Virtual Ballistic Testing of Kevlar Soft Armor: Predictive and Validated Modeling of the V0-V100 Probabilistic Penetration Response using LS-DYNA®

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Abstract

Over 15 years of worldwide research into the ballistic impact modeling of woven aramid fabrics used in soft armor based on yarn-level fabric finite element models has been unable to achieve any quantitatively-predictive and validated capability to predict the V_0-V_{100} probabilistic penetration response of the fabric against various threats. For the first time ever, we demonstrate such a capability and the comprehensive framework behind it that brings together highly focused research across several fronts enabling a close synergistic interplay between experiments, statistical analysis, and finite element modeling. The exemplar scenario chosen to demonstrate this capability comprises a fully-clamped, single-ply, Kevlar S706 plain-weave fabric impacted by two types of 0.22 cal projectiles: a 11-gr sphere and a 17-gr FSP. The fabric model comprises individually-modeled 3D yarns with a user-defined material model. Observed stochastic variability in material properties and testing are mapped into the model to enable probabilistic outcomes. The model accurately predicts the experimental V_0-V_{100} curves for both the 0.22 cal projectiles. The model also captures the spread in projectile residual velocities over the range of penetrating experimental test shots conducted, including variability in projectile exit trajectories.

The Current State of FEA for Ballistic Impact Modeling of Composite Armor

The design and testing of fabric (soft armor, e.g. Kevlar) and composite (hard armor, e.g. S2-glass/epoxy) armor continues to be predominantly guided by destructive experimental testing: the resulting high material, labor, equipment, and testing costs with associated long lead times serve as a barrier to the rapid exploration of and early-stage inception of new weaves, materials, and processes into soldier and vehicle armor platforms. While virtual prototyping and virtual testing (VP-VT) of such armor will be disruptive in the field, the current reliance is on historical empirical databases and iterative trial-and-error, build-and-shot approaches. Computer models and simulation tools such as finite element analysis (FEA) do provide some input and guidance to the armor design and performance evaluation process, however their tool maturity levels (TML) continue to be very low and from a practical perspective, they are currently incapable of reducing dependence on experimental prototyping and destructive testing in any significant way. Thus most of the current work on developing FEA models of ballistic impact of fabric/composite armor remain largely academic exercises, and worse still, many rely on blind model calibrations or 'knob-turning' simply to match some experimental impact test dataset that itself may be questionable. Consider the task of modeling the ballistic impact of woven Kevlar fabrics used in body armor. Figure (1) demonstrates the many elements that must be individually addressed and synergistically brought together as part of a comprehensive framework, in order to successfully create a predictive modeling capability that accounts for the complex multi-scale and probabilistic material response. Over several years and across different organizations, Nilakantan [1-14] has put in place such a comprehensive framework that has simultaneously advanced the state-of-the-art in associated experimental test methodologies, virtual microstructure and mesh generation techniques, constitutive material modeling and UMAT implementation, statistical analysis and mapping techniques, and finite element impact modeling. Initial identification of this framework was critical to the later success of this work. However in the literature, a similar dedicated effort and comprehensive framework for both fabric and composite armor is rarely seen amongst any research group. Instead, it appears that the efforts of many academic research groups are siloed and disparate, focusing only on isolated modeling tasks or on isolated experimental testing with little coordination or coherence amongst themselves; with most studies simply geared towards generating journal publications, yet claiming to some degree of having developed advanced or validated models that "*could be used to design improved and lightweight armor*". Over 15 years of such research efforts and practices have failed to produce a quantitatively predictive modeling capability for the probabilistic penetration response of fabric and composite armor.

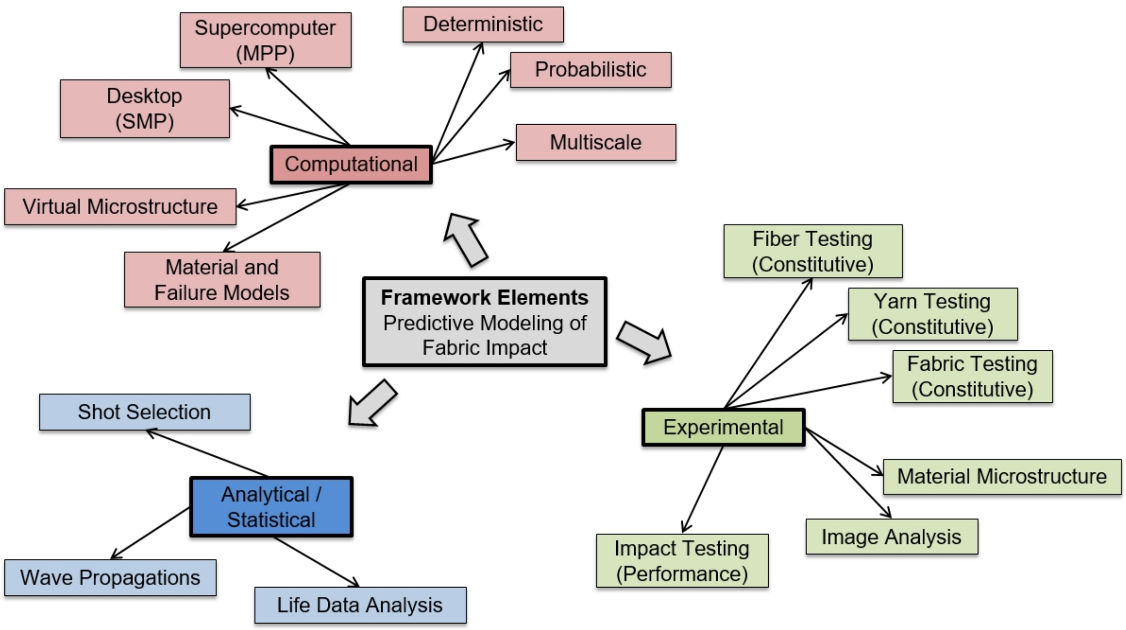
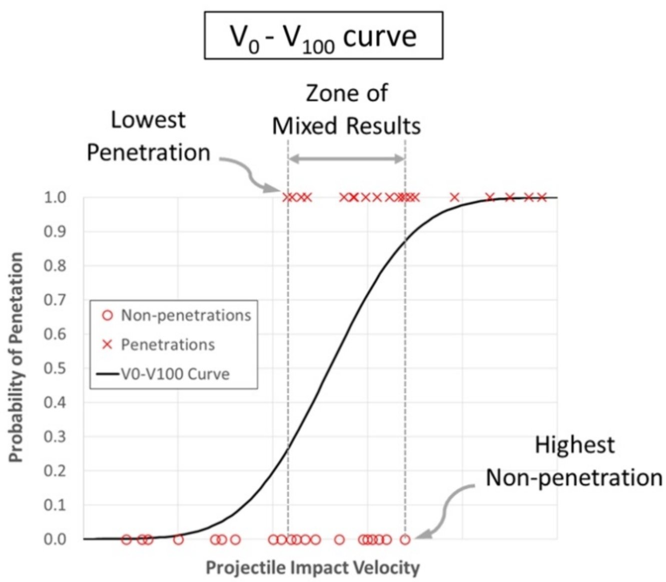


Figure 1. The various experimental, computational, and statistical elements as part of a comprehensive framework required for the predictive modeling of the ballistic impact of woven fabrics

Unfortunately, this will continue to be the case unless a comprehensive framework is first developed and then all the elements such as those shown in Figure (1) are tackled as part of a comprehensive strategy with strong interplay and data flow between the various elements (e.g. experiments guide and validate the models, models help refine experimental methodologies and test conditions, V&V protocols, TML assessments, etc.). In the United States, another potential barrier remains the lack of long-term funding commitments (e.g. 5-10 years) by various DoD agencies and corresponding program managers and scientists therein, that may themselves tend to be siloed and sometimes lacking in long-term research vision and the depth of technical expertise needed to address such a complex problem, resulting in the pursuit of several disparate short-term (e.g. <= 3 years) research programs that do not always align towards a well-defined overarching goal and fails to properly leverage previous/ongoing work. This has been particularly true over the past 15 years for Kevlar-based fabric impact modeling. An interesting report by the US Army Research Lab [15] alludes to this problem within DoD labs: "*managers in the labs often have some technical background to include research, but in many cases their research record is rather average or even mediocre. While not incompetent in the management of science, they often lack the ability to understand diligent progress in quality basic research, relying on metrics to compensate for their lack of technical prowess. This results in acceptable—but not stellar—management and likely causes the uncertainty in managers when determining whether a researcher is truly playing in a sandbox or not*". In the past decade, '*buzz-word*' and '*over-hyped*' armor research has become widespread amongst DoD-funded 6.1 basic research, especially biomimetic armor and nanotechnology - nanocomposite armor, however almost none of these technologies have been feasibly demonstrated at scale and remain academic exercises at small coupon levels geared towards generating highly-cited journal publications, moreover many claim without any serious basis for doing so that their work "*may help materials scientists develop lightweight and effective body armor for soldiers, police, and others*". Unfortunately, many millions of research dollars and a decade later, the words '*may help*' have still not yet translated to '*have helped*'.

Deterministic vs Probabilistic Penetration Responses

The penetration response of woven fabric armor is probabilistic in nature, based on several sources of intrinsic and extrinsic stochastic variability encompassing the fabric (e.g. material properties, weave architecture and geometry), projectile (e.g. material properties), and testing (e.g. impact location, projectile trajectory). For example, the fiber diameter, the fiber and yarn tensile strength, and inter-yarn friction are statistical in nature while the precise projectile impact location relative to the yarns and the precise projectile orientation prior to impact can be random in nature. Figure (2a) displays the V_0-V_{100} curve or Probabilistic Velocity Response (PVR) curve, where V_x represents the projectile impact velocity V that has an X% probability of completely penetrating through the fabric target. The test shots are separated into non-penetrations (*at y=0*) and penetrations (*at y=1*). A Normal distribution is used to represent the V_0-V_{100} curve using Maximum Likelihood Estimation (MLE). The mean (μ) of the distribution represents the well-known V_{50} velocity parameter.



(a) **(b)**

Figure 2. (a) V_0-V_{100} curve and ZMR (b) V_{50} velocity as a misleading performance metric

Other distributions such as Logistic have also been used [16]. The region between the lowest penetrating shot velocity (V_P) and highest non-penetrating shot velocity (V_{NP}) such that $V_P < V_{NP}$ is referred to as the Zone of Mixed Results (ZMR), a consequence of the various intrinsic and extrinsic sources of stochastic variability during testing. Two metrics often used to assess and compare the performance of body armor systems are the back-face signature (BFS) and V_{50} velocity. The maximum allowable BFS, which determines if the armor provides sufficient protection against behind-armor blunt trauma (BABT) is 44 mm for 80% of all test shots at a 95% confidence level, and it should never exceed 50 mm [16]. The V_{50} velocity, which represents the projectile impact velocity that has a 50% probability of completely penetrating the armor target, can be estimated from a relatively few number of test shots (e.g. less than a dozen). However the V_{50} metric is not a very informative parameter. Instead, velocity performance metrics at the tail of the V_0-V_{100} curve, such as the V_1 or $V_{0.1}$ velocity, provide a better metric for armor applications, but require a large number of test shots to estimate with confidence (the precise probability level is determined based on acceptable risk). This issue is schematically demonstrated in Figure (2b) where the conclusion that hypothetical body armor system #1 is superior to #2 based on its higher V_{50} velocity is misleading because it has a lower V_1 velocity.

Material and Methods

Due to space restrictions, this section will only very briefly overview the experimental testing, statistical analysis, and finite element modeling methodologies developed and deployed as part of the comprehensive framework. For complete details, the reader is referred to other recent publications of Nilakantan et al. [1-3]. Figure (3) displays the ballistic test range comprising a smooth-bore gas gun with a gated velocity sensor and targeting laser cross-hairs, high speed cameras to track the projectile 3D trajectory and velocity, and the fabric target which uses a special sandwiched picture-frame construction with adhesive grip-taped inner surfaces to prevent fabric slippage. The fabric target comprises a fully-clamped, single-ply of greige Kevlar S706 fabric (nominal areal density 180 g/m^2, yarn span of 0.747 mm, 600 denier Kevlar KM2 yarns) with an exposed area of 101.6 mm x 101.6 mm. The 0.22 cal, 11-gr spherical projectile has a diameter of 5.556 mm, mass of 0.691 g, and is comprised of stainless steel (grade 440C). The 0.22 cal, 17-gr FSP projectile has a diameter of 5.461 mm, length of 6.142 mm, mass of 1.096 g, and is comprised of alloy steel (grade 4340). A total of 38 test shots are conducted for the sphere and 39 for the FSP projectile. Each fabric target is shot once at the center. The outcome (penetration=1, non-penetration=0) is recorded along with the projectile impact velocity (V_i), and residual velocity (V_r) in the case of penetrations. A statistical analysis is then conducted using SenTest (Neyer Software LLC [17]) to determine the V_0-V_{100} curve.

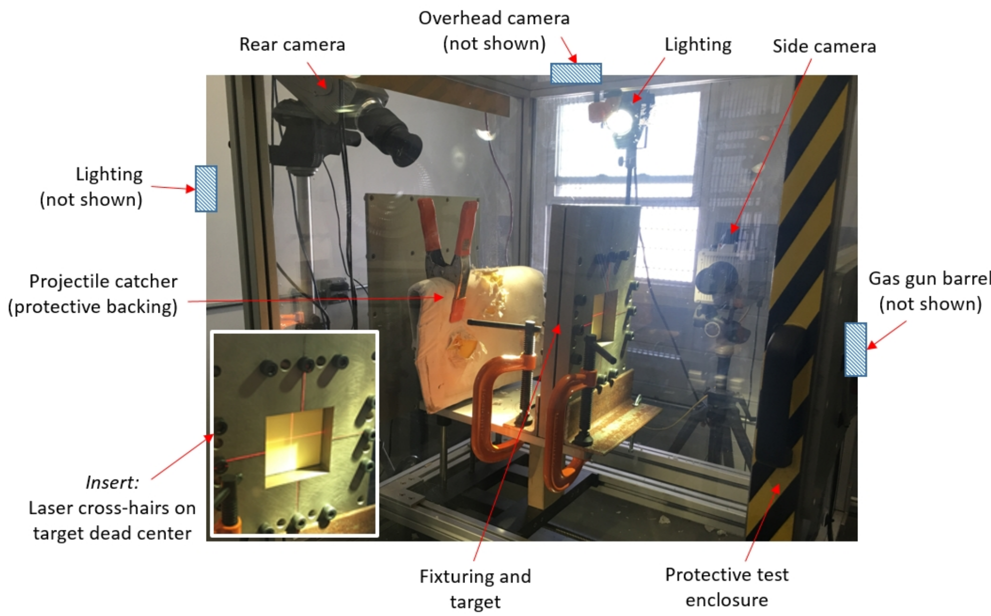
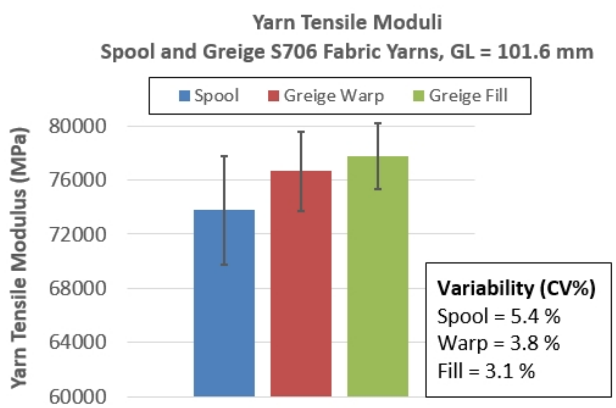


Figure 3. Ballistic test range and fabric target

Figure (4) displays the 600 denier Kevlar KM2 yarn tensile moduli and strengths at a gage length of 101.6 mm, for spool-extracted and greige fabric-extracted yarns. The yarns demonstrate statistical variability in both the tensile modulus and strength. The fabric extracted yarns demonstrate weaving strength degradations with the warp yarns showing greater extents of degradation. Another source of variability considered in this study is the inter-yarn frictional interactions. These have been previously experimentally characterized by Nilakantan et al. [12] using single yarn pull-out tests at varying rates from Kevlar S706 fabric patches under varying pre-tensions. Figure (5a) displays optical cross-sections of the greige fabric warp and fill yarns with the corresponding FEA mesh. Detailed validation of the virtual microstructure using image analysis against the experimental microstructure is available in Nilakantan et al. [3]. The yarns are discretized with single-integration point 3D hexahedral elements and assigned to a special user–defined material model. This UMAT overcomes the limitation of using the LS-DYNA in-built material model *MAT_002 along with zero Poisson ratios for the 3D homogenized yarns, which has been the standard practice in many previous FEA studies of fabric impact. Figure (5b) displays the FEA setup of the impact test scenario with the FSP projectile and a 101.6 mm x 101.6 mm fabric target. While a set of clamping fixtures is modeled for visualization, the boundary nodes of the fabric model are fully constrained across all degrees of freedom to simulate a perfectly clamped boundary. Figure (6) compares the spherical and FSP projectiles with their corresponding FEA meshes. The projectile is discretized with tetrahedral elements and assigned to a rigid material as no projectile deformation was observed during the experimental testing. Figure (7) displays close-ups of the impact site with the spherical and FSP projectiles. The vertical axis of rotation indicates the extent of projectile rotation (i.e. orientation of the flat impact face) just prior to impact. The sources of experimentally characterized variability need to be mapped into the FEA model in order to enable probabilistic responses. In this study, for the very first time ever, at least four sources of statistical variability have been simultaneously incorporated into the FEA model:

1. statistical yarn tensile strength
2. statistical yarn tensile modulus
3. statistical inter-yarn friction
4. random projectile impact location
5. random projectile rotation (for the FSP projectile only)



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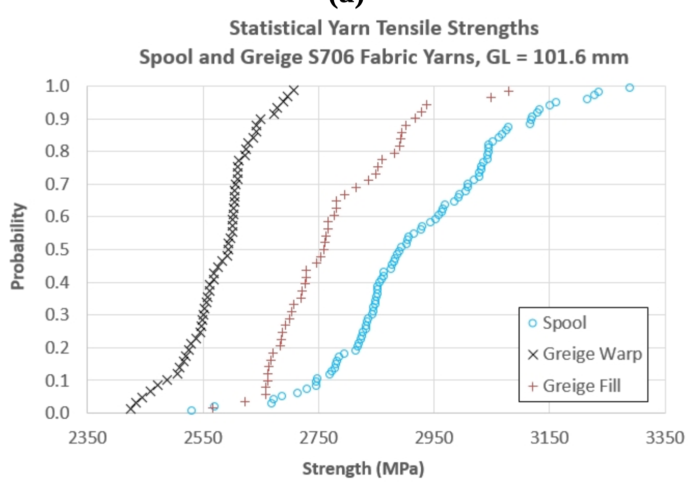


(b)

Figure 4. 600 denier Kevlar KM2 yarn properties at a gage length of 101.6 mm (a) Yarn tensile moduli (b) Yarn tensile strengths

Figure (8) displays an exemplary mapping of the experimental statistical greige warp and fill yarn tensile strengths (see Figure 4b) onto the individual warp and fill yarns of the fabric FEA model. In this mapping process, random numbers are used to query the statistical test data in order to determine the tensile strength assigned to each yarn. To verify the mapping process, a histogram of tensile warp and fill yarn strengths is generated for each fabric FEA model and then compared to the experimental yarn strength distributions. Once the strengths have been mapped, the corresponding greige warp and fill yarn tensile modulus is selected and mapped onto the yarns (see Figure 8), since each experimental yarn tensile test provides one combination of yarn tensile strength and modulus. The process is repeated to obtain the yarn strength mappings and corresponding yarn moduli for all the fabric FEA models (i.e. a total of 38 mappings for the spherical projectile impact scenario, and 39 for the FSP). Figure (9) displays the mapping of the statistical inter-yarn friction coefficients. Contact definitions are created between each of the 137 individual warp and 137 individual fill yarns in the fabric FEA model. Each warp-fill yarn contact pair, of which there are 137^2 combinations, is associated with a unique friction coefficient.

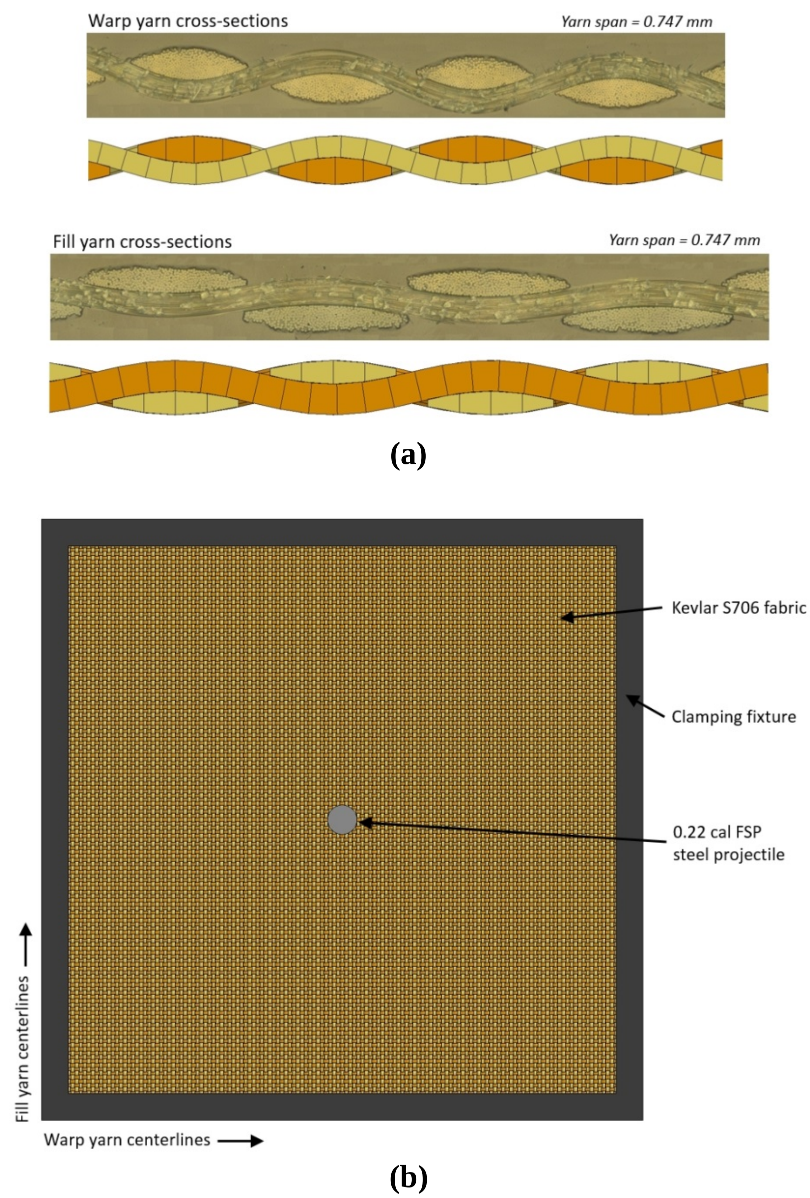


Figure 5. Fabric finite element models (a) Material and virtual yarn cross-sections (b) Impact test setup (*from the FSP projectile impact scenario*)

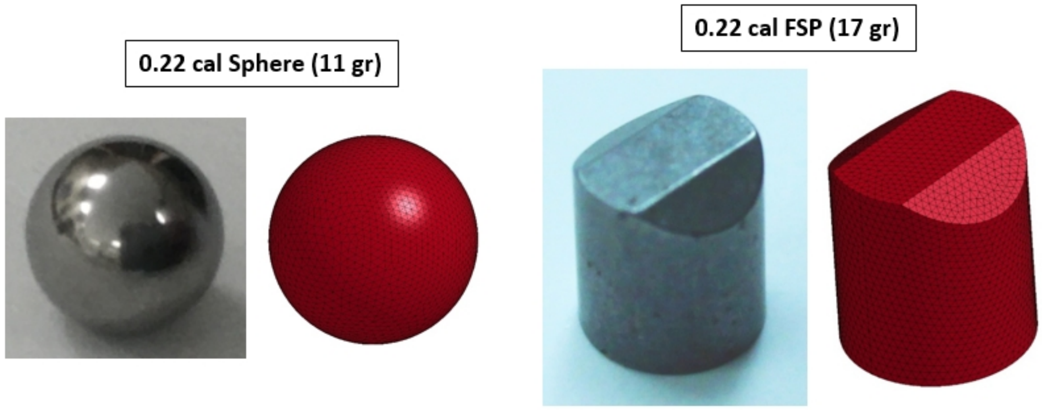


Figure 6. Experimental and virtual projectiles

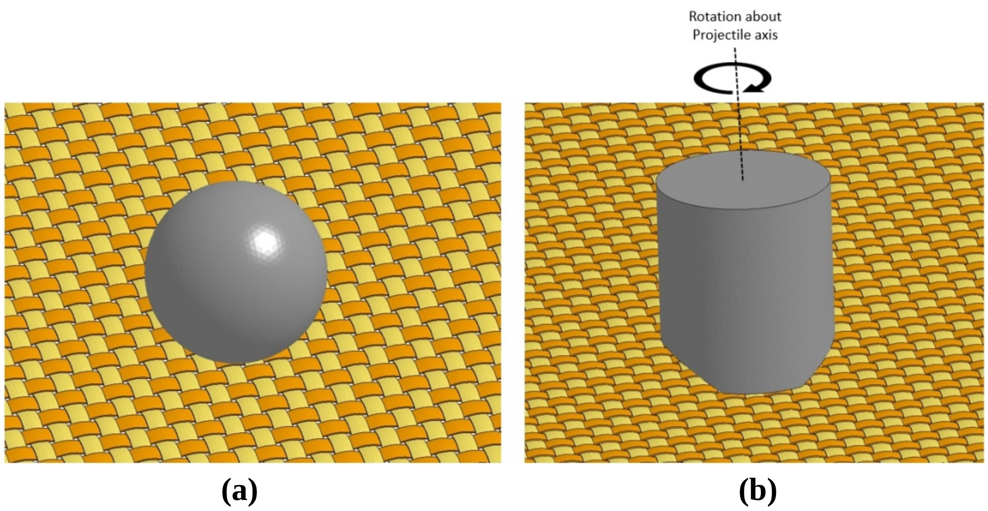


Figure 7. Close-up at the impact site (a) spherical projectile (b) FSP projectile

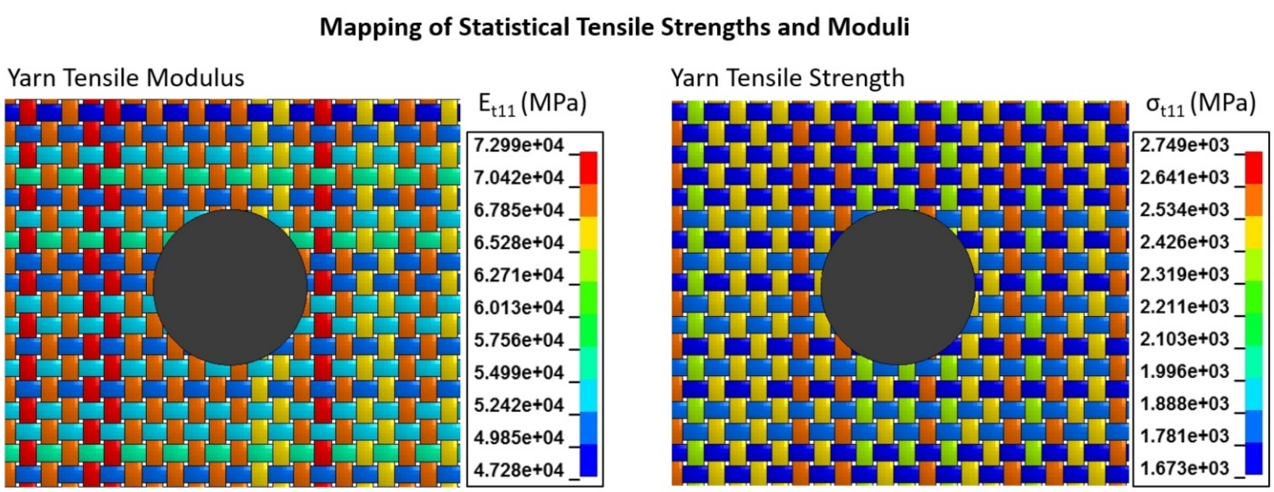


Figure 8. Mapping of statistical yarn tensile modulus and strength onto the individual yarns of the fabric finite element model (*from the FSP projectile impact scenario*)

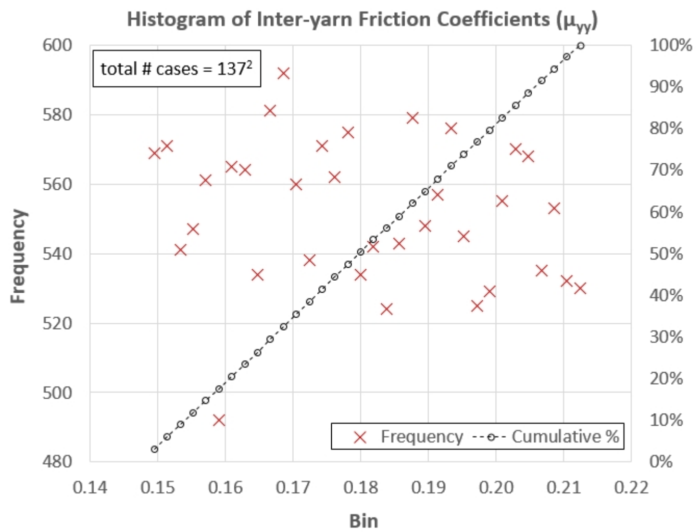


Figure 9. Mapping of statistical inter-yarn friction (*from the FSP projectile impact scenario*)

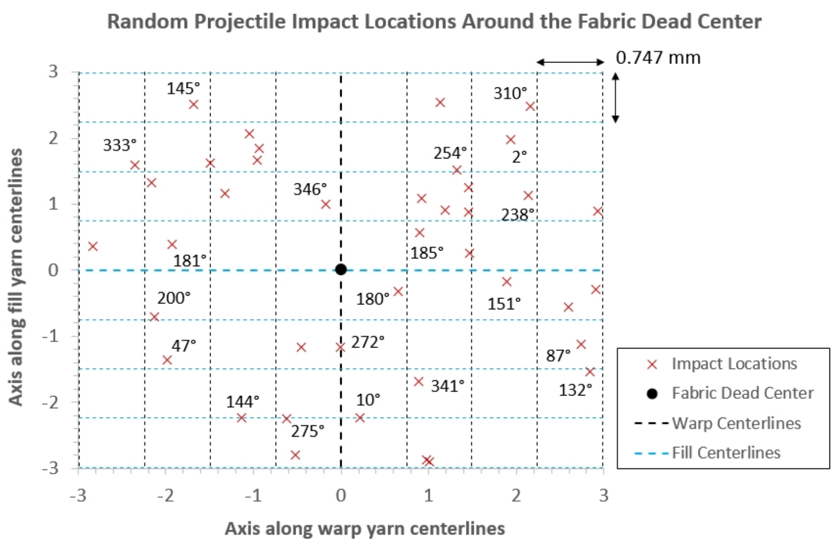
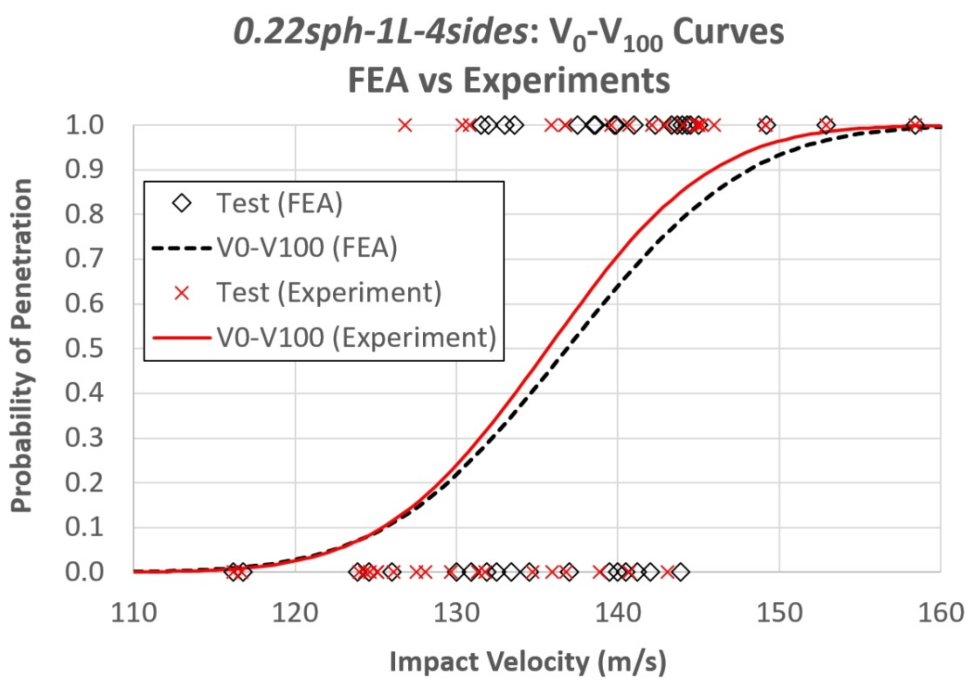


Figure 10. Random projectile impact locations and rotations (*from the FSP projectile impact scenario*)

Figure (10) displays the random projectile impact locations used in the 39 fabric FEA models generated for the FSP projectile impact scenario. For each random impact location, there is also a randomly assigned projectile rotation between 0° and 360° (see Figure 7b), some of which have been shown in Figure (10) for illustration. With the mapping process completed, a FEA simulation procedure very similar to the experimental procedure is adopted to generate the numerical fabric V_0-V_{100} curve for the given impact scenario. 38 fabric FEA models with unique mappings are created to compare against the 38 experimental fabric targets for the spherical projectile impact scenario, and similarly 39 for the FSP projectile impact scenario. Impact simulations are then executed on each model using LS-DYNA, with varying projectile impact velocities. Each fabric model is impacted once by the projectile around its dead center. The outcome of each test (penetration=1, non-penetration=0) along with the residual projectile velocity is used determine the next impact velocity, and finally to generate the numerical fabric V_0-V_{100} curve. During experimental testing with a single gas gun, test shots can only proceed one at a time. However computationally, multiple FEA simulations representing several test shots can be executed in parallel, leading to a more efficient determination of the V_0-V_{100} curve.

Results and Discussion

Figure (11) compares the experimental and FEA simulation results for the 0.22 cal spherical projectile impact scenario. Figure (11a) compares the experimental and numerical V_0-V_{100} curves, and there is excellent agreement between both. ***This constitutes the main result of this work, and is the world's first successful numerical prediction of the V_0-V_{100} curve using a yarn-level fabric FEA model.***



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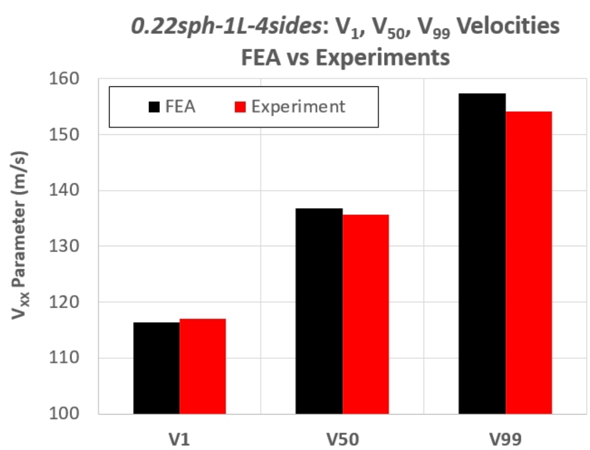
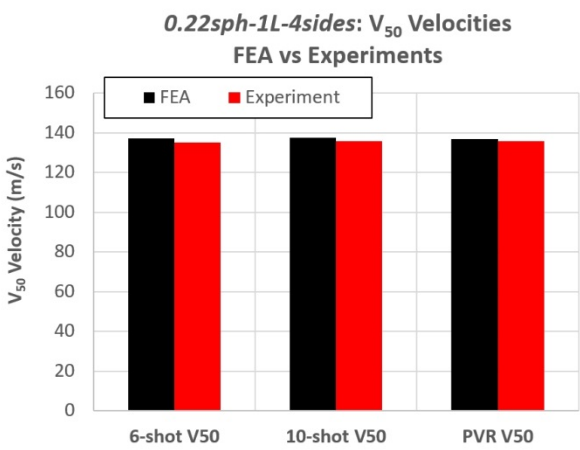
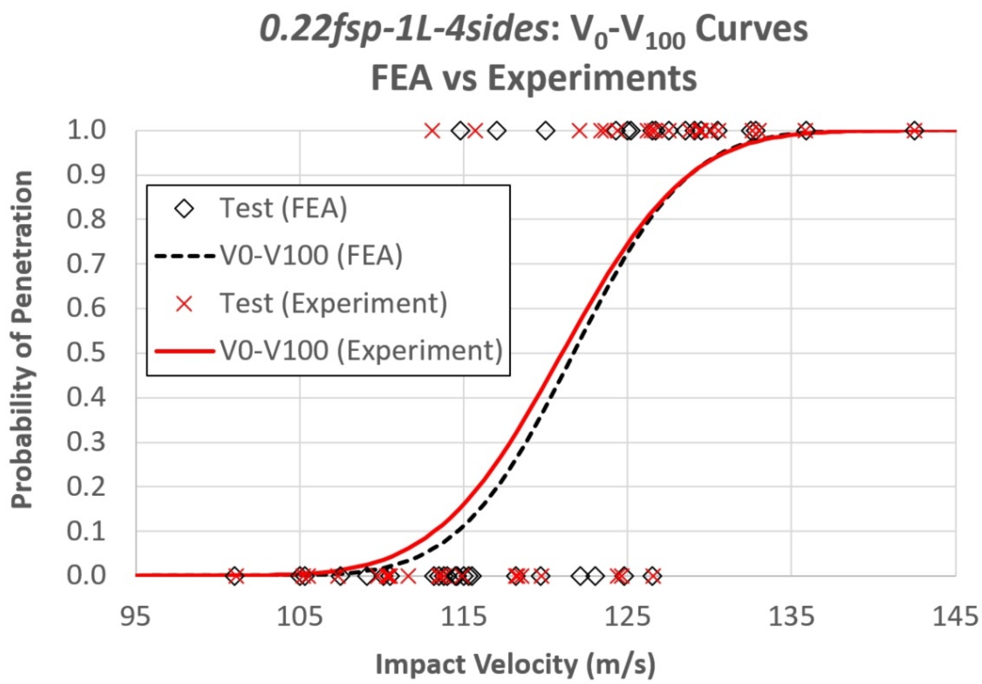




(b) **(c)**

Figure 11. Comparison of experimental and FEA results for the spherical projectile impact scenario (a) V_0-V_{100} curve and test shot data (b) V_1, V_{50}, and V_{99} velocities (c) V_{50} velocities



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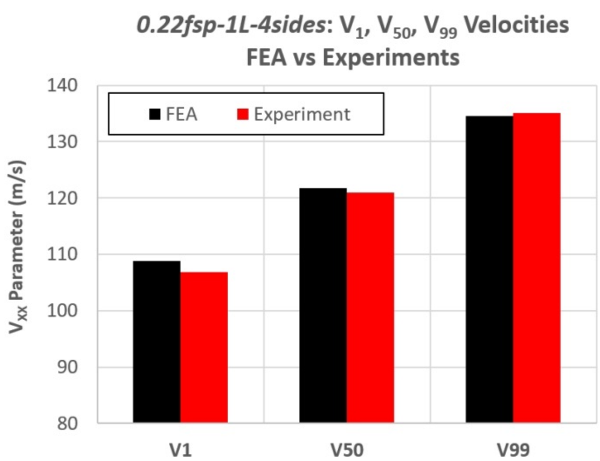

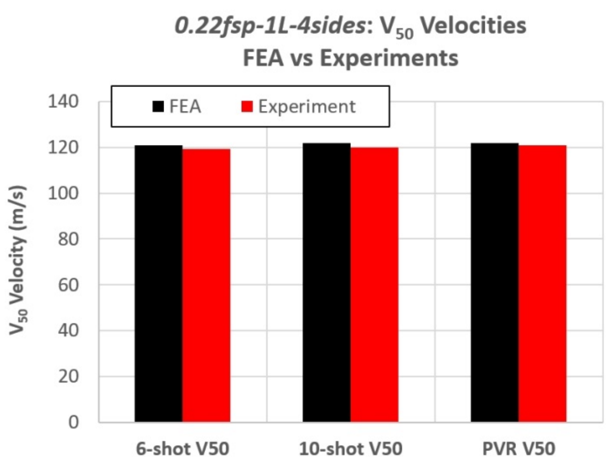

(b) **(c)**

Figure 12. Comparison of experimental and FEA results for the FSP projectile impact scenario (a) V_0-V_{100} curve and test shot data (b) V_1, V_{50}, and V_{99} velocities (c) V_{50} velocities

Figure (11a) also displays the 38 experimental and 38 numerical test shot impact velocities, with non-penetrations located at y=0.0 and penetrations at y=1.0. There is excellent agreement between the highest non-penetrating impact velocity (experimental V_i = 143.08 m/s, numerical V_i = 143.90 m/s) and good agreement between the lowest penetrating impact velocity (experimental V_i = 126.83 m/s, numerical V_i = 131.50 m/s), while the second lowest experimental penetrating V_i was 130.36 m/s. Figure (11b) compares the V_1, V_{50}, and V_{99} velocities, once again there is excellent agreement between the experimental and FEA simulation results. They are as follows in m/s (experimental, FEA): V_1 (117.08, 116.36), V_{50} (135.64, 136.85), and V_{99} (154.20, 157.33). Figure (11c) compares the experimental and numerical V_{50} velocities. The 6-shot V_{50} velocities were computed from the raw experimental and numerical test data sets by computing the average of the three highest non-penetrating and three lowest penetrating impact velocities, while five shots each were considered for the 10-shot V_{50} velocities. The 'PVR V_{50}' corresponds to the mean (μ) of the Normal distribution that is used to generate the V_0-V_{100} curve. For both the experiments and FE simulations, all V_{50} velocities were in excellent agreement. Figure (12) similarly compares the experimental and FEA simulation results for the 0.22 cal FSP projectile impact scenario. Once again, there is excellent agreement between the experimental and numerical V_0-V_{100} curves as seen in Figure (12a). ***This also constitutes the main result of this work, that the same framework has been successfully demonstrated for a different impact scenario.*** There is excellent agreement between the highest non-penetrating impact velocity (experimental V_i = 126.55 m/s, numerical V_i = 126.50 m/s) and between the lowest penetrating impact velocity (experimental V_i = 113.09 m/s, numerical V_i = 114.80 m/s), while the second lowest experimental penetrating V_i was 115.70 m/s. Figure (12b), which compares the compares the V_1, V_{50}, and V_{99} velocities, shows excellent agreement as follows in m/s (experimental, FEA): V_1 (106.89, 108.82), V_{50} (120.98, 121.68), and V_{99} (135.08, 134.54). Figure (12c) compares the experimental and numerical V_{50} velocities with excellent agreement.

Future Work

This work is far from being complete. The immediate next steps are to scrutinize the various assumptions made in the model, through further controlled experiments as well as parametric FEA studies and sensitivity analysis. The framework will also need to be validated for a larger-sized single-ply fabric target, to verify the process of mapping in corresponding yarn strength distributions at that particular (i.e. larger) gage length. Eventually, the framework will need to be applied to multi-ply fabric targets. Aside from issues of fixturing required to prevent boundary slippage during testing, further controlled experiments and modeling will be needed to characterize other fiber, yarn, and fabric deformation and failure modes characteristic of multi-ply fabric targets such as transverse compression and transverse shearing. Improved FEA material and failure models will need to be implemented that may require orthotropic elastic-plastic and rate effects. The use of backed targets (e.g. against backing clay or human surrogate materials) will add further complexity and requirements. To reduce computational time, the probabilistic methods presented in this study need to be coupled with multi-scale fabric models such as the Hybrid Element Analysis method developed by this author, that has previously shown large savings in run times and memory requirements while preserving the accuracy of deterministic baseline predictions. On the statistical side, improved shot selection and statistical analysis methods are needed to determine the minimum number of tests and spread in impact velocities and outcomes required for more efficient and accurate determinations of the V_0-V_{100} curve. We are beginning to address these and several other issues in a systematic manner using the framework and methods presented in this study as the basis.

Conclusions

This work represents the world's first fully validated and predictive probabilistic penetration modeling (i.e. V_0-V_{100} response) of a woven fabric subjected to ballistic impact, utilizing a fabric finite element model with individually modeled yarns. A probabilistic computational framework and mapping methodology was defined along with the necessary critical experimental tests at appropriate length scales and the necessary statistical analyses. While experimental validation of this probabilistic computational framework has been presented for two impact scenarios (viz. fully-clamped, single-ply fabric target against 0.22 cal sphere and FSP projectiles), this framework can readily be extended to other Kevlar fabric weave architectures as well as other continuous-filament woven fabrics comprised of materials such as UHMWPE (Spectra, Dyneema) and aramid (Twaron). The development of predictive computational techniques that can explicitly account for the experimentally characterized sources of statistical variability and generate a validated probabilistic penetration response will be disruptive in the field of armor design and modeling. Such a virtual capability will enable the rapid exploration of a vast conceptual design space comprising fiber material and weave architecture, at a fraction of the cost of prototyping such designs and experimentally characterizing the ballistic impact response. The work presented here demonstrates the first and feasible pathway towards that direction.

Acknowledgements and Disclaimer

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