

# IMPROVED INTERYARN FRICTION AND IMPACT RESPONSE OF SURFACE FIBRILIZED ARAMID FABRIC

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## ABSTRACT

As aramid fabrics grow in use in ballistic applications such as soft body armors, the improvement of their ballistic properties continues to garner great research interest. Of these properties, interyarn friction is considered to be highly important given that it dictates the fabrics' energy absorption mechanism. In this work, a novel surface fibrilization method of aramid fibers is used to improve the ability of aramid fabric to dissipate ballistic energy. The same method has been previously shown to considerably improve the interfacial and interlaminar properties of aramid fiber polymer matrix reinforced composites. The ballistic performance of bare and fibrilized fabrics was evaluated using tow pullout and impact testing. Fibrilized fabrics showed a 7 times higher pullout energy and a 10 m/s increase in  $V_{50}$  velocity, compared to that of untreated fabrics, while conserving its original strength. Reinforcement mechanisms were finally investigated using scanning electron microscopy imaging. The presented results provide a fast and simple aramid fabric fibrilization technique that enhances the impact response of aramid-based soft body armors.

## 1. INTRODUCTION

Aramid fabrics' high impact resistance make them a popular choice for protection against blasts and projectiles in applications such as soft body armors and armor plating of military vehicles [1–3]. These fabrics' excellent ballistic properties are derived from that of the individual aramid fibers (Kevlar®, Twaron®), known for their high specific strength and tensile tenacity as well as their lightweight and flexibility [4,5]. Moreover, aramid fabrics' weave architecture and yarn-yarn and fiber-fiber interfacial interactions heavily contribute to its unique energy dissipation properties. However, many ballistic applications still require the use of these fabrics in conjunction with heavy metallic and ceramic components in order to provide the required ballistic protection, thus hindering user's motion due to increased armor weight and reduced flexibility [6]. Therefore, in order for aramid fabrics to completely replace conventional, heavy

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*SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.*

materials in ballistic applications, further benign improvement of its ballistic properties is required.

Various studies have been conducted to improve the ballistic performance of dry woven aramid fabrics, ranging from numerical analysis and modeling to experimental studies and mechanical testing. Experimentally, the energy absorption of the fabric was found to be roughly proportional to the areal density but not to the mesh density or weave tightness [7]. Hybrid fabrics composed of a combination of Kevlar® and carbon fiber were also found to exhibit superior ballistic performance [8], while the difference in the performance of the plied versus spaced configuration was concluded to be dependent on the geometry and application of the projectile used [9,10]. Other studies focused on the effects of fiber twist and yarn crimp on the ballistic performance of the fabric. Rao et al. optimized the tensile strength of fibers through twist angle of 7 degrees [11]. Other projectile properties, such as geometry and mass [7], angle of incidence [12], and point of impact [13] were all also found to have significant impact on the ballistic performance and energy dissipation mechanisms of a woven fabric.

The primary energy dissipation mechanism of aramid fabrics relies on friction between fabric yarns during impact, which directly correlates to the fiber-fiber interfacial properties of the fabric. Recently, many fiber surface modification techniques, such as lubrication [14,15], coatings [16–18], and interphase design [19,20], have been proposed to improve impact response through increased interyarn friction. Dischler et al. reported superior distribution of ballistic energy of aramid fabrics with the interyarn friction improving due to a 2  $\mu\text{m}$  pyrrole thick coating applied to aramid fibers [21]. Lee et al. reported improved impact resistance at higher strain rates with no loss of fabric flexibility through the use of colloidal shear thickening fluids coatings. The improved properties at high strain rates were explained by the transfer of loading concentrations from the primary yarns into the entirety of the aramid fabric [22]. However, shear thickening fluids fail to provide any impact protection at lower strain rates or against stabbing attacks [23]. The improvement to the ballistic performance of the fabric obtained using the discussed surface modification techniques confirms the important role of interfacial properties in the impact response and behavior of aramid fabrics.

Interphase design is another highly popular interface reinforcing technique in woven fabrics and fiber reinforced composites. The technique aims to graft nanomaterials onto the surface of the fiber, therefore reducing the mobility of both fiber and tows, and increasing the sliding friction between yarns [19,20]. Labarre et al. also showed a 230% increase in yarn pullout peak load by grafting multi-wall carbon nanotubes onto the surface of aramid fibers [17]. However, the grafting method requires processes that use high operating temperatures, such as chemical vapor deposition (CVD), causing them to be incompatible with polymer fibers. Hydrothermal growth of vertically aligned ZnO nanowires has allowed the ability to benignly graft nanomaterials on the surface of aramid fibers while preserving its strength [24,25]. Galan et al. reported a 228% improvement in the interfacial strength of carbon fiber reinforced composites with optimized ZnO nanowires grafted to the surface of the fiber [26]. Hwang et al. also showed the ability to tailor the interyarn friction of ZnO nanowires coated aramid fabrics through controlling nanowire morphology, and observed up to 22.7 times higher energy absorption than that of a neat fabric [27,28]. Finally, Malakooti et al. reported a 66% increase in impact resistance of ZnO nanowires coated aramid fabrics compared to that of neat fabric, when impact tests are performed at

intermediate velocities [29]. This improvement in impact response was attributed to the increase in mechanical interlocking and contact area between neighboring aramid fibers [30,31].

Recently, Nasser et al. reported a fibrilization technique of aramid fabric using a dissolution and deprotonation basic solution to form pseudo-wiskerized aramid fibers [32]. The treatment enriches the aramid surface with polar functional groups, resulting in a reinforcement mechanism that relies on a combination of improved chemical interaction and mechanical interlocking. The fibrilized fibers were found to possess a 128% improved interfacial shear strength with the epoxy matrix, while also preserving the tensile strength of the fibers. In this work, the duration of the fibrilization process was studied to achieve optimal interyarn friction and ballistic performance in aramid fabrics. The effect of fibrilization on the interyarn friction of aramid fabrics was studied using tow pullout testing and the impact response was quantified through measurement of  $V_{50}$  speeds using an instrumented gas gun system. As received, cleaned aramid fabrics were also subjected to tow pullout and ballistic testing for comparison. The tow pullout peak load and  $V_{50}$  speeds were found to increase by more than 500% and 10 m/s respectively in fibrilized aramid fabrics. Finally, scanning electron microscopy (SEM) was employed to gain further understanding of the interfacial reinforcement mechanism during pullout and impact loading by inspecting specimens pre and post testing.

## **2. EXPERIMENTATION**

### **2.1 Fiber treatment and morphology characterization**

Fibrilization of aramid fabric was performed using the method described by Nasser et al. [32]. Aramid unidirectional tape strips (Kevlar® KM2® Plus, style 790 scoured, CS-800, received from JPS Composite Materials) were cleaned in acetone and ethanol to remove residual organic contaminants and sizing on the fabric surface and then dried at 100 °C for 12 hours under vacuum. A basic solution consisting of 1.5 g of potassium hydroxide (KOH) (ACS certified; Fisher Scientific) in 500 mL of dimethyl sulfoxide (DMSO) (ACS certified; Fisher Scientific) was stirred for 30 mins before adding the unidirectional tape to the beaker. The strips were soaked in the solution for 2, 5, 7 and 10 hours, respectively. The treated strips were then washed with ethanol and dried at 80 °C under vacuum for 16 hours. As received aramid fabric were also cleaned using a similar process for comparison. The changes to the aramid fabric's morphology, pre and post-mechanical testing, were imaged through SEM using a JEOL 7800 FLV field-emission scanning electron microscope.

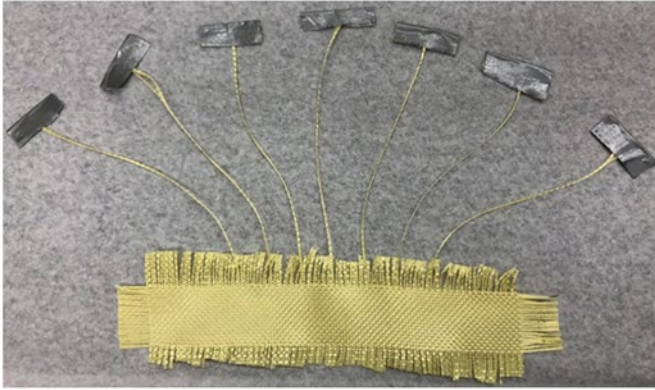
### **2.2 Tensile strength testing**

The strength of the treated fibers was tested through textile fabric tensile tests. Rectangular tensile specimens containing 20 yarns and having a gauge length of 75 mm were prepared from each set of bare and treated aramid fabrics (statistics were calculated from 12 specimens for each set of fabric). Three plies of fabrics were bonded to each side of the fabric at the ends of the specimens by a high shear strength epoxy (Loctite® 9430™ Hysol®) and were used as tabs to provide proper gripping during testing. All samples were tested in the weft (fill) direction using an Instron universal load frame (Model 5982) with a 100 kN load cell and at a cross-head speed of 300 mm/min. The specimens were strained until full failure before identifying the ultimate tensile strength and elongation of the fabrics.

### 2.3 Tow pullout and high velocity impact testing

The sliding friction between tows was measured using tow pullout testing under controlled transverse tension. The test was performed through a custom designed tow pullout setup similar to that described by Hwang et al. (Figure 1B) [33]. Aramid fabric samples of approximately 165 mm in width and 127 mm in length were prepared by manually removing the transverse yarns to provide a 114 mm overhang of free yarn, while the remaining fabric, consisting of 20 transverse tows, was clamped in the direction of the pull and was kept constant for all experiments. The treated fabric patches were clamped between a fixed column and an adjustable link, where a lead screw was used to adjust the clamping distance and thus apply lateral tension to the fabric. The tow pullout tests were performed by pulling a single tow from the taught, preloaded fabric using an Instron 5982 machine equipped with a 100 kN load cell, at a pullout rate of 50 mm/min and an applied transverse tension of 100 N. Tabs were added to the free end of 7 tows for proper gripping, having a spacing of 10 tows between tabbed tows. Finally, all 7 tow samples were pulled in the warp direction only, as marked in Figure 1A. Also, ballistic impact tests were performed using a custom designed, instrumented, compressed air driven, gas gun setup as described in Stenzler et al. [34]. The velocity of the projectile was obtained by recording the time required for it to block the incident light by traveling between two photoresistors placed 19.05 mm (3/4 inch) apart at the end of the barrel (Figure 1C). A hemispherical face ,4130 alloy steel projectile with a mass of 29 g and a diameter of 11.4 mm was used to impact the fabric targets consisting of three cross-shaped aramid fabric plies with a square target area of 7.8 x 7.8 cm<sup>2</sup>. The samples were clamped from all four sides using a steel plate with recessed bars as shown in Figure 1D. The applied torques to the steel plates and bars screws were controlled using a torque-wrench to ensure uniform clamping and prevent any target slippage during impact. A clay trap was also placed 2 inches behind the target and was examined for penetration after each firing of a projectile. For each set of aramid fabric, 10 targets were shot and the V<sub>50</sub>BL(P) ballistic performance was calculated by taking the arithmetic mean of the three highest non-penetrating and the three lowest complete penetrating impact velocities into the clay trap.

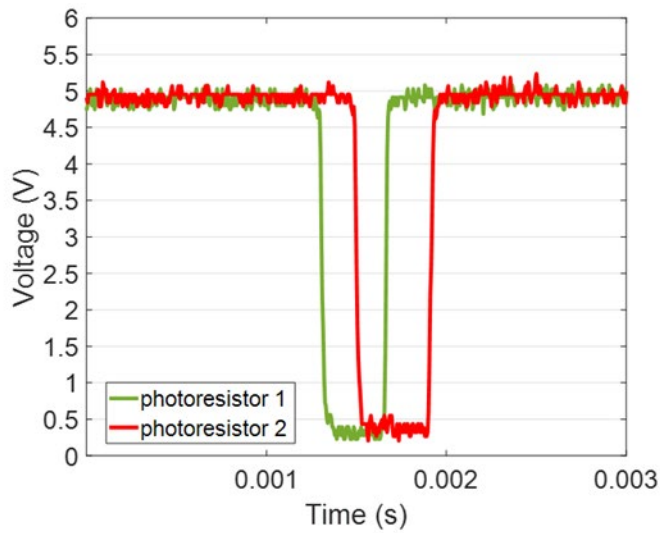
A)



B)



C)



D)



Figure 1. A) Treated aramid fabric sample for tow pullout. B) Tow pullout testing experimental setup. C) Photoresistors recorded signals as projectile exits the barrel. D) Cross-shaped, 4 sided clamped shot aramid fabric.

### 3. RESULTS

#### 3.1 Surface morphology

The changes to the surface morphology of the aramid fabric post-fibrilization is studied through the SEM micrographs as shown in Figure 2. The soaking of the macroscale fibers inside the basic solution form randomly oriented aramid surface fibrils of different aspect ratios and diameters. Treatment duration was previously investigated and short treatment periods were

found to be optimal, as they reduce the breakage of inter-chain hydrogen bonds and allow for a larger amount of the newly formed fibrils to remain attached to the macroscale fiber surface [32]. The presence of these fibrils have also been demonstrated to improve mechanical interlocking between aramid fabrics and polymers such as epoxy at the level of the fiber-matrix interface [32]. High aspect ratio fibrils are long enough to cover multiple neighboring fibers and the crossing points of tows in both weft and warp direction. Such fibrils can bridge between neighboring fibers and form inter-fiber structures that help with the impact resistance of the aramid fabric against phenomena such as bowing. These inter-fiber structures can also largely increase the interyarn friction in the fabrics by introducing stronger mechanical interlocking between neighboring yarns. It should also be noted that the fibrilized aramid fabrics displayed no increase in weight or decrease in flexibility, therefore conserving important and desired characteristics of aramid fibers in ballistic applications.

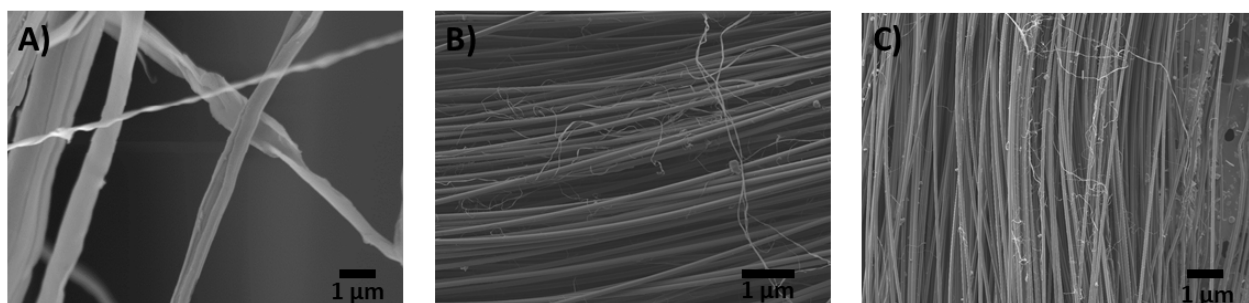


Figure 2. Scanning electron microscopy images of the bare and the treated fibers. A) Generated fibrils. B) Fibers after a 2 hours treatment. C) Fibers after a 5 hours treatment.

### 3.2 Tensile strength

The relationship between aramid fabrics' high tensile properties and excellent ballistic performance has been previously established in the literature. Nilakantan et al. reported direct correlation between the ballistic performance of woven fabric and its corresponding yarn tensile strength, where a decrease in mean strength of the yarn resulted in reduction of fabric's  $V_{50}$  velocity [35]. Therefore, improving the interyarn friction of the aramid fabric should occur while simultaneously maintaining the individual strength of the fiber or fabric. To ensure that the fibrilization process causes no degradation of tensile properties of aramid fabrics, textile fabric tensile testing of bare and treated samples is performed at quasi-static tensile loading according to ASTM D5353. As seen in figure, a 7.5% and 6.8 % decrease in tensile strength and elastic modulus respectively is observed in aramid fabric treated for 10 hours. The expected decrease in the tensile properties of the fabric is due to weakened yarn and individual fiber strength due to the prolonged hydrolysis process occurring inside the basic treatment solution. Therefore, this indicates that treatment periods longer than 10 hours will be expected to offer no reinforcement to the ballistic performance of the aramid fabric. The slight increase in tensile strength of fabrics treated for 5 hours can be attributed to the potentially increased interyarn friction between the tows. It can then be concluded that the tensile strength of aramid fabrics is not at the risk of degrading for fibrilization treatment periods of less than 10 hours, and its ballistic performance will not decrease within that range.

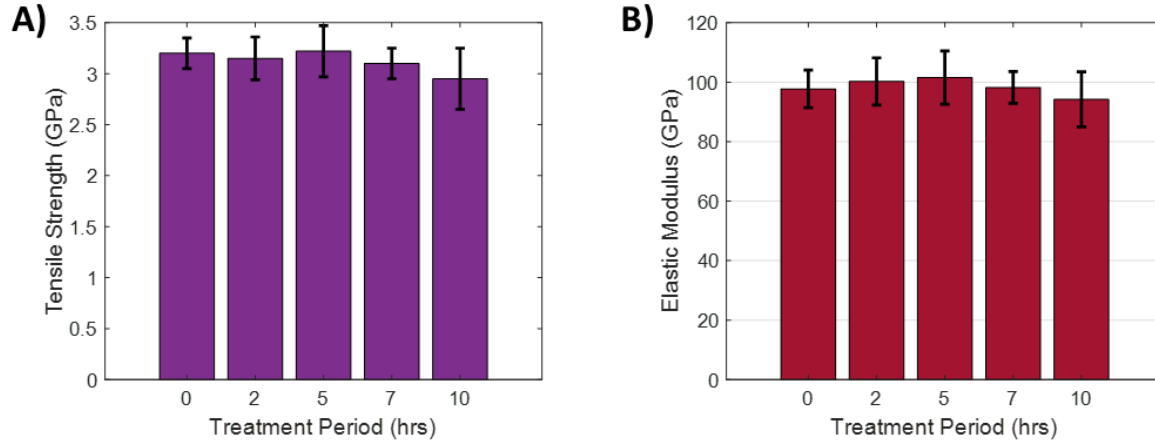


Figure 3. A) Tensile strength of the bare and the fibrilized aramid fabric. B) Elastic modulus of the bare and the fibrilized aramid fabric.

### 3.3 Interyarn friction

The effect of the fibrilization treatment on the energy absorption capacity of the aramid fabrics is evaluated using single tow pullout testing under controlled transverse tension as seen in the experimental setup shown in Figure 1. The load-displacement curves are recorded at the same preload transverse tension of 100 N before integrating them to obtain the pullout energy. The uniformity and repeatability of both the fibrilization treatment and the tow pullout testing process is ensured by testing 7 tows per fabric. The averaged pullout energy and peak pullout load of the bare and fibrilized fabrics can be seen in Figure 3. Both pullout load and pullout energy were found to increase by more than 157 % and 194 %, respectively, after only a 2 hours of fibrilization treatment. The maximum increase in pullout properties is found after a treatment period of 5 hours showing an increase of 550 % and 665 % in peak load and pullout energy respectively. By studying the recorded peak load-displacement curves, it can be deduced that the loaded tow initially experiences static friction, highlighted by the first recorded peak. This is followed by a large drop in the load as the specimen undergoes kinetic friction as it passes through the first transverse tow. The increase in static friction before uncrimping is attributed to the improved mechanical interlocking between fibrilized fibers, indicating increased interyarn friction. Further decrease in load along with certain local peaks are recorded as the loaded yarn passes through all remaining transverse tows. Such pullout behavior agrees well with that of other cases of aramid fabric treatment methods reported in previous studies, such as polymeric and ZnO nanoparticles coatings [29]. Examining the tow pullout samples using SEM imaging following testing shows dense bundles and layers of dispersed fibrils, as fibrilized aramid fibers can be seen at the yarn-crossing points of treated aramid fabrics, whereas bare fabrics display no sign of excessive fibrilization (Figure 6). In addition to the treatment generated fibrils, the abrasive loading to which samples are subjected during a tow pullout generates aramid surface fibrils through the breakage of the hydrogen bonds responsible for holding individual polyamide macromolecules together. Therefore, the increased surface fibrils found in treated fabrics post-testing are the result of both the initial fibrilization treatment, and the breakage of hydrogen bonding during abrasive loading. These microstructures allow for an increase in interyarn friction through mechanical interlocking, resulting in the observed improvement in the initial peak load and pullout energy of the fabric. Thus, the considerable enhancement to the interyarn



friction of aramid fabrics after short treatment periods shows its ability to translate into increased impact resistance, leading to a more desired characteristic of improved ballistic performance. It should also be noted that a saturation behavior is also observed in interyarn friction improvement, as 7 and 10 hours treatments show a 20.4 % and 24.54 % decrease in pullout energy when compared to that of a 5 hours treatment, respectively. Nonetheless, these set of fibers still showed a minimum a 437% increase in pullout energy when compared to that of bare fabrics. The cause behind such a trend is the decrease in surface fibril density as the ones generated at early treatment stages start to detach, decreasing the effectiveness of the mechanical interlocking due to the treatment [32].

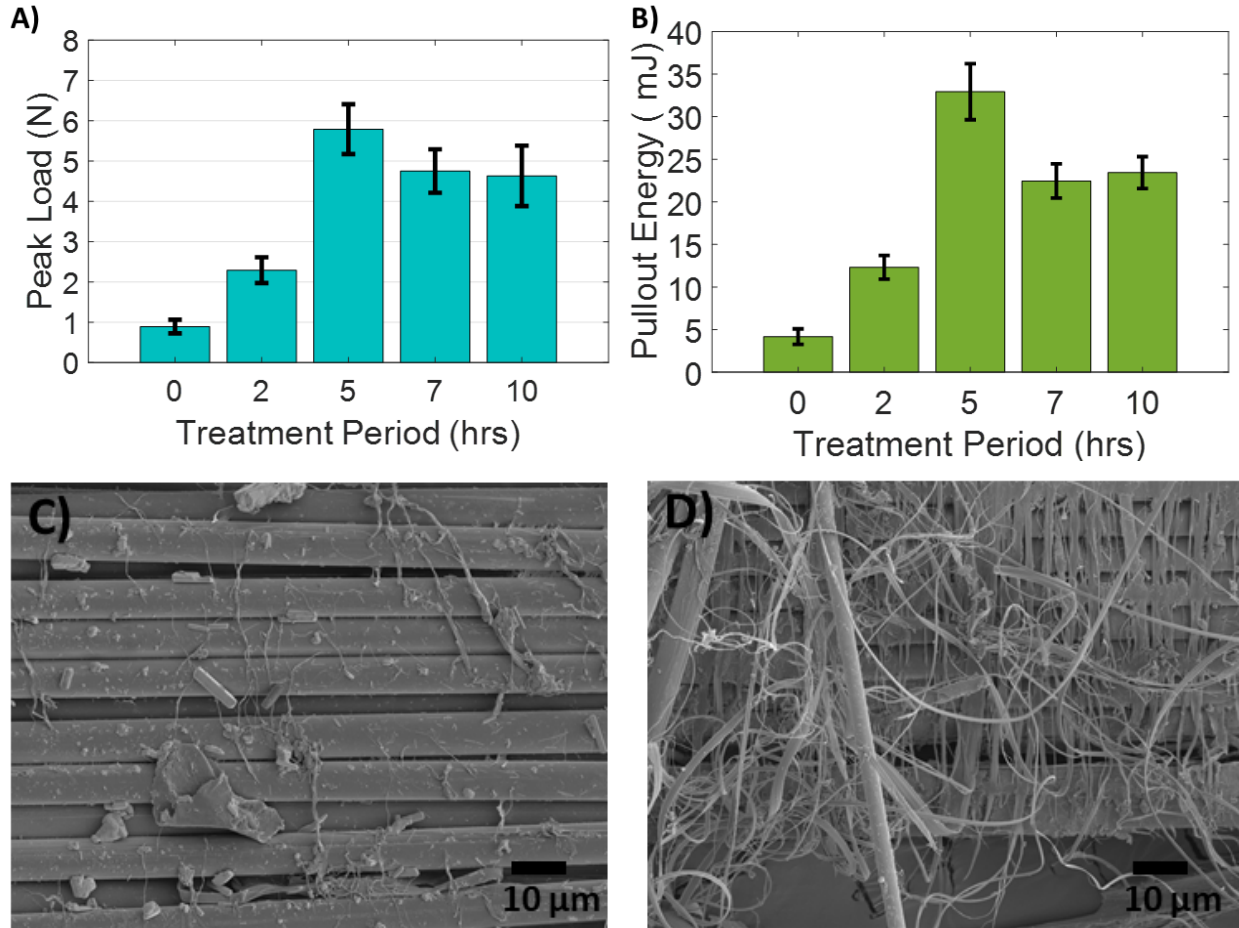


Figure 4. A) Comparison of average peak load values for varying treatment durations. B) Comparison of pullout energy for varying treatment durations. C) SEM images at yarn-crossing points of bare aramid fabrics post-testing. D) SEM images at yarn-crossing points of treated aramid fabrics post-testing.

### 3.4 Impact response

The impact resistance of the treated aramid fabrics is evaluated by conducting impact tests at velocities ranging from 80 m/s to 110 m/s. Given that a 5 hours treatment was found to be most optimal for minimal aramid fabric tensile strength loss, and maximal interyarn friction, the impact fabric specimens were treated for the same period. Obtaining the  $V_{50}$  speed is considered the



standard method for evaluating the impact resistance of woven fabrics, as it represents the speed limit up to which the target is reliably impenetrable by a specific projectile. The samples require to be properly clamped from all sides in order to avoid any slippage and thus inaccurate impact response measurements. The projectile's velocity for each impact test, along with whether penetration occurred or not, are presented in Table 1. Penetration is defined as having the projectile reach the clay trap, placed 2 inches behind the target. For impact speeds less than 88 m/s, both bare and treated aramid fabrics offer complete ballistic protection, dissipating all of the impact's kinetic energy and preventing the projectile from reaching the clay trap. As projectile's velocity is increased into the intermediate range of 88-98 m/s, the impactor penetrates bare aramid fabrics at certain speeds but not the treated fabric. The observed higher impact resistance in treated aramid fabric is primarily attributed to the fabrics' increased interyarn friction that limits the mobility of neighboring fibers and tows, and thus reduces the possibility of a wedge-through projectile penetration due to bowing. As the impact velocities reach over 97 m/s, complete penetration of the projectile is observed in treated fabrics. At such projectile speeds, the aramid fabric fails to absorb all of the projectile's kinetic energy resulting in projectile penetration before being stopped by the clay trap. The calculated  $V_{50}$  of the treated aramid fabric is observed to be approximately 10 m/s higher than that of bare fabric, pointing to an enhanced impact response due to fibrilization. The limited improvement in ballistic performance of 12 %, relative to that of interyarn friction of 550%, is primarily due to fabric failure under impact loading being caused by a combination of multiple failure modes and mechanisms. The high strain rate loading conditions during impact testing excite p-phenylene terephthalamides (PPTA) bonds beyond their activation energy, promoting primary bonds breakage and brittle fracture [36]. Therefore, the ability of aramid yarns to complete failure is independent of its interfacial properties, and primarily dictated by fibers and yarns strength. With that, the contribution of other failure modes limits the effect of interfacial reinforcement on the overall impact resistance performance of aramid fabrics. Post-testing imaging of specimens allows for better interpretation of the role of the fibrilization treatment as an impact resistance reinforcement mechanism. At low speeds, the projectile does not penetrate the target but still deforms to the fabric, where the bare fabric experiences larger deformations around the blast area due to bowing in comparison to the treated fabric. The second and third plies also displayed greater damage in the bare case. The observed difference in bowing behavior is proportional the mobility of the tows and fibers within the fabric. As complete penetration is observed at higher projectile speed, aramid fabrics exhibits a different failure mode. adjacent yarns and fibers in bare fabric are able to easily slide, causing traces of yarn pullout around the blast area, as well as a cross shaped yarn pullout (Figure 5) due to the 4-sided clamping of the sample. This phenomenon is considerably less present in treated fabrics, due to the decreased yarn mobility through the generated surface fibrils. Moreover, the blast hole caused by the penetrating projectile is considerably smaller in treated fabrics than bare ones, indicating a reduction in the ability of the projectile to wedge through the fabric's yarns. These results display the translation of the improvement in interyarn friction through fibrilization treatment into an enhancement in the impact response of aramid woven fabrics.

Table 1. Details of all the reported impact tests for bare and treated aramid fabrics.

| Untreated aramid fabric |                   | Fibrilized fabric  |                   |
|-------------------------|-------------------|--------------------|-------------------|
| Impact speed (m/s)      | Failure mode      | Impact speed (m/s) | Failure mode      |
| 83.2                    | Did not penetrate | 95.2               | Did not penetrate |
| 87.7                    | Did not penetrate | 97.2               | Did not penetrate |
| 88.6                    | Penetrated        | 98.2               | Penetrated        |
| 90                      | Did not penetrate | 99.2               | Penetrated        |
| 92.9                    | Penetrated        | 100.2              | Did not penetrate |
| 93.7                    | Did not penetrate | 101.6              | Penetrated        |
| 95.2                    | Penetrated        | 102.8              | Penetrated        |
| 97.6                    | Penetrated        | 103.5              | Did not penetrate |
| 99.7                    | Penetrated        | 104                | Did not penetrate |
| 102.9                   | Penetrated        | 105.8              | Penetrated        |

**Figure 7.** Comparison between aramid fabrics and treated aramid fabrics (bottom row) after impact: A) Untreated aramid fabric after low velocity, non-penetrating impact (below 90 m/s). B) Treated aramid fabric after low velocity, non-penetrating impact (below 90 m/s). C) Untreated aramid fabric after high velocity, fully penetrating impact (above 100 m/s). D) Treated aramid fabric after high velocity, fully penetrating impact (above 100 m/s).

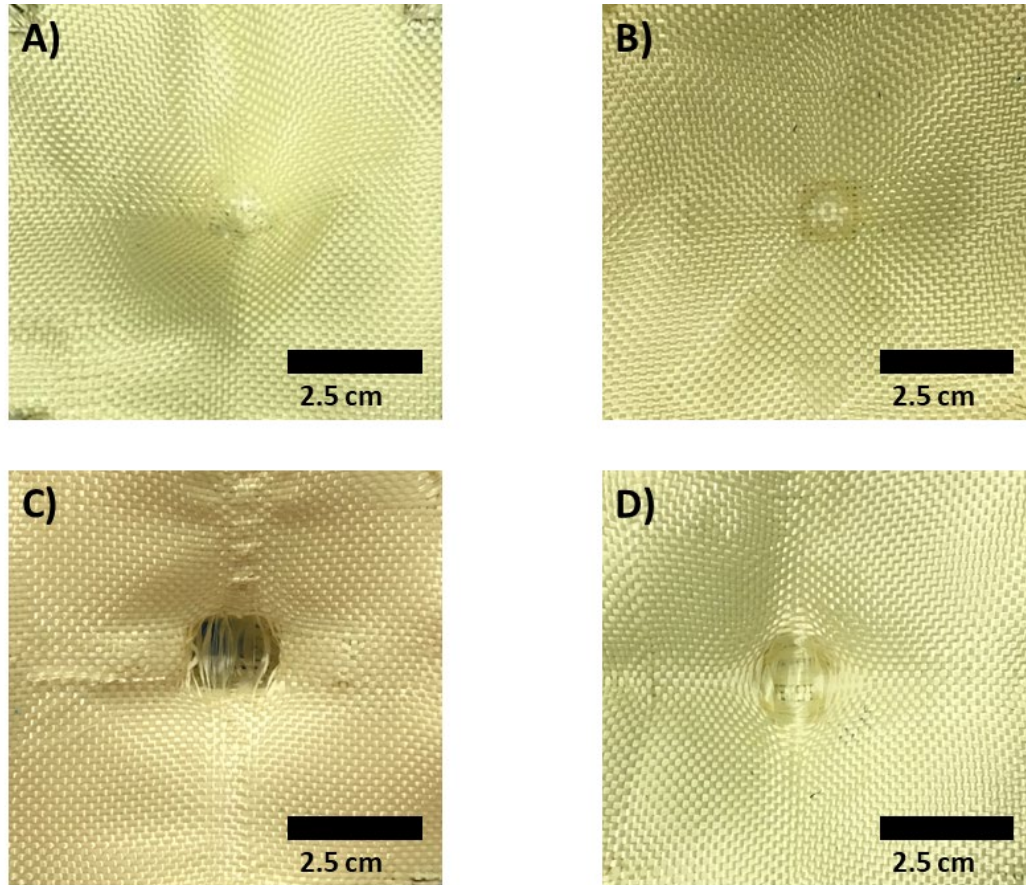


Figure 5. Comparison between aramid fabrics and treated aramid fabrics (bottom row) after impact: A) Untreated aramid fabric after low velocity, non-penetrating impact (below 90 m/s).

B) Treated aramid fabric after low velocity, non-penetrating impact (below 90 m/s). C) Untreated aramid fabric after high velocity, fully penetrating impact (above 100 m/s). D) Treated aramid fabric after high velocity (above 100 m/s).

#### 4. CONCLUSIONS

In this study, fibrilization was reported as a viable technique to improve the pullout behavior and impact resistance of aramid (Kevlar® KM2 Plus) fabrics. Aramid fibers are treated inside a strongly basic solution, generating microscale to nanoscale fibrils on the surface of the fibers that help improve interfacial interaction between neighboring yarns and fibers inside a woven aramid fabric without degrading it. The interyarn friction of the fibrilized aramid fabric was enhanced, showing up to seven times higher pullout energy absorption, and extensional delays in pullout failure compared to bare aramid fabrics. The failure mode and corresponding load-displacement curves confirms that mechanical interlocking between fibrilized fibers and tows is the primary reason for the enhanced pullout performance. The treated fabric also showed substantial increase of  $V_{50}$  velocity when subjected to impact testing in a 4-side clamped resulting from the

improvement in interyarn friction and reduced fabric deformation, as both yarns and fibers' mobility becomes limited. Given that the proposed treatment preserves the strength, light weight, and flexibility of the aramid fabric, this simple and low-cost fibrilization method has great potential to be incorporated into the production of high performance soft body armors.

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