



# Kevlar KM2 Yarn and Fabric Strength Under Quasi-Static Tension

by Thomas J. Mulkern and Martin N. Raftenberg

ARL-TR-2865

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**ARL-TR-2865****October 2002**

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Thomas J. Mulkern and Martin N. Raftenberg

Weapons and Materials Research Directorate, ARL

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## Abstract

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Kevlar KM2, 600 denier, was Instron tested in quasi-static, uniaxial tension to determine its strength. Specimens included both single yarns and 68-yarn-wide, single-ply strips of plain-woven fabric (Style 706). Never-woven single-yarn specimens were tested with varying degrees of initial twist. Strength of the untwisted, never-woven yarn was  $2.66 \pm 0.04$  GPa. The twist multiplier was 1.2. Single warp-oriented and fill-oriented yarns were extracted from Style 706 fabric, tested, and found to have strengths of  $2.06 \pm 0.01$  and  $2.20 \pm 0.05$  GPa, respectively. The single-ply fabric specimens of both warp and fill orientations were tested and found to have strengths of  $2.23 \pm 0.04$  and  $2.67 \pm 0.04$  GPa, respectively. The strength effects of weaving, finishing, yarn extraction, and inter-yarn contact are discussed.

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## **Acknowledgments**

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The authors thank Philip M. Cunniff of the U.S. Army Natick Soldier Center and Dr. Brian Scott of the DuPont Corporation for very helpful discussions. We also thank Linda L. Ghiorse, Dr. Bruce Burns, and Edward Rapacki of the U.S. Army Research Laboratory, all of whom reviewed the manuscript and provided helpful comments.

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## 1. Introduction

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Plies of plain-woven Kevlar fabrics are the usual components of “soft” body armor (National Institute of Justice Standard levels 1–3A.) According to the DuPont Corporation (undated), “Kevlar KM2 is a new, very high strength, high toughness [form of Kevlar] designed for improved ballistic fragmentation resistance and energy absorption capacity.” The various forms of Kevlar, such as KM2, 29, and 49, are all composed of the same paraphenylene terephthalamide (PPTA) monomer. The forms differ in the degree of crystallinity, which reflects the degree of molecular alignment and hydrogen bonding between neighboring molecules (Scott 2001).

Table 1 compares single-yarn quasi-static strength of KM2 to those of other forms of Kevlar. Here,  $\sigma_{fail}$  is the yarn *strength*, or maximum stress attained on a tensile stress-strain curve. The KM2 strength results were obtained from publications by H. H. Yang of DuPont. Note that KM2 is distinguished by a relatively large value for  $\sigma_{fail}$ .

Table 1. Strength of Kevlar yarns.

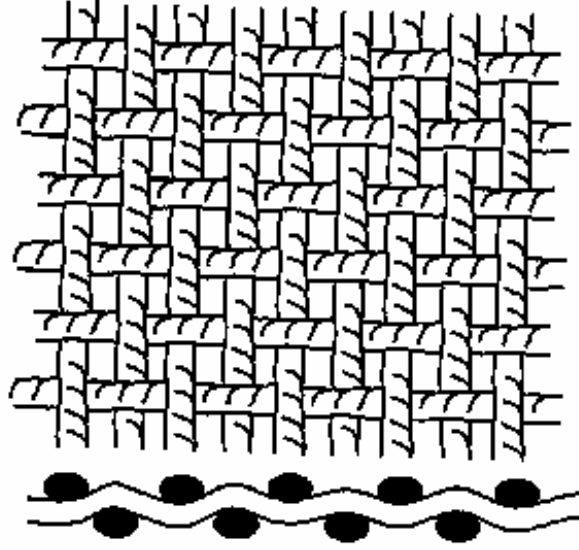
| Yarn Type  | $\sigma_{fail}$<br>(GPa) |
|------------|--------------------------|
| Kevlar 29  | 2.9 <sup>a</sup>         |
| Kevlar 49  | 2.9 <sup>a</sup>         |
| Kevlar 68  | 3.1 <sup>a</sup>         |
| Kevlar 119 | 3.1 <sup>a</sup>         |
| Kevlar 129 | 3.4 <sup>a</sup>         |
| Kevlar 149 | 2.3 <sup>a</sup>         |
| KM2        | 3.3 <sup>b</sup>         |

<sup>a</sup>Yang (1993), p. 26.

<sup>b</sup>Yang (2000), p. 219.

The strength values in Table 1 do not make clear the degree of initial twist applied to the yarn. One goal of the present study is to directly examine the dependence of strength upon the initial twist for the case of KM2.

Yarns are generally not pretwisted in a woven fabric, so that strength measurements in untwisted single yarns are most relevant to fabric properties. Figure 1 sketches a single ply of a plain weave; this ply consists of a family of warp yarns orthogonal to a family of fill (weft) yarns. The creation of the ply involves the processes of weaving and finishing, both of which can incur damage to the individual yarns. A second goal of the present study is to bound the damage associated with these processes. To that end, 600-denier yarns aligned with the warp and the fill directions were extracted from a ply of KM2. Strengths of these extracted yarns were compared



Source: Reproduced from Warner (1995), p. 271.

Figure 1. Plain weave construction, composed of two mutually orthogonal families of warp and fill yarns.

with strength measurements for untwisted, never-woven yarns. Any damage incurred during yarn extraction would have contributed to the observed differences.

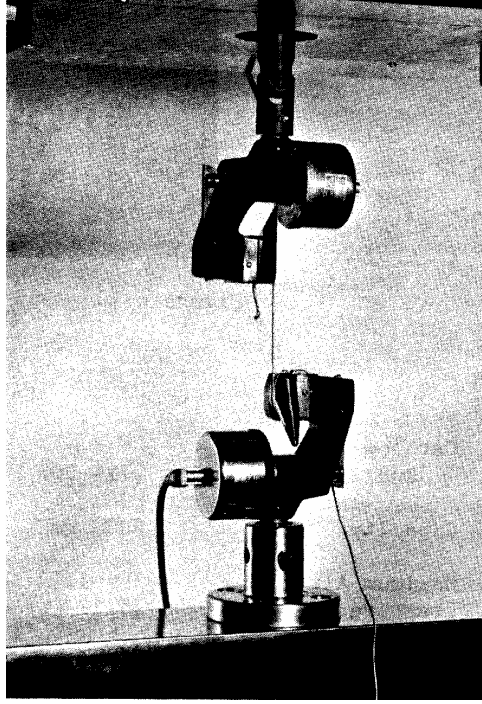
Finally, quasi-static tensile data are presented from 68-yarn-wide specimens of plain-woven 600-denier KM2 fabric (style 706) loaded along either the warp or the fill direction. Fabric strength results derived from these measurements are compared with strength results from untwisted single-yarn specimens.

---

## 2. Methods

### 2.1 Yarn Tests

Each test involved a single yarn of Kevlar KM2 loaded in uniaxial tension. American Society for Testing and Materials (ASTM) Standard D2256-97 (ASTM 2000) provided guidance for the tests. An Instron 5500 tensile machine was employed with two Instron Cord and Yarn Grips (Figure 2). Each specimen had an initial length of 50 cm. Each end was clamped into the capstan grip and then wrapped once around the grip. At the start of the test, a central portion about 25 cm in length was not in contact with either grip. The crosshead separation rate was maintained at 2.12 mm/s. The specimen was elongated until rupture. The applied force was sampled 25 times/s. The maximum detected force value was denoted  $F_{fail}$  and converted to strength,  $\sigma_{fail}$ , by the following procedure:



Source: Reproduced from Instron Corp. (undated), p. 6.5.

Figure 2. Instron cord and yarn grip employed in the single-yarn tests.

A yarn of 600-denier KM2 contains 400 filaments (Scott 2001). A single filament has a circular cross-section and a nominal diameter of  $12\text{ }\mu\text{m}$  (Yang 1993, pp. 28, 30), which corresponds to a filament cross-sectional area of  $1.13 \times 10^{-4}\text{ (mm)}^2$ . A KM2 yarn's cross-sectional area,  $A_{yo}$ , is therefore  $0.0452\text{ (mm)}^2$ . The yarn's strength is defined by

$$\sigma_{fail} = \frac{F_{fail}}{A_{yo}}. \quad (1)$$

Six series of single-yarn tests were conducted and are denoted Y, XW, XF, TA, TB, and TC.

Specimens used in series Y were obtained from DuPont. Each specimen had never been woven and was untwisted. Nine different specimens were studied (Y1–Y9.) Specimens used in series TA, TB, and TC were also obtained from DuPont. These specimens were twisted prior to the test by the amounts  $\tau_o$ , measured in turns per centimeter and given in Table 2.

Table 2. Specimen initial twist for each single-yarn test series.

| Test | $\tau_o$<br>(turns/cm) |
|------|------------------------|
| Y    | 0.0                    |
| XW   | 0.0                    |
| XF   | 0.0                    |
| TA   | 0.69                   |
| TB   | 1.30                   |
| TC   | 1.93                   |

Specimens used in series XW and XF were extracted from plies of style 706 fabric. This fabric is composed of plies of plain-woven 600-denier yarns of KM2. Six specimens of warp-direction yarns (XW1–XW6) and seven of fill-direction yarns (XF1–XF7) were studied. All warp-direction yarns were extracted from a single ply. All fill-direction yarns were extracted from a different single ply. The extraction procedure applied the ravel strip method (ASTM 1995). An individual yarn was gripped by hand at the edge of a single ply and pulled.

## 2.2 Fabric Tests

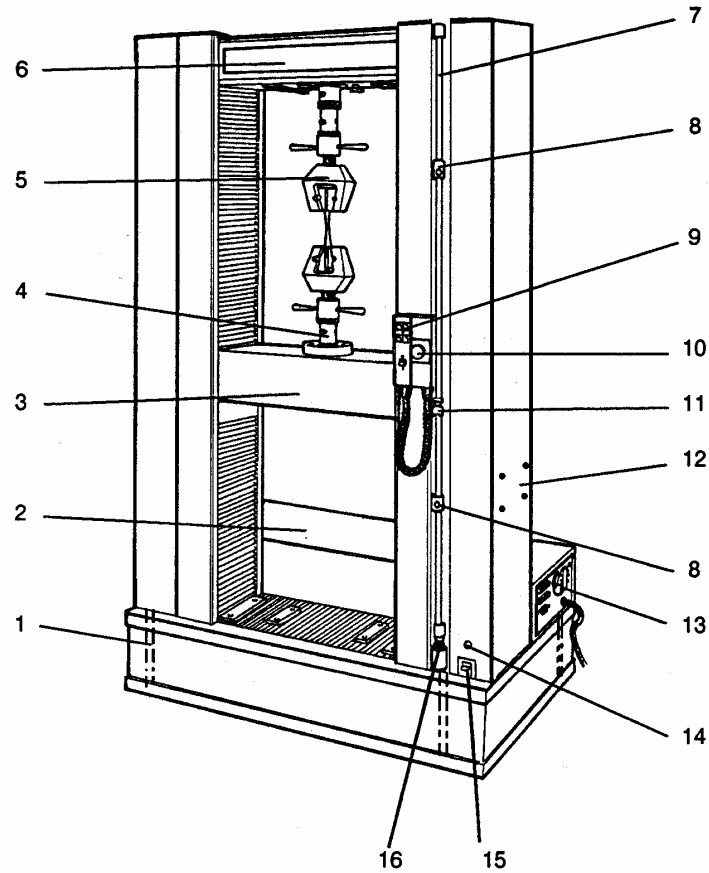
ASTM Standard D5035-95 (ASTM 1995) again provided guidance for the tests. The uniaxial tension tests were performed with an Instron 4505 load frame such as that shown in Figure 3. The Instron load cell was rated at 100-kN maximum load. Instru-Met capstan webbing grips (Figure 4) were used in place of the “wedge action grips” in Figure 3. Figure 5 shows a specimen clamped in preparation for a test.

All specimens were created by the ravel strip method (ASTM 1995) from the same sheet of style 706 fabric. Each specimen had an initial length of 1.219 m and a width of 68 yarns. Style 706 KM2 fabric contains 34 yarns/in (Scott 2001), so the specimen’s width was 50.8 mm. At each end of the specimen, a length of 50 mm was clamped into the capstan grip. The specimen was then wrapped twice around each capstan grip. During each test, the load frame crossheads moved at the constant rate of 2.12 mm/s. Force was sampled 25 times/s.

Specimens were pulled until rupture. Strength,  $\sigma_{fail}$ , was computed from the maximum force measurement,  $F_{fail}$ , using

$$\sigma_{fail} = \frac{F_{fail}}{68 A_{yo}} \quad . \quad (2)$$





- 1 Levelling Adjusting Feet (one at each corner)
- 2 Rear Cover
- 3 Moving Crosshead
- 4 Load Cell
- 5 Wedge Action Grips (option)
- 6 Fixed Crosshead
- 7 Limits Rod
- 8 Limit Stop (Upper and Lower)
- 9 Handset Controls
- 10 Emergency Stop Button
- 11 Limit Adjustment Screw
- 12 Mounting Holes for Support Arm Assembly  
(also available on left-hand side)
- 13 Frame Interconnection Panel
- 14 A.C. Mains Indicator
- 15 A.C. Mains On/Off Switch/Breaker
- 16 Limit Flag Adjustment Block

“Wedge action grips” no. 5 were replaced with the capstan grips.

Source: Reproduced from Instron Corp. (1988), pp. 1–4, 5.

Figure 3. Instron 4505 loading frame.

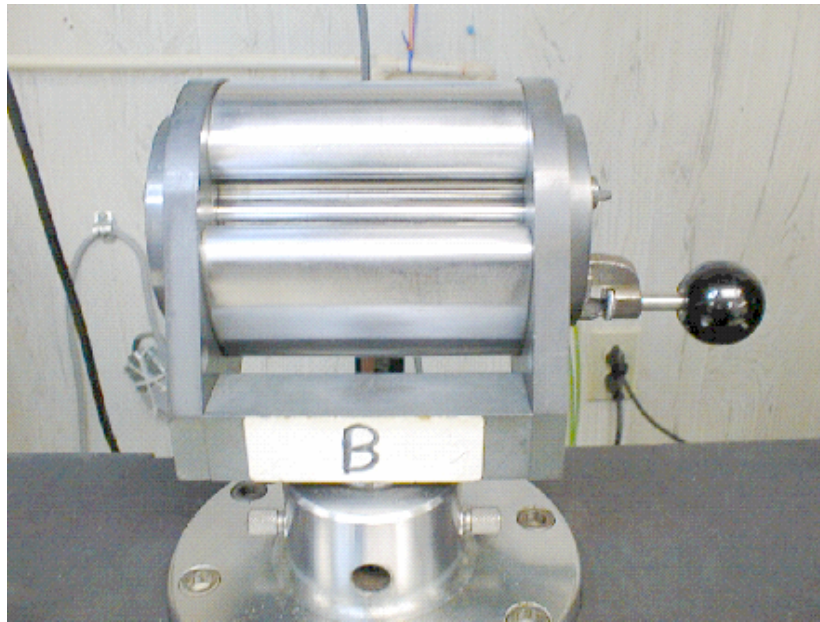


Figure 4. An Instru-Met capstan webbing grip used in the tests.

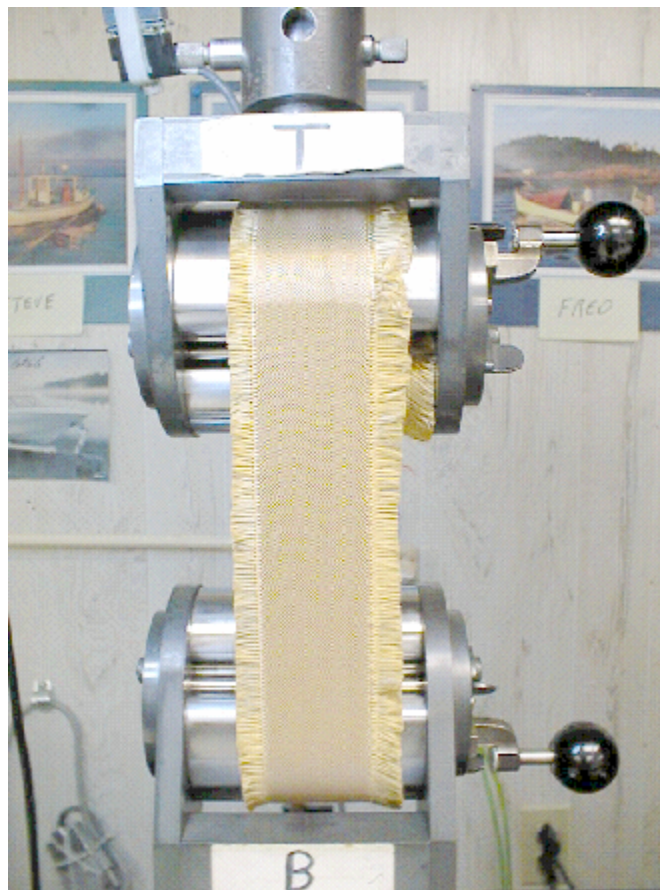


Figure 5. A specimen clamped in the Instron 4505 apparatus.

Twelve specimens were tested. Six were elongated along the warp direction and had the fill direction associated with the width. These are Tests W1–W6. The other six were elongated along the fill direction and had the warp direction associated with the width. These are denoted Tests F1–F6.

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### 3. Results

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#### 3.1 Single-Yarn Tests

##### 3.1.1 Initial-Twist Effects on the Strength of Never-Woven Yarn

Results from series Y, TA, TB, and TC are presented in Table 3 and Figure 6. In this and in subsequent tables, “s.d.” denotes “standard deviation” and “s.e.” denotes standard error of the mean. The latter equals  $\text{s.d.}/\sqrt{N}$ , where  $N$  is the number of tests in the series (Taylor 1997). All strength values from series Y are smaller than any values from TA, TB, or TC. There is overlap in strength values from the three series involving nonzero twist.

The strength values were  $2.66 \pm 0.04$  GPa for the nine Y series tests,  $3.21 \pm 0.05$  GPa for the nine TA series tests,  $3.36 \pm 0.04$  GPa for the eight TB series tests, and  $3.28 \pm 0.03$  GPa for the six TC series tests. Thus, as illustrated in Figure 7, measurable strength increase occurred as the initial twist was increased from zero (Y) to 0.69 turns/cm (TA) to 1.30 turns/cm (TB). Further increase of initial twist to 1.93 turns/cm was accompanied by a slight decrease in strength (TC).

##### 3.1.2 Strength of Untwisted Yarn: Never-Woven, Extracted Warp, and Extracted Fill

Results from series XW and XF, involving single-yarn specimens that had been extracted from woven fabric, are presented in Table 4 and Figure 8. As stated in section 2.1, XW and XF specimens had been oriented along the warp and fill directions, respectively, prior to extraction. Results from untwisted, never-woven yarns, series Y, are added to Table 4 and Figure 8 for comparison. The strength values for the Y, XW, and XF series were  $2.66 \pm 0.04$ ,  $2.06 \pm 0.01$ , and  $2.20 \pm 0.05$  GPa, respectively.

Yarns that were extracted from woven fabric (series XW and XF) exhibited smaller strength values than yarns that were not previously woven (series Y.) Of the extracted yarns, those that had been woven in the warp direction (XW) exhibited generally smaller strengths than those that had been woven in the fill direction (XF), although there was some overlap.

Table 3. Y, TA, TB, TC series results.

| Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) |
|------|--------------------------|------|--------------------------|------|--------------------------|------|--------------------------|
| Y1   | 2.84                     | TA1  | 2.99                     | TB1  | 3.40                     | TC1  | 3.24                     |
| Y2   | 2.66                     | TA2  | 3.03                     | TB2  | 3.51                     | TC2  | 3.30                     |
| Y3   | 2.58                     | TA3  | 3.13                     | TB3  | 3.46                     | TC3  | 3.13                     |
| Y4   | 2.73                     | TA4  | 3.28                     | TB4  | 3.23                     | TC4  | 3.36                     |
| Y5   | 2.42                     | TA5  | 3.38                     | TB5  | 3.25                     | TC5  | 3.33                     |
| Y6   | 2.77                     | TA6  | 3.32                     | TB6  | 3.39                     | TC6  | 3.33                     |
| Y7   | 2.78                     | TA7  | 3.23                     | TB7  | 3.33                     | —    | —                        |
| Y8   | 2.61                     | TA8  | 3.15                     | TB8  | 3.31                     | —    | —                        |
| Y9   | 2.56                     | TA9  | 3.38                     | —    | —                        | —    | —                        |
| mean | 2.66                     | mean | 3.21                     | mean | 3.36                     | mean | 3.28                     |
| s.d. | 0.13                     | s.d. | 0.14                     | s.d. | 0.10                     | s.d. | 0.08                     |
| s.e. | 0.04                     | s.e. | 0.05                     | s.e. | 0.04                     | s.e. | 0.03                     |

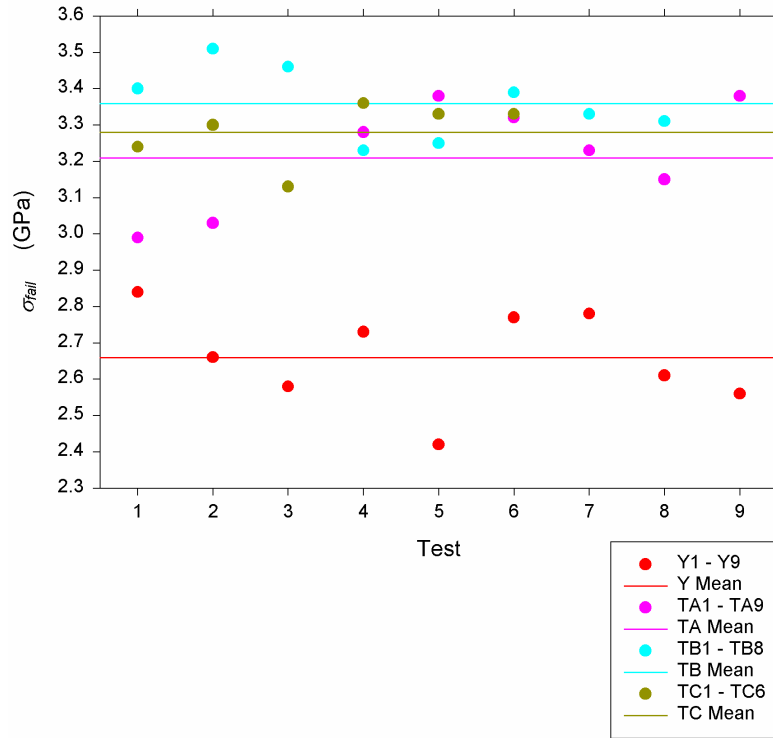


Figure 6. Strength results for single yarns with various degrees of initial twist.

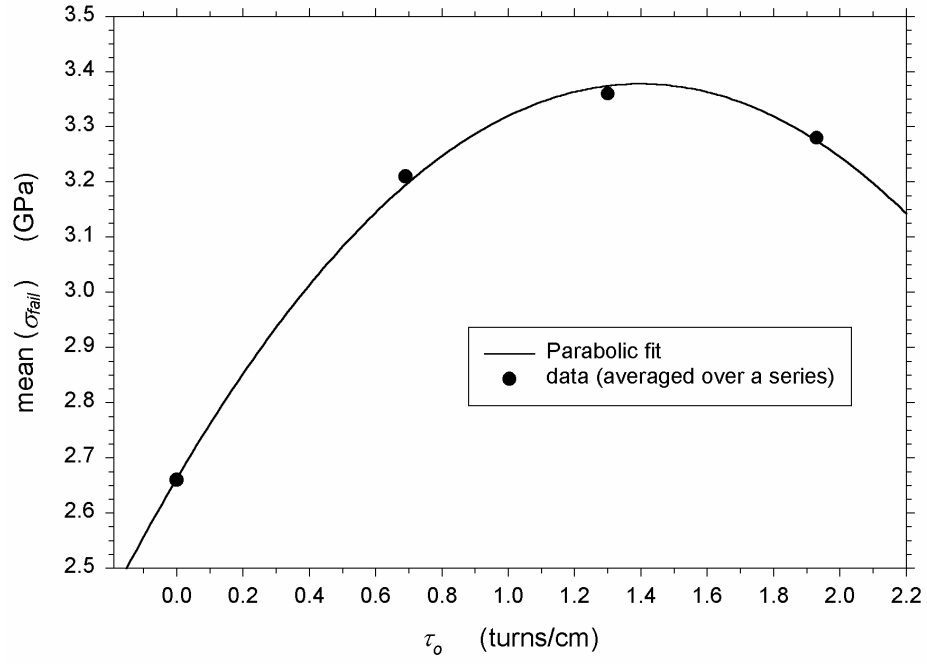


Figure 7. Strength results for never-woven single yarns vs. the degree of initial twist.

Table 4. Y, XW, XF series results.

| Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) |
|------|--------------------------|------|--------------------------|------|--------------------------|
| Y1   | 2.84                     | XW1  | 2.03                     | XF1  | 2.27                     |
| Y2   | 2.66                     | XW2  | 2.09                     | XF2  | 2.43                     |
| Y3   | 2.58                     | XW3  | 2.07                     | XF3  | 2.16                     |
| Y4   | 2.73                     | XW4  | 2.10                     | XF4  | 2.05                     |
| Y5   | 2.42                     | XW5  | 2.02                     | XF5  | 2.17                     |
| Y6   | 2.77                     | XW6  | 2.06                     | XF6  | 2.23                     |
| Y7   | 2.78                     | —    | —                        | XF7  | 2.06                     |
| Y8   | 2.61                     | —    | —                        | —    | —                        |
| Y9   | 2.56                     | —    | —                        | —    | —                        |
| mean | 2.66                     | mean | 2.06                     | mean | 2.20                     |
| s.d. | 0.13                     | s.d. | 0.03                     | s.d. | 0.13                     |
| s.e. | 0.04                     | s.e. | 0.01                     | s.e. | 0.05                     |

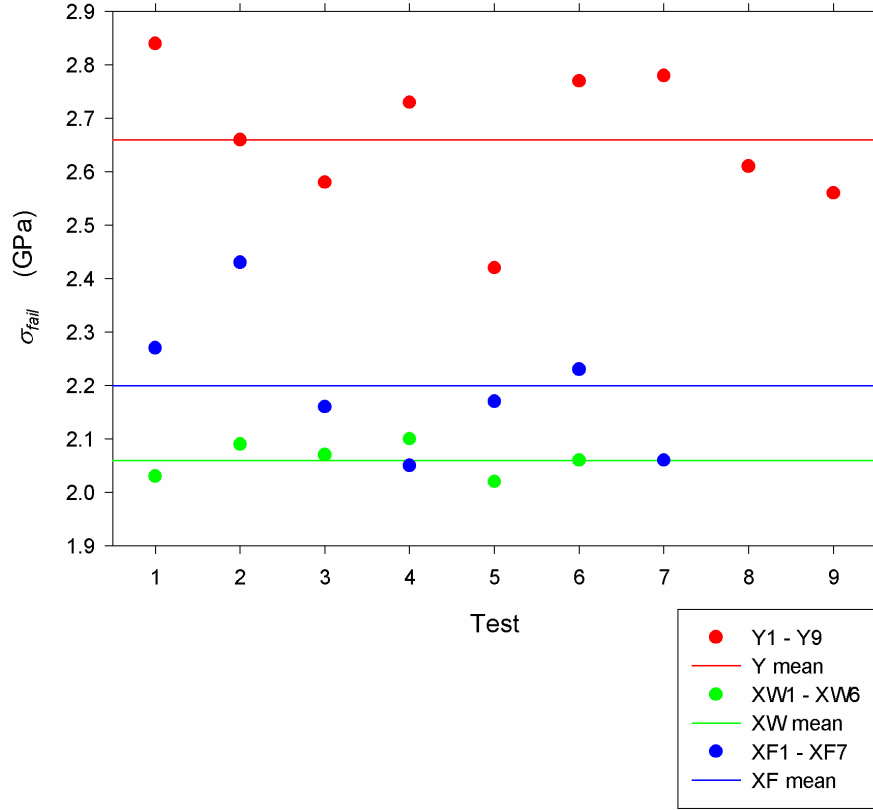


Figure 8. Strength results for untwisted single yarns.

### 3.2 Single-Ply Fabric Tests

Results from series W and F are presented in Table 5 and Figure 9. The strength for series W was  $2.23 \pm 0.04$  GPa, and that for series F was  $2.67 \pm 0.04$  GPa. Each value in series F is larger than any value in series W.

## 4. Discussion

### 4.1 Initial-Twist Effects on the Strength of Never-Woven Yarn

The dependence of yarn strength upon the amount of initial twist has been previously studied in the case of Kevlar (Yang 1993, pp. 34, 35). Yang (1993) does not identify the type of Kevlar used in the study, but does report that the denier, gauge length, and strain rate were 1500, 254 mm (10 in), and 0.0017/s (0.10/min), respectively. Yang (1993) defines a twist multiplier (TM) by

Table 5. W and F series results.

| Test | $\sigma_{fail}$<br>(GPa) | Test | $\sigma_{fail}$<br>(GPa) |
|------|--------------------------|------|--------------------------|
| W1   | 2.33                     | F1   | 2.77                     |
| W2   | 2.07                     | F2   | 2.69                     |
| W3   | 2.18                     | F3   | 2.47                     |
| W4   | 2.23                     | F4   | 2.75                     |
| W5   | 2.31                     | F5   | 2.61                     |
| W6   | 2.28                     | F6   | 2.72                     |
| mean | 2.23                     | mean | 2.67                     |
| s.d. | 0.10                     | s.d. | 0.11                     |
| s.e. | 0.04                     | s.e. | 0.04                     |

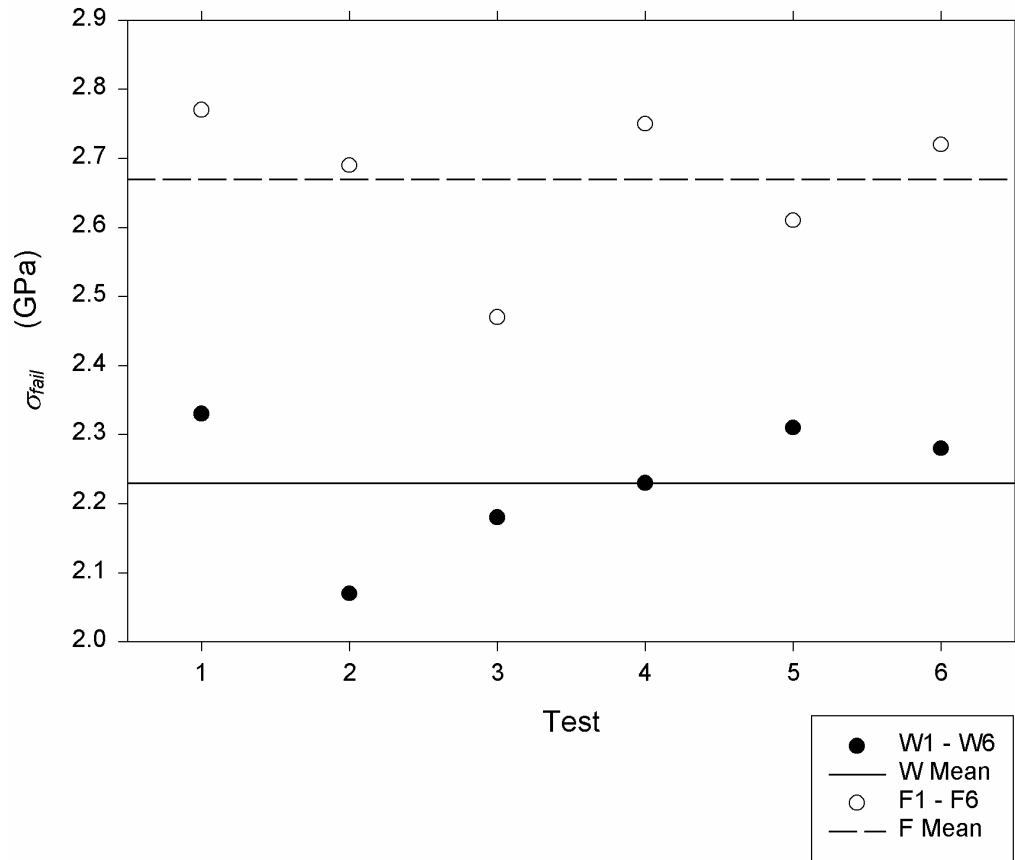


Figure 9. Strength results from the fabric tests.

$$TM = \frac{\tau_o (\text{turns/in}) \sqrt{\text{denier}}}{73} = \frac{\tau_o (\text{turns/cm}) \sqrt{\text{denier}}}{29}, \quad (3a)$$

and states without qualification that “a twist multiplier of 1.1 is optimal for Kevlar yarns” (p. 34). For the special case of 600 denier, equation (3a) reduces to

$$TM|_{600\text{denier}} = 0.84 \tau_o. \quad (3b)$$

The least-squares-error parabolic fit to the four data points in Figure 7 is

$$\text{mean}(\sigma_{fail}) = 2.66 \text{ GPa} + (102 \text{ GPa A cm}) \tau_o / (0.366 \text{ GPa A cm}^2) \tau_o^2, \quad (4)$$

which is added to the figure. Here,  $\tau_o$  is in turns/cm. This parabola attains its maximum of 3.37 GPa corresponding to a  $\tau_o$  of 1.39 turns/cm (3.54 turns/in). From equation (3b), the TM value associated with this maximum strength is 1.2, in agreement with the value of 1.1 cited by Yang.

The initial increase in  $\sigma_{fail}$  with increasing  $\tau_o$  has been attributed at least in part to frictional effects between filaments within the yarn. When a filament within a twisted yarn breaks, although it can no longer support an axial load at the breakage point, remote from that point the filament can still support a load because of frictional contact with neighboring yarns (Hearle 1969; Warner 1995, pp. 268, 269).

As noted in section 1 (Table 1), Yang (2000) reports a strength of 3.3 GPa for KM2 with no discussion of the corresponding degree of initial twist. This strength value is similar to our mean results of 3.21, 3.36, and 3.28 GPa from series TA, TB, and TC, respectively. On the other hand, this strength result in Yang (2000) is substantially larger than our result of 2.66 GPa from series Y. These comparisons strongly suggest that the result in Yang (2000) was based on specimens with non-zero initial twist.

#### 4.2 Strength of Untwisted Yarn; Never-Woven, Extracted Warp, and Extracted Fill

As noted in section 3.1.2, untwisted yarns that had been extracted from woven fabric (series XW and XF) exhibited smaller strength values than untwisted yarns that were not previously woven (series Y). The damage that produced these strength reductions relative to the baseline Y series can be attributed to some combination of three possible sources: the weaving, the subsequent finishing (especially the scouring), and the yarn extraction procedure.

As also noted in section 3.1.2, of the extracted yarns, those that had been woven in the warp direction (series XW) exhibited generally smaller strengths than those that had been woven in the fill direction (XF). This observation is consistent with the notion that greater damage was inflicted on the warp yarns than on the fill yarns during one or more of the weaving, scouring, and extraction processes. The weaving process involves several steps that can incur damage to



yarns. The scouring process involves pulling the woven fabric along the warp direction, so that greater damage is generally inflicted upon warp yarns than on fill yarns. Finally, because the warp yarns were more crimped than the fill yarns, they are likely to have suffered more damage during extraction.

### 4.3 Strength of Single-Ply Fabric–Warp and Fill

Strengths found for fabric specimens pulled along the warp direction (series W) were without exception smaller than those found for fabric specimens pulled along the fill direction (series F.) This observation is qualitatively consistent with that of section 4.2, namely that XW yarns had generally smaller strength than XF yarns. The notion of greater damage inflicted on warp yarns than on fill yarns during the weaving and/or scouring processes is supported once again. The yarn extraction procedure discussed in section 4.2 does not apply to the W and F series.

### 4.4 Single-Ply Fabric Strength Compared With Untwisted Yarn Strength

Strength results from series W and F are compared with those from series Y, XW, and XF in Figure 10.

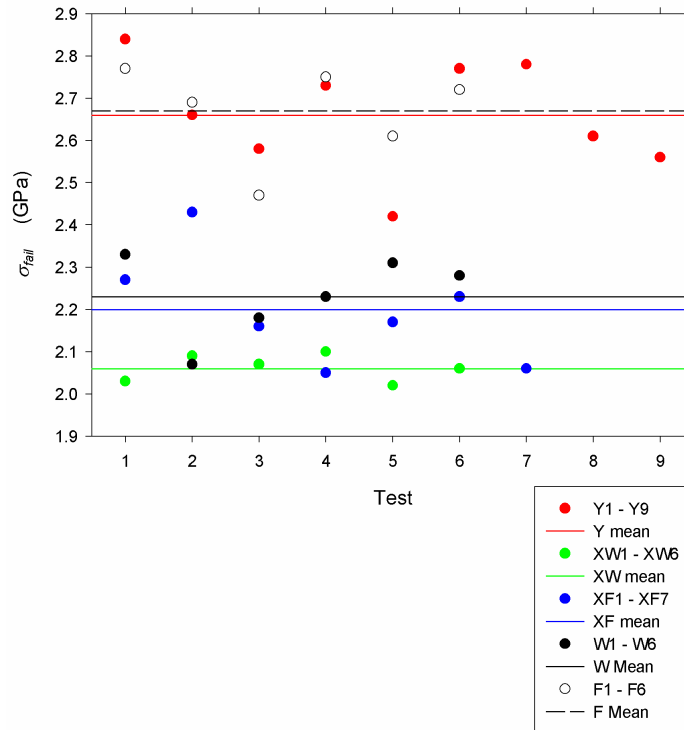


Figure 10. Strength results for untwisted yarns compared with those for fabric.

The F series strength results ( $2.67 \pm 0.04$  GPa) are similar to Y results ( $2.66 \pm 0.04$  GPa.) The XF series strength results ( $2.20 \pm 0.05$  GPa) are substantially smaller than both the F series and Y series results. To summarize,  $XF < F = Y$ . The most plausible interpretation is that F and XF suffered equal strength degradations during weaving and scouring, and  $XF < F$  because of damage during extraction in the case of XF and/or inter-yarn contact in the case of F. Furthermore, according to this interpretation, the strength increase in the F series due to inter-yarn contact happened to offset the strength decrease incurred during weaving and scouring, thereby producing the result  $F = Y$ .

F series strength increase arising from inter-yarn contact can be understood with the aid of Figure 1. In the plain weave pattern shown, each fill yarn is in direct contact with every warp yarn and hence in indirect contact with every other fill yarn. If a particular fill yarn were to undergo local rupture, that yarn should still be able to support a degree of axial tensile load because of frictional contact with other yarns.

The W series strength results ( $2.23 \pm 0.04$  GPa) are substantially smaller than the Y series results. The XW series strength results ( $2.06 \pm 0.01$  GPa) are substantially smaller than the W series results. To summarize,  $XW < W < Y$ . The observation that  $W < Y$  implies that significant damage was incurred by warp yarns during weaving and finishing. The observation that  $XW < W$  can be attributed to damage during yarn extraction in the case of XW and/or to inter-yarn contact in the case of W (refer again to Figure 1).

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## 5. Summary

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Single yarns of 600 denier Kevlar KM2 were tested in quasi-static, uniaxial tension. The strength of never-woven, untwisted yarn specimens that were obtained from DuPont was  $2.66 \pm 0.04$  GPa.

Three different degrees of initial twist were imposed on never-woven yarns, 0.69, 1.30, and 1.93 turns/cm. The corresponding strengths were  $3.21 \pm 0.05$ ,  $3.36 \pm 0.04$ , and  $3.28 \pm 0.03$  GPa, respectively. A parabolic fit was obtained to these strength vs. twist data. On the basis of this parabolic fit, a maximum strength of 3.37 GPa was found to correspond to an initial twist of 1.39 turns/cm. The twist multiplier was found to be 1.2, in agreement with that reported for Kevlar in Yang (1993). It was proposed that the KM2 strength value of 3.3 GPa reported in Yang (2000) corresponds to a state of near-optimum twist.

Warp-oriented and fill-oriented yarns were extracted from plain-woven, 600-denier KM2 fabric (Style 706). The strengths of extracted warp and fill yarns, tested in an untwisted state, were found to be  $2.06 \pm 0.01$  and  $2.20 \pm 0.05$  GPa, respectively. Comparison of these values with the never-woven, untwisted strength of  $2.66 \pm 0.04$  GPa led to the conclusion that substantial

strength degradation was incurred during one or more of the weaving, finishing (especially scouring), and yarn extraction processes. Furthermore, this degradation was significantly greater for warp than for fill yarns.

Finally, 68-yarn-wide, single-ply specimens of plain-woven, 600-denier KM2 fabric were tested in quasi-static, uniaxial tension. Warp-oriented and fill-oriented fabric specimens had strengths of  $2.23 \pm 0.04$  and  $2.67 \pm 0.04$  GPa, respectively. These fabric strengths are larger than those found for extracted warp and fill yarns. The mechanism of frictional contact being adjacent yarns was speculated to account for the added strength in the case of woven fabric.

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## List of Symbols

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|                 |                                                                                    |
|-----------------|------------------------------------------------------------------------------------|
| $A_{yo}$        | initial cross-sectional area of a yarn                                             |
| $F_{fail}$      | maximum force exerted on the specimen                                              |
| $N$             | number of tests in a given series                                                  |
| $\sigma_{fail}$ | strength (maximum First Piola-Kirchhoff stress, corresponding to specimen failure) |
| $\tau_o$        | initial twist of a yarn specimen                                                   |

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| 13. ABSTRACT (Maximum 200 words)<br>Kevlar KM2, 600 denier, was Instron tested in quasi-static, uniaxial tension to determine its strength. Specimens included both single yarns and 68-yarn-wide, single-ply strips of plain-woven fabric (Style 706). Never-woven single-yarn specimens were tested with varying degrees of initial twist. Strength of the untwisted, never-woven yarn was $2.66 \pm 0.04$ GPa. The twist multiplier was 1.2. Single warp-oriented and fill-oriented yarns were extracted from Style 706 fabric, tested, and found to have strengths of $2.06 \pm 0.01$ and $2.20 \pm 0.05$ GPa, respectively. The single-ply fabric specimens of both warp and fill orientations were tested and found to have strengths of $2.23 \pm 0.04$ and $2.67 \pm 0.04$ GPa, respectively. The strength effects of weaving, finishing, yarn extraction, and inter-yarn contact are discussed. |                                                             |                                                                  |                                    |  |
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