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Wet Strength of Kevlar 29 Ribbon Parachute Fabrics

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R. H. Ericksen* and L. Oreart†
Sandia Laboratories, Albuquerque, N. Mex.

The effect of moisture on the strength of Kevlar 29 ribbon parachute fabrics was investigated. Individual yarn samples and various fabrics were soaked in water for periods of 15-60 min. Yarn strength did not change; however, fabric strength was reduced. The reductions ranged 3-13% depending upon the fabric construction. Additional experiments eliminated factors such as the weaving process, yarn swelling, and increased abrasion in the presence of moisture as possible mechanisms. Other tests demonstrated that increased interyarn friction occurs when moisture is present. These results suggest that the moisture-enhanced friction restrains highly loaded filaments from adjusting their position and relieving stress concentrations. Specific construction parameters governing the amount of strength reduction were not defined in this study. However, it is evident that wet strength should be considered in parachute material selection and design.

Introduction

THE high tenacity of Kevlar 29‡ fiber in comparison with that of other textile fibers makes it attractive for use in parachutes where reductions of weight and bulk are of particular importance. Experience to date[1-3] indicates that replacement of nylon 66 by Kevlar 29 in some ribbon parachutes can achieve weight reductions of 50-60%, with slightly higher reductions in pack volume.

Many parachute applications involve prolonged storage under a wide range of temperature and humidity environments. The effect of moisture on Kevlar 29 yarn has been investigated. Du Pont[4] data indicate no loss in yarn strength after a 100 h exposure in tap water. Laboratory tests by Abbott, et al.,[5] showed 167 tex Kevlar 29 yarn to have identical rupture tenacity when tested in water at 25°C and in air at 25°C.

During the course of study of the high strain rate deformation of Kevlar 29 parachute fabrics[6] it was observed that the quasi-static rupture strength of wet Kevlar 29 webbing was approximately 9% lower than that of dry samples from the same lot of webbing. This result had not been expected based upon the available yarn data and suggests that moisture may influence webbing strength through a mechanism connected with the woven structure rather than influencing the yarn strength per se. The present investigation was initiated to examine how moisture affects the strength of Kevlar 29 ribbon parachute components, and to establish the extent and possible origin of the strength loss.

Procedure

Material

Several Kevlar 29 woven and braided textiles were examined. The construction parameters for each are summarized in Table 1. Yarn test samples were obtained from spools of material manufactured by Du Pont or from yarn removed from woven materials. In the latter case, the filling yarns were cut along one edge of the fabric and a number of warp yarns were carefully removed for testing. Individual filament samples were obtained by separating filaments from the yarns.

Moisture Exposure

Yarn Tensile Tests

Yarn tests were carried out using a table model Instron machine at crosshead speeds in the range of 1-5 cm/min (within a given test series a constant crosshead rate was maintained, specific values are tabulated in the results section). Grooved capstan grips were used with a nominal sample gage length of 28 cm. In the case of wet samples only the center half of the gage length was moistened; the portions of the sample that contracted the grips were dry. Pieces of absorbant paper toweling were used to keep moisture from seeping down from the moist portion into the lower grip.

Fabric Tensile Tests

Fabric tests were performed using Instron screw-driven or hydraulic test machines. Crosshead displacement rates were in the range of 0.5-5 cm/min; but, as in the yarn tests, rates remained constant for a given series. Nominal gage length was 48 cm.

Three types of grips were used:

1) 10.2-cm diam split capstans—used for heavy webbings. Rosin was used on the capstan surface to reduce slippage.

2) 2.5 cm-diam, double fixed pin (USAF/FDL design) grips—used for ribbons and tape.

3) 7.6 cm-diam wire capstans—used for braid.

The general test configuration used is shown in Fig. 1.

Loop Tests

Static and sliding yarn loop tests were utilized for both wet and dry samples following the methods described by Smith, Lau, and Backer.[7] For static loop tests the two ends of the top loop were gripped together in the top grooved capstan attached to the load train and the bottom loop gripped in a similar fashion on the moving crosshead. In the sliding loop tests the sample configuration was the same except that one of the ends of the bottom loop was held in a capstan mounted to the test machine frame rather than the moving crosshead. For the sample configuration used, approximately 0.75 mm of the lower loop would slide through the top loop during the test.

Static loop tests were carried out for filaments as follows: Single filament loops were mounted across a 15 cm rec-

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*Member Technical Staff.

†Engineering and Science Assistant.

‡Kevlar 29 is an aramid fiber produced by E. I. Du Pont de Nemours and Co., Wilmington, Del.

Table 1 Fabric construction

Material Type Class	Width, mm	Minimum rupture strength, kN	Warp Tex	Warp Ply	Warp Total ends	Fill Tex	Fill Ply	Fill Picks/cm	Weave
IV-1 tape	19	2.2	22	1	90	22	1	15	Plain
XI-14s ribbon	51	4.4	22	1	164	22	1	18	Plain
XI - 9a ribbon	51	8.9	44	1	142	44	1	18	Plain
VI - 10 webbing	25	42	167	3	76	167	1	3	2/2 HBT[a] center reverse
VII-6 webbing	29	62	167	2	140	167	2	5.5	5/1 HBT center reverse
			Yarn tex			Plied yarn		Yarn twist turns/cm	Picks/cm
IX braid	16	8.9	167			3		0.4	2.6

[a] Herring bone twill.

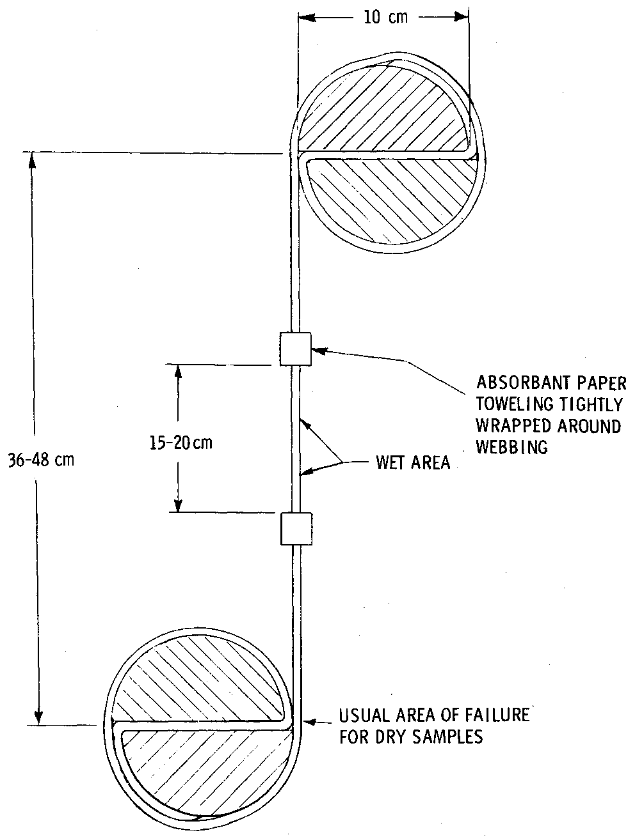


Fig. 1 Test configuration for quasistatic wet and dry tests of 42 and 60 kN webbings of Kevlar 29.

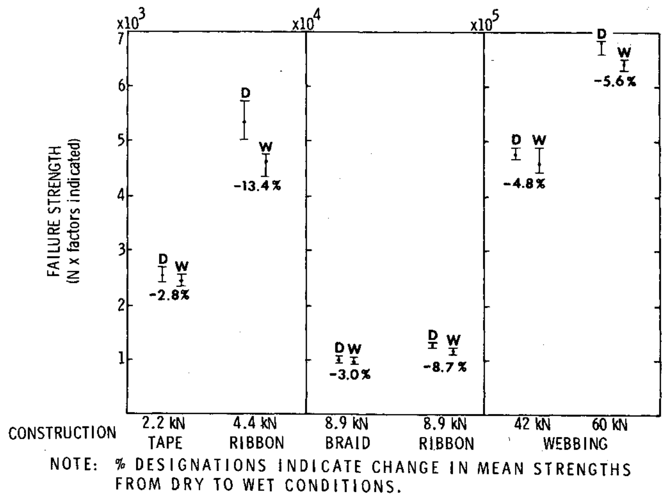


Fig. 2 Wet vs dry failure strengths for various Kevlar 29 constructions.

tangular slot in a piece of heavy paper using Eastman 910 adhesive. The mounted sample was then positioned in the testing machine and gripped using Instron fiber clamps. The paper was cut away leaving the fiber loop free. For the wet loop tests, mounted loops were soaked in a beaker of tap water for 60 min prior to testing.

Yarn Pullout Tests

The filling yarns at one end of a length of fabric were raveled out leaving a 18 cm fringe of protruding warp yarns. A centrally located yarn was individually fastened in a capstan grip attached to the moving crosshead of an Instron machine. The fabric end of the sample was gripped using flat-faced grips such that a 31 cm length of the test yarn remained in the fabric side. A slit cut across the warp near the top grip allowed a 30 cm length of the test yarn to be pulled out. This procedure was used to obtain extraction force vs yarn-length-removed curves for wet and dry samples.

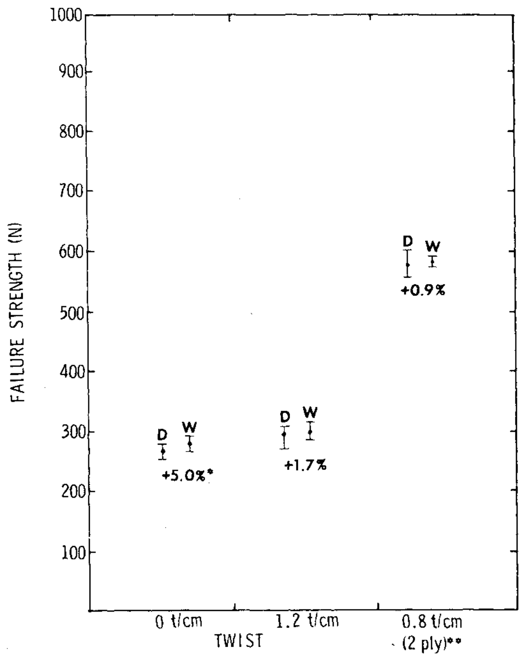
Simulated Yarn Crimp Tests

A test fixture was developed in an earlier study[8] that allowed a yarn sample to be deformed with a portion of its gage length threaded through a series of 0.05 cm diameter rigid steel wires spaced at intervals of 0.076-0.32 cm. The fixture was counterweighted in the Instron so no additional tensile force was applied to the sample other than that required to strain the yarn sample. Wet and dry yarns were tested using this technique at a crosshead displacement rate of 2 cm/min.

Results

Wet vs Dry Tests on Different Fabrics

Rupture strength data for the fabrics tested are summarized in Fig. 2. In all cases the average failure load for the wet fabric samples was lower than that of the dry ones. The percentage reduction in strength presented in Fig. 2 was not constant but varied with the different structures, compared with the parameters summarized in Table 1. The largest change observed was 13% for a 5.1 cm, 8.9 kN ribbon. No correlation has yet been established between percent strength decrease and any particular fabric construction parameter or



* % DESIGNATIONS INDICATE CHANGES IN MEAN STRENGTHS FROM DRY TO WET CONDITIONS

** YARNS REMOVED FROM WOVEN STRUCTURE

Fig. 3 Wet vs dry failure strength for 167 tex yarns of Kevlar 29.

the degree of yarn packing. The percent reduction in strength obtained for a given fabric construction was reproducible when tests on lots of at least five samples were repeated several weeks later. This result indicates that the strength reduction is in some way dependent upon constructional features and not on minor variations in laboratory test conditions or lot differences.

Moisture Effects in Yarns

Samples of 167 tex yarn were tested, including some removed from the woven structures. The rupture strength data obtained during these tests are summarized in Fig. 3. Moisture had no adverse effect on yarn strength in contrast to the results for woven fabrics. In fact, the tenacity of the wet samples was slightly higher than that of those yarns tested under nominally dry conditions. These results corroborate data reported previously.[5] Since individual yarns previously tested for wet strength had not been subjected to the weaving operation, a sample of the 29 mm, 62 kN webbing was dissected and divided into two lots for wet and dry testing. The results, also shown in Fig. 3, were the same as those for the other yarns—a slight increase in tenacity for the wet samples. This result eliminates the weaving operation as a source of any warp yarn modification which might alter yarn properties in a wet environment. Since no adverse change in yarn strength was observed in individual yarn tests, the moisture-induced degradation is evidently caused by yarn-to-yarn interactions during fabric deformation.

Yarn Pullout Tests

Pulling individual yarns out of a woven structure gives an indication of the frictional and geometrical restraint to yarn motion within that structure. Warp pullout tests were carried out on wet and dry samples of several different fabrics; a typical set of data is shown in Fig. 4. In all cases a greater force was required to pull a yarn from a wet sample than from a dry one. Moreover, moistening a dry sample during a pullout test produces an immediate increase in pullout force, indicating this effect is a surface phenomenon as there is no time for volume diffusion to occur. Although only small amounts of yarn-to-yarn motion would be present during fabric extension, increased interaction due to moisture could increase abrasion or stress concentrations, causing a reduced failure strength.

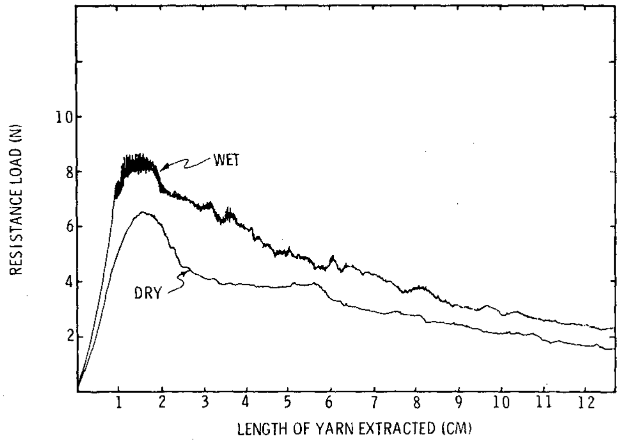
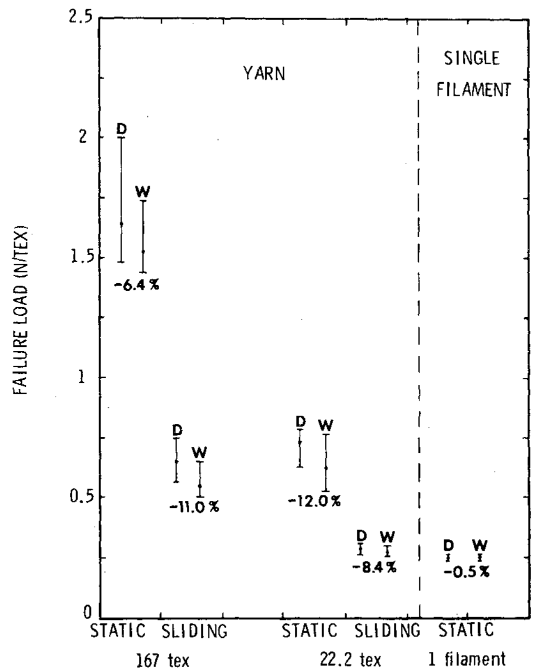


Fig. 4 Typical yarn extraction curve from 62 kN webbing.



NOTE: % DESIGNATIONS INDICATE CHANGES IN MEAN STRENGTHS FROM DRY TO WET CONDITIONS.

Fig. 5 Yarn and single filament loop tests.

Yarn Swelling

An increase in yarn diameter caused by moisture absorption could conceivably result in a reduction in fabric strength, since warp crimp increases with yarn diameter. It has been shown that increased warp yarn crimp reduces the strength of woven Kevlar structures.[9] The latter result was obtained by altering the pick spacing in woven structures. In the case of a 60 kN webbing, a change in pick spacing from 4 to 6 picks/cm lowered the strength from 70 to 63 kN.[9] By calculating changes in yarn geometry using typical geometric values for the appropriate Kevlar webbing and based on a 4% moisture absorption,[4] it was concluded that fiber swelling was an unlikely mechanism for the observed degradation.

Loop Tests

Static and sliding yarn loop test data is summarized in Fig. 5 for single-ply 22 tex and two-ply 167 tex Kevlar yarn samples. The latter samples were removed from webbings and are identical to those which showed no change of wet vs dry in the yarn tensile tests described previously. In all cases a lower loop strength resulted from the presence of moisture, which is in contrast to the simple tensile data. The 0.75 mm of relative motion during the sliding loop tests is considerably larger than is expected to occur during deformation of a woven fabric. No definite trend of increased strength loss in the moist sliding tests vs the dry sliding tests could be established. In the case of 167 tex yarn the percent change due to moisture was larger for the sliding loop than for the static loop (−11 sliding vs 6.4 static) whereas for the 22 tex yarn the reverse change was obtained (−8.4 sliding vs −12 static). In all cases the sliding test strength was less than half that of the static test strength. Failure in the sliding loop tests always took place in the moving loop.

Examples of sliding and static loop test sample surfaces were examined after testing using scanning electron microscopy. No difference in surface appearance was observed between the wet or dry samples.

Static loop tests were also carried out using individual filament samples. In contrast to the static loop yarn data, no change in loop strength was observed when the samples were moistened. These data are also shown in Fig. 5.

Simulation of Yarn Crimp

Results obtained in the crimp simulation fixture are presented in Figs. 6 and 7. The yarn strength decreased as the simulated fill spacing decreased. Whereas all the data obtained on samples not using the simulation fixture (i.e., 0 picks/cm in Figs. 6 and 7) showed about the same or slightly higher strength when wet, the reverse trend was obtained when mechanical crimp was introduced. The moist sample strengths are progressively lower than the dry strengths as the simulation fill spacing was decreased. The effect was also more pronounced in the twisted samples.

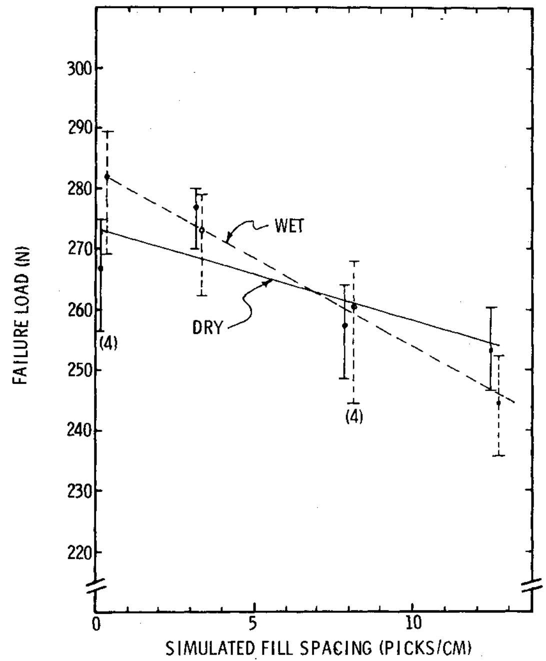


Fig. 6 Failure strengths of 167 tex yarn of zero twist in fill simulation fixture.

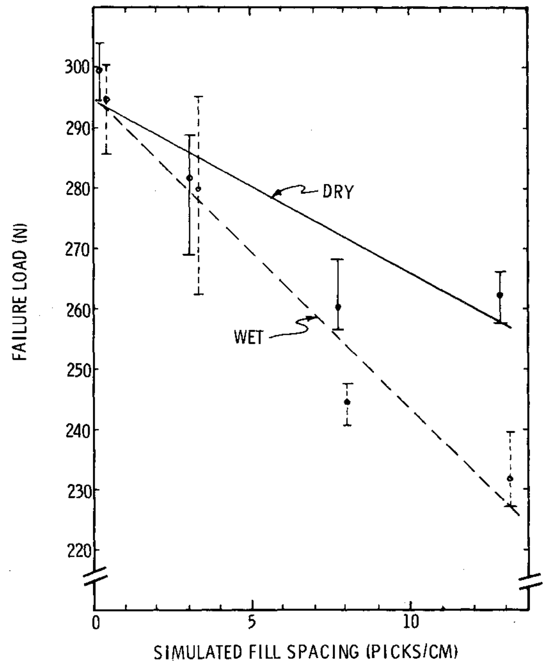


Fig. 7 Failure strengths of 167 tex yarns of 0.4 turns/cm twist in full simulation fixture.

Discussion

The data obtained in this investigation establish that moisture present during tensile loading of woven or braided structures of Kevlar 29 will reduce failure loads by as much as 13%. This phenomenon is peculiar to fabrics in that moisture does not degrade the strength of yarns loaded in tension. Although yarn breaking strength is measured in simple tension, when a fabric is loaded in tension the yarns are subjected to a more complex state of stress. Forces exerted on a yarn can include combinations of tension, bending, lateral compression, surface shearing, and unbending.[7] In addition, the yarn cross-sectional shape changes during fabric deformation.[10] A large number of parameters are required to specify a fabric construction and all lead to a complicated interaction between the yarn deformation modes. It has been well documented that a reduced yarn strength translational efficiency§ is obtained in woven or brained structures.[11] Some structures are less efficient than others and the fabric construction parameters which control yarn strength translational efficiency for Kevlar are not understood. Therefore the additional variable, moisture, is most likely to interact with those structural features in a complicated way.

Data obtained in the present study can be used to eliminate some of the possible origins of the observed moisture phenomenon. For example, tensile data from yarns removed from woven fabrics exhibit the same moisture response as yarns from the manufacturers' spools, indicating no perculiar degradation in yarn strength has been introduced during weaving. This factor will not be considered further as a potential mechanism for the moisture effect. Likewise, as pointed out in the Results section, yarn swelling does not account for the observed degradation.

As Smith, Lau, and Backer have pointed out,[7] a static loop test combines tensile, bending, and lateral compression deformation modes while the sliding loop test adds abrasion (surface shearing) and unbending. Sliding yarn strength is adversely affected by moisture to about the same degree as the static loop yarn strength, even though both wet and dry sliding loop strengths are considerably reduced below those obtained in the static tests. This result suggests that moisture does not significantly increase either the abrasion or unbending deformation modes. Moreover, the data were obtained using a relatively large amount of sliding between the yarns. During tensile deformation of a woven fabric, only

§Yarn strength translational efficiency is the webbing strength divided by the theoretical rupture strength obtained if every warp yarn shared the load equally with no loss in strength due to the interactive effect of filling yarn.

very small changes in yarn contact points should occur. Thus, our sliding yarn loop tests should have magnified any effect in these modes.

A second observation is that although moisture degrades the static loop strengths of yarns, the static loop strengths of individual filaments were not affected (Fig. 5). An individual filament loop test should subject the filament to more severe bending than would occur in a yarn test. Indeed, the failure load was proportionally reduced to a much lower value in the filament loop tests. This result could imply that a yarn structure is necessary for the moisture effect to manifest itself. However, the moisture effect might be masked by the greatly reduced failure strength of a filament in the loop test configuration.

Data from the yarn pullout tests establish that a considerable increase in interyarn frictional force occurs in the presence of moisture. Therefore, when the fabric is subjected to uniaxial stress the normal pressure exerted by warp on filling and vice versa will be increased. Under any loading condition some filaments will be subjected to higher stresses as a result of their position in the structure and the yarn geometry will change to equalize the forces. A possible explanation for the effect of moisture is suggested from these observations since the swelling, increased abrasion, and weaving parameters have been ruled out. An increased interyarn friction may reduce the ability of filaments in a yarn to readjust to a more favorable position to carry the imposed loads. This amounts to a stress concentration in the presence of moisture or an exacerbation of factors contributing to the reduced yarn strength translation efficiency in a woven or braided fabric. Until the parameters which control the strength efficiency of dry woven Kevlar fabrics are better understood, it is not likely that a more detailed mechanism for the moisture degradation can be established.

The model described above is consistent with observations obtained using the fill simulation fixture. In simulation tests the yarns are loaded while woven through steel wires. The wires should deflect in the same manner regardless of the moisture content of the test sample. The yarns are observed to flatten as they come in contact with the wires. In simulation tests the data in Figs. 6 and 7 show an effect of yarn twist on the moisture response. A structural effect with yarn twist as one of the variables is expected, based upon our woven fabric results noted above. The two ribbon structures tested exhibited the largest percentage decrease in strength when tested exhibited the largest percentage decrease in strength when tested wet. Other than being of a wide, thin geometry compared with the other structures tested, there were no definite structural parameters that could be identified as contributing factors.

Until sufficient information is available to allow prediction of moisture degradation as a function of fabric construction parameters, it will be necessary to test each parachute component individually or allow an overall wet strength reduction factor of about 13% in parachute materials selection. This reduction is not large enough to limit the application of Kevlar in view of the large weight and volume savings already demonstrated in comparison with nylon parachutes.[2] Factoring the magnitude of this effect into design of a parachute system eliminates an unknown variable from the overall factor of safety parameter.

Conclusions

1) The presence of moisture on Kevlar 29 narrow fabrics reduces tensile strength by 3-13%.

2) Factors such as the weaving process, yarn swelling, and increased abrasion in the presence of moisture were eliminated as possible mechanisms.

3) Moisture was shown to increase interyarn friction. It is suggested that a reduction in the ability of highly loaded filaments to readjust their position in the structure causes the decrease in strength observed in moist samples.

4) Until the structural parameters which govern the amount of strength reduction in a given fabric construction are determined, it will be necessary to test each parachute component individually or to allow an overall wet strength reduction factor of about 13% in parachute materials selection.

Acknowledgment

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