistic impact modeling, there have been numerous publications in the literature by other authors dealing with various topics within this broad research area. Their lack of inclusion in the list of cited references is in no way meant to diminish their contribution to the scientific literature; merely that it was beyond the intended scope of this paper.

ACKNOWLEDGEMENTS

Computation for portions of the work described in this paper was supported by the University of Southern California Center for High-Performance Computing and Communications (hpcc.usc.edu). GN and SN acknowledge current support (2012-2014) from the M.C. Gill Composites Center. GN acknowledges previous support (2007-2012) by the Army Research Laboratory (ARL), Aberdeen Proving Grounds, MD andmany helpful discussions and technical input provided by Dr. Eric Wetzel (ARL) and Dr. James Zheng (PEO-Soldier).

REFERENCES

[1] Nilakantan G, Nutt S. Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor. Composite Structures Accepted, 2014.

[2] Nilakantan G, Nutt S. Effects of clamping design on the ballistic impact response of soft body armor. Composite Structures 2014;108:137-150.

[3] Nilakantan G. Filament-level modeling of Kevlar KM2 yarns for ballistic impact studies. Composite Structures 2013;104:1-13.

[4] Nilakantan G, Gillespie Jr. JW. Yarn pull-out behavior of plain woven Kevlar fabrics: Effect of yarn sizing, pull-out rate, and fabric pre-tension. Composite Structures 2013;101:215-224.

[5] Nilakantan G, Wetzel ED, Bogetti TA, Gillespie Jr. JW. A deterministic finite element analysis of the effects of projectile characteristics on the impact response of fully clamped flexible woven fabrics. Composite Structures 2013;95:191-201.

[6] Nilakantan G, Gillespie Jr. JW. Ballistic impact modeling of woven fabrics considering yarn strength, friction, projectile impact location, and fabric boundary condition effects. Composite Structures 2012;94(12):3624-3634.

[7] Nilakantan G, Wetzel ED, Bogetti TA, Gillespie Jr. JW. Finite element analysis of projectile size and shape effects on the probabilistic penetration response of high strength fabrics. Composite Structures 2012;94(5):1846-1854.

[8] Nilakantan G, Keefe M, Wetzel ED, Bogetti TA, Gillespie Jr. JW. Effect of statistical yarn tensile strength on the probabilistic impact response of woven fabrics. Composites Science and Technology 2012;72(2):320-329.

[9] Nilakantan G, Keefe M, Wetzel ED, Bogetti TA, Gillespie Jr. JW. Computational modeling of the probabilistic impact response of flexible fabrics. Composite Structures 2011;93:3163-3174.

[10] Tabiei A, Nilakantan G. Multi-scale ballistic impact simulation of dry woven fabric with elastic crimped fibers. International Journal of Vehicle Structures and Systems 2011;3(2):74-79.

[11] Nilakantan G, Abu-Obaid A, Keefe M, Gillespie Jr. JW. Experimental evaluation and statistical characterization of the strength and strain energy density distribution of Kevlar KM2 yarns: exploring length-scale and weaving effects. Journal of Composite Materials 2011;45(17):1749-1769.

[12] Nilakantan G, Keefe M, Bogetti TA, Gillespie Jr. JW. Multiscale modeling of the impact of textile fabrics based on hybrid element analysis. International Journal of Impact Engineering 2010;37(10):1056-1071.

[13] Nilakantan G, Keefe M, Bogetti TA, Adkinson A, Gillespie Jr. JW. On the finite element analysis of woven fabric impact using multiscale modeling techniques. International Journal of Solids and Structures 2010;47(17):2300-2315.

[14] Tabiei A, Nilakantan G. Ballistic impact of dry woven fabric composites: A review. Applied Mechanics Reviews 2008;61(1):010801-010813.