

# Using LS-DYNA<sup>®</sup> to Computationally Assess the $V_0$ - $V_{100}$ Impact Response of Flexible Fabrics Through Probabilistic Methods

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## Abstract

*The probabilistic nature of the impact performance of flexible woven fabrics arises from a number of sources. The statistical nature of yarn tensile strengths on impact response is modeled in this study. Currently the probability of penetration of a fabric at a given velocity ( $V_x$  is the impact velocity having a probability of penetration of  $x$  ranging from 0 to 100%) is determined experimentally, by shooting fabric panels over a range of velocities and fitting the response data to a likely probabilistic function. This approach requires a large number of experimental test shots associated with significant cost, labor, and time in order to generate statistically meaningful results. In this study, we use the finite element (FE) analysis to study the impact response of flexible woven fabrics. A probabilistic framework is developed, that maps experimentally obtained yarn tensile strength distributions directly onto the FE model comprised of a yarn level architecture. Multiple impact simulations are run using a Monte Carlo approach. Through this novel probabilistic approach, the  $V_0$ - $V_{100}$  response of flexible woven fabrics can be predicted numerically. Further, a direct relationship between the statistical nature of yarn material properties and the probabilistic impact response of fabrics is established. This correlation allows an investigation into the effects of weaving and scouring degradations on the impact performance.*

**Keywords:** plain weave fabric, textile composite, probabilistic modeling,  $V_0$ - $V_{100}$ , impact response, finite element analysis, LS-DYNA

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## Introduction

The impact response of flexible woven fabrics used in impact resistant applications is probabilistic in nature. Such applications include personnel and vehicle protection against high energy impacting projectiles. Probabilistic parameters such as the  $V_{50}$  velocity are commonly used to assess the impact performance of these textile systems. The  $V_{50}$  velocity is the velocity at which there is a fifty percent probability of penetration. A more useful basis for assessing the impact performance is through the probabilistic velocity response (PVR) curve or  $V_0$ - $V_{100}$  curve.

This curve describes the probability of penetration as a function of impact velocity. There are many sources of variability which contribute to the probabilistic impact nature of textile structures and can be broadly categorized into intrinsic and extrinsic sources. Intrinsic sources comprise the geometrical and material parameters of the textile structure. For example the cross sectional area of a filament varies along its length and the arrangement and straightness of filaments within a yarn varies from one yarn to the next. The tensile strength of each filament within a yarn varies and as a consequence the yarn tensile strength varies from one yarn to another. Extrinsic sources of variability deal with sources external to the actual textile structure, particularly with the experimental impact testing conditions. For example the fabric pretension, clamping pressure, shot location, slippage from underneath the grips, projectile trajectory, and projectile characteristics such as size, shape, and surface roughness may vary from one test to another. Extrinsic sources of variability are sometimes detrimental to the study as they affect the response data in a manner which may bias or mask the ‘true’ probabilistic impact properties of a textile structure. While some sources of variability can be measured and characterized, other sources cannot and are difficult to control. For example experimental testing can be used to measure the tensile strength of yarns and then statistical methods can be used to characterize the yarn strength distribution. However fabric slippage from underneath the grips during experimental impact testing is very difficult to control or characterize. Similarly the exact shot location is difficult to experimentally control, which includes both impact point with respect to the fabric dead center and whether that impact point is at or in-between a yarn cross-over, which in turn could affect the outcome of the impact event.

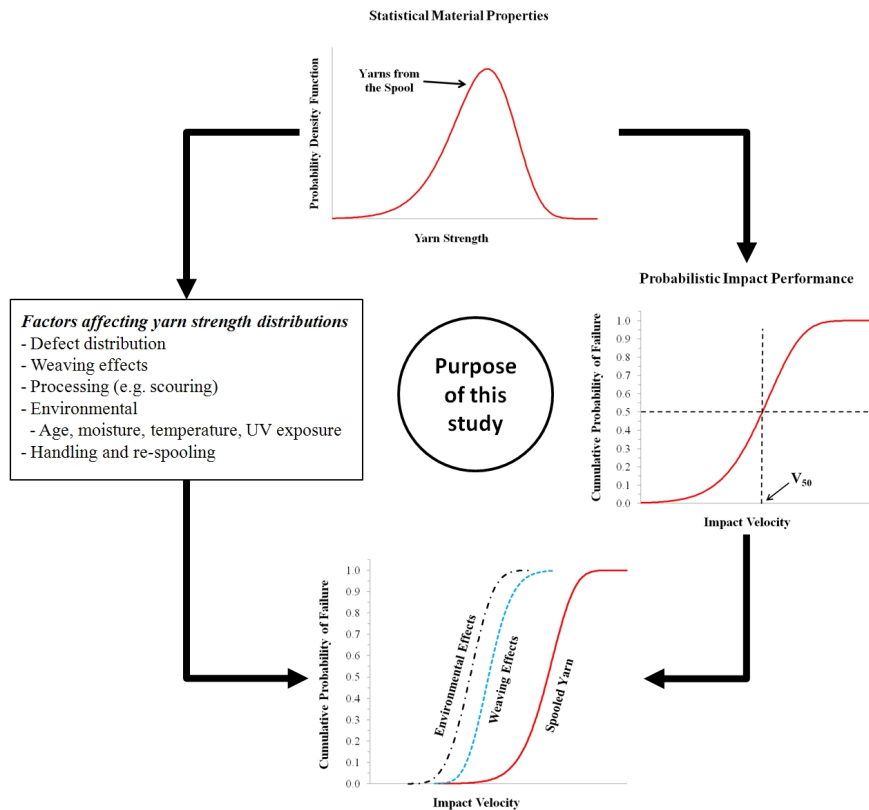


Figure 1. Summary of probabilistic impact modeling approach

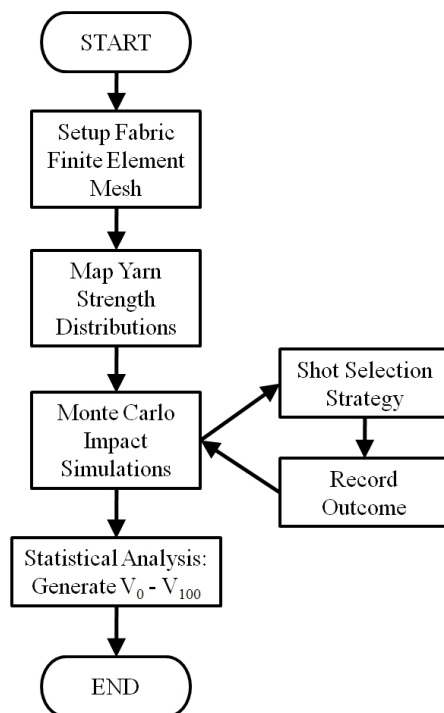
It is essential to be able to fully understand the effect of system variability on the probabilistic impact performance. It is also essential to develop a robust method that provides a systematic means to quantify the effect of each source of variability on the overall impact performance which would lead to the development of improved protective fabric systems. To this end we have developed a probabilistic computational framework that allows us to isolate and study the effect of many of the sources of variability on the probabilistic impact performance. For this study we choose to investigate the effect of statistical yarn tensile strengths on the probabilistic impact performance. By using a computational approach, many of the extrinsic sources of variability that could not be controlled experimentally can now be controlled in a precise manner.

Figure (1) provides an overview of this study. Statistical distribution functions are used to characterize the tensile strength distribution of the yarns that comprise the woven fabric structure. The computational probabilistic framework allows the effect of this strength distribution on the PVR curve to be studied. In addition, there are many factors that affect the statistical nature of yarn strengths. For example weaving processes and surface treatment processes such as scouring tend to degrade yarn strengths which in turn affect the statistical strength distributions. Similarly environmental factors such as temperature and moisture also affect the strengths. Using this framework, the effect of these weaving and scouring processes on the probabilistic impact performance can also be studied.

For the past decade the finite element analysis of woven fabric impact has been based on deterministic methods [1]. While these numerical studies proved useful in understanding yarn-yarn and projectile-fabric interactions, and mechanisms of deformation and energy dissipations, they lacked the ability to predict the probabilistic impact performance of fabrics. Instead of considering the statistical nature of yarn strengths, these previous models assume that all yarns within the fabric have the same strength. To highlight the limitation of this assumption, consider the experimental impact testing of fabrics used to generate the PVR curve. The PVR curve consists of a zone of mixed results (ZMR) in which some penetrating shots have an impact velocity lower than some non-penetrating shots. This behavior cannot be captured by a deterministic model unless some extrinsic factors, such as shot location or boundary conditions, are randomly varied with each impact condition. In contrast, a probabilistic model that includes intrinsic factors such as yarn strength variability is likely to generate a ZMR. For example a projectile may penetrate through a fabric if it engages a weaker set of yarns, however at that same impact velocity the projectile may not have penetrated had it engaged a stronger set of yarns. This underscores the limitation of deterministic based models. In this study we present a probabilistic computational framework and use it to relate the statistical nature of yarn strengths with the probabilistic impact performance. The effects of weaving and scouring on the impact performance are also studied.

### **Probabilistic Computational Framework**

Figure (2) provides an overview of the probabilistic computational framework. The first step is to create the finite element mesh of the woven fabric considered. A yarn level of resolution is selected where each yarn is homogenized (does not consider filament level architecture) and meshed using hexahedral elements. Dimensions of the yarn cross section and centerline undulations are obtained from micrographs. Next statistical yarn tensile strength distributions obtained from experimental testing are mapped onto the individual yarns of the FE model.



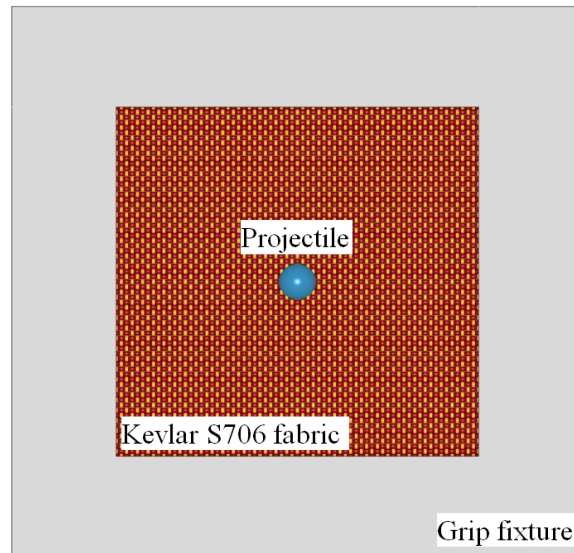
*Figure 2. Overview of computational probabilistic framework*

Thus each yarn within the fabric will be assigned to a particular tensile strength. It is important that the histogram of mapped strengths from the fabric model recreate the cumulative distribution function of the experimentally obtained statistical strength distribution to ensure that the mapping has been done correctly. Impact simulations are then run using a Monte Carlo method. This step involves creating multiple fabric FE models each having a unique strength mapping and then impacting it once at the center. For each impact simulation the outcome in terms of occurrence of penetration is recorded i.e. a non-penetration is assigned a value of zero while a penetration is assigned a value of one. Different shot selection strategies can be employed to choose the impact velocity for each test such as the Langlie [2] and Neyer-D [3] methods. Once the requisite number of tests has been completed, statistical analysis techniques are used to generate the PVR curve using the impact velocity and outcome for each test. This process involves fitting the data of impact velocity ( $x$ -axis) and probability of penetration ( $y$ -axis) using distributions such as the normal, lognormal, and logistic with the maximum likelihood estimator (MLE) method. For example the Neyer-D method uses a normal distribution to generate the PVR curve, while the standard NIJ 0101.06 [4] recommends using the logistic distribution with the MLE method.

### Test Case Study

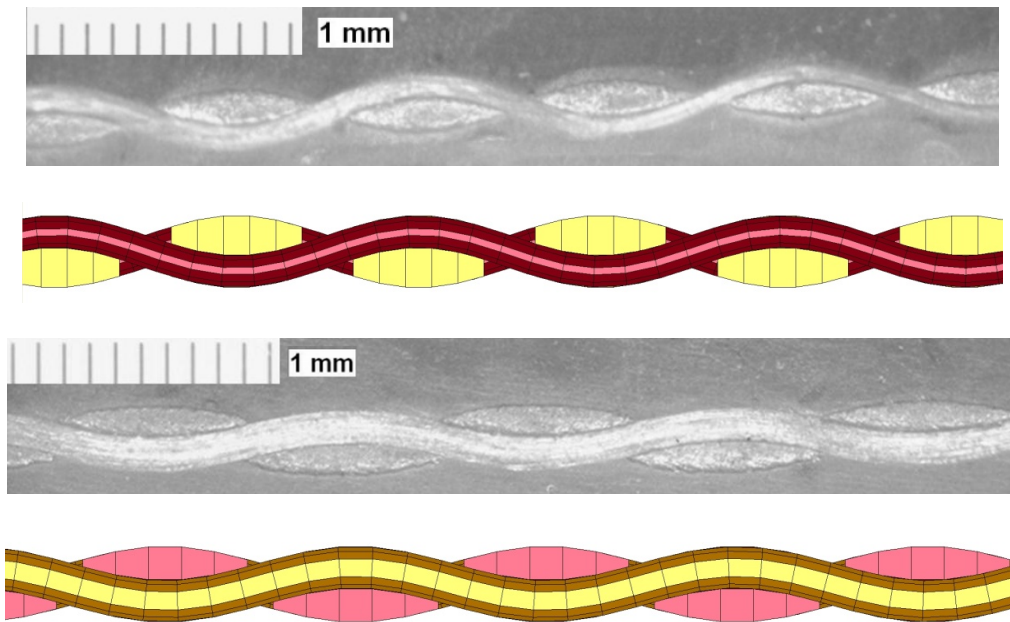
To demonstrate this probabilistic computational framework, we consider the impact of a plain weave Kevlar S706 fabric by a spherical projectile at the center of the fabric. The total in-plane dimensions of the fabric are 76.2 mm  $\times$  76.2 mm and the fabric is perfectly gripped on all four

edges (zero displacement boundary condition). The exposed area of the fabric is  $50.8 \times 50.8$  mm. The projectile is a 0.22 caliber smooth steel ball bearing with a mass of 0.692 g and a diameter of 5.556 mm. Figure (3) displays the numerical set up of the impact case.



**Figure 3. Computational setup of the fabric impact test**

This Kevlar S706 fabric is comprised of 600 denier Kevlar KM2 yarns with a count of 34 yarns per inch in the warp and fill directions, and an areal density of  $180 \text{ g/m}^2$ . Figure (4) displays micrograph images of warp and fill yarns in a Kevlar S706 fabric and the corresponding FE mesh. The yarns are modeled using single integration point solid elements (*LS-DYNA Type 1*). Five elements are used across the yarn width and one element through the thickness. By using an enhanced assumed strain stiffness hourglass form (*LS-DYNA Type 9*), it becomes possible to model the yarns with only one through-thickness element instead of the usual two elements as has been used in Refs. [5,6]. This simplification leads to dramatic savings in the model computational requirements. The left and right sides of the yarn cross sections are truncated to prevent generation of degenerate elements. Due to the homogenized yarn model that neglects filament level architecture, the filament volume fraction needs to be computed in order to adjust the material properties. The filament volume fractions are obtained by dividing the actual yarn cross sectional area (calculated based on manufacturer provided data on average filament diameter and number of filaments per yarn) by the finite element yarn cross sectional areas. The calculated volume fractions are as follows: (warp) 76.02% and (fill) 66.54%. The yarns are assigned a linear orthotropic elastic material model (*LS-DYNA Type 2*). The values of the three components of the shear modulus ( $G_{xy}$ ,  $G_{yz}$ ,  $G_{zx}$ ) are 148 MPa and those of the Poisson ratio ( $\nu_{xy}$ ,  $\nu_{yz}$ ,  $\nu_{zx}$ ) are 0.0 [7]. The tensile modulus of a single 600 denier Kevlar KM2 fiber is 82.6 GPa [8]. Accordingly, the tensile modulus of the homogenized finite element warp and fill yarns can be obtained by scaling the filament modulus by the filament volume fraction according to the simple rule of mixtures, yielding ( $E_{\text{warp}}$ ) 62.8 GPa and ( $E_{\text{fill}}$ ) 55.0 GPa. Yarn failure is incorporated using an element erosion technique based on a maximum principal stress failure criterion (*LS-DYNA \*MAT\_ADD\_EROSION*). The grips are modeled using rigid shell elements. Since it is desired to model a perfectly clamped system, with no fabric slippage, the nodes of the



**Figure 4. Micrographs and corresponding finite element model of the Kevlar S706 fabric (top) Warp trajectory with fill cross sections and (bottom) fill trajectory with warp cross sections**

yarn elements underneath the grips are constrained across all six degrees of freedom. The projectile is modeled using shell elements. Since the projectile was observed to undergo no deformation during comparable experimental impact tests, a rigid material model (*LS-DYNA Type 20*) was used for the projectile. An eroding surface to surface type contact algorithm was used between the projectile and the fabric (*LS-DYNA Type 14*). An eroding single surface type contact algorithm (*LS-DYNA Type 15*) was used for the warp and fill yarns at the impact region where yarn failure is observed to occur, while an automatic surface to surface type contact algorithm (*LS-DYNA Type a3*) was used for the yarns everywhere else. A coefficient of friction of 0.23 is used between the projectile and fabric, and 0.18 between the yarns of the fabric.

With the FE model set up, next the statistical yarn strength distributions obtained from the experimental tensile testing need to be mapped onto the individual yarns. Details of the experimental yarn testing and statistical analysis are available in Ref. [9]. Because of the homogenized nature of the yarn model, the measured yarn strengths need to account for the filament volume fractions of the warp and fill yarns. Figure (5) displays the adjusted statistical distributions of yarn strengths for 600 denier Kevlar KM2 yarns obtained from a spool, and extracted from the warp and fill directions of greige and scoured Kevlar S706 fabrics, with a gage length of 50.8 mm. The strength data has been adjusted by the computed warp and fill volume fractions. Each median rank in Figure (5) represents the cumulative probability of failure at a particular strength. Since the warp and fill yarns have different volume fractions, there are two spool strength distributions in Figure (5) that will be mapped separately onto the warp and fill yarns. The mappings lead to three fabric models (i) fabric with spool-based strengths (hypothetical baseline model) (ii) fabric with greige yarn strengths (iii) fabric with scoured yarn strengths. Figure (6) displays four sample mappings using spool based yarn strengths wherein the mapped strengths (refer to the color legend) of the warp and fill yarns pertain to the adjusted strength distributions shown in Figure (5). In this particular implementation, the entire yarn has

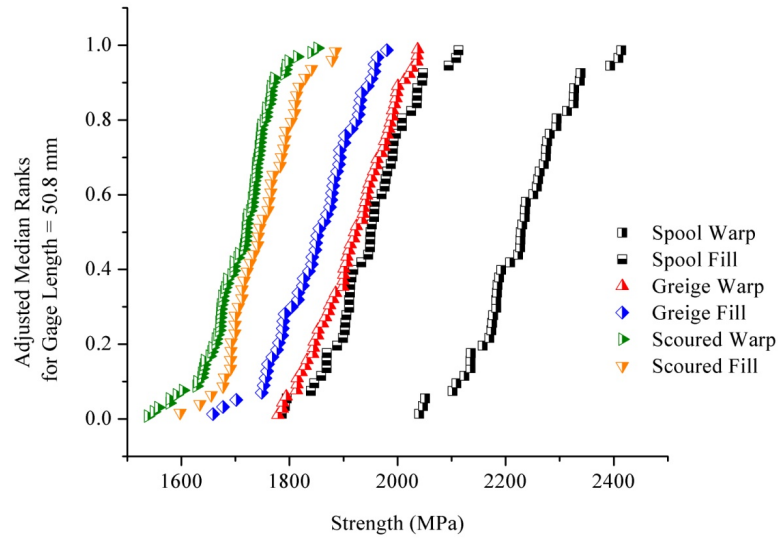


Figure 5. Adjusted strength distributions for the 50.8 mm gage length yarns

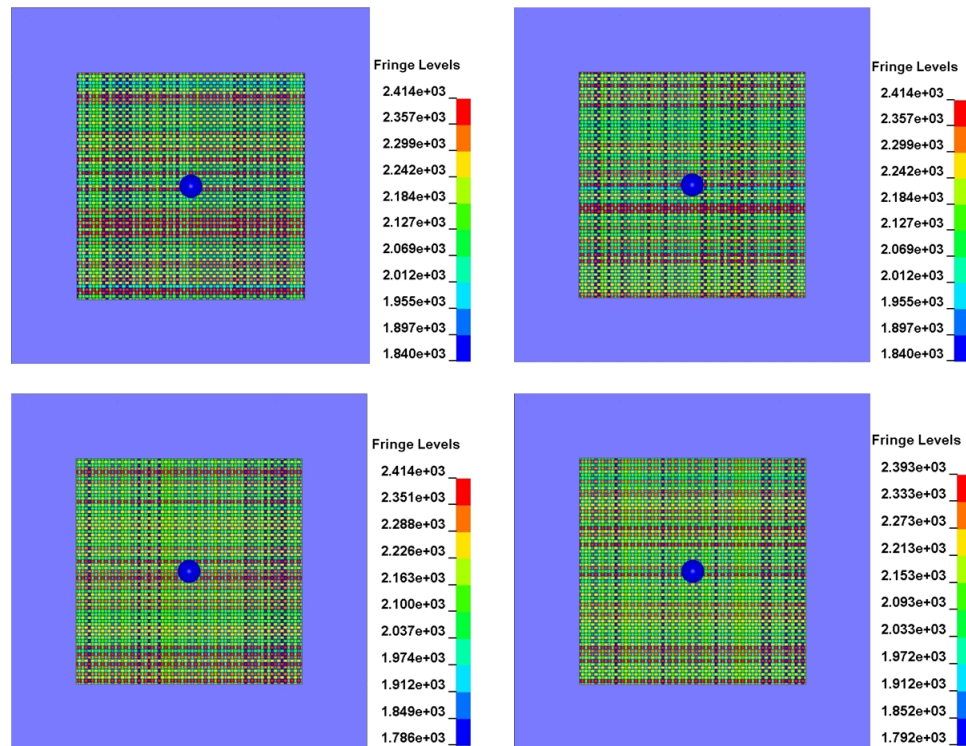
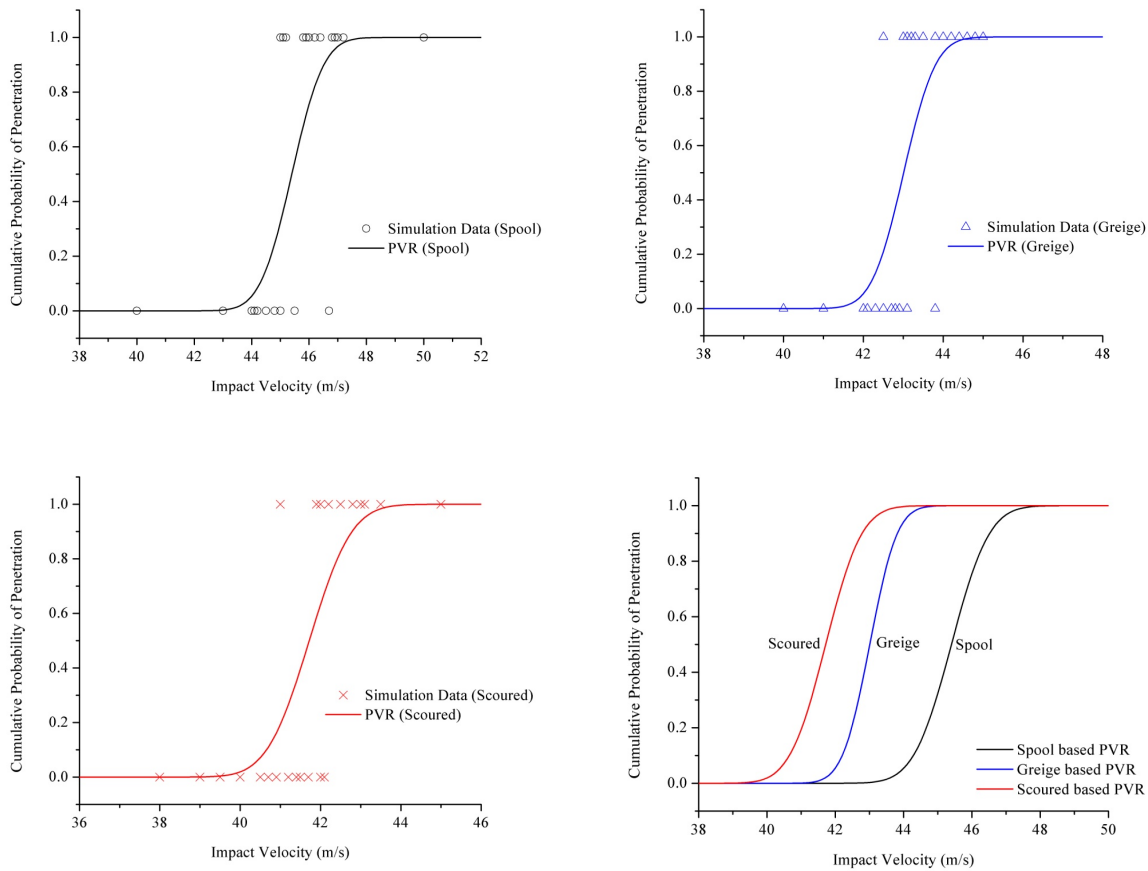


Figure 6. Sample yarn strength mappings using the spool-based adjusted strength distributions

been assigned to the same strength. This simplification will always result in yarn failure at the location of peak stress along a yarn, which is typically at or near the impact location, as seen

during the experimental impact testing of fabrics. Other mapping techniques are also possible, such as an element-by-element mapping method where each solid element in the yarn is assigned to a particular strength. An element-based strength mapping could predict failures at points outside of the peak stress location along a yarn, if the mapping randomly places high yarn strengths at the peak stress location and lower strengths outside of the peak stress location. A further consideration is that measured yarn strength is highly dependent on gage length due to the probabilistic nature of flaw presence in a yarn [9]. For the present simulations with the small fabric size, the longitudinal wave reaches the fabric boundaries well before the first instant of yarn failure, and this ensures that the entire length of yarn is loaded during most of the impact event. Therefore, we use strength distributions based on 50.8 mm gage lengths. For each of the three fabric model cases, thirty mappings are created for the subsequent Monte Carlo impact simulations.



**Figure 7. Simulation test data and PVR curves for the fabric models with yarn strengths based on (top left) spool, (top right) greige, and (bottom left) scoured conditions (bottom right) Comparison of PVR curves**

Methods such as Langlie and Neyer-D are often used during experimental impact testing to guide the choice of shot velocities. These strategies use the simple, binary penetration responses (no penetration ‘0’ or penetration ‘1’) of previous tests to determine the next shot velocity, thus tests proceed one at a time. This approach makes sense during experimental testing when only one gas



Table I. Normal distribution parameters used to fit simulation data

	<i>Spool</i>	<i>Greige</i>	<i>Scoured</i>
# shots	30	30	30
MLE estimate of $\mu$ (m/s)	45.40	43.01	41.72
MLE estimate of $\sigma$ (m/s)	0.87	0.63	0.83
$CV = \sigma/\mu$ (%)	1.92	1.46	1.99

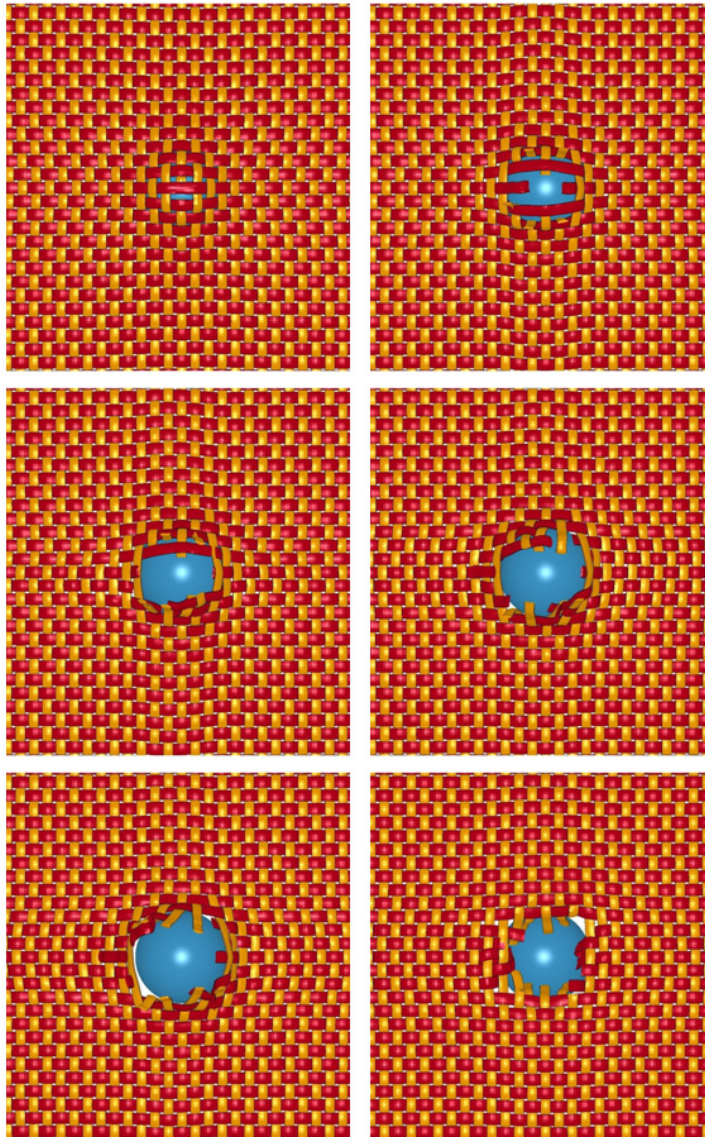
Table II. Comparison of probabilistic impact performance

	$V_1$ (m/s)	% drop in $V_1$	$V_{50}$ (m/s)	% drop in $V_{50}$	$V_{99}$ (m/s)	% drop in $V_{99}$
<b>Spool Based</b>	43.37	-	45.40	-	47.42	-
<b>Greige Fabric</b>	41.54	4.22	43.01	5.26	44.47	6.22
<b>Scoured Fabric</b>	39.79	8.25	41.72	8.11	43.65	7.95

gun or impactor is available. However a computational approach allows multiple simulations to be run simultaneously. Moreover the residual projectile velocity for penetrating cases is predicted directly by the simulation, unlike experimental testing where expensive equipment and data reduction techniques are often necessary to obtain such data. Using the residual velocity to guide the next shot velocity or set of shot velocities helps to converge upon the ZMR more rapidly than if only binary-type outcome data is used. In the present study, simulations were performed in simultaneous groups to rapidly generate penetration responses. The responses of each round of testing, including residual velocity values, were used to guide selection of the next set of simulation velocities, with a goal of achieving a large ZMR. Once the thirty runs for each fabric model have been conducted, the impact velocity data is plotted against the binary-type outcome data (0 or 1). This data set is then fit to a normal distribution function using the MLE method. Once the parametric distribution parameters have been determined, the entire PVR or  $V_0$ - $V_{100}$  curve can be generated. Since the normal distribution is symmetric, the mean ( $\mu$ ) corresponds to the  $V_{50}$  velocity. Figure (7) displays the results of all simulations for each fabric model. The ZMR is clearly identifiable in each figure, where some of the non-penetrating shots have a higher impact velocity than some of the penetrating shots. This important experimental phenomenon (ZMR) has been successfully captured by the computational probabilistic framework. Table (I) lists the parameters of the normal distribution ( $\mu$ =Mean,  $\sigma$ =Standard deviation) used to fit the simulation data. In Figure (7) the PVR curves are represented by the smooth lines, which are fitted to the data points (shown by the color symbols) that represent the outcome of each simulation run. Figure (7) also compares the PVR curves for the three fabric models. Compared to the spool strength based model, a clear shift towards the left in the greige and scoured fabric PVR curves can be seen indicating the weaker strength distributions of the greige and scoured fabrics have resulted in a poorer impact performance.

Table (II) lists the  $V_1$ ,  $V_{50}$ , and  $V_{99}$  velocities for the three fabric models, as well as the percentage drops in each velocity with respect to the hypothetical spool strength-based fabric. The mean experimental tensile strength of the yarns from the spool is 2.92 GPa [9]. Compared to this mean strength, the warp and fill yarns from the greige and scoured fabrics show percentage

strength reductions as follows [9]: 13.9% (greige warp), 5.14% (greige fill), 23.4% (scoured warp), and 10.3% (scoured fill). These reduced strength values result in a 5.26% drop in the  $V_{50}$  velocity of the greige fabric to 43.01 m/s and a 8.11% drop in that of the scoured fabric to 41.72 m/s, compared to the  $V_{50}$  velocity of 45.40 m/s for the spool strength-based fabric. The  $V_1$  and  $V_{99}$  velocities for the greige fabric respectively showed drops of 4.22% and 6.22% compared to the spool strength-based fabric while those for the scoured fabric were 8.25% and 7.95% respectively. For this fabric impact scenario where the fabric is gripped on all four sides, the primary mode of energy absorption is by tensile deformation of the yarns.



*Figure 8. Spool strength based fabric impacted at 45.9 m/s, deformation states at time instants of (a)155  $\mu$ s (b) 165  $\mu$ s (c) 170  $\mu$ s (d)175  $\mu$ s (e) 180  $\mu$ s (f) front view - 245  $\mu$ s*

The kinetic energy component of the fabric due to momentum transfer between the projectile and fabric is smaller, while the energy dissipated by frictional sliding between the yarns is very small. Thus the tensile strength of the yarns is a predominant factor that controls the penetration

event. It is important to note that the magnitude of the percentage drops in  $V_1$ ,  $V_{50}$ , and  $V_{99}$  velocities of the greige and scoured fabrics compared to the spool strength based fabrics were smaller than the respective drops in tensile yarn strengths. One reason is that the projectile engages multiple warp and fill yarns at the impact region. Thus the drop in impact performance is largely dependent on the nature of yarn strengths (combination of strong and weak yarns) in the impact region, the number of yarns engaged, as well as the type of fabric architecture since complex load transfer occurs between the woven warp and fill yarns after the first initiation of yarn failure at the impact region.

The strength data for spool, greige, and scoured yarns showed different mean strengths, but similar degrees of scatter, as measured by the coefficient of variation which varied between 3.59% to 4.12%. It is not surprising then that the PVR curves for fabrics composed of spool, greige, and scoured yarns show different  $V_{50}$  values, but also show similar coefficient of variation values which vary between 1.46% and 1.99%. This trend is visually apparent in Figure (7) where the widths or degrees of uprightness of the three PVR curves appear similar to each other. Figure (8) displays a few deformation states during penetration of the projectile through the fabric for the spool strength based fabric impacted at 45.9 m/s, which is slightly faster than the  $V_{50}$  velocity. Yarn failure is unsymmetrical about the fabric dead center which agrees with experimental observations, since the projectile engages yarns of different strengths around the impact region. The projectile is seen to penetrate through a hole smaller in size than the projectile's diameter. During this time the projectile pushes apart the unbroken warp and fill yarns at the periphery of the hole, which is accompanied by a rise in the projectile-fabric frictional energy dissipation. Quasistatic yarn properties have been used in this study due to the lack of such data at high strain rates [1]. However once such data is available it can be easily incorporated into this probabilistic framework.

## Conclusions

A novel probabilistic computational framework has been developed that simulates the effect of statistical yarn strength on the probabilistic penetration performance of a woven fabric. This model maps experimentally obtained yarn strengths directly onto the individual yarns of the fabric FE model. The framework was applied to Kevlar S706 greige and scoured fabrics. Using the results (projectile impact velocity and penetration history) from the Monte Carlo based impact simulations, probabilistic velocity response (or  $V_0$ - $V_{100}$ ) curves were generated for fabrics based on spool, greige, and scoured Kevlar KM2 yarn strengths. The predicted  $V_{50}$  velocity of the fabric based on the spool strengths was 45.40 m/s while that of the greige and scoured fabrics were respectively 43.01 m/s and 41.72 m/s. These trends in  $V_{50}$  can be directly attributed to the differences in yarn strength distributions for the spool, greige, and scoured yarns used in the model. These results show that degradations in inherent yarn strength can directly lead to decreases in a the  $V_{50}$  value of a fabric. Furthermore, the implementation of probabilistic yarn strength models directly enabled the prediction of a probabilistic fabric penetration response, a behavior that is rarely captured in traditional fabric impact simulations.

Using this probabilistic computational framework, by first isolating each source of variability for a given impact scenario and understanding its effect on the probabilistic impact performance, these highly coupled sources of variability (both intrinsic and extrinsic) can then be combined together in various fashions to understand their overall effect on the probabilistic impact

performance. Many investigations that cannot be accomplished or controlled precisely through experimental methods can be systematically conducted through this probabilistic computational study. One example includes fabric slippage from underneath the fixtures during experimental impact testing which is very difficult to control and has a pronounced effect on the outcome, however fabric boundary conditions can be closely controlled in numerical simulations.

It is envisioned that the simple probabilistic computational framework presented in this study will pave the way forward for more advanced probabilistic computational models that significantly improve the degree of accuracy and predictability of impact simulations over the deterministic models from the past few decades, and ultimately will reduce the dependence on experimental impact testing leading to significant savings in time and cost.

### **Acknowledgements**

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### **References**

- [1] Tabiei A, Nilakantan G. Ballistic Impact of Dry Woven Fabric Composites: A Review. *Appl.Mech.Rev.* 2008;61(1):010801.
- [2] Langlie HJ. A reliability test method for 'one-shot' items. Technical Report U-1792, Ford Motor Company, Aeronutronic Division, Newport Beach, CA 1965.
- [3] Neyer BT. A D-optimality-based sensitivity test. *Technometrics* 1994;36(1):61-70.
- [4] Ballistic Resistance of Personal Body Armor. National Institute of Justice, NIJ Standard-0101.04 Rev. A 2001.
- [5] Nilakantan G, Keefe M, Gillespie Jr. JW, Bogetti TA. Novel Multi-scale Modeling of Woven Fabrics for use in Impact Studies. 10th International LS-DYNA Users Conference, Dearborn, MI, USA June 8-10, 2008.
- [6] Duan Y, Keefe M, Bogetti TA, Cheeseman BA, Powers B. A numerical investigation of the influence of friction on the energy absorption by a high-strength fabric subjected to ballistic impact. *International Journal of Impact Engineering* 2006;32:1299-1312.
- [7] Duan Y, Keefe M, Bogetti TA, Powers B. Finite element modeling of transverse impact on a ballistic fabric. *International Journal of Mechanical Sciences* 2006;48:33-43.
- [8] Kim J, McDonough WG, Blair W, Holmes GA. The modified-single fiber test: A methodology for monitoring ballistic performance. *Journal of Applied Polymer Science* 2008;108:876-886.
- [9] Nilakantan G, Abu-Obaid A, Keefe M, Gillespie Jr. JW. Experimental evaluation and statistical characterization of the strength distribution of Kevlar KM2 yarns: Accounting for length scale and weaving effects. Submitted to *Journal of Composite Materials* March 2010.