

Program Final Report
PFR-3244

Parametric Study of functional fiber insertion into woven fabric

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2 December 2020

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This material is based upon work supported under Air Force Contract No. FA8702-15-D-0001.

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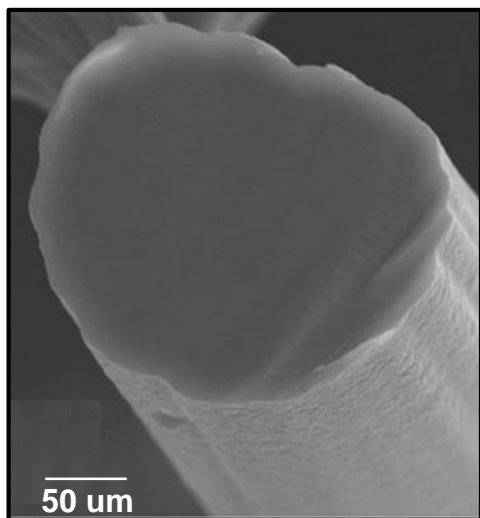
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Functional Fiber Microsystems

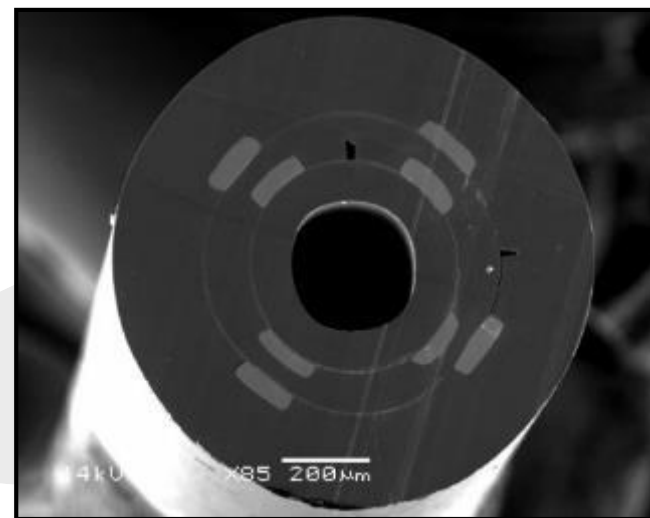
Traditional Fiber



- **Single Material**
- **No Architecture**
- **Single Functionality**



Functional Fiber Microsystem



Sorin *et al.*, Nano Letters 9, 2009

- **Multimaterial - Metals, Semiconductors, Insulators**
- **Complex Device Architecture**
- **Multifunctional Capabilities**

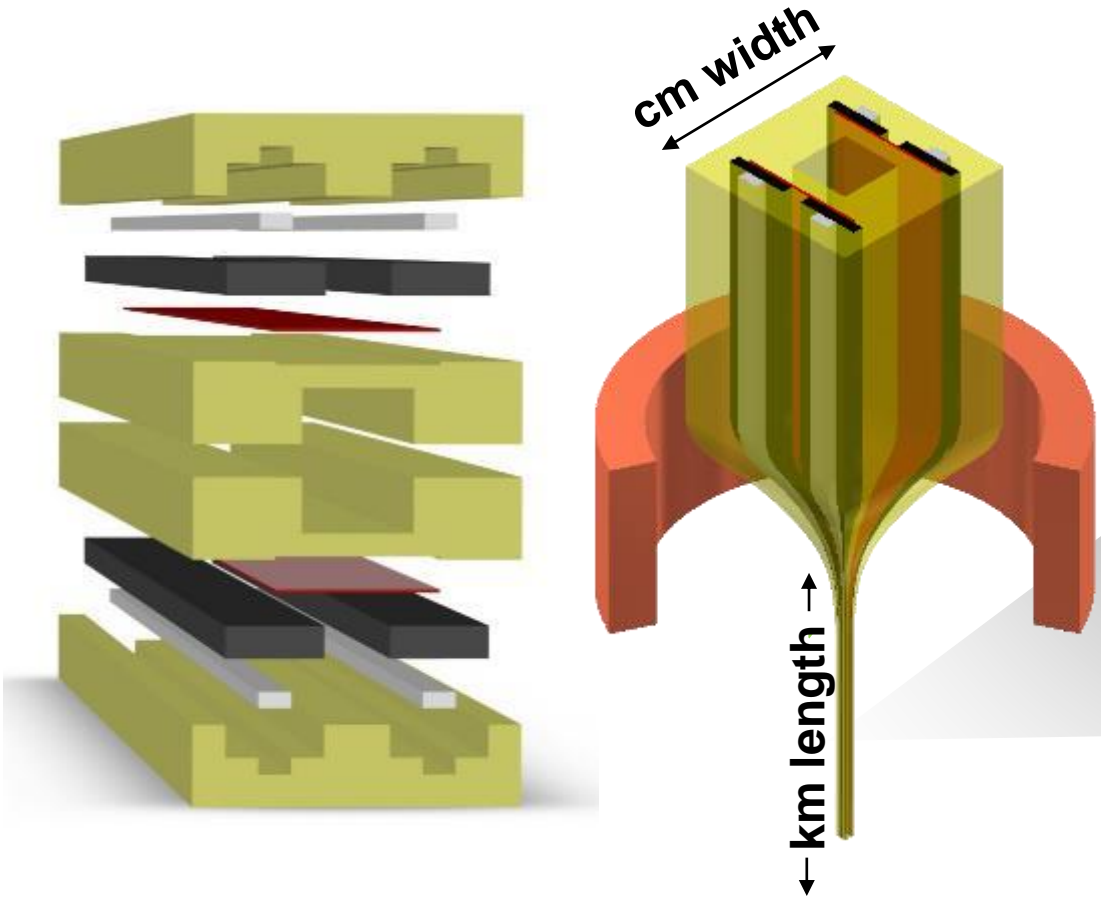
Materials processing approaches are emerging that enable microelectronic device functionality at the length scales and cost of optical fiber



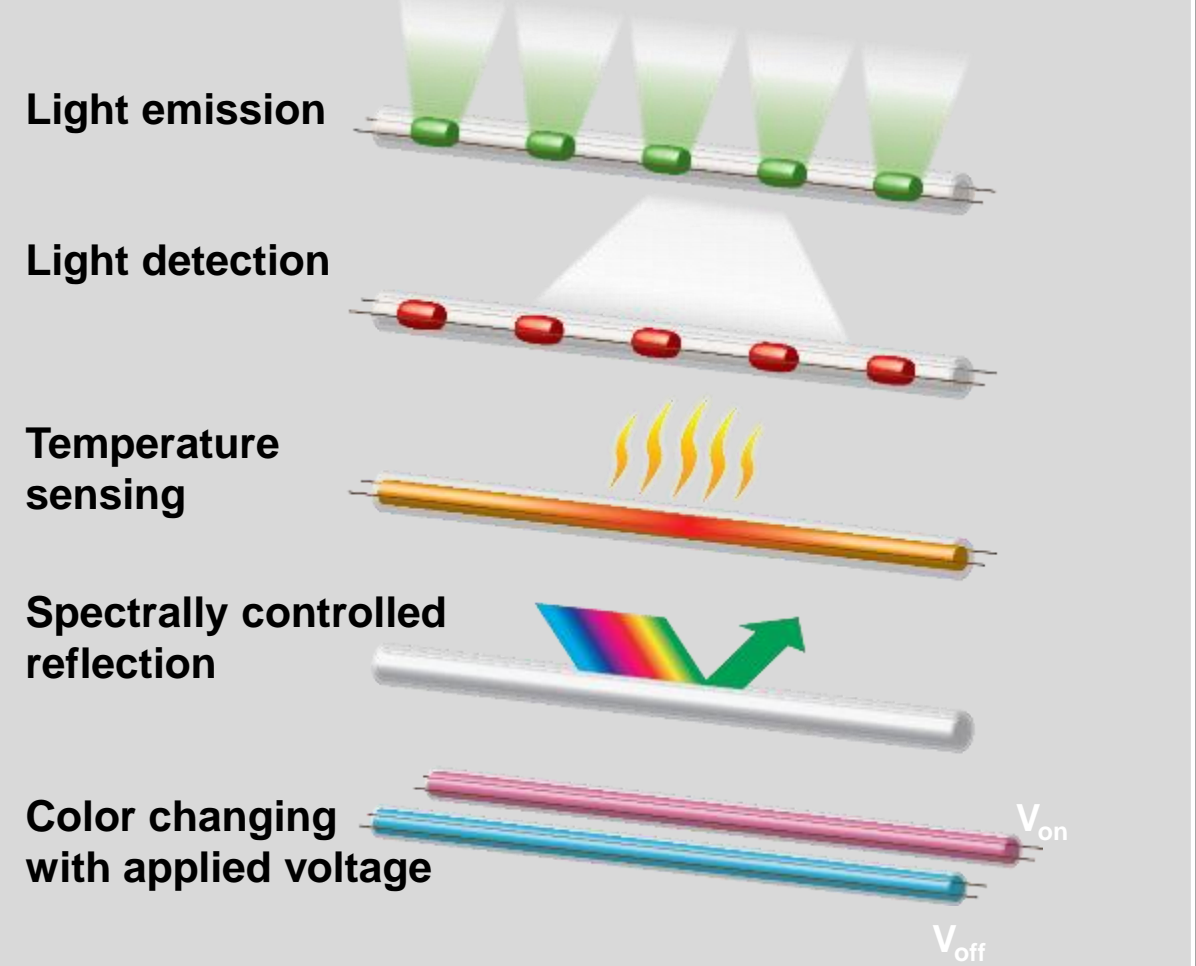
Preform to Fiber Drawing

A Pathway to Functional Fiber Microsystems

Preform Assembly & Thermal Draw



Fiber Applications

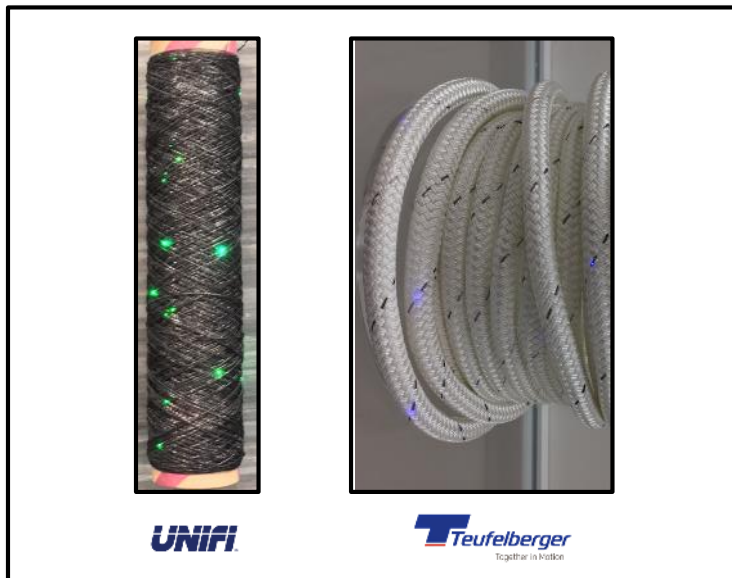




Functional Fiber Microsystem Textile Integration

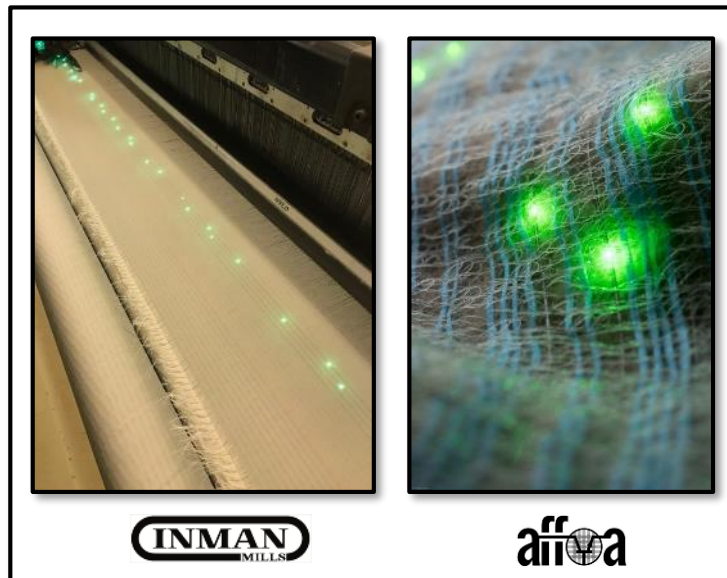


Yarns & Ropes



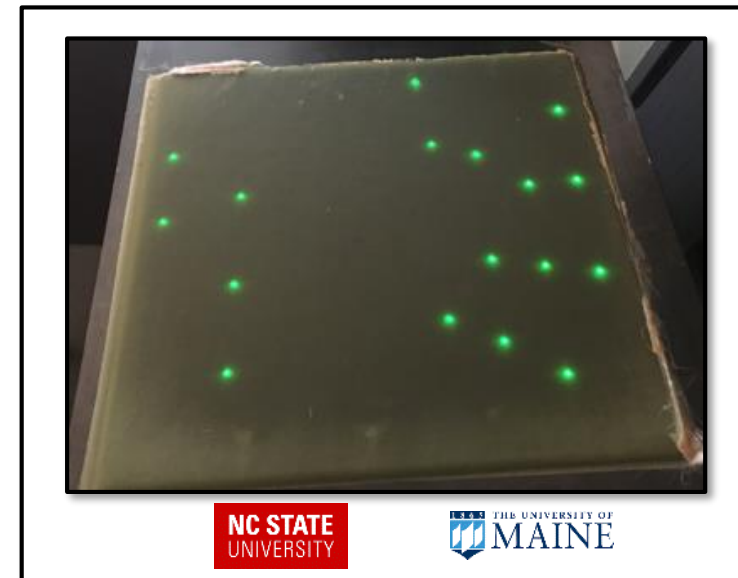
- Natural / synthetic fiber blends
- Multi-filament yarns
- Diameter range: 300 μm – 30 cm

Wovens, Nonwovens, & Knits



- Wovens: weft insertion
- Tubular and flatbed knitting
- Advanced nonwoven filters

Composites



- Glass fiber
- Carbon fiber
- Advanced thermoplastics

Functional fiber microsystems have been integrated into commercial processes, but what effect does this have on the textile's original performance characteristics?

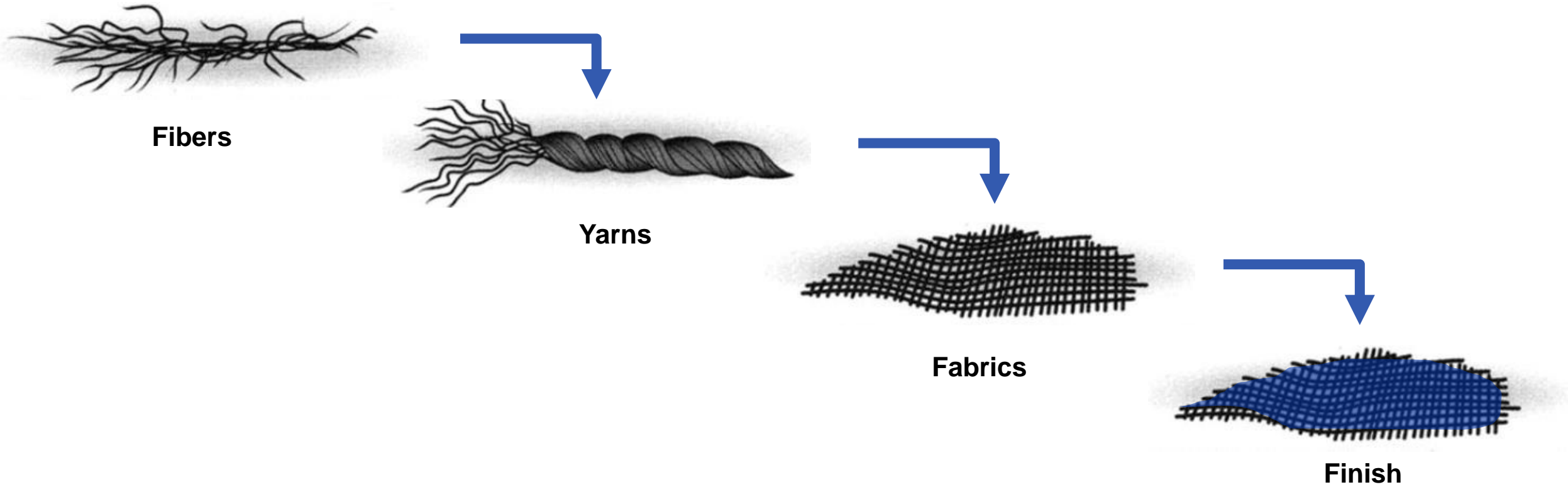


Outline

- Introduction
- • **Parametric Study**
 - Scope
 - Methodology
 - Results
- Limitations on Fabrication
- Summary & Conclusions



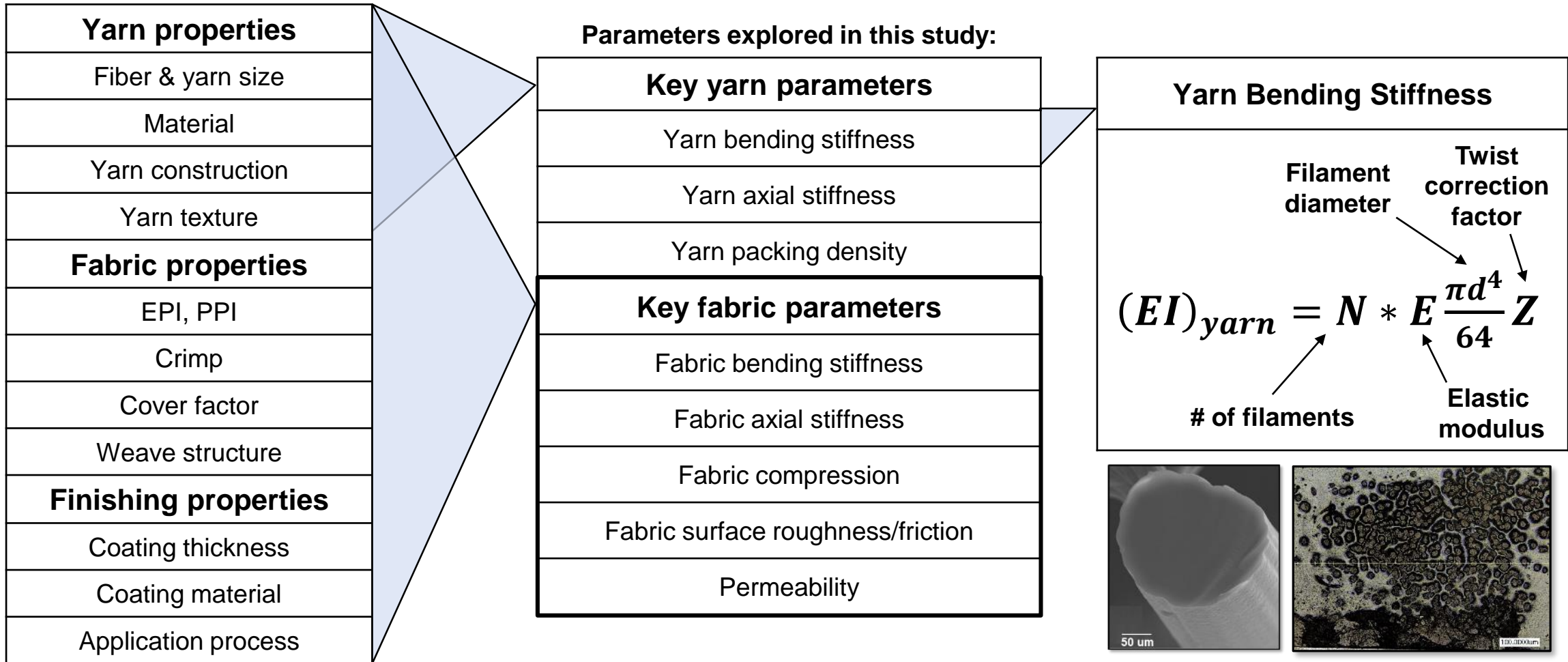
Elements of a Fabric





Yarn and Fabric Properties Affect Textile Performance

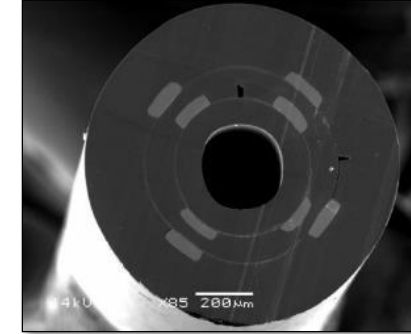
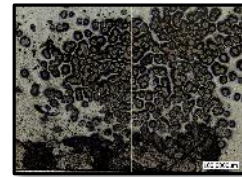
Many properties define a yarn, however these properties can be distilled down to a few key parameters that contribute to a fabric's performance.





Key Yarn Properties

Traditional yarns and smart yarns are similar, but they are not the same.



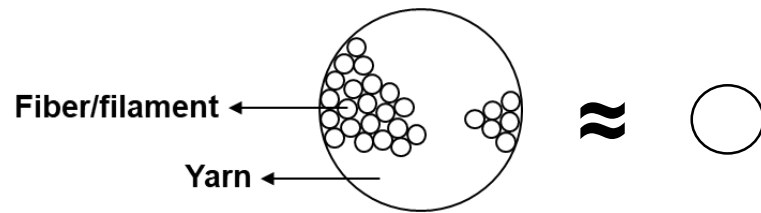
	Traditional Yarn	Smart Yarn
Yarn diameter	0.06 – 0.8 mm	0.1 – 2 mm
Filament diameter	0.01 – 0.05 mm	0.1 – 2 mm
Number of filaments	Multifilament	Monofilament
Material	Natural, polymeric	Polymers, conductors, semiconductors



Yarn Equivalent Bending Stiffness Example Case

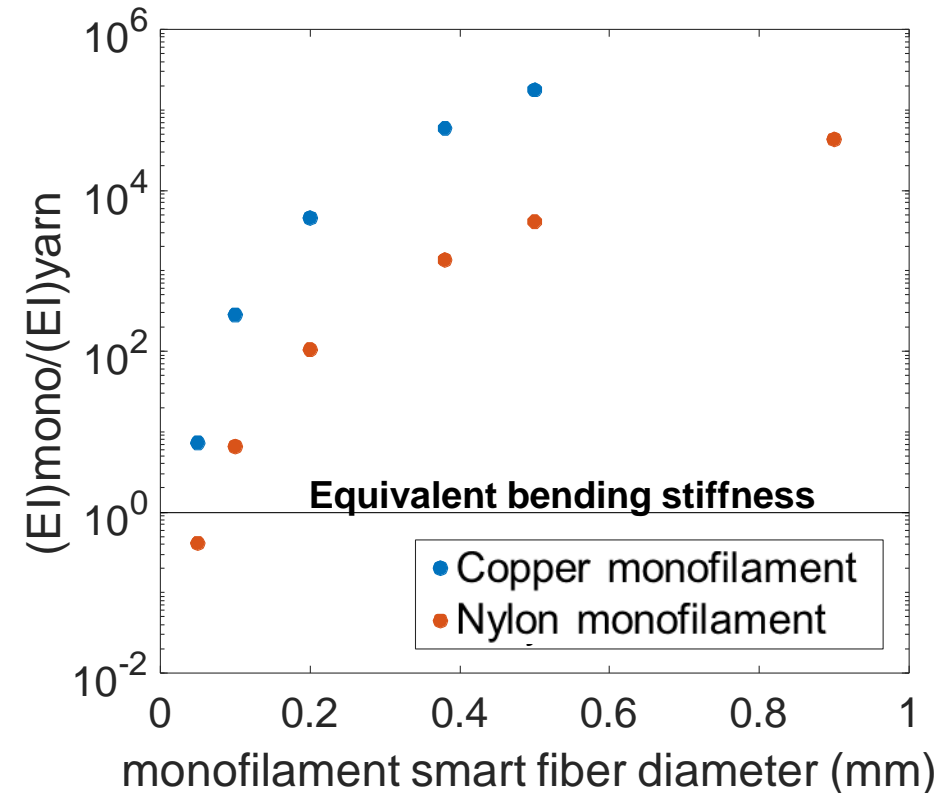
260 denier multifilament yarn

(68 filaments with 0.022 mm diameter, 0.181 mm equivalent yarn diameter)



For a homogenous fabric, the goal is to replace traditional yarn with smart fiber 1:1 in weft.

When $\frac{(EI)_{monofilament}}{(EI)_{yarn}} = 1$, monofilament and traditional yarn have equal bending stiffness.



For a monofilament smart yarn to have a bending stiffness comparable to a 260 denier traditional yarn, it must be less than 0.1 mm diameter



Parametrized Study of 2D Woven Fabrics Using Surrogate Smart Fibers

How can the incorporation of functional fibers add electronic capability while still preserving a textile's original performance characteristics?

Fabric Classes



Parachute
70D rip-stop Nylon



Combat Uniform
Cotton-Nylon blend



Pack
~500D Nylon



Luggage
1000D Nylon

Light weight → Heavy weight

Scope of Study

Cotton

Nylon/Poly
Plain weave
100D, 500D, 1000D

Webbing

+

Surrogate smart fibers
Nylon monofilaments
0.1 mm, 0.2 mm, 0.5 mm,
0.9 mm diameters
10% & 50% cover factor

Finishing
PU coating, laminate

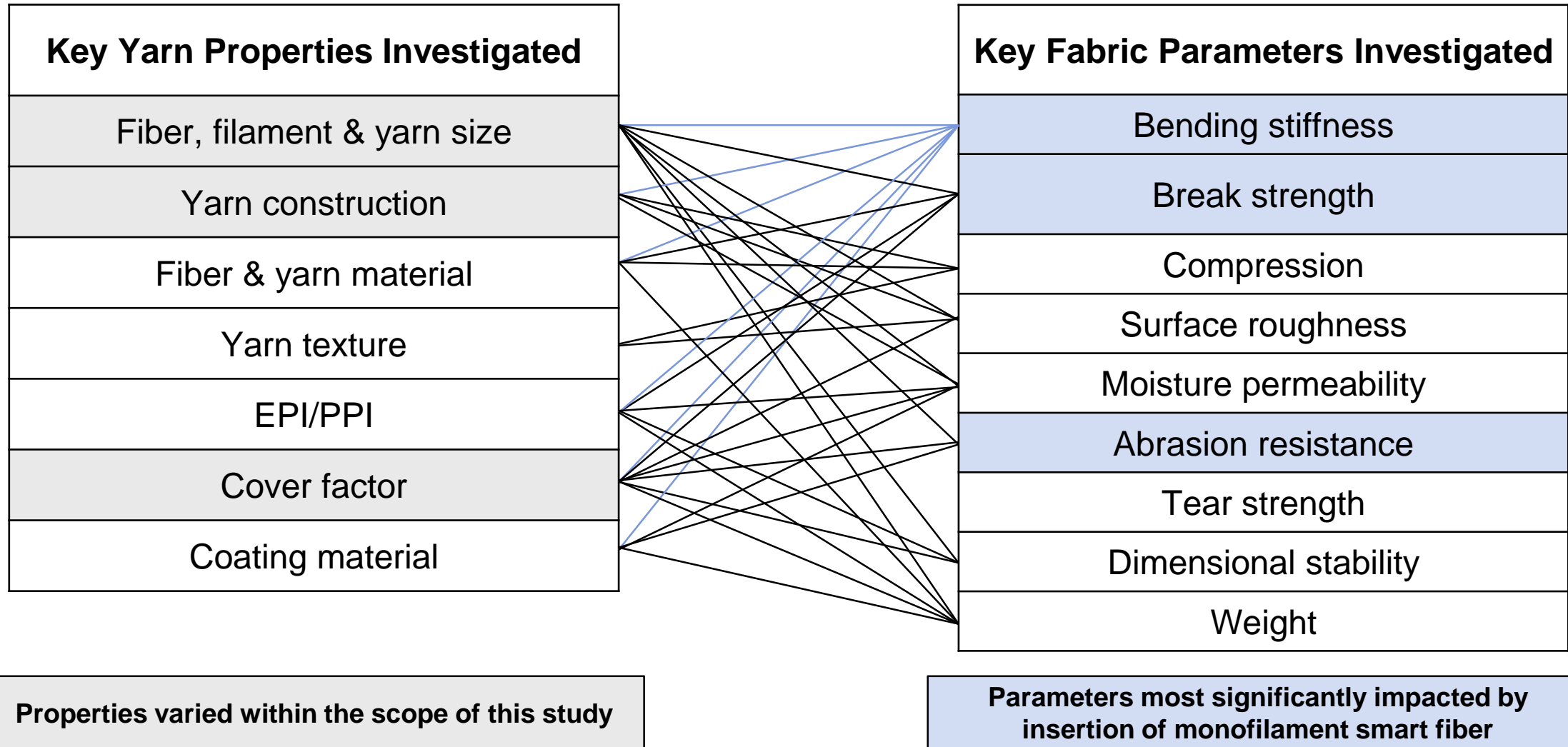
Samples will be subjected to a suite of ASTM standard tests targeting mechanical properties and the hand of the fabric.

Samples with and without smart fiber surrogates will be fabricated and samples with smart fiber surrogates will be compared against control samples.

Goal of the study is a matrix linking fiber/fabric properties with performance parameters, providing a starting set of fiber requirements



Yarn Properties and Fabric Parameters Investigated



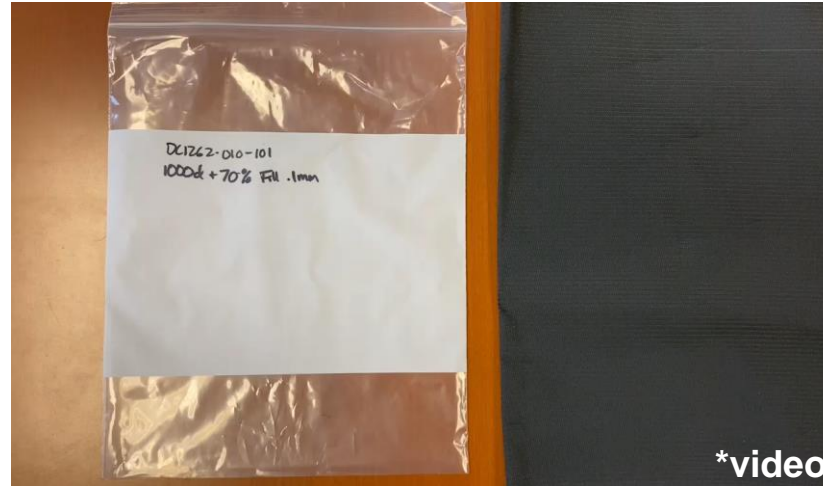


Photographic Comparison of Fabric Bending Stiffness

1000 d control

1000 d + 70% cover 0.1 mm

1000 d + 70% cover 0.9 mm



El ratio	1000 d control	1000 d + 70% cover 0.1 mm	1000 d + 70% cover 0.9 mm
Yarn	1	0.751	4930
Fabric, 70% cover	1	1.90	1200

El = bending stiffness

El ratio = ratio of bending stiffness of sample to control

- **0.1 mm monofilament at 70% cover qualitatively behaves similar to the 1000 d control, both at the yarn and fabric level.**
- **0.9 mm monofilament is much stiffer than the 1000d control, both at the yarn and fabric level.**

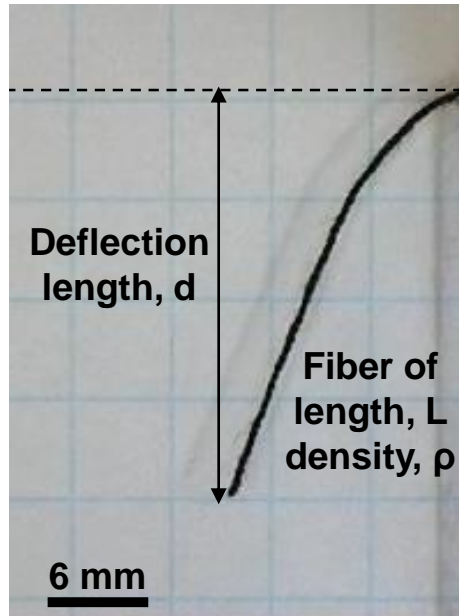
Initial experimental samples qualitatively agreed with theoretical performance predictions. Further testing will help quantify.



Yarn Bending Stiffness

A cantilever bend test was utilized to experimentally measure bending stiffness of both the monofilament and traditional yarns used in our study.

Cantilever bend test set up



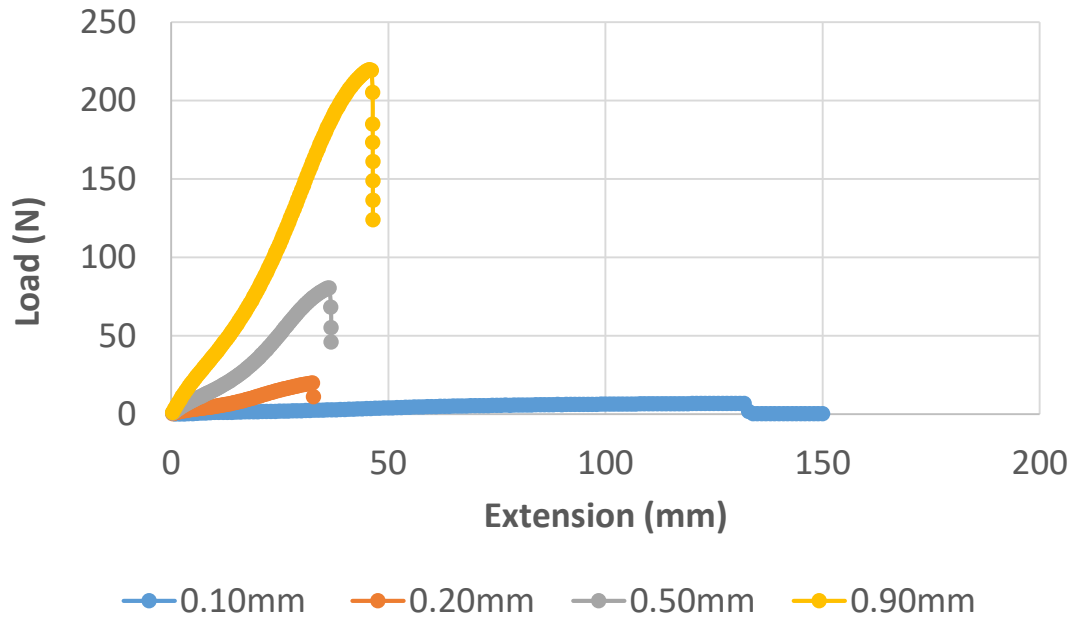
	experimental bending stiffness (Pa*m ⁴)
100D poly	8.79286E-10
500D nylon	7.39089E-09
1000D poly	1.15952E-08
0.1 mm nylon	4.90734E-08
0.2 mm nylon	3.53603E-07
0.5 mm nylon	7.60616E-07
0.9 mm nylon	8.8061E-06



Yarn Break Strength

A tensile test was utilized to experimentally measure break strength of both the monofilament and traditional yarns used in our study.

Monofilament - Load vs. Extension

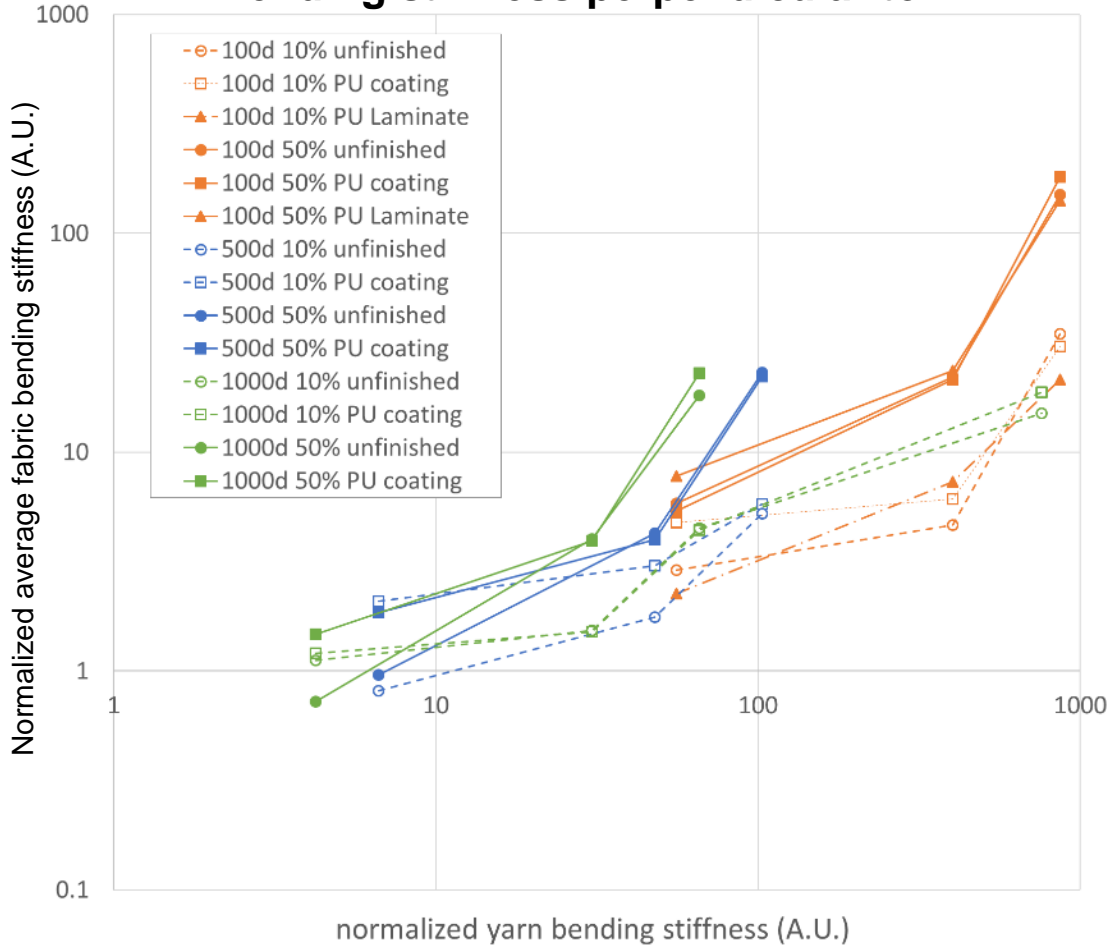


	Max Load (N)	
	Average	stdv
100D poly	4.23	0.133
500D nylon	19.4	0.59
1000D poly	77.3	2.40
0.1 mm nylon	6.76	0.173
0.2 mm nylon	18.5	0.810
0.5 mm nylon	81.0	1.10
0.9 mm nylon	221	5.02



Fabric Bending Stiffness Results Summary

Bending stiffness perpendicular to fill



- Range of yarn bending stiffness values were tested by utilizing different diameter monofilaments
- Yarn and fabric stiffness were normalized to their respective control fabric and yarn:

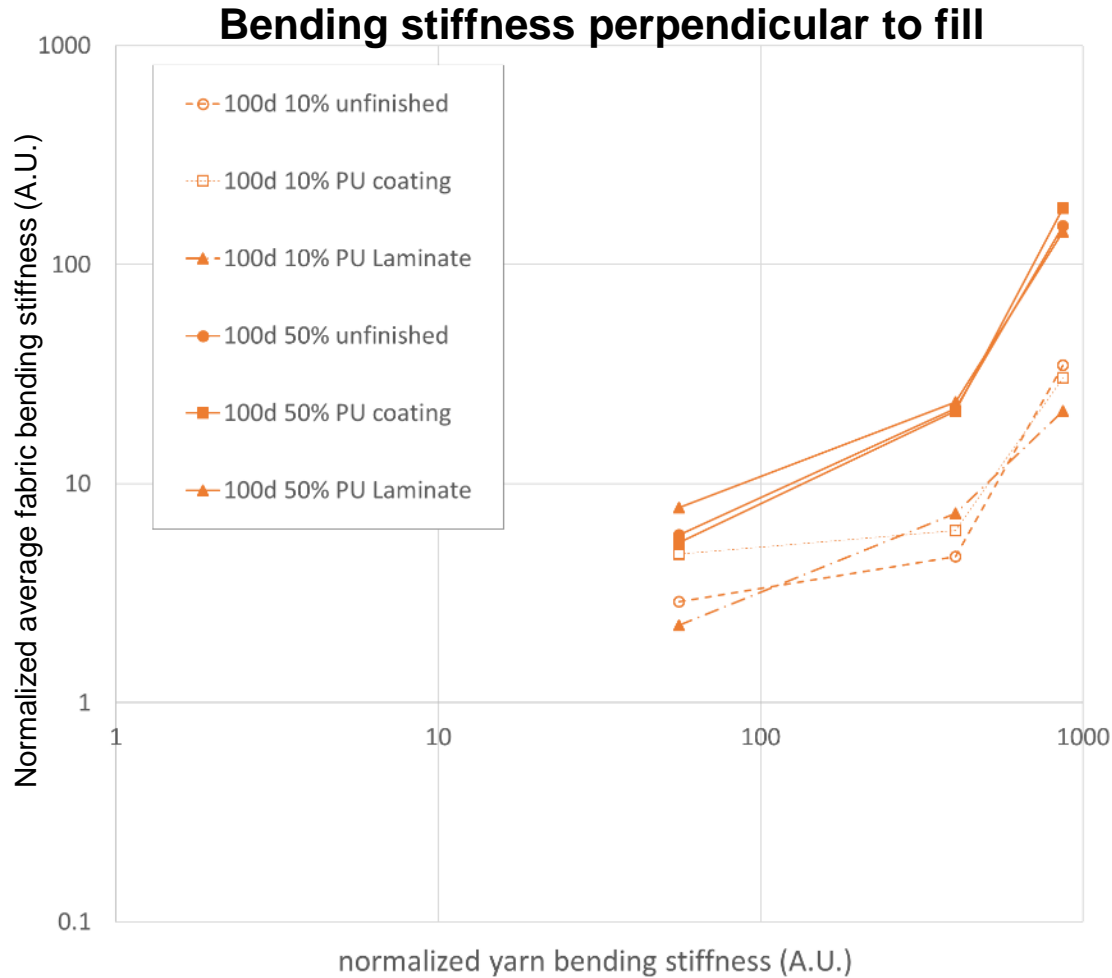
$$\text{Normalized yarn bending stiffness} = \frac{\text{monofilament bending stiffness}}{\text{control yarn bending stiffness}}$$

$$\text{Normalized fabric bending stiffness} = \frac{\text{monofilament fabric bending stiffness}}{\text{control fabric bending stiffness}}$$

In nearly all cases tested, insertion of monofilament increased the fabric bending stiffness



Dominant Fabric Bending Stiffness Contributors



- Range of yarn bending stiffness values were tested by utilizing different diameter monofilaments
- Yarn and fabric stiffness were normalized to their respective control fabric and yarn:

$$\text{Normalized yarn bending stiffness} = \frac{\text{monofilament bending stiffness}}{\text{control yarn bending stiffness}}$$

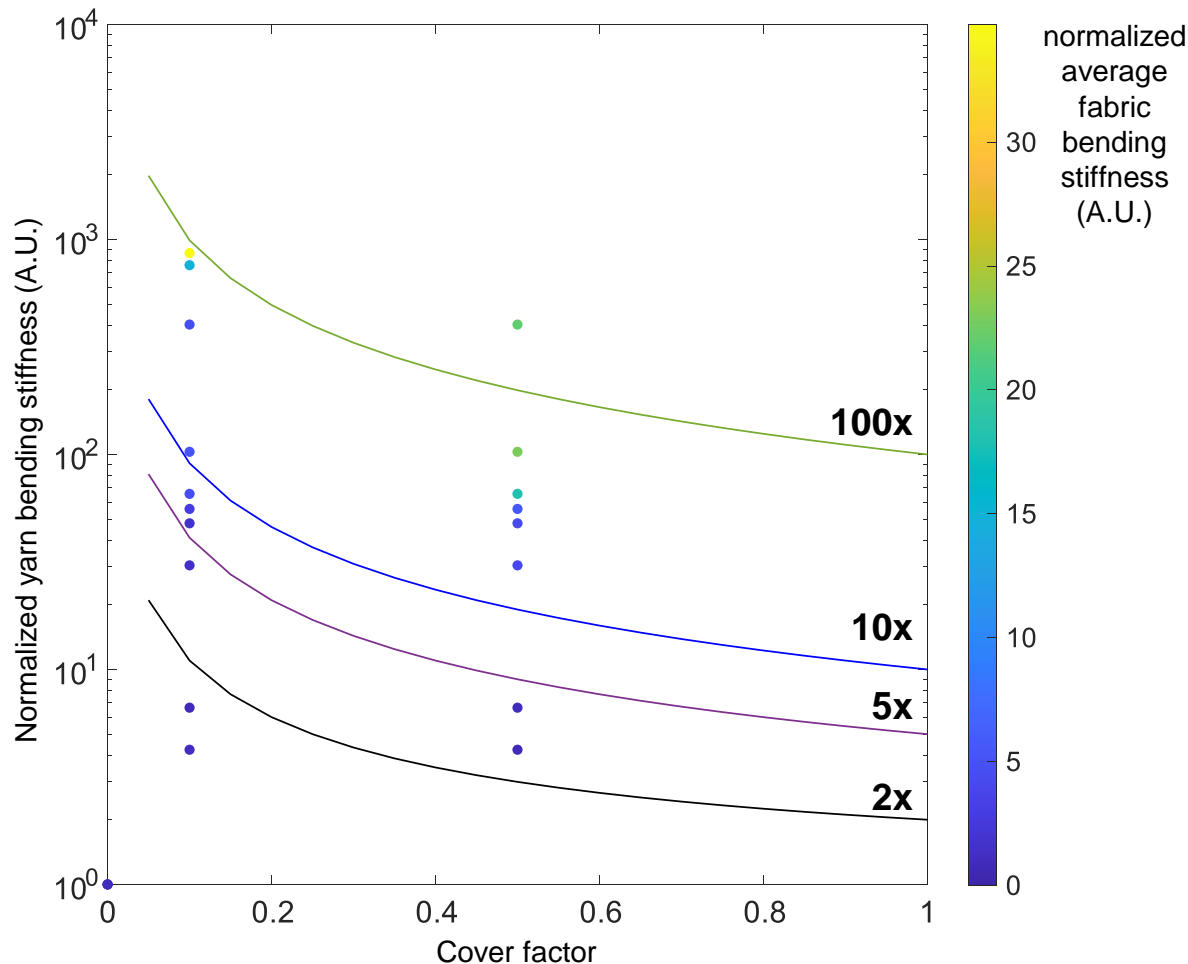
$$\text{Normalized fabric bending stiffness} = \frac{\text{monofilament fabric bending stiffness}}{\text{control fabric bending stiffness}}$$

- Material and weight of finishes applied are representative of military grade fabrics

Yarn bending stiffness and cover factor dominate bending stiffness, even when considering applied finishes



Fabric Bending Stiffness – Fiber requirement



- Range of yarn bending stiffness values were tested by utilizing different diameter monofilaments
- Yarn and fabric stiffness were normalized to their respective control fabric and yarn:

$$\text{Normalized yarn bending stiffness} = \frac{\text{monofilament bending stiffness}}{\text{control yarn bending stiffness}}$$

$$\text{Normalized fabric bending stiffness} = \frac{\text{monofilament fabric bending stiffness}}{\text{control fabric bending stiffness}}$$

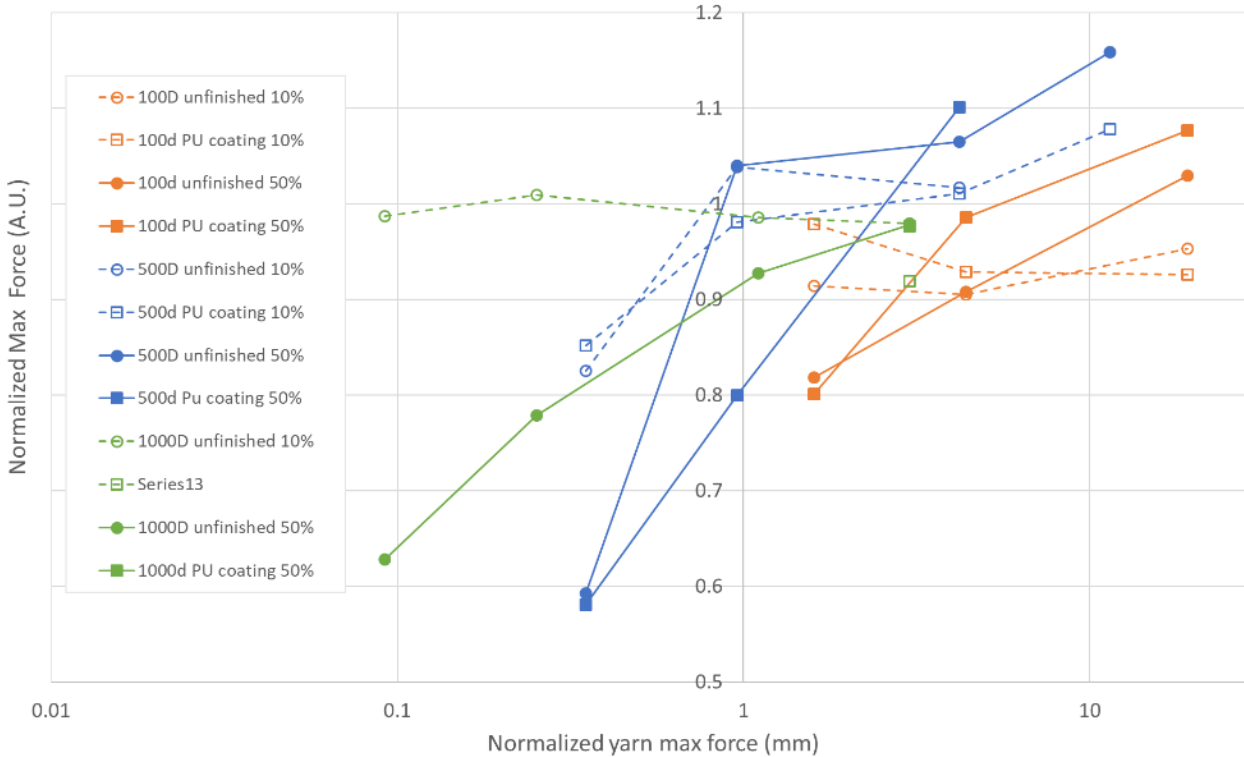
- Data fit to simple fabric bending stiffness model for curves of constant fabric bending stiffness
- An average fabric bending stiffness within 5x of control fabric is not noticeable by touch

Fabric bending stiffness is determined by both yarn bending stiffness and cover factor. For example to maintain 5x fabric bending stiffness, yarn with ~40x stiffness may only be inserted up to ~10% cover factor.



Fabric break strength

Fabric break strength (perpendicular to fill)



- Fabric and yarn maximum break force are normalized to respective control fabric and yarn

$$\text{Normalized yarn max break force} = \frac{\text{monofilament max break force}}{\text{control yarn max break force}}$$

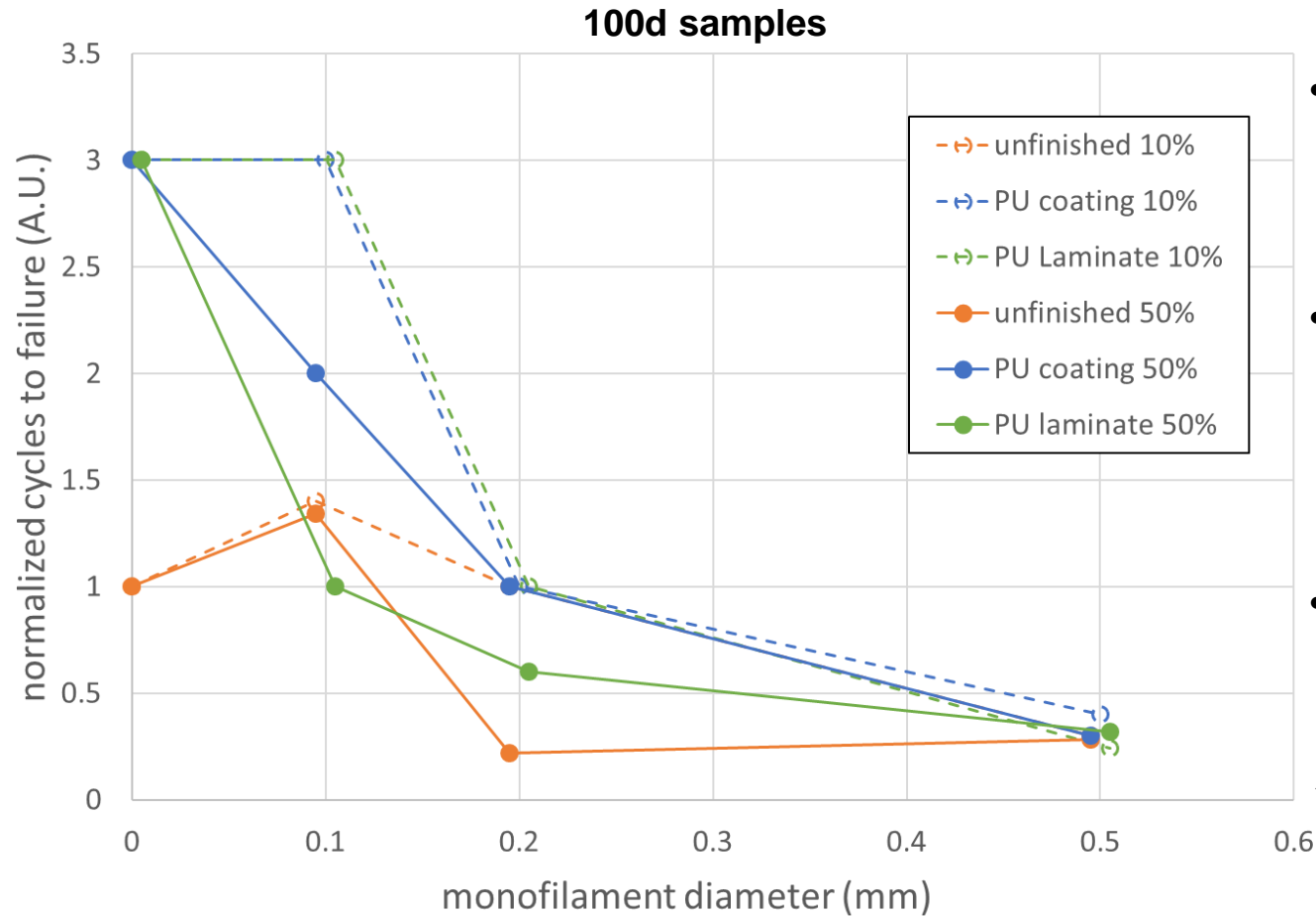
$$\text{Normalized fabric max break force} = \frac{\text{monofialment fabric max break force}}{\text{control fabric max break force}}$$

- Fabric break strength results from combined effect of several tested parameters (yarn break strength, PPI, cover factor), however the exact relationship still needs to be determined

Fabric break strength is dependent on multiple parameters with further analysis still necessary to make recommendations for fiber requirements



Abrasion – Fiber requirement



- Fabric finishes often applied to enhance abrasion resistance and reduce moisture permeation
- The 1 oz PU dip coating and 0.02” thick PU back side laminate used in this study are representative of typical finishes used in military grade fabrics
- Cycles to failure are normalized to the unfinished control:

$$\text{Normalized cycles to failure} = \frac{\text{fabric sample cycles to failure}}{\text{unfinished control fabric cycles to failure}}$$

Increased abrasion resistance due to application of a finish coating or laminate is negated by the insertion of monofilaments larger than 0.1 mm in diameter and/or at high cover factor



Example case: Textured Nylon Duck Cloth

What requirements must a monofilament smart fiber meet for integration into textured nylon duck cloth (MIL-DTL-32439)?

Type III 500 denier, class 3 – 8 oz/sq yd, water repellent/back coated

Fabrication Specifications:

500d textured continuous filament nylon

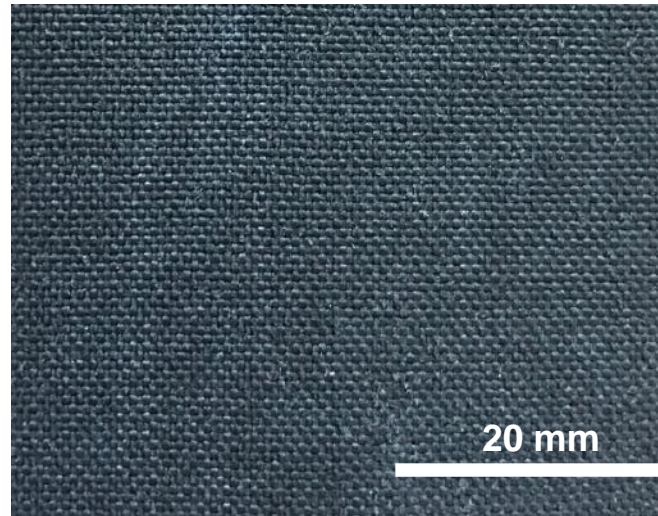
plain weave

scour and heat set

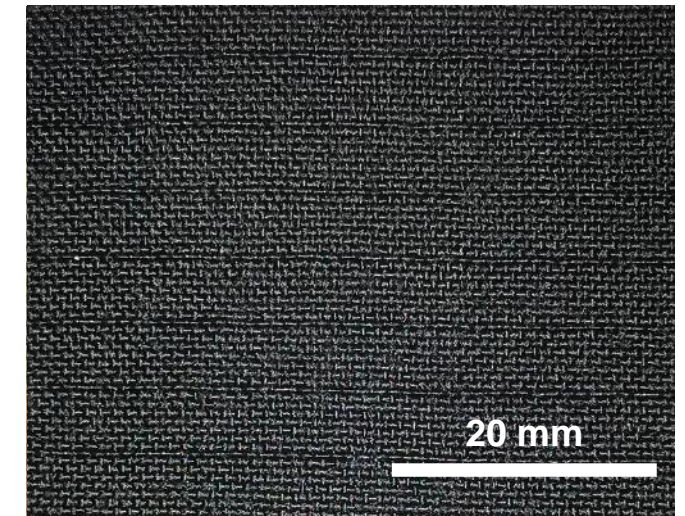
PU backside coating

Performance Specifications:

Type III	Weight (oz/sq yd)		Yarns per inch (minimum)		Stiffness (lb)	Break strength, lbs (minimum)	
	Min	Max	Warp	Fill	Warp & Fill	Warp	Fill
Class 3	7.0	8.0	48	35	0.034	300	225
Nylon mono	7.59		50	43	0.027	326	295



500d PU coated control



500d PU coated, 10% cover 0.2 mm monofilament

Fabric with 0.2 mm diameter monofilament at 10% cover factor will meet 500d textured nylon specification



Example Case: Textured Nylon Duck Cloth with Copper Wire

What requirements must a monofilament smart fiber meet for integration into textured nylon duck cloth (MIL-DTL-32439)?

Type III 500 denier, class 3 – 8 oz/sq yd, water repellent/back coated

Fabrication Specifications:

500d textured continuous filament nylon
 plain weave
 scour and heat set
 PU backside coating

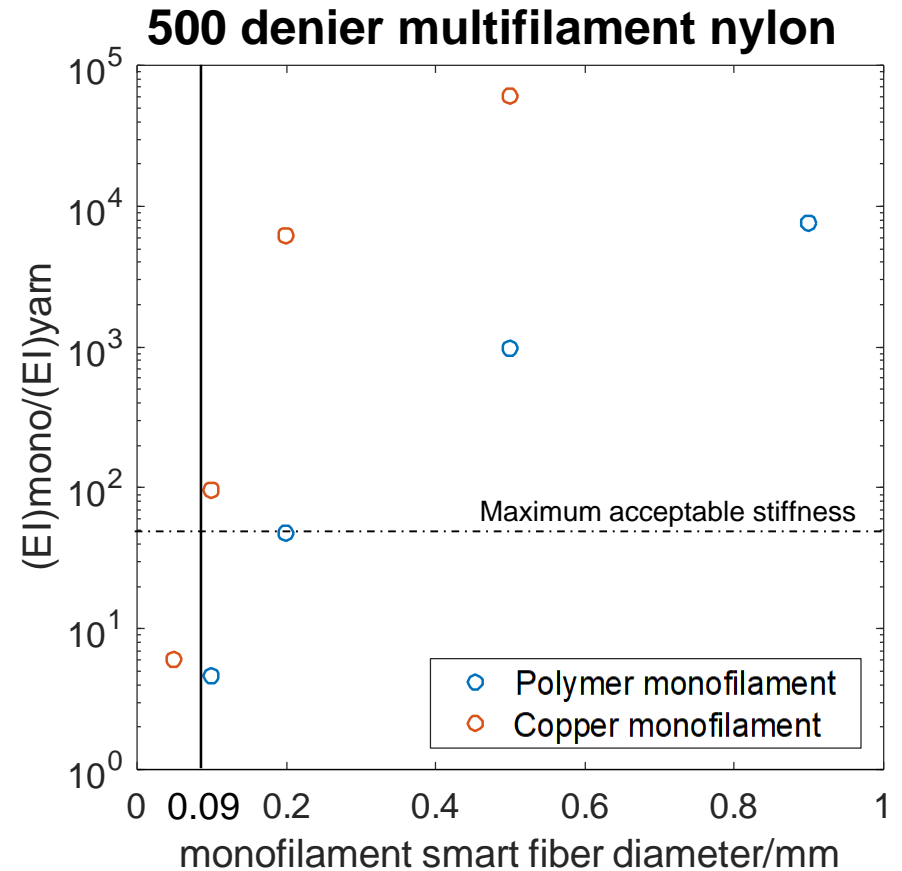
Performance Specifications:

Type III	Weight (oz/sq yd)		Yarns per inch (minimum)		Stiffness (lb)	Break strength, lbs (minimum)	
	Min	Max	Warp	Fill	Warp & Fill	Warp	Fill
Class 3	7.0	8.0	48	35	0.034	300	225
Nylon mono	7.59		50	43	0.027	326	295
Cu wire	10.5		50	43	0.027	TBD	TBD

Initial Comparisons

0.09 mm copper wire at 5% cover factor:

- Fabric bending stiffness and PPI/EPI comparable to Nylon monofilament sample
- 1.4x increase in weight compared to control
- Break strength TBD



Functional fabric would require copper wires to have diameters <100 μm and <5% cover factor to match fabric bending specification with further testing necessary to determine requirements for remaining specifications



Limitations Identified During Woven Fabric Fabrication

Scour and heat set

No monofilament

	100D Poly	500D Nylon	1000D Poly
N/A	10 yards	10 yards	10 yards

10% cover factor

	100D Poly	500D Nylon	1000D Poly
0.1 mm	10 yards	10 yards	10 yards
0.2 mm	10 yards	10 yards	10 yards
0.5 mm	10 yards	10 yards	10 yards
0.9 mm			10 yards

50% cover factor

	100D Poly	500D Nylon	1000D Poly
0.1 mm	10 yards	10 yards	10 yards
0.2 mm	10 yards	10 yards	10 yards
0.5 mm	10 yards	10 yards	10 yards
0.9 mm			10 yards

Polyurethane dip coating

No monofilament

	100D Poly	500D Nylon	1000D Poly
N/A	10 yards	10 yards	10 yards

10% cover factor

	100D Poly	500D Nylon	1000D Poly
0.1 mm	10 yards	10 yards	10 yards
0.2 mm	10 yards	10 yards	10 yards
0.5 mm	10 yards	10 yards	10 yards
0.9 mm			10 yards

50% cover factor

	100D Poly	500D Nylon	1000D Poly
0.1 mm	10 yards	10 yards	10 yards
0.2 mm	10 yards	10 yards	10 yards
0.5 mm	10 yards	10 yards	10 yards
0.9 mm			10 yards

Polyurethane Laminate

No monofilament

	100D Poly
N/A	10 yards

10% cover factor

	100D Poly
0.1 mm	10 yards
0.2 mm	10 yards
0.5 mm	10 yards
0.9 mm	

50% cover factor

	100D Poly
0.1 mm	10 yards
0.2 mm	10 yards
0.5 mm	10 yards
0.9 mm	

During fabrication several samples from original scope were unable to be made due to large mismatch between functional monofilament diameter and yarn diameter



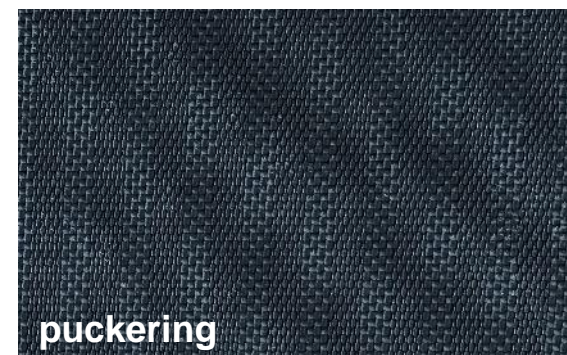
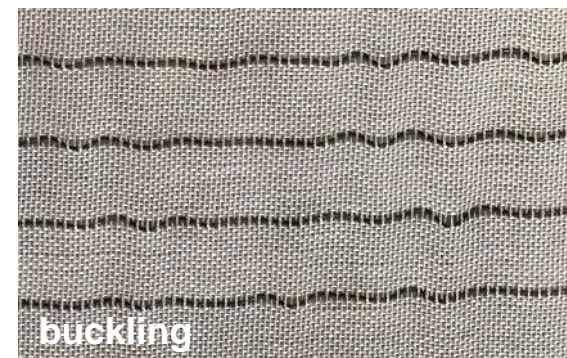
Discontinued due to fabrication challenges



Woven Fabric Defects Identified After Fabrication

Additional defects have been identified that were not in original test plan but need to be considered for future performance tests

- 1. Stiffer functional monofilaments lack of flexibility alter the way the warp and weft are interlocked. This lead to reduced dimensional stability, and situations where the monofilament fibers easily slipped out of the fabric.**
- 2. Differential shrinkage due to material mismatch between functional fibers and yarns can cause fabric to pucker and monofilaments to buckle within the fabric**
- 3. Appearance of fabric could be significantly altered in some cases going from opaque to nearly transparent due to stiffer monofilaments stretching out base fabric yarn**





Functional Fiber Requirement Summary

- **When designing a smart fabric, the yarn parameters most meaningful to consider are yarn size, bending stiffness and cover factor**
- **For the most seamless integration, smart monofilaments and traditional base yarn should have similar yarn properties**
- **To best maintain the traditional fabrics intrinsic performance when inserting monofilaments, low cover factor will generally be recommended**
- **For applications where high cover factor is not necessary, it is worthwhile to consider alternative integration techniques rather than during weaving**
- **Functional fiber architectures should move away from monofilament structure in order to better match traditional yarn properties**



Acknowledgements

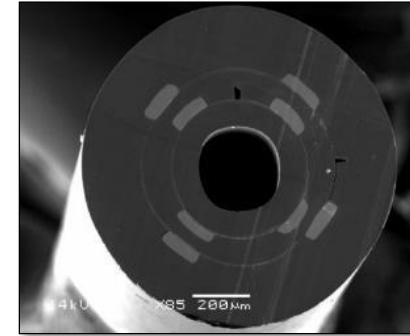
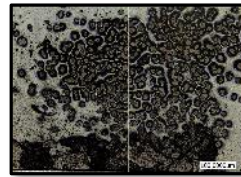
- **Austin Coon**
- **Erin Doran**
- **Danielle Froio-Blumsack**
- **Emily Holtzman**
- **Kate Young**
- **Shawn Redmond**
- **Shaun Berry**
- **Michael Rickley**
- **Tairan Wang**
- **Mordy Rothschild**
- **Warwick Mills**
- **Textile Materials Evaluation Team at CCDC-SC**
- **Textile Technology Center at Gaston College**
- **AFFOA**

Backup Slides



Key Yarn Performance Parameters

Traditional yarns and smart yarns are similar, but they are not the same.



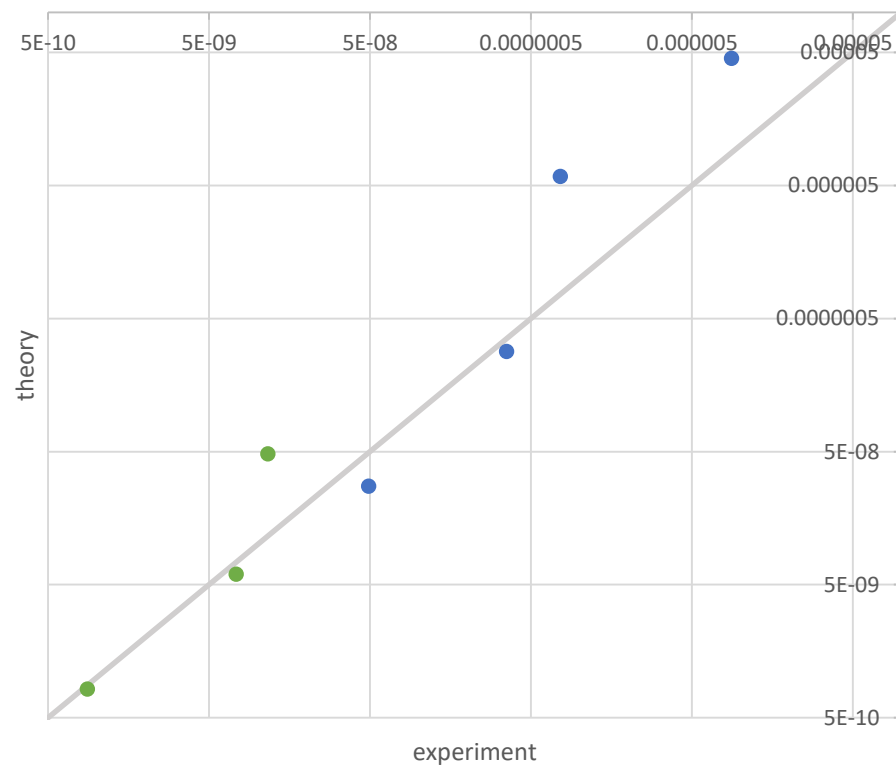
	Traditional Yarn	Smart Yarn
Yarn packing	< 1	1
Bending stiffness	$10^{-10} - 10^{-8} \text{ Pa}\cdot\text{m}^4$	$10^{-8} - 10^{-6} \text{ Pa}\cdot\text{m}^4$
Axial stiffness	$10^2 - 10^3 \text{ Pa}\cdot\text{m}^2$	$10^2 - 10^3 \text{ Pa}\cdot\text{m}^2$

There are distinct differences between traditional yarn and smart yarn performance parameters due to differences in the yarn properties.



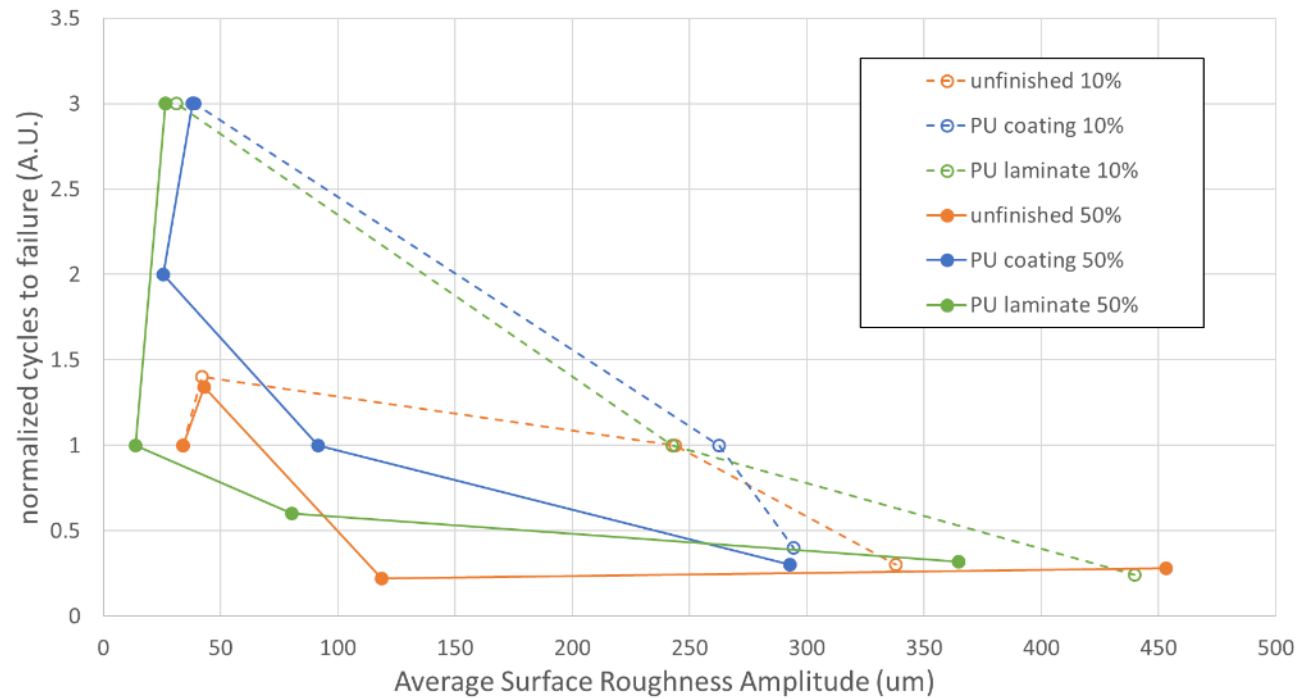
Yarn Bending Stiffness

	experimental bending stiffness (Pa*m ⁴)	theoretical bending stiffness (Pa*m ⁴)
100D poly	8.79286E-10	8.197E-10
500D nylon	7.39089E-09	5.995E-09
1000D poly	1.15952E-08	4.812E-08
0.1 mm nylon	4.90734E-08	2.749E-08
0.2 mm nylon	3.53603E-07	2.827E-07
0.5 mm nylon	7.60616E-07	5.829E-06
0.9 mm nylon	8.8061E-06	4.509E-05

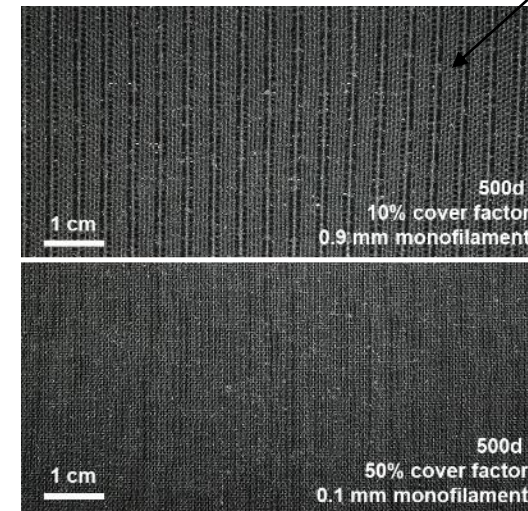




Abrasion – Surface Roughness



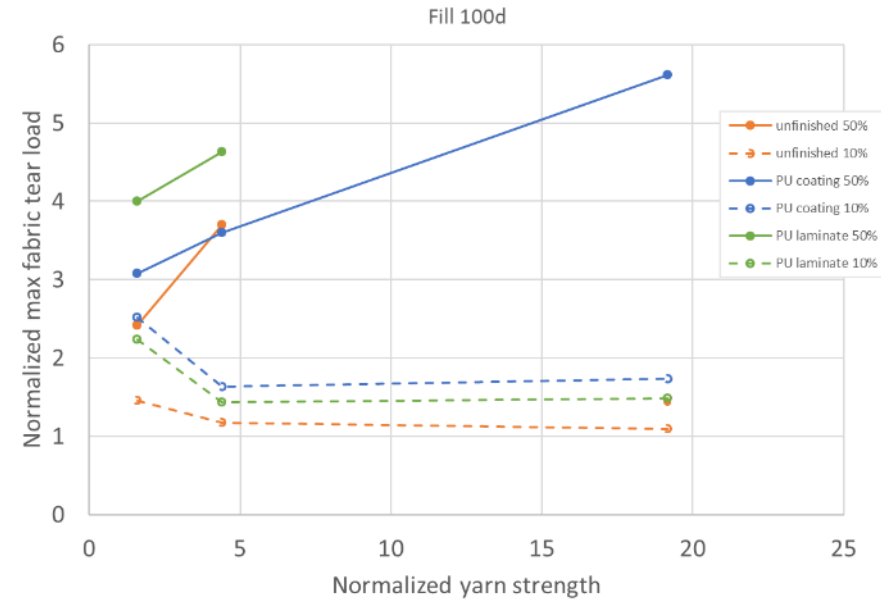
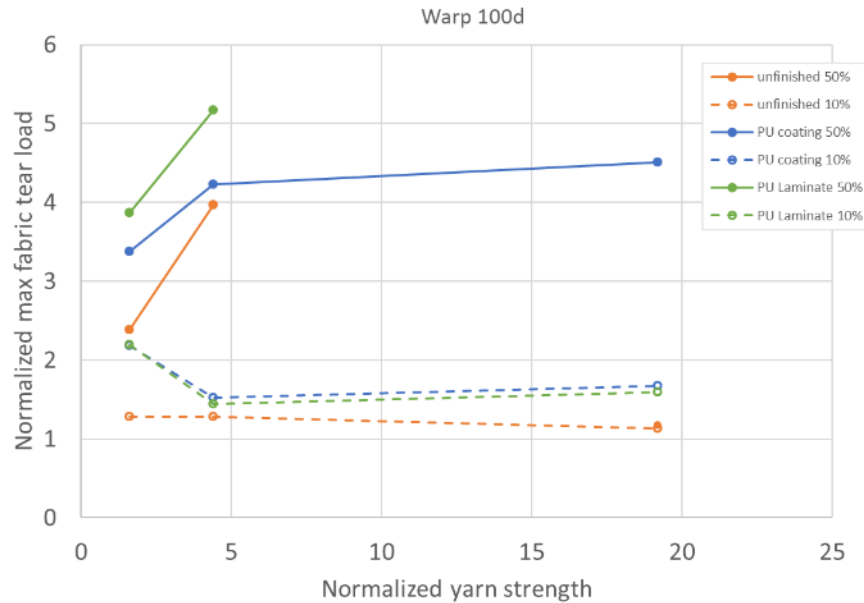
Failure generally occurs along spine of monofilament



Average surface roughness amplitude can be used as a predictor for abrasion performance. Increased surface roughness leads to reduced cycles to failure.



Tear Strength

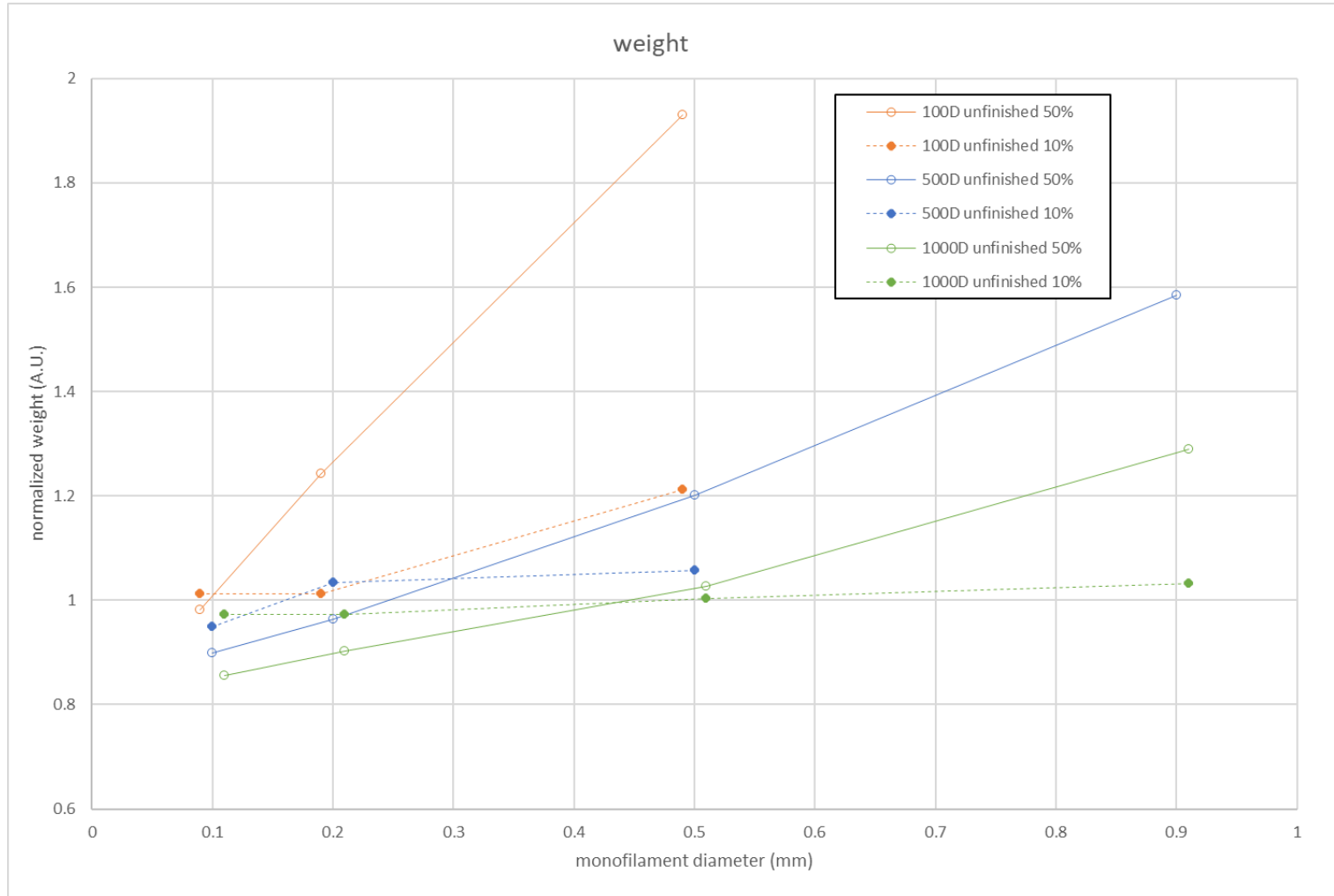


- **Maximum fabric tear load and yarn strength are normalized to control fabric and yarn of corresponding denier and finish**
- **Tear behavior is similar in both the warp and weft directions.**
- **At low cover factor, base yarn behavior dominates.**
- **As monofilament diameter (and strength) increase, monofilaments are held less tightly by warp yarns, likely causing monofilaments to slip during tear test**

Monofilament insertion overall increases fabric tear strength, however cover factor is more significant contributor than relative yarn strength due to monofilaments slipping within the fabric.



Weight

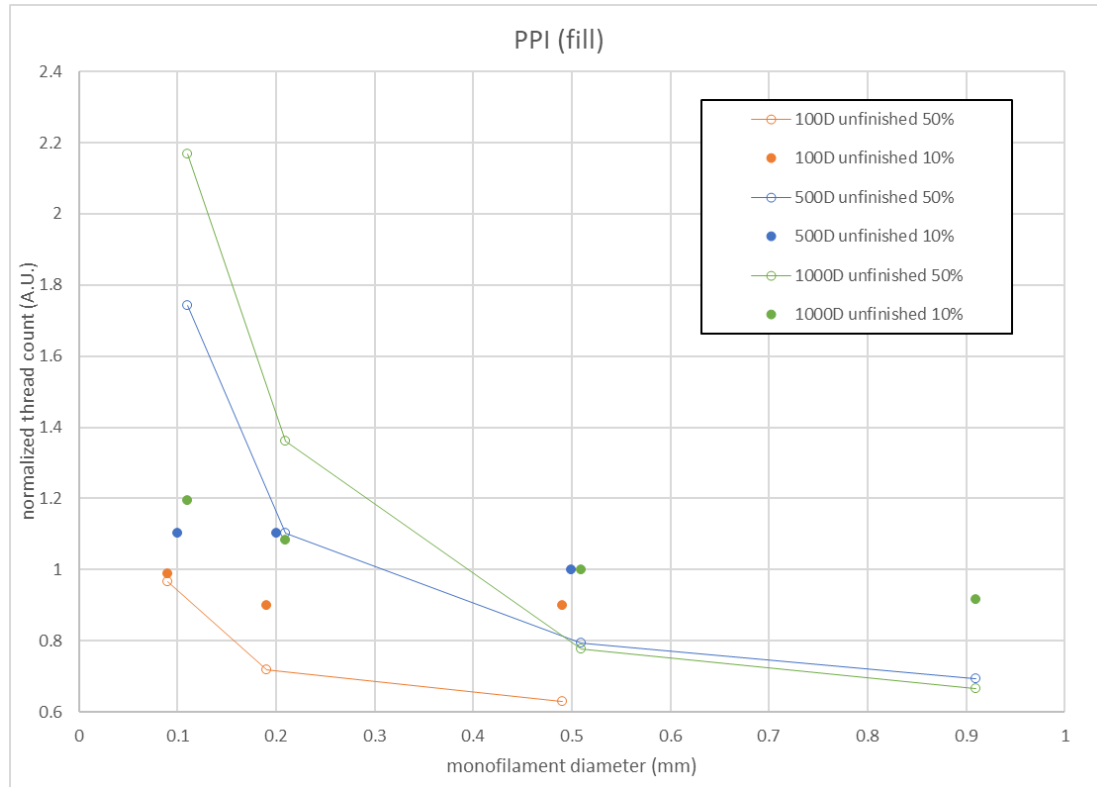


- Total fabric weight is the sum of constituent parts
- 0.1mm diameter Nylon monofilament comparable mass to 100D yarn, lower mass than 500D and 1000D yarns
- Larger denier host fabric can accommodate larger (ie. greater mass) smart fibers
- Small smart fibers in a large denier host reduce overall weight

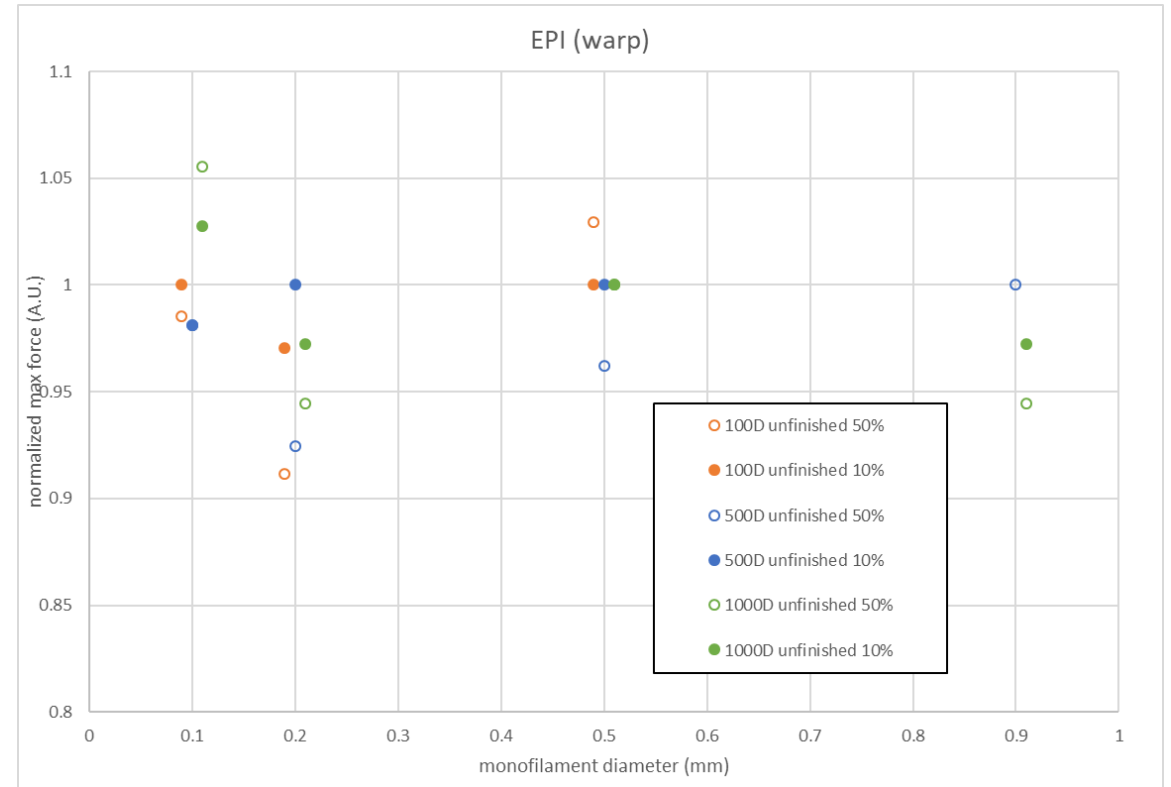


Dimensional Stability

PICKS (PPI)



WARP (EPI)



- No monofilaments in the warp, so thread count (EPI) stays close to EPI of control (w/in 5%)
- PPI decreases with increased filament diameter, most dramatically with higher fill (50%)
- When filament is smaller than host yarn, PPI is greater than 1.
- The larger the mismatch between host and monofilament yarn diameter, the greater delta in normalized thread count

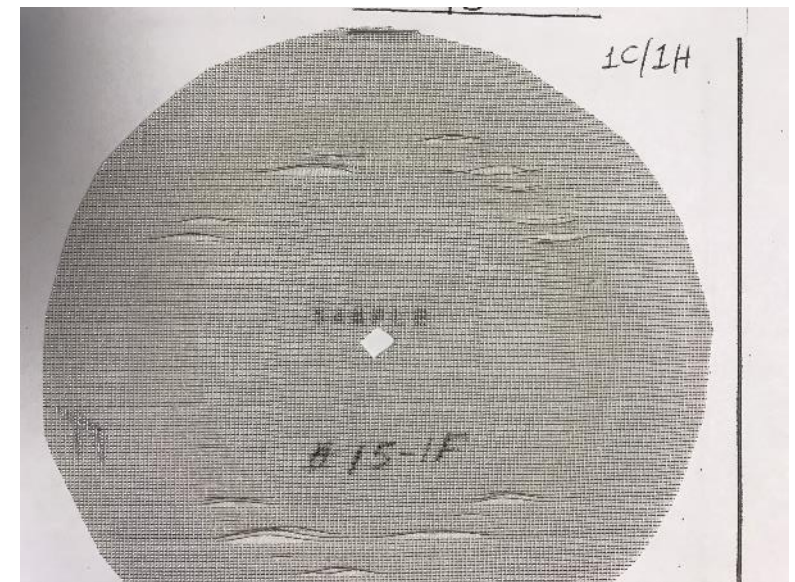
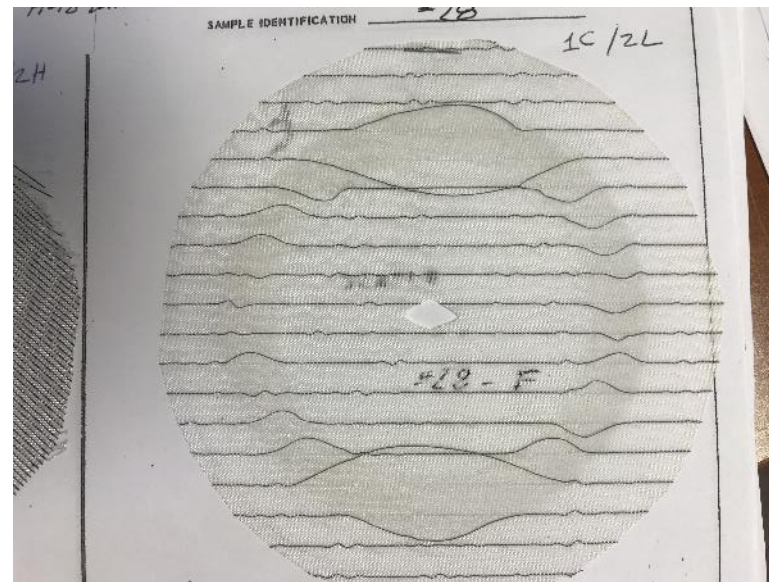
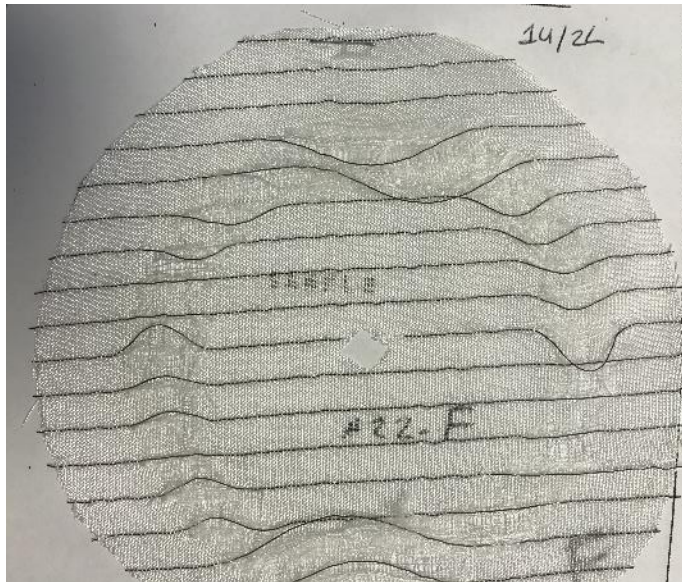
Fabric weight	100D	500D	1000D
Equivalent diameter (mm)	~0.101	~0.250	~0.320



Abrasion

Failure mode: hole (subjective)

Failure generally occurs at warp thread over monofilament insertion





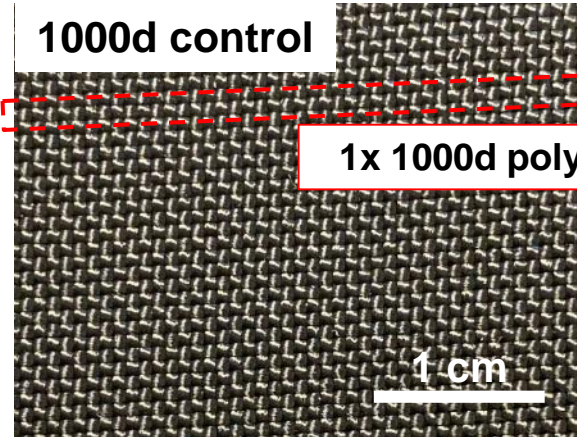
Increased Transparency With High Monofilament Fill



1000 d control



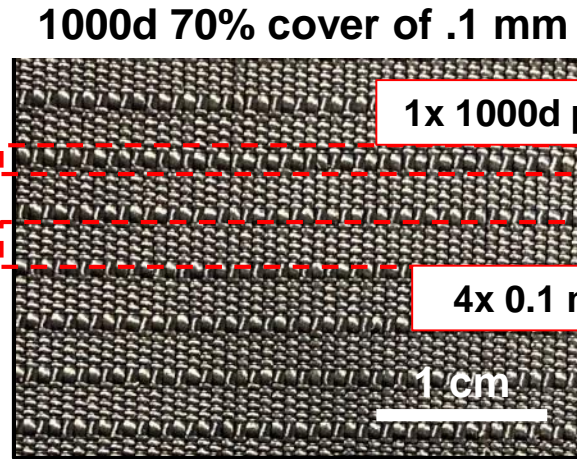
1000 d + 70% cover of 0.1 mm



1000d control

1x 1000d polyester yarn

1 cm



1000d 70% cover of .1 mm

1x 1000d polyester yarn

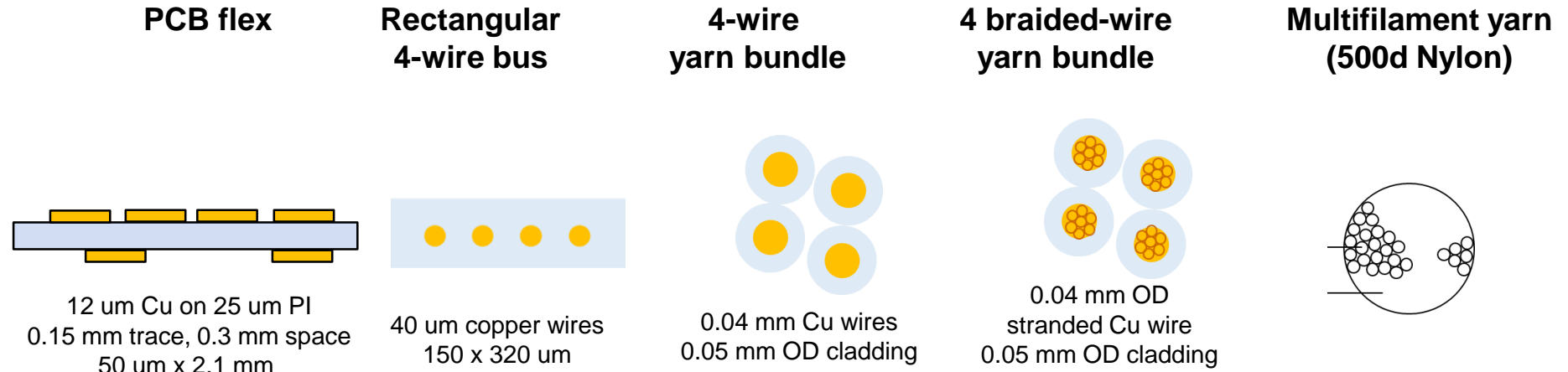
4x 0.1 mm monofilament

1 cm

Monofilaments are packed adjacent to one another, leaving gaps between the smooth sides of adjacent monofilament. This results in higher transparency fabric compared to the control sample.



Alternative Integration Strategies & Fiber Architectures



	PCB flex	Rectangular 4-wire bus	4-wire yarn bundle	4 braided-wire yarn bundle	Multifilament yarn (500d Nylon)
$(EI)_x$ (Pa*m ⁴) (bending stiffness x)	4.31 E-07	2.83 E-07	5.47 E-08	4.03 E-09	5.9 E-09
$(EI)_y$ (Pa*m ⁴) (bending stiffness y)	1.11 E-04	5.69 E-06	5.47 E-08	4.03 E-09	5.9 E-09

While flex PCB technology is comparable to a monofilament 4-wire fiber architecture, multifilament fiber architectures will allow for reduced bending stiffness still maintaining the size of conductor elements.



Example case: Textured Nylon Duck Cloth

What requirements must a monofilament smart fiber meet for integration into textured nylon duck cloth (MIL-DTL-32439)?

Type III 500 denier. Class 3 – 8 oz/sq yd, water repellent/back coated:

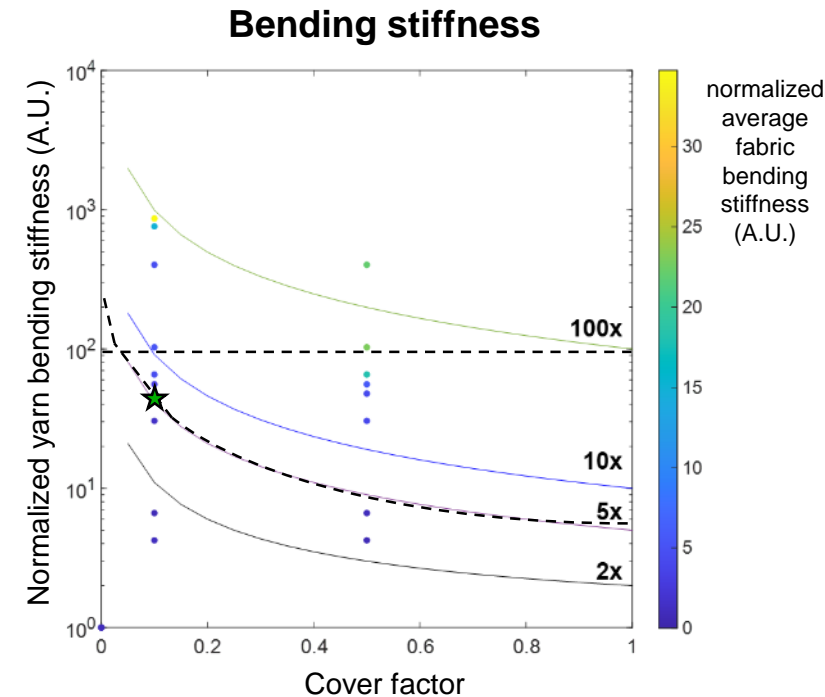
Fabrication Specifications:
 Textured continuous filament nylon
 500d
 plain weave
 scour and heat set
 PU backside coating

Performance Specifications:

Type III	Weight (oz/sq yd)		Yarns per inch (minimum)		Stiffness (lb)	Break strength, lbs (minimum)	
	Min	Max	Warp	Fill	Warp & Fill	Warp	Fill
Class 3	7.0	8.0	48	35	0.034	300	225

Assuming control fabric meets specification:

1. 500d samples with solid polymer monofilament up to 0.5 mm diameter is within 5% of control weight and EPI/PPI. This provides upper bound on fiber diameter.
2. Monofilament diameter of 0.5 mm in 500d base yarn provides upper bound on bending stiffness.
3. To maintain bending stiffness within 5x of control fabric, cover factor & yarn stiffness must remain below 5x curve.
4. Confirm that yarn stiffness and cover factor meet break strength requirement.



Insertion of 0.2 mm diameter monofilament at 10% cover factor meets 500d textured nylon specification.