Experimental and Numerical Testing of the V_{50} Impact Response of Flexible Fabrics: Addressing the Effects of Fabric Boundary Slippage

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Abstract

The impact testing of woven fabrics comprised of high strength and high modulus yarns is probabilistic in nature. This paper presents results from the experimental impact testing of 50.8 mm×50.8 mm scoured Kevlar S706 fabric samples held on four sides and impacted at the center by a 0.22 caliber ball bearing projectile. The V_{50} velocity response is obtained by performing impact experiments over a range of velocities and fitting the data to a normal distribution function. The impacted fabric samples show varying extents of slippage from underneath the fixtures. The effect of clamping pressure on the extent of fabric slippage is studied by varying the torque on the four bolts used to hold the fixtures together. Results from the experimental testing are compared against numerical predictions which did not consider fabric slippage effects. A simple new method to numerically model fabric slippage is developed and implemented into our computational probabilistic framework. Simulations are run using a Langlie method to obtain the new V_{50} velocity response of a Kevlar S706 fabric with spool based strength mappings and with boundary slippage present. Comparisons are then made between the experimental and numerical results.

Keywords: plain weave fabric, probabilistic modeling, V_{50} velocity, impact response, finite element analysis (FEA), experimental testing, LS-DYNA®

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Introduction

In Ref [1] a probabilistic computational framework was presented that studied the effects of the sources of variability on the probabilistic impact response of flexible woven fabrics. In particular the effect of the statistical nature of yarn strengths was isolated and its effect on the V_0-V_{100} response was studied. The effects of weaving and scouring processes that degraded yarn strengths were studied by comparing the probabilistic impact response of greige and scoured Kevlar S706 fabrics against a baseline fabric model based on the strength distribution of yarns obtained from a spool. The entire study was computational in nature and impact simulations were run using the dynamic finite element code LS-DYNA®. In this paper, results from the experimental impact testing of scoured Kevlar S706 fabrics under the same impact testing conditions as those used in Ref [1] are presented and discussed. The issue of fabric slippage from underneath the fixtures and its effect on the V_{50} velocity is experimentally studied by varying the clamping pressure between the plates and the fabric. A simple new technique for numerically modeling fabric slippage is incorporated into the probabilistic computational framework presented in Ref [1]. Impact simulations are then run using the Langlie method to determine the new V_{50} velocity of a Kevlar S706 fabric with spool based strength mappings and with boundary slippage present. These new numerical results are then compared against both the numerical results from Ref [1] and the experimental results presented herein.

Setup of the Experimental Impact Testing

Figure (1) displays the experimental test fixture. The scoured Kevlar S706 fabric is held between two steel plates. The plates are bolted together at the four corners. Two layers of grip tape are each placed between the Kevlar fabric and the upper and lower steel plates, with the abrasive side of the grip tape facing the fabric. The purpose of the grip tape is to improve the frictional contact between the fabric and plate and reduce fabric slippage. The total in-plane area of the fabric is 101.6 mm × 101.6 mm. The upper and lower plates each have in-plane dimensions of 152.4 mm × 152.4 mm with a central square hole having a side of 50.8mm. Thus the exposed area of the fabric is 50.8 mm × 50.8 mm. The fabric is oriented with the warp and fill yarns respectively parallel to the sides of the plates. A smooth bore helium gas gun is used to shoot a

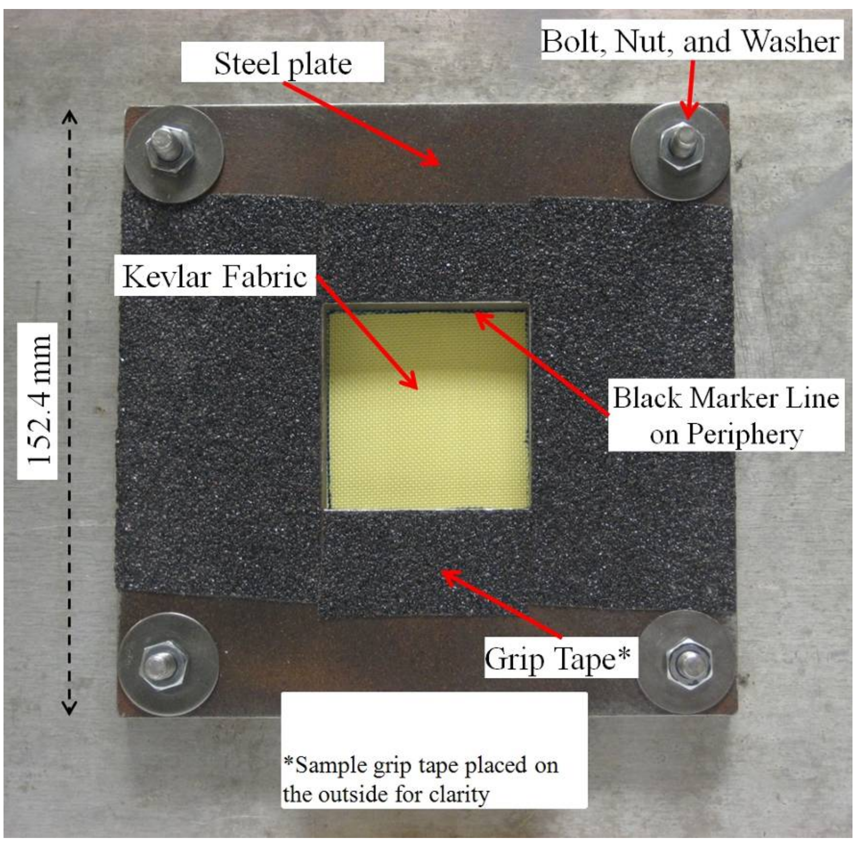


Figure 1. Experimental test setup

0.22 caliber spherical steel projectile at the center of each fabric sample. Measurements on 100 projectiles determined an average mass of 0.6920 g, with a standard deviation of 0.0018 g. Each fabric sample is shot only once. After each test the binary penetration response (no penetration '0' or penetration '1') is recorded. The Neyer-D [2] method is used to choose the shot velocities for each test. A total of 10 impact tests are conducted. Although the Neyer-D method is intended to determine the entire V_0-V_{100} response, since only 10 tests have been conducted for the scoured fabric, only the V_{50} velocity will be extracted for later comparisons with the numerical results. In order to determine the extent of fabric slippage, a dark line is drawn using a marker at the periphery of the exposed fabric prior to each test. After the test has been completed, a photograph of the fabric sample is taken. The inward displacement of the black line towards the projectile represents the extent of fabric slippage.

The extent of fabric slippage from underneath the plates depends on a number of factors such as surface roughness of the plates, type of fabric, clamping pressure, type of grip tape (if any), and impact velocity. An ideal testing scenario would involve zero boundary slippage similar to the numerical studies from Ref [1]. However this condition is not possible experimentally and as a consequence the V_{50} velocity is affected by the extent of slippage. Thus it is important to understand the effect of slippage on the impact response. In this study, the effect of clamping pressure on the V_{50} velocity is studied by varying the amount of torque applied to tighten the four bolts that hold the two steel plates together. The bolts have a major diameter of 1/4 in. (6.35 mm) with 20 threads per inch. The nuts have a width of 7/16 in. (11.113 mm) and height of 7/32 in. (5.556 mm). The bolt-nut fit class is #2. Four test cases are studied, where the torque applied to each bolt is as follows: (*1*) 0.56 N-m (*2*) 3.39 N-m (*3*) 11.30 N-m, and (*4*) 16.95 N-m. All these test cases use grip tape. A fifth case is also studied where the applied torque is 3.39 N-m and no grip tape is used. This fifth case will allow the effect of grip tape on the V_{50} velocity to be studied.

Results from the Experimental Impact Testing

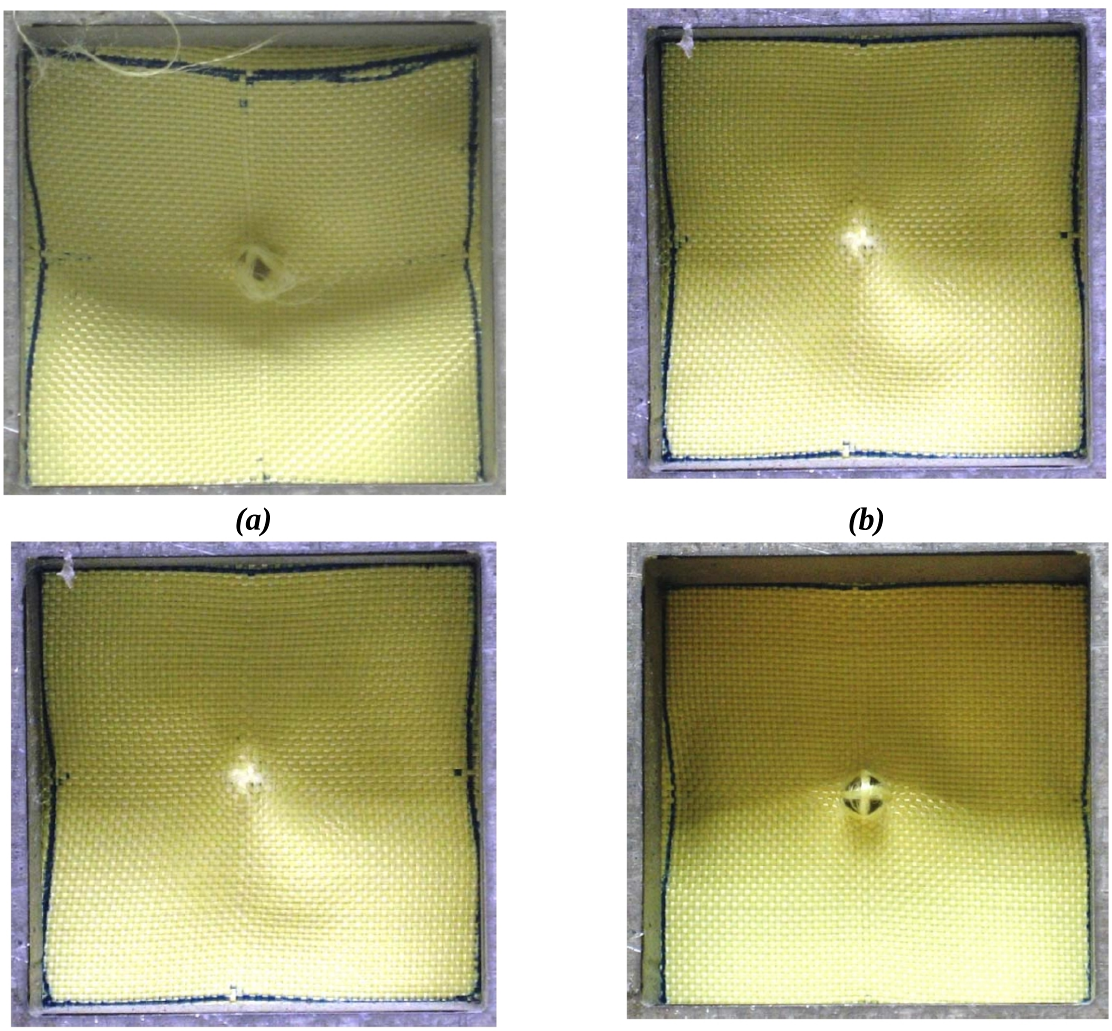
Table (I) presents the results from the experimental impact testing of the scoured Kevlar S706 fabrics held with varying clamping pressures. Cases 1 to 4 utilize grip tape between the fabric and the fixture plates. The Neyer-D method requires a set of initial conditions or guess values to start the process. Since this method fits the experimental data (impact velocity and binary penetration outcome) using a normal distribution, the required initial conditions include a low and high estimate of the mean (μ) and an estimate of the standard deviation (σ). Since the normal distribution is symmetric about the mean, the mean also corresponds to the V_{50} velocity. The

TABLE I. EXPERIMENTAL V_{50} VELOCITIES OF THE SCOURED KEVLAR S706 FABRICS

			Neyer-D Initial Conditions						
Case #	**Torque**	**Grip Tape**	**Low V_{50} Est**	**High V_{50} Est**	**Std Dev Est**	**V_{50} (μ)**	**Std Dev (σ)**	**High NP**	**Low CP**
	N-m		*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
1	0.56	Yes	51.8	112.8	12.2	96.6	8.69	101.5	93.4
2	3.39	Yes	91.4	121.9	12.2	121.4	5.72	125.6	121.3
3	11.30	Yes	100.6	161.5	12.2	120.6	2.56	121.2	120.0
4	16.95	Yes	112.8	143.2	12.2	121.7	4.99	118.8	111.3
5	3.39	No	73.1	83.8	12.2	82.7	3.15	83.7	81.3

initial guess values are listed in the fourth to sixth columns of Table (I). The responses of the 10 tests for each case are fit to a normal distribution using a maximum likelihood estimator technique, resulting in the reported μ or V_{50} (column 7) and σ (column 8) values. The last two columns respectively represent for each case the highest impact velocity corresponding to a non-penetration (NP) and lowest velocity corresponding to a complete penetration (CP). Note that in all cases the velocities of the highest NPs are greater than the velocity of the lowest CPs.

Due to the low number of tests for each case, the reported μ and σ values should only be considered estimates. However, in all cases a zone of mixed results (ZMR) was achieved, defined as a band of test velocities greater than the lowest CP velocity and lesser than the highest NP velocity. The presence of a ZMR in the experimental data reflects the probabilistic behavior of the fabric, and improves the ability of the estimator technique to determine reasonable μ and σ values corresponding to measured fabric responses. The ZMR is a consequence of the system variability that includes both intrinsic and extrinsic factors [1]. For example consider the statistical nature of yarn strengths which is an intrinsic source of variability. If the projectile engages a set of stronger yarns it may not penetrate through the fabric for a given impact velocity. Now at that same impact velocity, had the projectile engaged a set of weaker yarns, it



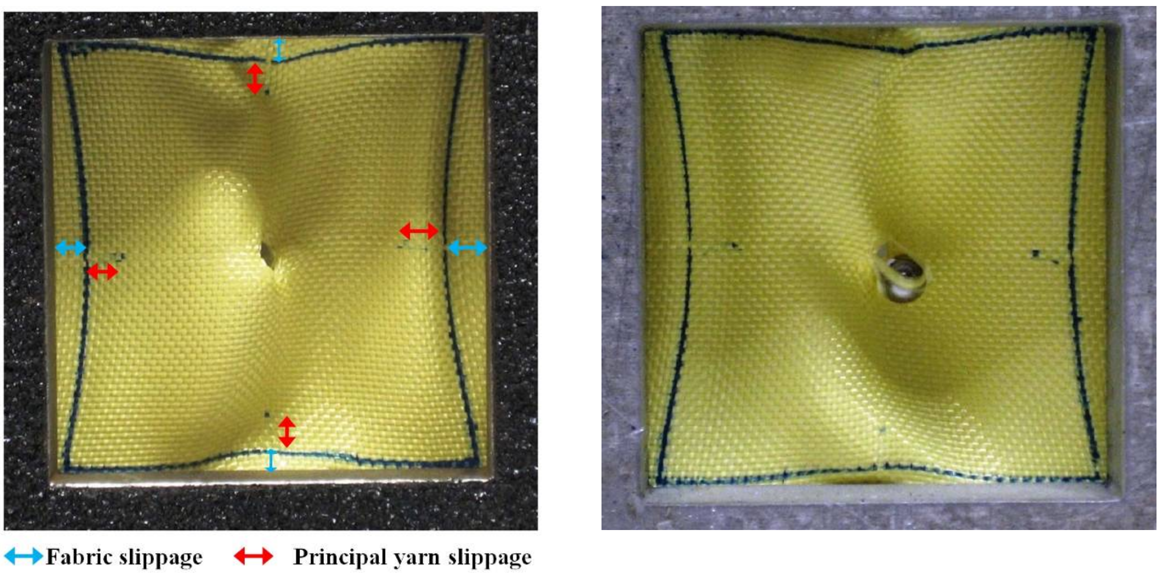
(a) ***(b)***

(c) ***(d)***

Figure 2. Rear view of the highest non-penetrating velocity samples for (a) case 1 (b) case 2 (c) case 3 (d) case 4

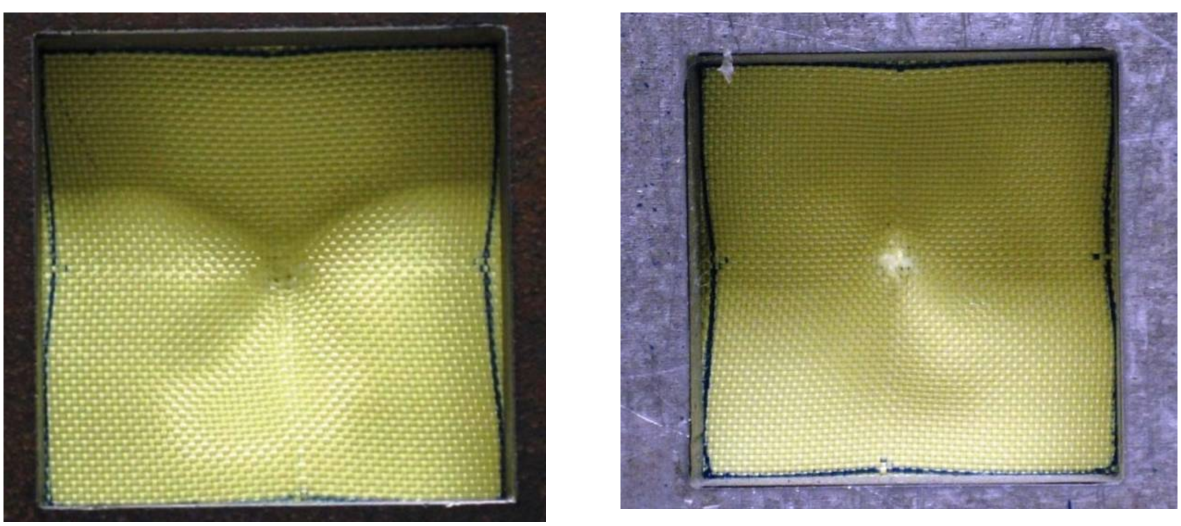
may have penetrated through the fabric. This example shows how system variability can lead to a ZMR.

Figure (2) shows rear views of the highest NP impacts for cases 1-4. As bolt torque increases, the edge slip decreases, with the biggest reductions in edge slip occurring between cases 1 and 2. The measured V_{50} values for cases 2-4 are similar, with a significantly lower V_{50} for case 1 (see Table I). Figures (3) and (4) respectively display the fabric samples from case 5 and case 2 that correspond to the highest NP impact velocity. Recall that for case 5 and case 2 the applied bolt torque remains the same (3.39 N-m), however case 5 does not include grip tape. The inclusion of the grip tape has resulted is lesser edge slip for case 2 with a higher V_{50} velocity. One can conclude from these trends (see Figures 2-4) that (*i*) with the use of grip tape the V_{50} velocity



(a) *(b)*

Figure 3. Highest non-penetrating velocity sample for case 5 (a) front view (b) rear view

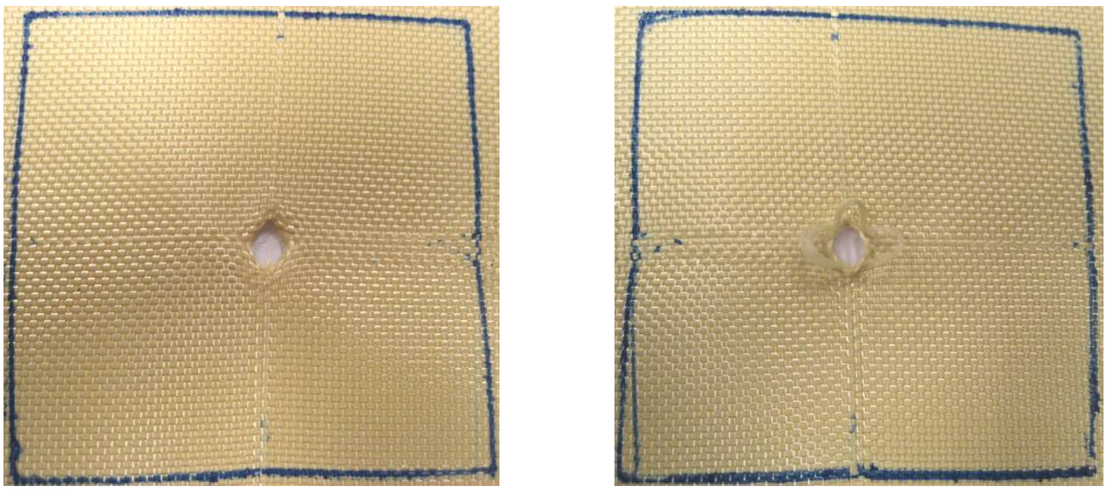


(a) *(b)*

Figure 4. Highest non-penetrating velocity sample for case 2 (a) front view (b) rear view

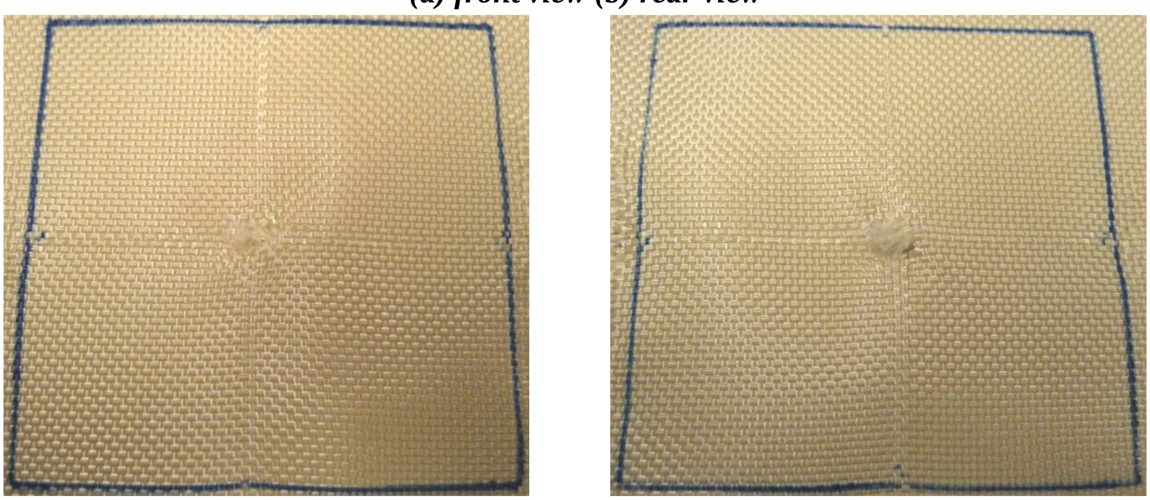
increases with deceasing edge slip (*ii*) for the same bolt torque (or clamping pressure) the V_{50} velocity increases with the use of grip tape, or said differently, for the same bolt torque the V_{50} velocity increases with decreasing edge slip (which was brought about by adding grip tape). At this point, we haven't yet studied how the V_{50} velocity varies with bolt torque but without the use of grip tape. One may reasonably conclude, based on the discussion that follows that even for this scenario the V_{50} velocity will increase with decreasing edge slip.

A close examination of Figure (3) (case 5) shows that two forms of edge slip are occurring. One slip mode corresponds to fabric slippage, in which a continuous membrane of fabric is pulled from the gripped edges. The other slip mode is principal yarn slippage. The principal yarns for a plain-woven orthogonal fabric are defined as the warp and fill yarns that are directly impacted by the projectile. These principal yarns are subject to the highest impact loads, and therefore often exhibit the highest strains and displacements during impact. As a consequence these yarns are most likely to either fail during impact or get pulled out from underneath the grips depending on



(a) **(b)**

Figure 5. Lowest completely penetrating velocity sample for case 1
(a) front view (b) rear view



(a) **(b)**

Figure 6. Lowest completely penetrating velocity sample for case 2
(a) front view (b) rear view

the nature of clamping. From Figure (3) it can be seen that these principal yarns are pulled from the gripped edges greater distances than the average fabric slip motion. These yarns translate relative to the test fixture and relative to the bulk fabric. Adding grip tape and increasing bolt torque (comparing Figures 2-3) leads to decreasing amounts of fabric slip and principal yarn slip.

Figure (5) displays the lowest CP impact velocity fabric sample from case 1, impacted at 93.4 m/s (see Table I). Similarly Figure (6) displays the lowest CP impact from case 2, impacted at 121.3 m/s (see Table I). Examination of the lowest CP impacts for each case show that for cases 1 and 5, fabric penetration is primarily accommodated by fabric "windowing", in which the yarns are pushed laterally and the projectile passes between yarns. Little yarn or fiber fracture is observed in the impact region. Recall cases 1 and 5 correspond to high slip cases. This windowing with little yarn failure in the impact region is apparent in Figure (5) as indicated by the red arrow marks. In contrast, cases 2-4 show fiber and yarn fracture in the vicinity of the impact location, indicating that projectile penetration was at least partially accommodated by yarn failure. Recall cases 2-4 correspond to low slip cases. This greater degree of yarn failure with reduced pushing aside of the principal yarns is apparent in Figure (6) as indicated by the red arrow marks. It is reasonable to expect that edge slip decreases the likelihood of fiber and yarn failure while increasing the likelihood of windowing. Fabric slip permits greater backface deformation of the fabric, extending the duration of fabric-projectile interaction and providing more time for the yarns to slide past the projectile. Yarn slip decreases peak loads in the yarns, decreasing the likelihood of yarn fracture, while the translation of the principal yarns relative to the bulk fabric opens large inter-yarn gaps at the impact location that can permit the projectile to pass through the fabric.

Based on the observed V_{50} values for each case, windowing penetrations correlate with lower V_{50} values, while penetrations accommodated by yarn and fiber failure are associated with higher V_{50} values. Therefore it appears that edge slip decreases the measured V_{50} values by allowing windowing penetration without requiring yarn or fiber fracture.

It is important to note that, even for the high torque cases, edge slip is still present (see Figure 2), and what may appear visually to be a small amount of slip may actually result in a significant deviation from the behavior of a true no-slip edge condition. For example the strain to failure of 600 denier Kevlar KM2 yarns is typically around 3.5% which leads to an elongation to failure of approximately 1.78 mm for a 50.8 mm gage length. Examining the highest torque case (see Figure 2d), edge displacements of a few millimeters are present along the principal yarn directions. Allowing these few millimeters of yarn displacement therefore could be dramatically decreasing the induced strains in the principal yarns. A perfectly clamped yarn, in contrast, would likely exceed failure strains at lower impact energies, leading to a decrease in V_{50} value. Therefore it is likely that, if further reductions in edge slip were possible, we would see the V_{50} values decrease below those measured for cases 2-4. Said differently, the highest possible V_{50} values would occur when gripping is loose enough to permit some yarn sliding in order to minimize peak stresses in the principal yarns, but not so loose that massive fabric and yarn slip leads to windowing penetrations.

Numerical Modeling of Fabric Slippage

One common technique to numerically model fabric slippage is described in Ref [3]. This technique involves modeling the fixture plates with shell elements and applying either prescribed loads or displacements to the plates to achieve a particular clamping pressure on the fabric. The disadvantage of this method from a computational perspective is the significant increase in computational expense (processing power and memory requirements) considering the need to model the fabric in the larger gripped region and the additional contact algorithms required between the yarns within the gripped region and between the fabric and the plates. In addition, the run time is significantly increased because of the required dynamic relaxation or initial loading period as the clamping pressure is gradually applied to the fabric. Another disadvantage of this method, based on the physics of the impact event, is that the random nature of fabric slippage is not considered. Further the method described in Ref [3] treats the slippage as a case of only simple frictional sliding between the fabric and plates which can neither capture many of the mechanisms and interactions seen in the gripped region of the fabric with the use of grip tape such as filament abrasion and breakage, nor can it account for the decrease in experimental V_{50} velocity with increase in edge slippage due to the increase in fabric windowing effects. In fact numerical models often predict an increase in V_{50} velocity with an increase in edge slip which is in contradiction with the earlier experimental observations. In an earlier section the pronounced effects of grip tape on the impact performance predictions were highlighted. Obviously the numerical modeling of the actual grip tape would be an extremely difficult task which would also require a fabric model with a filament level architecture. A comparison between the V_{50} velocity predictions from the experimental testing (with slippage) and the numerical testing from Ref. [1] (without slippage) has shown a large divide. Clearly the effects of fabric slippage on the probabilistic impact performance need to be better understood. Thus as an initial attempt to

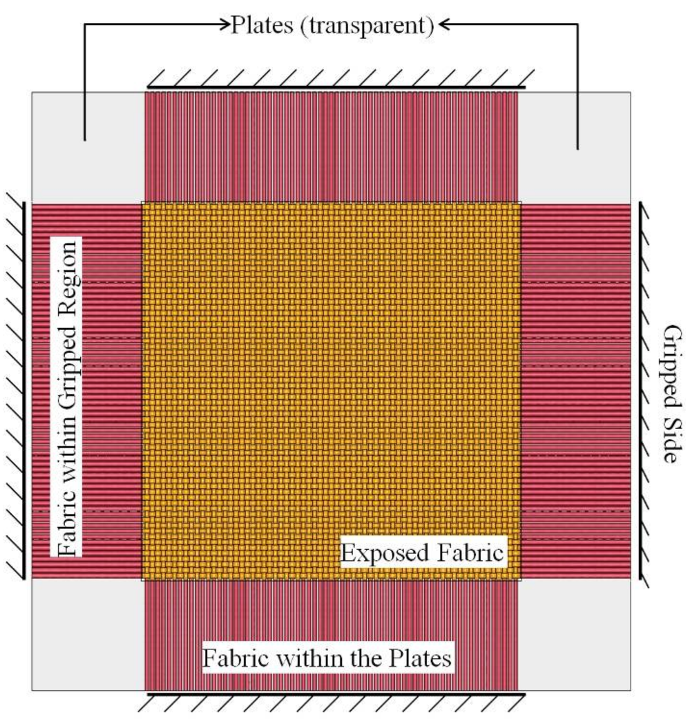


Figure 7. FE model set up

model the effects of fabric slippage, we will focus on a simple indirect technique that can mimic the extra energy dissipated by the interactions and deformations within the gripped region and feed that extra energy back into the system i.e. add that energy to the actual energy dissipated by only the exposed area of the fabric. Similar to the experimental study, the extent of slippage will be varied to assess its effect on the V_{50} velocity predictions. Starting with the FE model from Ref. [1], the fill yarns in the left and right gripped regions, and the warp yarns in the top and bottom gripped regions are removed from the model. All nodal constraints of the remaining yarns in the gripped region are removed and only the yarn ends are held by constraining the corresponding nodes at the end of the yarns. Thus the perfectly clamped and non-deforming yarns in the gripped region from Ref. [1] are now free to deform. The crimp in these yarns is then removed. The immediate advantage of this new method is that computational expense and the amount of 'contact' defined in the model is significantly reduced since a number of the warp and fill yarns in the gripped region have been removed. Figure (7) displays the FE model, where the yellow region corresponds to the exposed fabric while the red region corresponds to the yarns within the plates henceforth referred to as 'gripped yarns'. The mapped strength distribution of the exposed yarns follows that of the spool strength distributions [1]. The gripped yarns are assigned to an elastic-plastic material model (*LS-DYNA Mat #3*). The material density and longitudinal modulus of the gripped yarns remains the same as that of the exposed fabric. The tangent modulus (E_T) is assigned to 1 GPa while the yield stress (σ_Y) is parametrically varied as 20 MPa, 100 MPa, 200 MPa, and 1000 MPa which leads to four test cases. During an impact simulation when the longitudinal tensile stress in these gripped yarns reaches the yield stress, the resistance offered by the gripped yarns drops significantly and the yarns start to deform (elongate) more freely since the assigned tangent modulus is an order of magnitude smaller than the longitudinal elastic modulus. As the gripped yarns elongate, the boundaries of the exposed fabric are no longer constant, rather they get pulled inwards towards the projectile, similar to the slippage seen during an experimental impact test. As the gripped yarns elongate, they first develop elastic strain energy before reaching the yield stress and then dissipate plastic work. It is this combined energy that will attempt to mimic the extra energy dissipated within the actual gripped region of the fabric during experimental testing. By parametrically changing the yield stress of the gripped yarns, we are varying the extent of slippage in a crude attempt to replicate the effect of clamping pressure. Although this method cannot be used to definitively compare results with the experimental predictions in a quantitative sense, it could provide some insight into the effects of slippage which more importantly could help explain the large discrepancy between experimental predictions with slippage and numerical predictions without slippage. A Langlie [4] shot selection method is employed to guide the shot velocities during the Monte Carlo impact simulations in LS-DYNA. For each test case a total of sixteen simulations are run.

Results from Numerical Modeling of Fabric Impact with Slippage

Table (II) lists the predicted V_{50} velocities for the four numerical cases studied as well as the initial conditions for the Langlie method which include an upper and lower gate velocity. At the lower range of yield stresses (between 20 MPa and 100 MPa) the numerical V_{50} values are similar in magnitude to the experimental predictions. Figure (8) displays the shot velocities selected for each of the sixteen tests based on the Langlie method for the four test cases. The V_{50} velocity is computed by taking the average of the three highest non-penetrating velocities and three lowest penetrating velocities. As expected, the extent of fabric slippage reduces with an increase in yield stress of the gripped yarns.

TABLE II. NUMERICAL RESULTS

Case #	σ_Y *(MPa)*	Gate Low (m/s)	Gate High (m/s)	# Shots	V_{50} (m/s)
1	20	70	160	16	127.1
2	100	55	145	16	113.3
3	200	45	135	16	83.1
4	1000	25	115	16	49.8

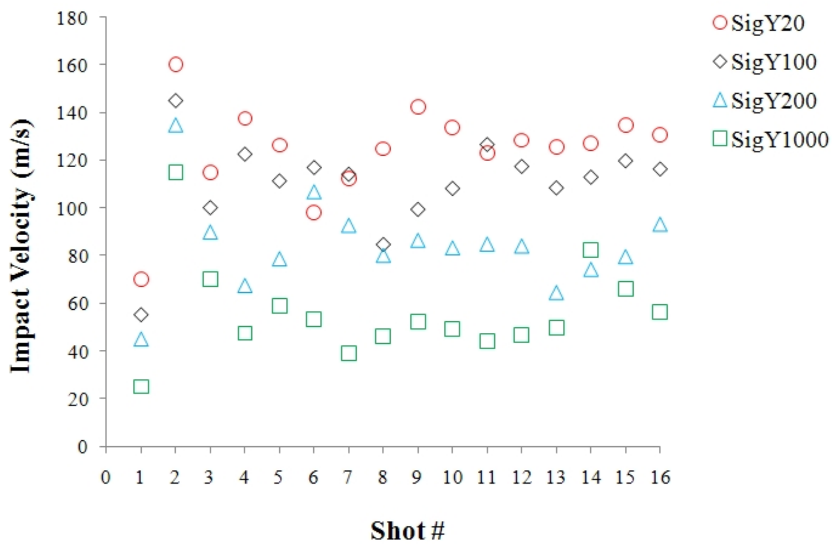
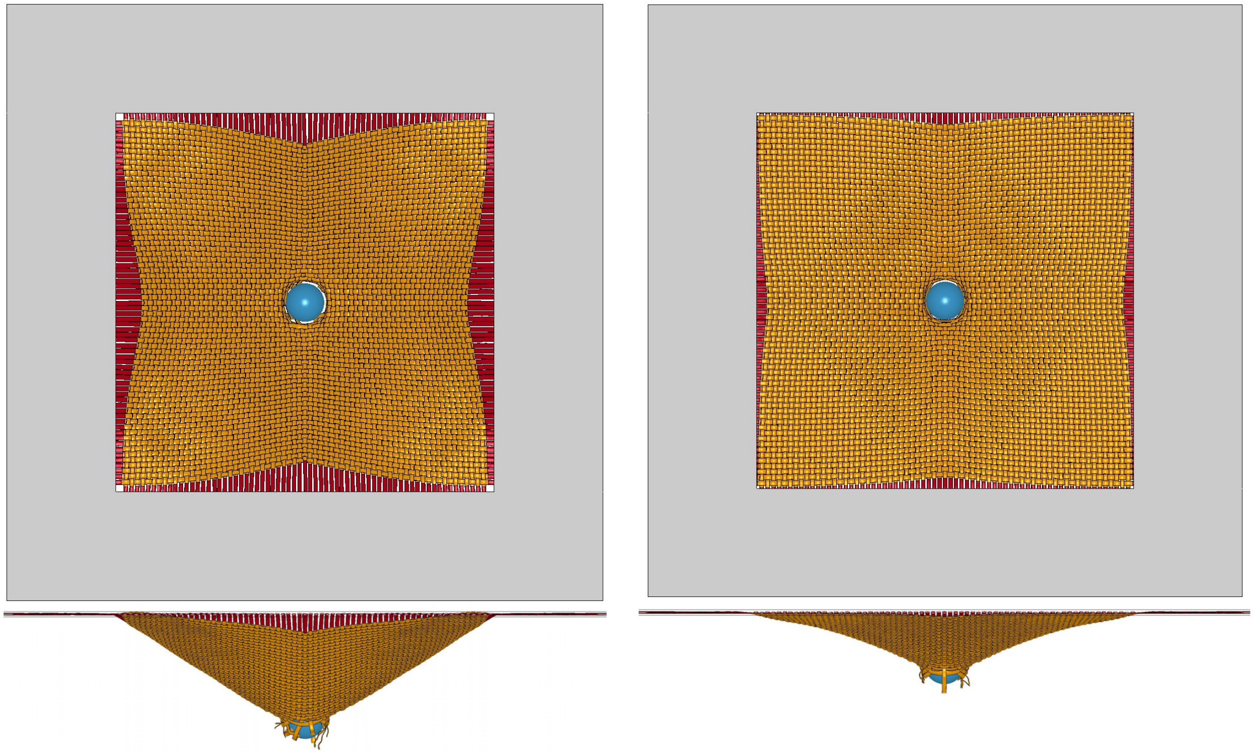


Figure 8. Langlie based test shot velocities

Figure (9) displays sample fabric deformation states for case 1 (σ_Y = 20 MPa) and case 3 (σ_Y = 200 MPa) with respective impact velocities of 126.9 m/s and 84.1 m/s which are close to their respective V_{50} velocities and correspond to non-penetrating impact cases. These deformation states also correspond to the time instants of maximum fabric slippage. For case 1, the gripped yarns quickly transition to the plastic region and begin to elongate more rapidly, which allow the boundaries of the exposed fabric to get pulled inwards to a greater extent. As a consequence the maximum fabric dynamic deflection also increases as seen from Figure (9a). However as the yield stress of the gripped yarns increases, as seen from Figure (9b), the extent of slippage and peak dynamic deflection reduces. Note that the extent of slippage appears symmetric on all four sides in contrast to the experimental results. To fully understand the effects of slippage in these numerical results, we first need to develop a technique to isolate the true impact performance of the fabric (i.e. exposed fabric) from the extra energy being introduced by the fabric slippage. Recognizing that the internal energy of the gripped yarns is the only source of this extra energy, one can subtract the peak internal energy of the gripped yarns at the time instant of projectile penetration or arrest from the initial projectile kinetic energy to get the 'adjusted' impact velocity.



(a) *(b)*

Figure 9. Sample deformation state for case with yield stress of (a) 20 MPa (b) 200 MPa

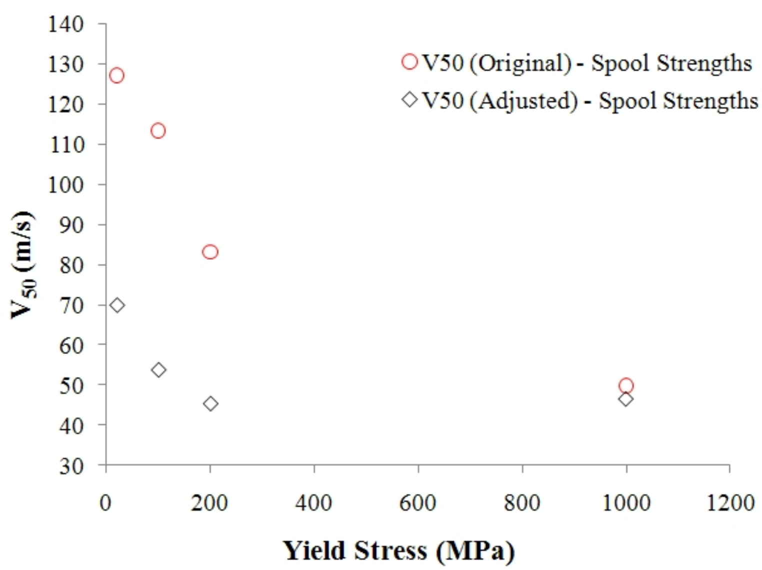


Figure 10. V_{50} velocities as a function of yield stress

Following the same procedure as before, the 'adjusted' V_{50} velocity can then be computed from the set of adjusted impact velocities by taking the average of the three highest non-penetrating and three lowest penetrating velocities. Note that by subtracting the extra energy from the initial projectile kinetic energy, the binary outcome of the simulation in terms of penetration does not change and this is important for the analysis. Figure (10) displays the original V_{50} velocities as a function of yield stress which is also reported in Table (II), as well as the adjusted V_{50} velocities. Interestingly the adjusted V_{50} velocities become consistent at around 46 m/s for yield stresses of 200 MPa and higher. Recall that in the experimental testing, the V_{50} velocity also became consistent at around 121 m/s for bolt torques of 3.39 N-m and higher. Also interesting is that these consistent adjusted V_{50} velocities are very similar in magnitude to the V_{50} velocity predicted from Ref [1], which was 45.4 m/s for the spool strength based fabric without slippage. Thus the procedure of removing the extra energy added by the gripped yarns has allowed us to isolate the true impact performance of the fabric as well as remove the effects of slippage. However this procedure has also provided some important insight. By partitioning the various components of energy dissipations during the simulations with slippage, it was observed that the large slippage seen in case 1 and case 2 caused a significant increase in the kinetic energy component of the exposed fabric resulting in the higher adjusted V_{50} velocities. However for case 3 and case 4 where the yield stress was higher, the lesser extent of slippage did not significantly alter the kinetic energy of the exposed fabric and so the adjusted V_{50} velocities matched the V_{50} velocity from Ref [1]. Thus an important observation is that fabric slippage not only introduces extra energy into the system (which by the procedure outlined earlier can be isolated) but also fundamentally changes the momentum transfer between the projectile and fabric, and this additional kinetic energy component, which cannot be easily isolated, leads to an undesirable alteration of impact performance predictions. Recall that from the experimental testing, it was also observed that large amounts of slippage (both bulk fabric slippage and principal yarn pullout) caused a windowing effect that led to a decrease in V_{50} velocity. However this simple numerical method of modeling slippage predicted an increase in V_{50} velocity with increasing extents of slippage (only bulk fabric slippage) in contrast to experimental trends. Clearly both this simple proposed method as well as the method outlined in Ref. [3] for modeling slippage neither provide a fully adequate representation of the complex mechanisms associated with fabric slippage nor the change in mechanisms when transitioning from small to large extents of slippage. Nevertheless the results from this numerical modeling effort has shown that even small extents of slippage can significantly alter the V_{50} velocity predictions and this was concluded by comparing the numerical results both with and without slippage against each other, as well as the experimental and numerical results. The large discrepancy in predictions clearly underscores the need in the literature for improved methods of modeling realistic fabric slippage.

Conclusions

This study presented results from the experimental impact testing of scoured Kevlar S706 fabrics held on four sides with an exposed square area of side 50.8 mm and impacted at the center by a 0.22 caliber spherical projectile. The V_{50} velocities became consistent at around 121 m/s for bolt torques of 3.39 N-m and higher with the inclusion of grip tape between the fabric and the grips. The grip tape resulted in lesser fabric slippage and higher V_{50} velocities compared to cases with the same bolt torque that did not use grip tape. The two experimental impact cases (torque of 0.56 N-m with grip tape and torque of 3.39 N-m without grip tape) associated with larger extents of slippage (both bulk fabric slippage and principal yarn pullout) resulted in an increased windowing effect which further resulted in lower V_{50} velocities compared to the other cases that showed smaller extents of fabric slippage and greater extents of yarn failure at the impact site which resulted in higher V_{50} velocities. The presence of fabric boundary slippage altered the impact performance predictions of the fabric and contributed to the large discrepancy with numerical predictions from Ref [1] that modeled perfectly clamped boundaries. A simple method to numerically model fabric slippage was implemented in the computational probabilistic framework and the new V_{50} velocities with slippage present were computed using the Langlie method for a fabric with spool based strength mappings. This involved assigning the yarns in the gripped region to an elastic-plastic material model with a very small tangent modulus and different yield stresses. The extent of slippage was controlled by parametrically varying this yield stress. By removing the extra energy associated with slippage, the adjusted V_{50} velocities were estimated and similar to experimental tests, they became consistent at around 46 m/s for yield stresses of 200 MPa and higher, which was very close to the V_{50} velocity of 45.4 m/s from Ref. [1] which corresponded to a fabric with spool based strengths and perfectly clamped boundaries. The trends from the numerical modeling of slippage showed an increase in the V_{50} velocity with an increase in fabric slippage and this was in contrast to the experimental trends.

Clearly it is undesirable to have fabric boundary slippage effects during testing which significantly alter modes of fabric deformation, failure, and energy dissipation. However current designs of experimental clamping fixtures cannot fully eliminate slippage. It is also very difficult to numerically model slippage in a realistic manner such that quantitative comparisons can be made with experimental results, especially because of the random nature of slippage, and the complexity of modeling both grip tape and a fabric with filament-level architecture. Thus a two pronged effort is urgently required to advance the state of the art in flexible fabric impact modeling and reduce the divide between experimental and numerical predictions–

1. *Design of new experimental test fixtures that minimize or eliminate slippage*: One potential design includes leaving the principal yarns unclamped and aligning the edges of the fixture plates parallel to the fronts of the transverse displacement wave. Preliminary experimental testing by our research group has shown promising results
2. *Improved numerical modeling of slippage*

Considering the complexity of realistic numerical modeling of slippage and the increased computational expense, it appears that designing improved experimental tests fixtures would be the first logical step. In the end no matter which effort is advanced it is clear that the effects of fabric slippage urgently need to be better understood and methods to eliminate it need to be developed as they are currently lacking from existing literature. The use of probabilistic computational methods to study the impact response of flexible fabrics has many significant advances over experimental methods however in the end even these computational models need some form of validation against experimental results, and as it stands such validation is not possible until the effects of fabric slippage have been completely addressed.

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