Testing and Modeling of Yarn Pullout in Plain Woven Kevlar Fabrics

Z. Dong and C.T. Sun
School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana 47907

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Background

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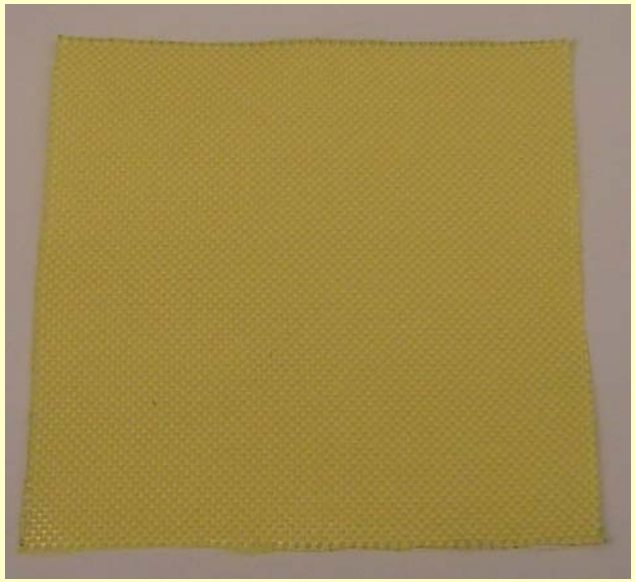


Oven dry
at 80 ^{0}C for
30 minutes

→ **Flexible Armor**

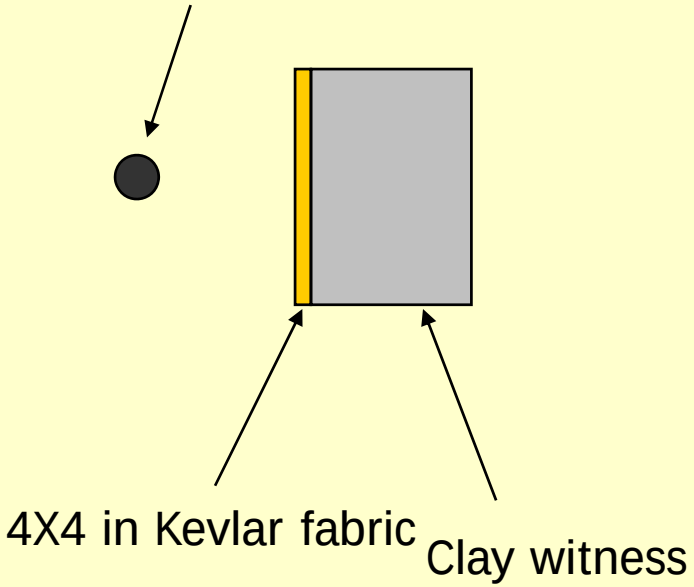
Colloidal Silica
71 nm average diameter
40.7 w% particle
from Nissan Chemical Co.

Kevlar KM2
plain woven fabric
from Hexel Co.

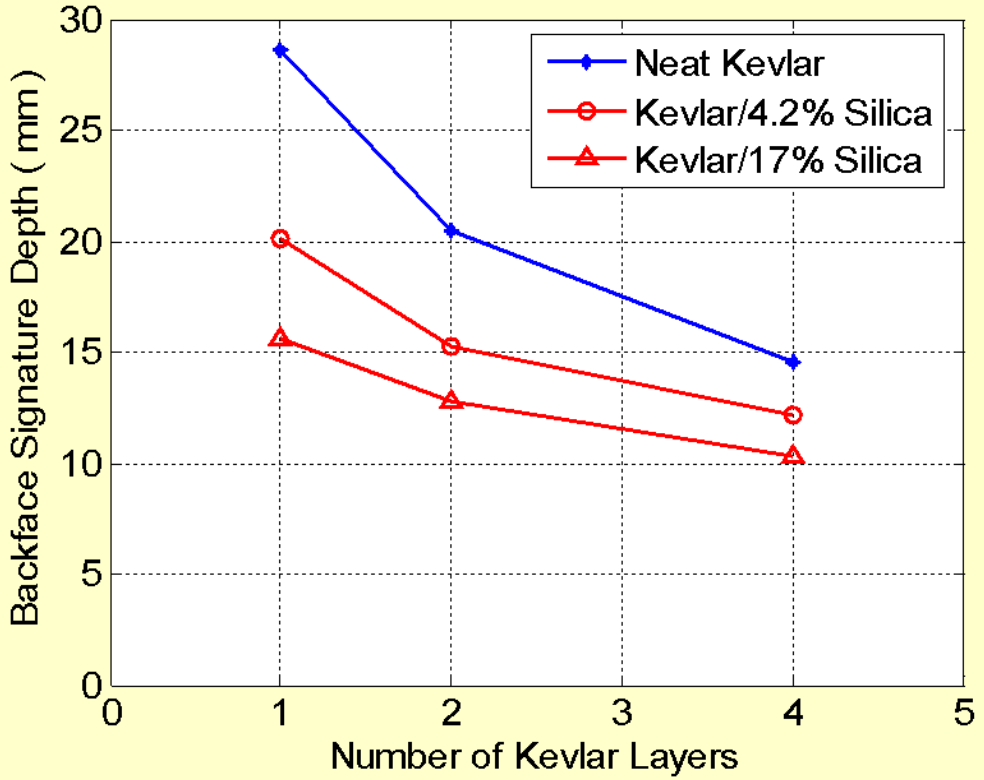
Effect of Silica Nano Particles in Kevlar Fabric

Ballistic Test

Projectile: steel ball
7 mm diameter
1.40 gram
119 ± 2 m/s



Result



Failure Mechanisms Observed From Experiment

Neat Kevlar:

- easy yarn pull-out
- perforation/partial perforation
- lower in-plane shear rigidity

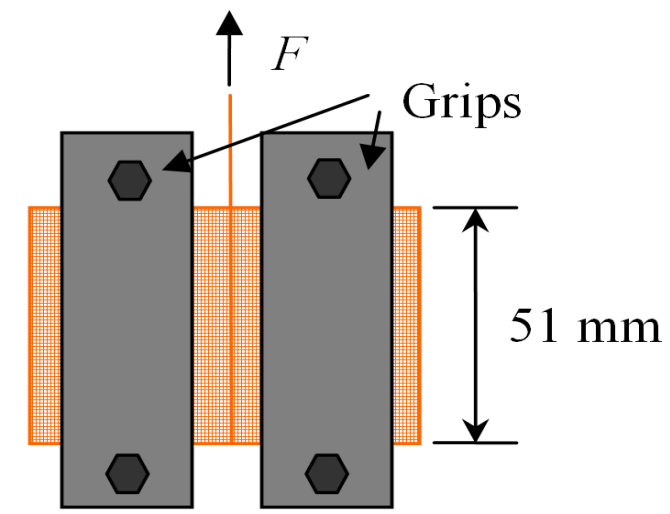
Neat Kevlar

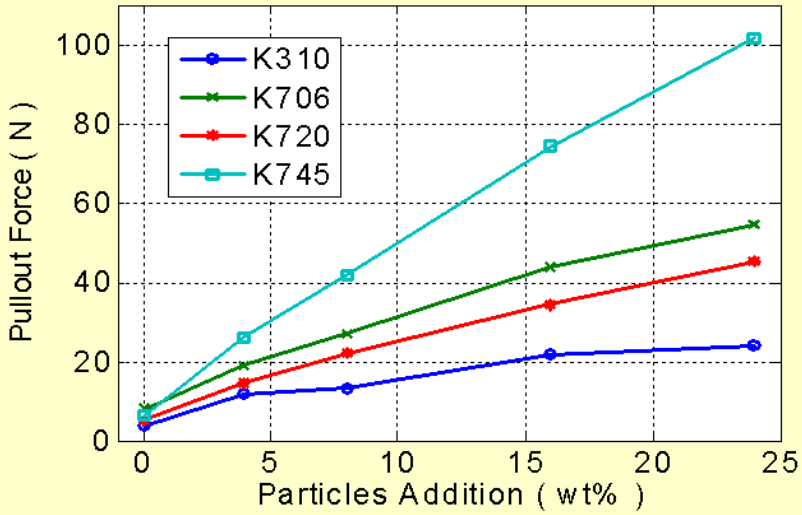
Kevlar with silica particles:

- no yarn pull-out
- no visible damage
- higher in-plane shear rigidity

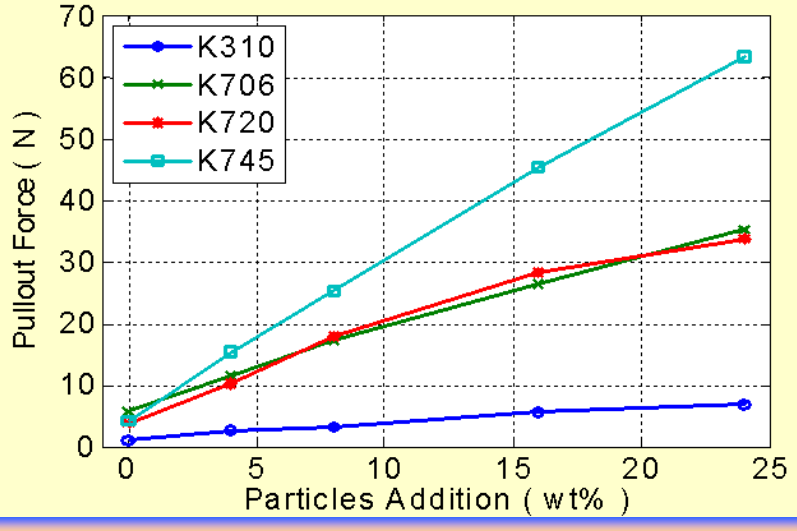
Kevlar with 17 wt% Silica

Yarn Pullout Tests





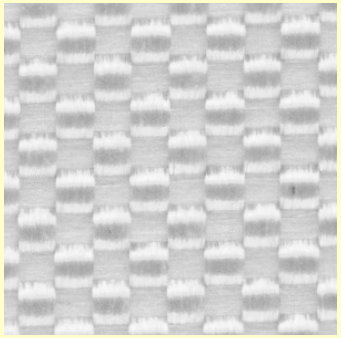
- Warp yarns need higher force
- Nanoparticles increase the pullout force



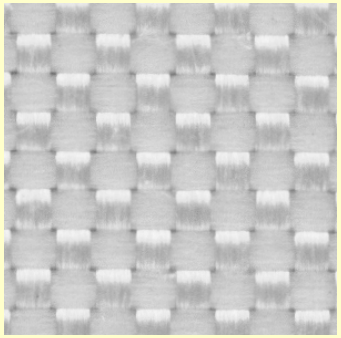
Objectives

- **D**esign and conduct yarn pullout experiments using five styles of Kevlar fabrics
- **I**dentify the important fabric features: count, weight, thickness, friction, yarn size, fiber type and diameter
- **D**evelop a finite element model to predict the yarn pullout force
- **P**erform parametrical studies to rank the importance of fabric features

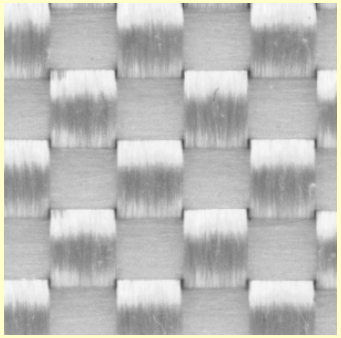
Kevlar Fabrics Used in This Study



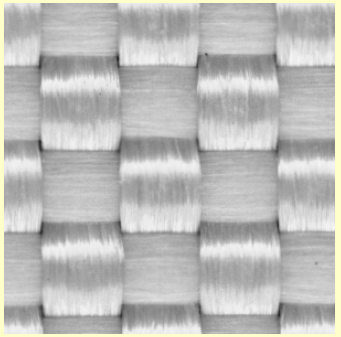
K310



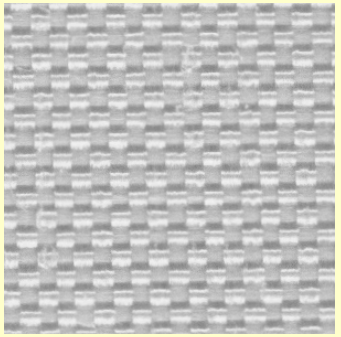
K706



K720



K745

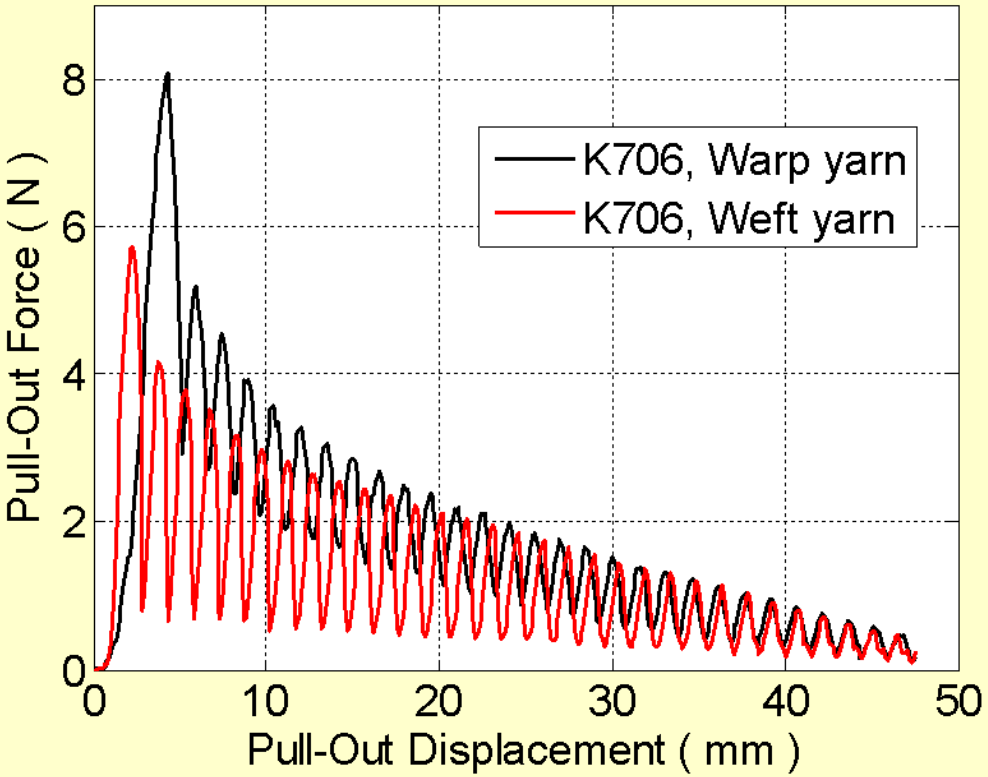


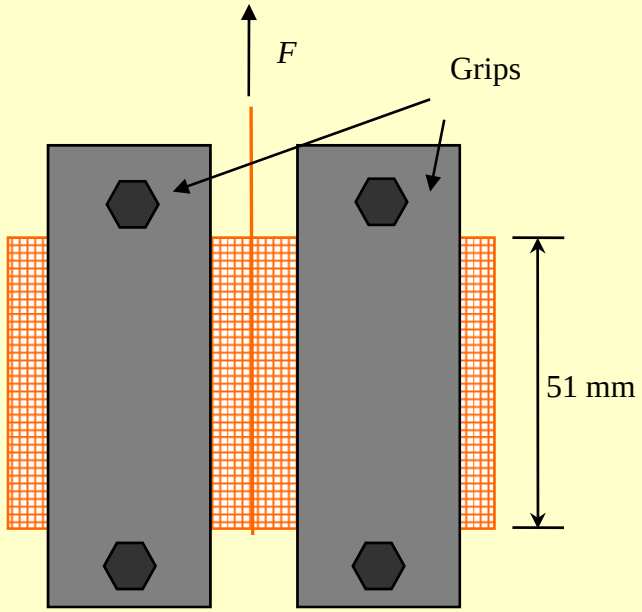
K779

From Hexcel

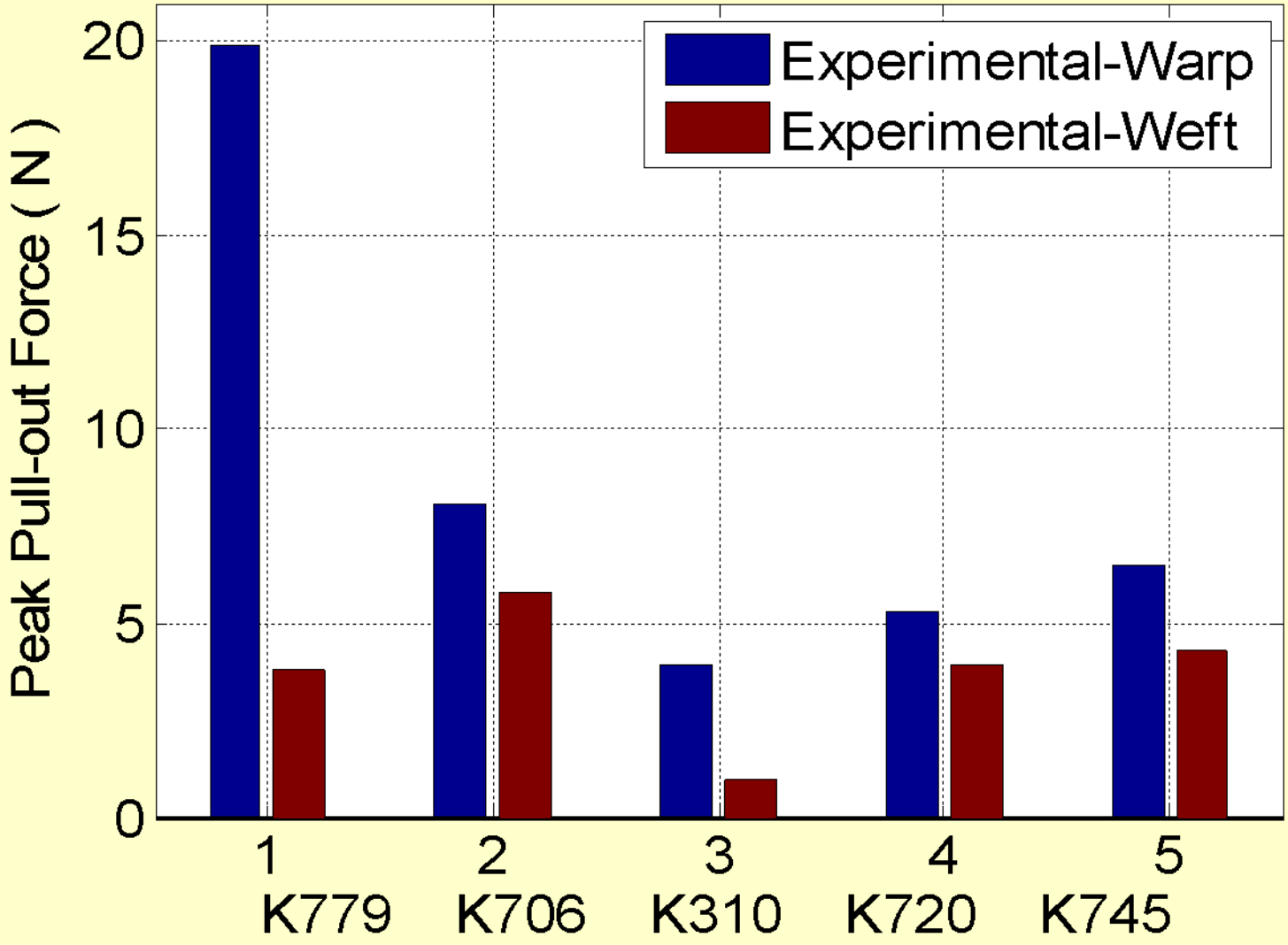
Fabric style	K310	K706	K720	K745	K779
Fiber type	Comfort	KM-2	129	29	159
Fiber modulus (GPa)	87.0	80.0	99.7	73.0	97.2
Yarn size (Denier)	400	600	1420	3000	200
Weight (g/m^2)	122	180	258	475	132
Warp/Weft count (Yarns/in)	35.5	34	20	17	70
Warp Strength (lbs/in)	530	775	978	1600	385
Weft Strength (lbs/in)	530	880	992	1800	530
Thickness (mm)	0.18	0.23	0.36	0.61	0.18

Single Yarn Pullout Test

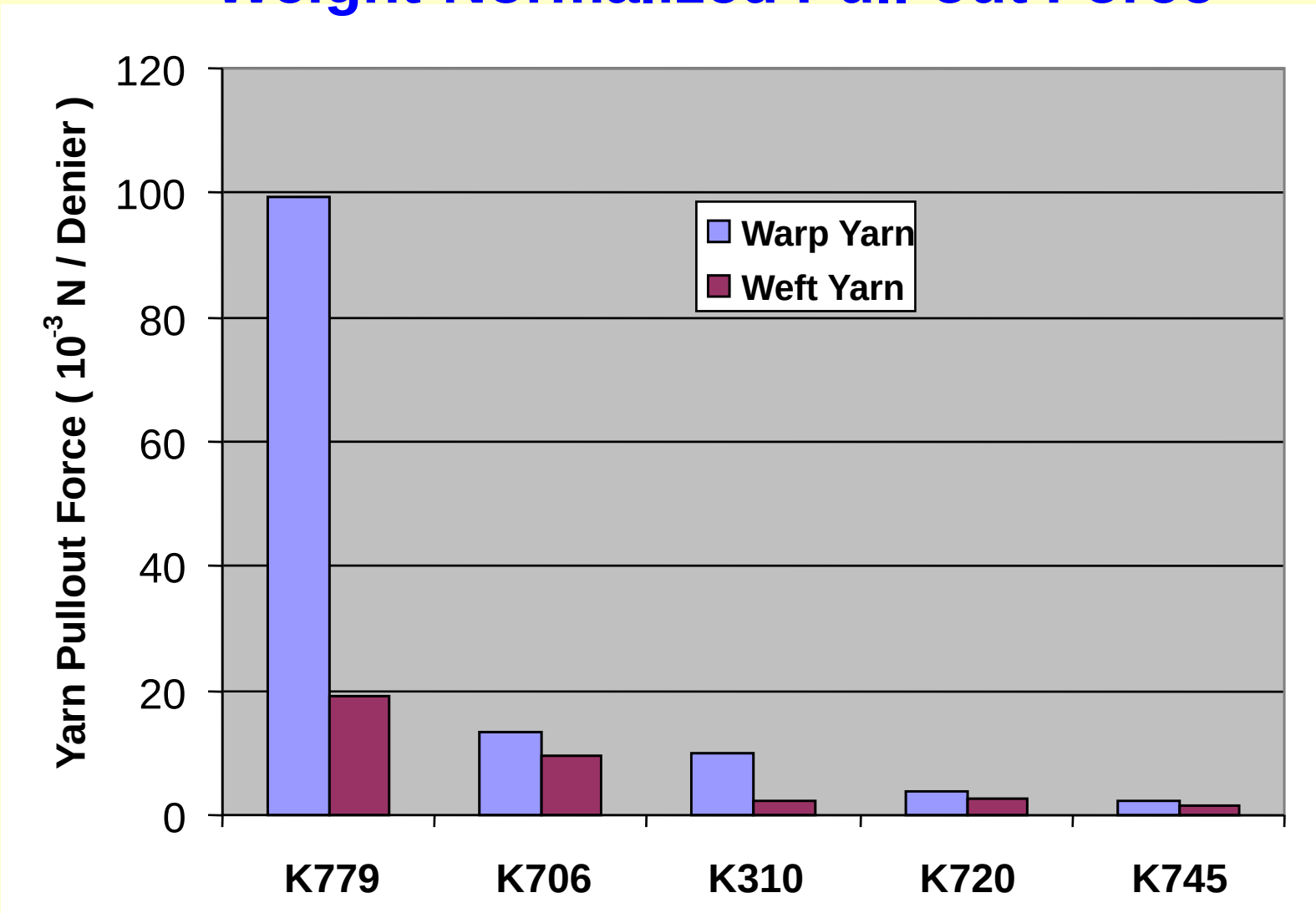




Single Yarn Pullout Force

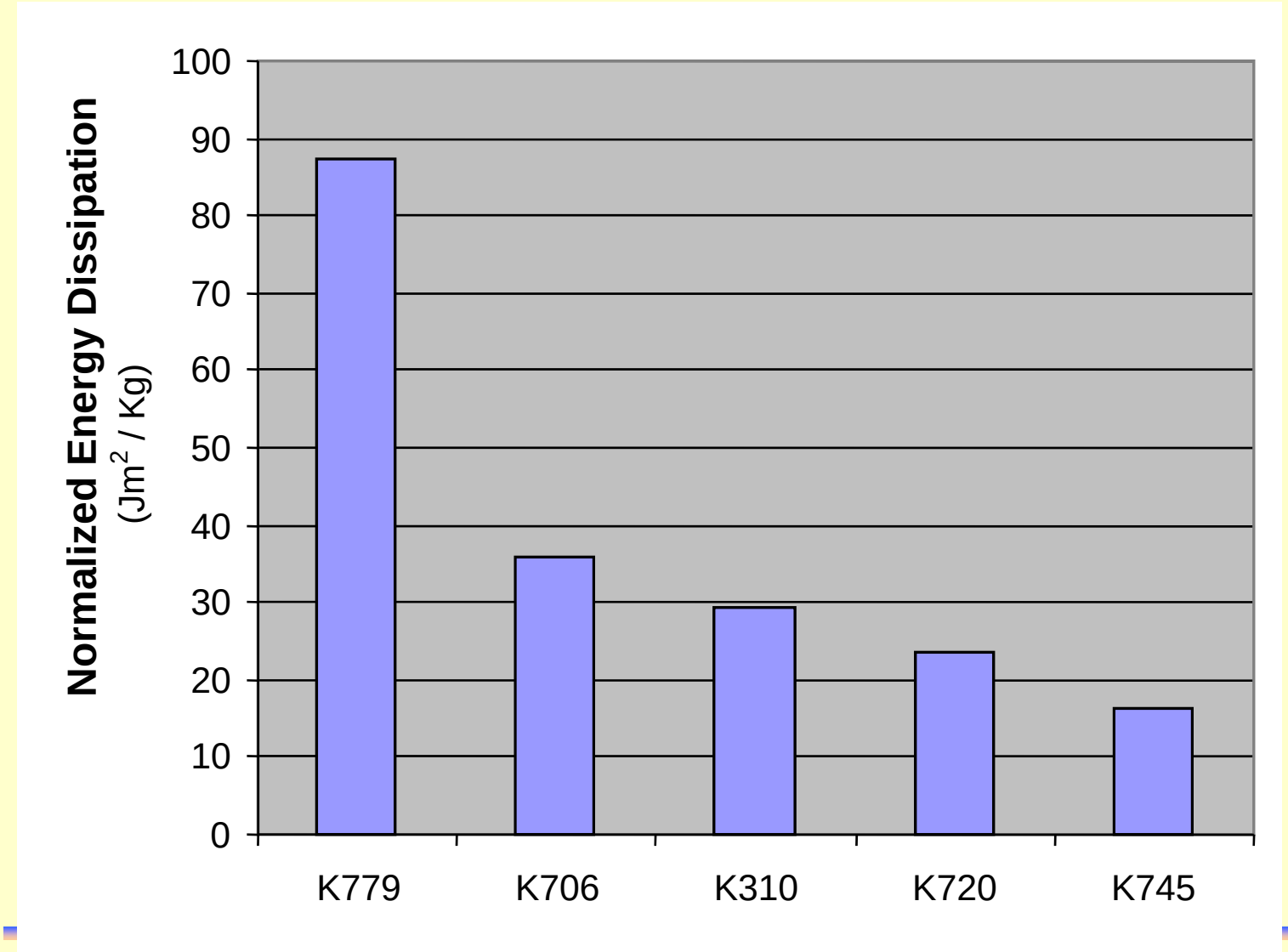


Weight-Normalized Pull-out Force

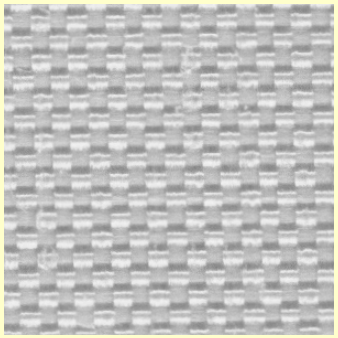


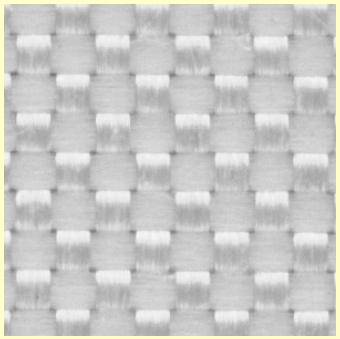
Dissipated Kinetic Energy in Ballistic Test

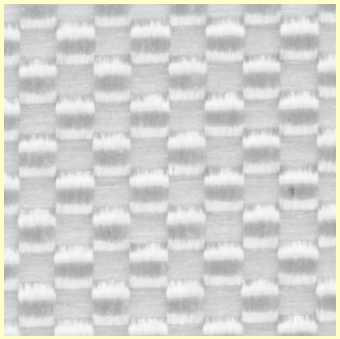
normalized by fabric weight

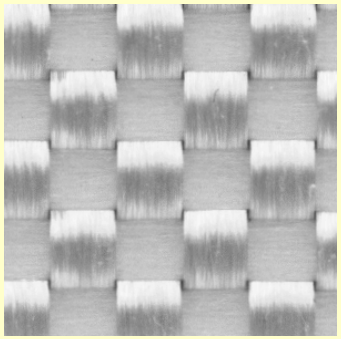


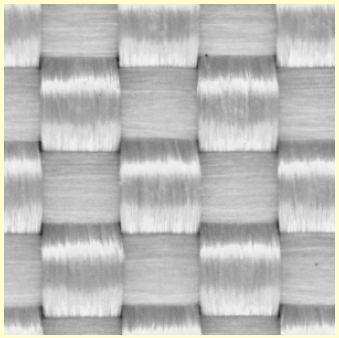
Single Yarn Pullout Test

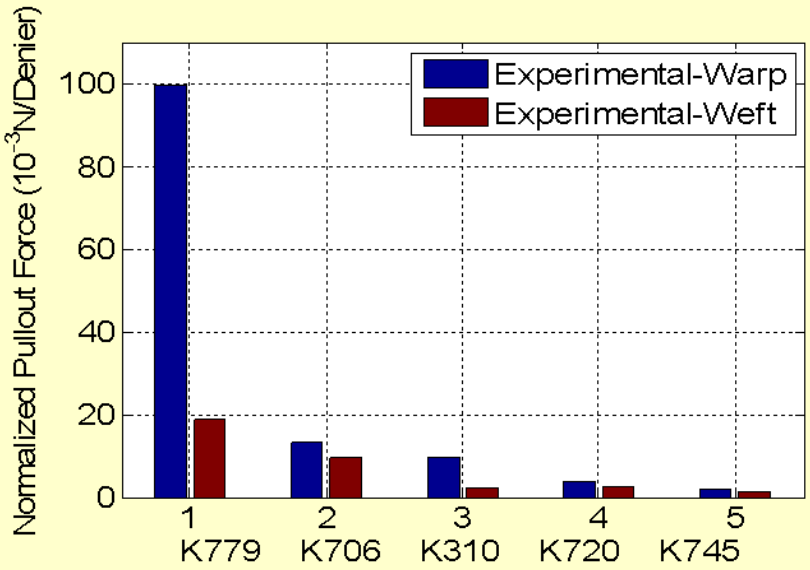

K779


K706


K310

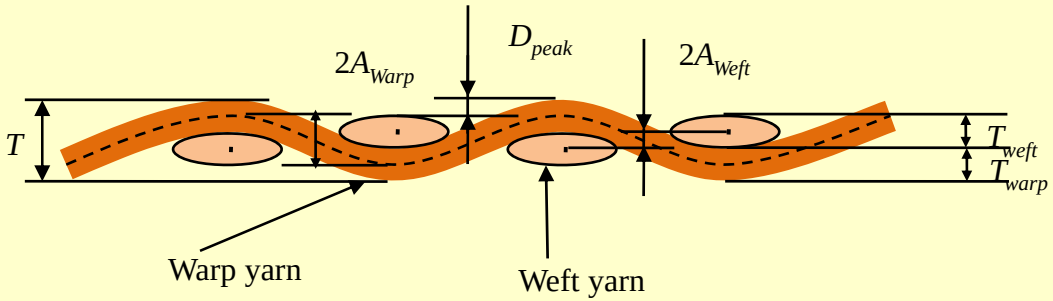

K720


K45

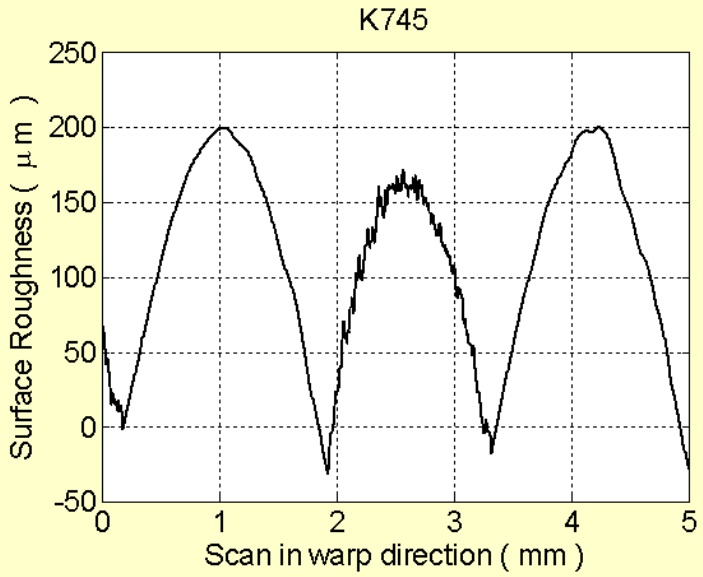


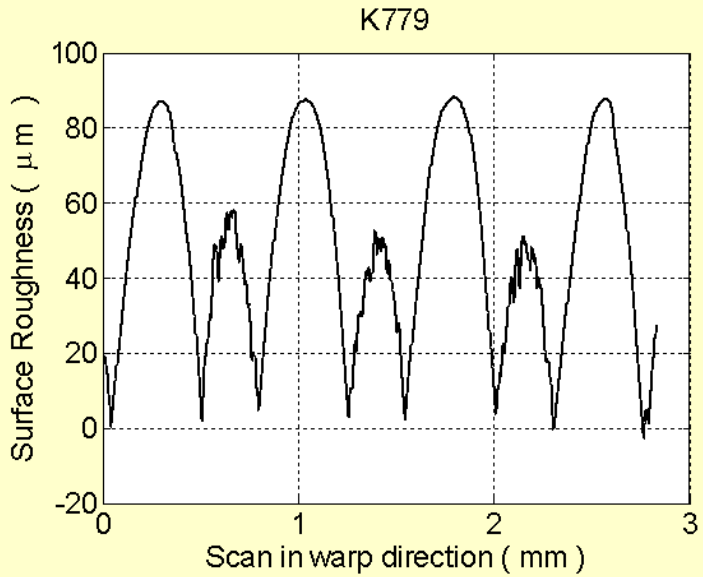
- Normalized by yarn size, denier
- The normalized force has positive correlation to the impact performance
- Fabric count is important

Waviness of Warp and Weft Yarns



- Alpha-Step IQ surface profiler
- Scan from left to right
- Scan both warp and weft directions
- Measure the height difference of warp/weft yarns D_{peak}



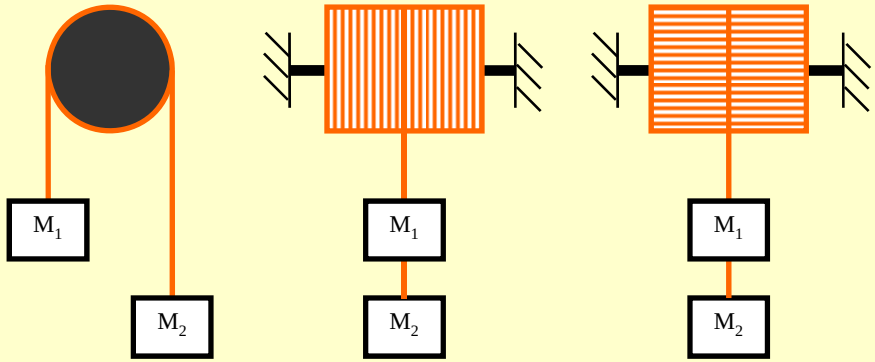


Waviness of Warp and Weft Yarns

- Calculate waviness A_{Warp} and A_{Weft} from D_{Peak}

Fabric Style	**K310**	**K706**	**K720**	**K745**	**K779**
Fabric thickness (micron)	180	230	360	610	180
D_{Peak} (micron)	30	10	20	30	35
A_{Warp} (micron)	52.5	60	95	160	54
A_{Weft} (micron)	22.5	50	75	130	18

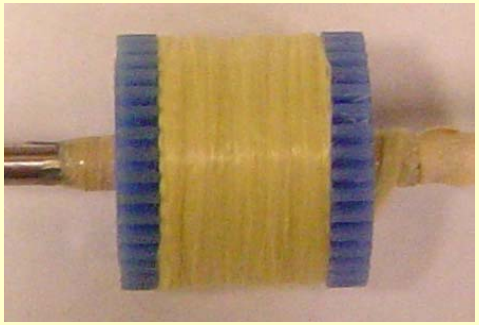
Friction of Yarns



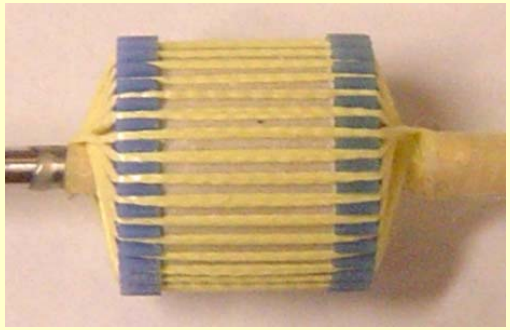
Parallel-Fiber Cross-Yarn

- Keep M_1 as constant
- Slowly increase M_2 till sliding

Drum without yarns



For parallel-fiber friction



For cross-yarn friction

Friction of Yarns

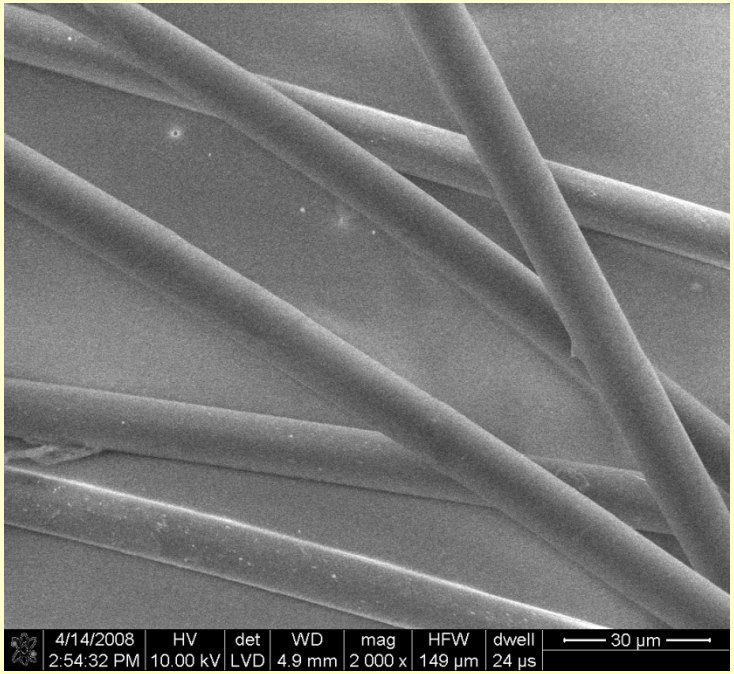
Constant coefficient of friction

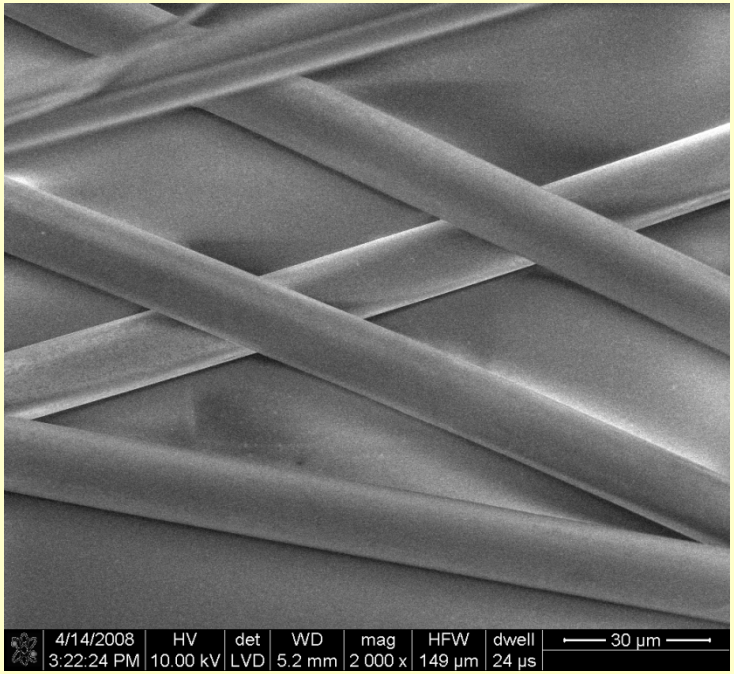
$$\mu = \frac{1}{\pi} \ln\left(\frac{M_2}{M_1}\right)$$

Fabric Style	**K310**	**K706**	**K720**	**K745**	**K779**
Cross-yarn friction	0.212	0.248	0.243	0.227	0.202
Parallel-fiber friction	0.333	0.389	0.390	0.327	0.336

Fiber Diameters

K310

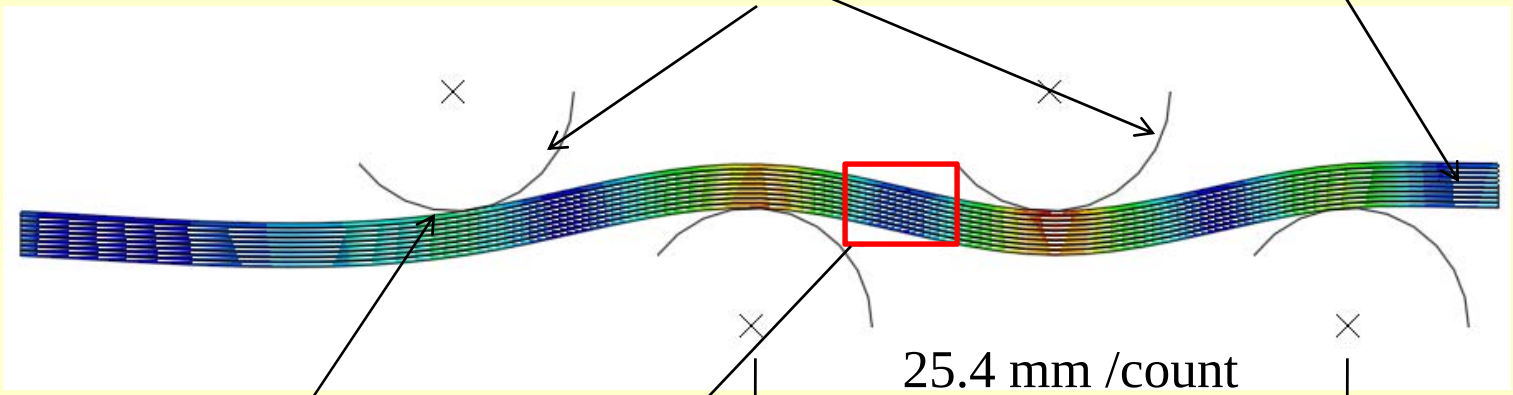




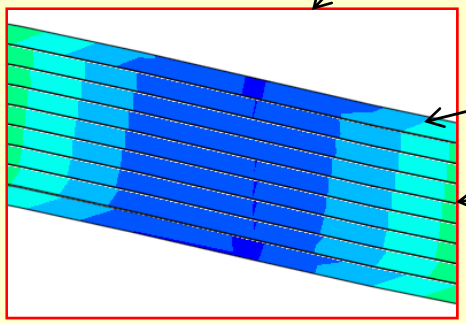
K745

Fabric style	**K310**	**K706**	**K720**	**K745**	**K779**
Fiber diameter (micron)	11.6	12.2	12.3	14.7	11.4

Yarn Pullout Simulations



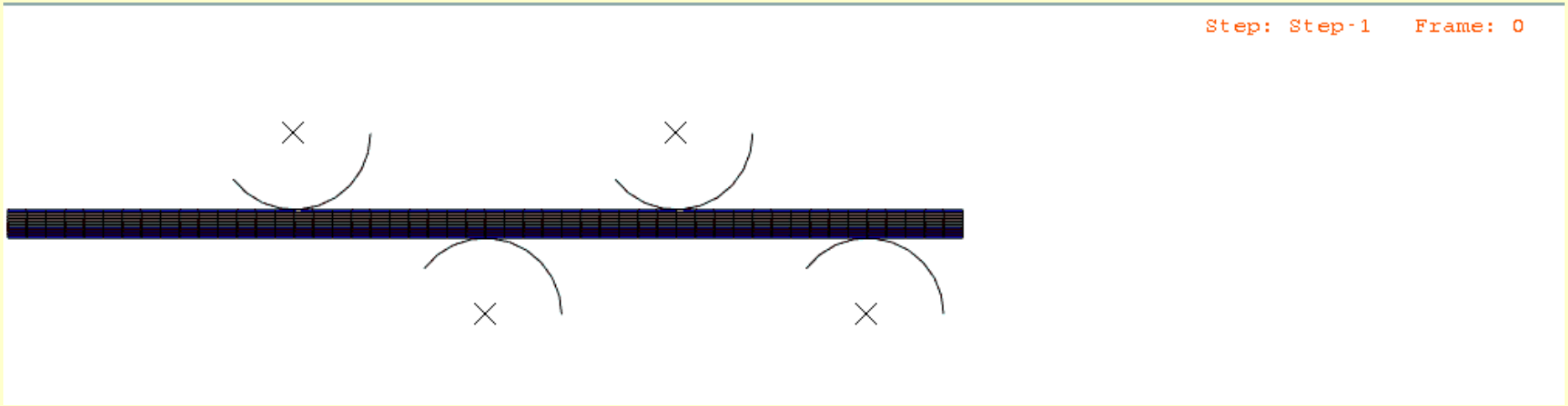
Interaction between cross yarns:
Cross-yarn friction



Kevlar fiber

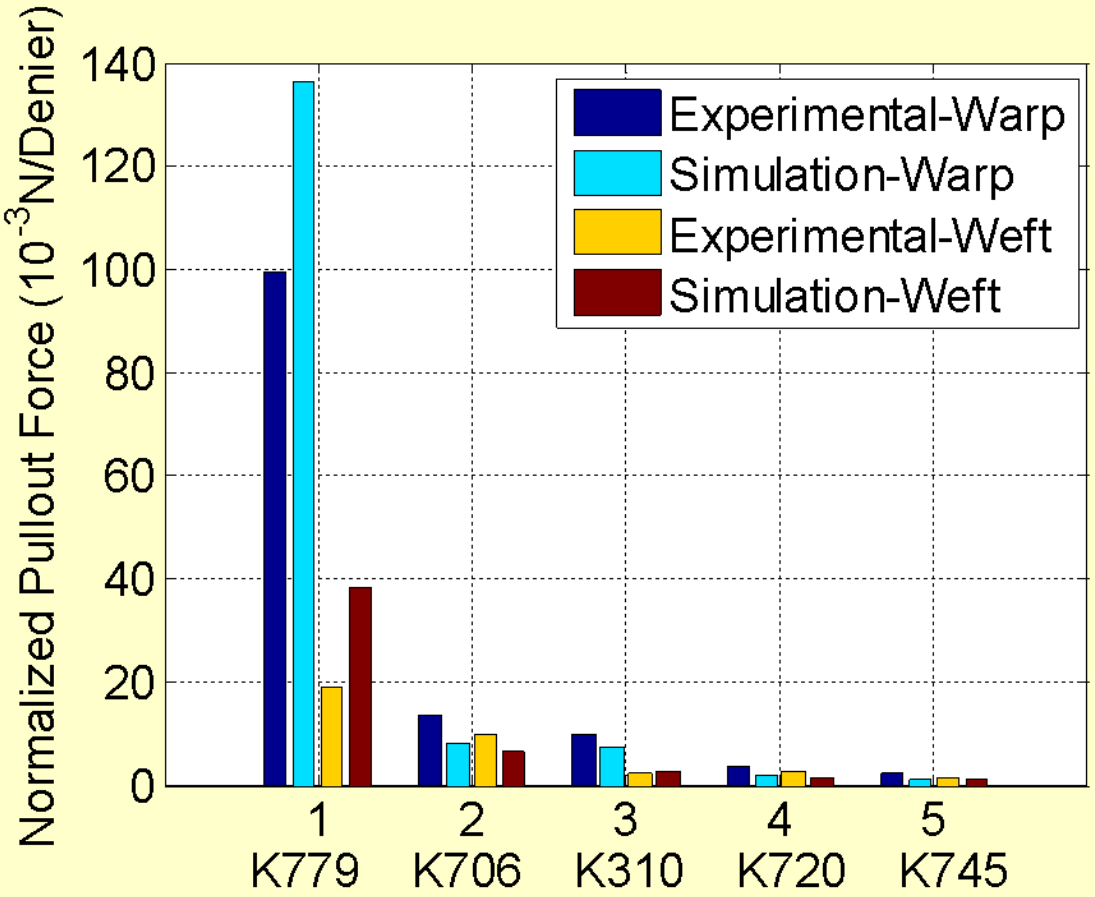
Interaction between adjacent fibers:
Parallel-fiber friction

Yarn Pullout Simulations

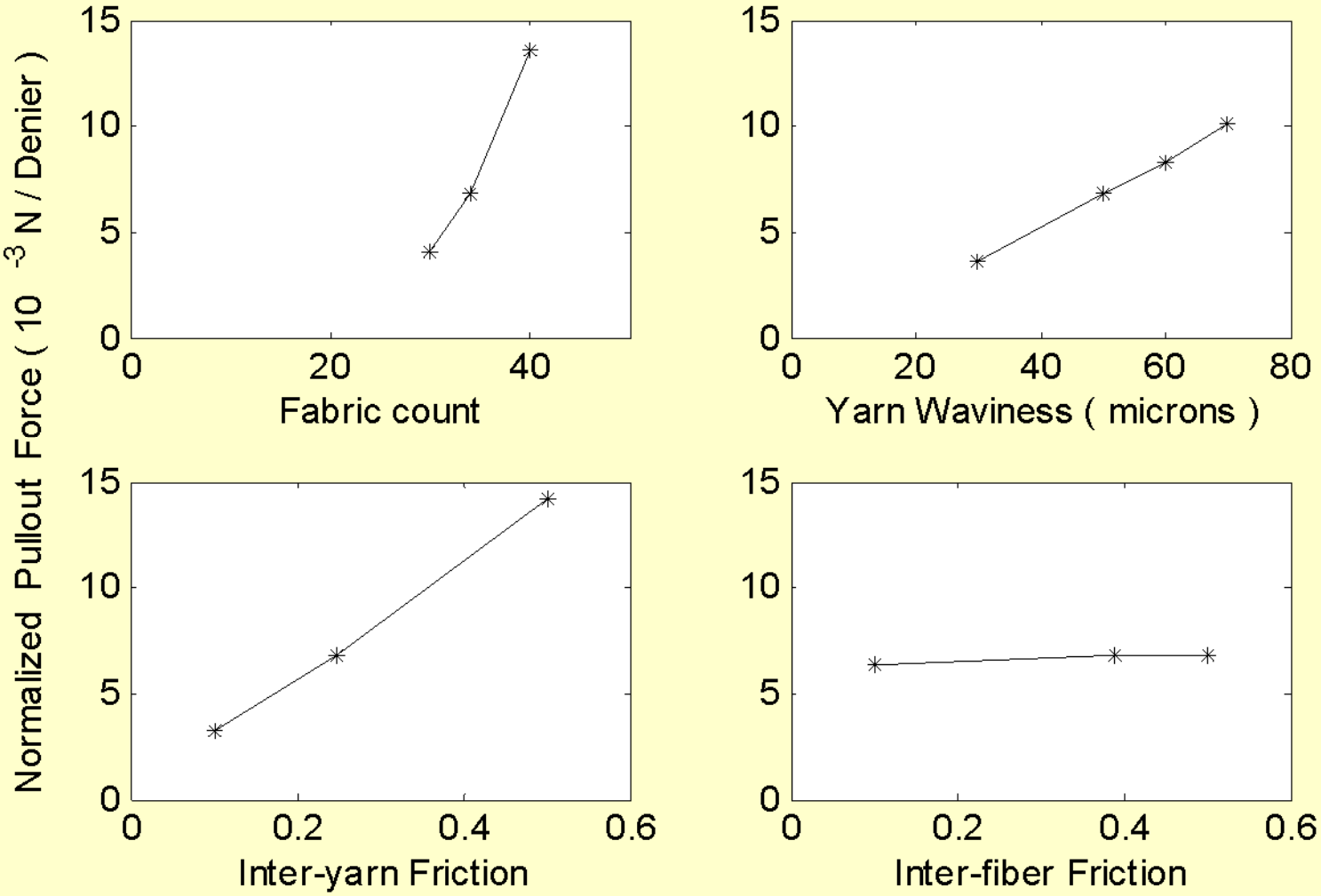


The peak pullout force was extracted from the simulations

Yarn Pullout : Comparing with Experiments



Parametrical Study



Summary

- **Y**arn pullout force has a positive correlation to the impact performance of the fabric
- **A** finite element model was developed to predict the yarn pullout force
- **F**actors that affect the yarn pullout force are fabric count, yarn waviness, cross-yarn friction
- **A**n efficient way to enhance the yarn pullout force is to increase fabric count and cross-yarn friction