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TECHNICAL REPORT
NATICK/TR-77/010

EFFECT OF NONUNIFORM YARN LENGTHS ON THE STRENGTH OF PRESSURIZED FABRIC TUBES

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May 1977

UNITED STATES ARMY
NATICK RESEARCH and DEVELOPMENT COMMAND
NATICK, MASSACHUSETTS 01760

Aero-Mechanical Engineering Laboratory

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NATICK/TR–77/010

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
EFFECT OF NONUNIFORM YARN LENGTHS ON THE STRENGTH OF PRESSURIZED FABRIC TUBES

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Earl C. Steeves

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Army Natick Research and Development Command
Natick, MA 01760

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
62723A
1Y762723AH98 AE 017

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Army Natick Research and Development Command
Attn: DRXNM–UE
Natick, MA 01760

12. REPORT DATE
October 1975

13. NUMBER OF PAGES
35

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release;
distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

FABRICS	PRESSURE STABILIZED BEAMS	PRESSURE VESSELS
YARNS	BEAMS (STRUCTURAL)	TENTAGE
WEAVING	PRESSURE STABILIZATION	STRENGTH REDUCTION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analysis of the load-deformation behavior and strength of pressurized fabric tubes having unequal yarn lengths is presented. This analysis models the loading of such a fabric by consideration of a series of axial members of unequal length and assumes a linear load-deformation behavior of the yarns. To obtain results the unequal lengths are chosen to be some mean length plus a randomly distributed variation about this mean. Using a normal distribution for the lengths, a computer simulation is used to compute

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20. (ABSTRACT (Cont'd)

the statistics of the failure load for fabrics having yarn lengths specified by the mean and standard deviation. These results show that significant strength reductions are possible as a result of weaving inaccuracies which result in yarns of unequal length.

PREFACE

The study reported here was undertaken to develope an understanding of the failure of some pressure stabilized beams and arches which were fabricated under contract using a three-dimensional weaving technique. The tubes failed at pressures well below the design pressure and it was speculated that the cause of these failures might be unequal length fill yarns caused by poor control of the fill yarn tension during weaving. These beams and arches were fabricated for use in 16 x 16 ft prototype tents as a part of our program to develope the pressurized rib concept for Army tentage.

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EFFECT OF NONUNIFORM YARN LENGTHS ON THE STRENGTH OF PRESSURIZED FABRIC TUBES

INTRODUCTION

The use of woven fabric tubes as pressure vessels requires the ability to design such tubes to resist the stress imposed by the pressure. For many geometries, the cylinder, sphere, and torus for example, the stresses resulting from internal pressurization are easily calculated. If the breaking strength of the fabric is known, then the design problem is quite simple. However, frequently only the breaking strenght of the yarn used to weave the fabric is known, and the design problem is then more complex because of reduction in strength due to weaving and the biaxial state of stress. One cause of these reductions in strength is in the inaccuracies of the weaving process which are typified by the woven cylinder in which the warp yarns run parallel to the axis and the fill yarns form the circumference of the cylinder. For the cylinder the design stress is the circumferential stress resisted by the fill yarns, and if the weaving process produces a cylinder in which the fill yarns are of differing lengths they do not all support the load equally and strength is reduced. The effect of this length variation on the strength of the fabric is the subject of this report.

ANALYSIS

The load-deformation behavior and the failure of woven cylinders subject to internal pressure will be analyzed. This analysis will include the effect of variations in the lengths of the fill yarns forming the circumference of the cylinder. In the pressurized cylinder the circumferential stress, N_θ, is the largest and is uniform throughout the cylinder. N_θ is given in terms of the pressure, P, and the radius, γ, as

$$N_\theta = P\gamma \tag{1}$$

For the purposes of analysis we can model the situation for varying length yarns as illustrated in figure 1. We consider a unit length along the axis consisting of J fill yarns of differing lengths and subject to a total force F. Since we are dealing with a unit length the magnitude of F is equal to $P\gamma$. The yarns are in tension, and because of the difference in length all do not support the load. This is modeled by a series of J axial members of varying lengths with the total load applied through a yoke which applies load only to shortest member at first, but as the deformation continues due to increased pressure, the longer yarns are contacted and begin to support the load. We take as a measure of the deformation the movement of the yoke, x. The lengths of the yarns are denoted by l_j and each yarn is assumed to obey the following linear deformation law

$$f_j = KU_j \qquad j = 1,2,3...J \tag{2}$$

where f_j and U_j are respectively the force in the yarn and the elongation of the yarn. Assuming that the numbers l_j are arranged in ascending order, the load-deformation behavior can be described as follows: When the load is first applied the shortest yarn supports all the load and continues to do so as the load increases until $x = U_1 = l_2 - l_1$.

Thus for

$$0 \leq x < (l_2 - l_1)$$

$$F = f_1$$

$$f_1 = Kx$$

$$x = F/K$$

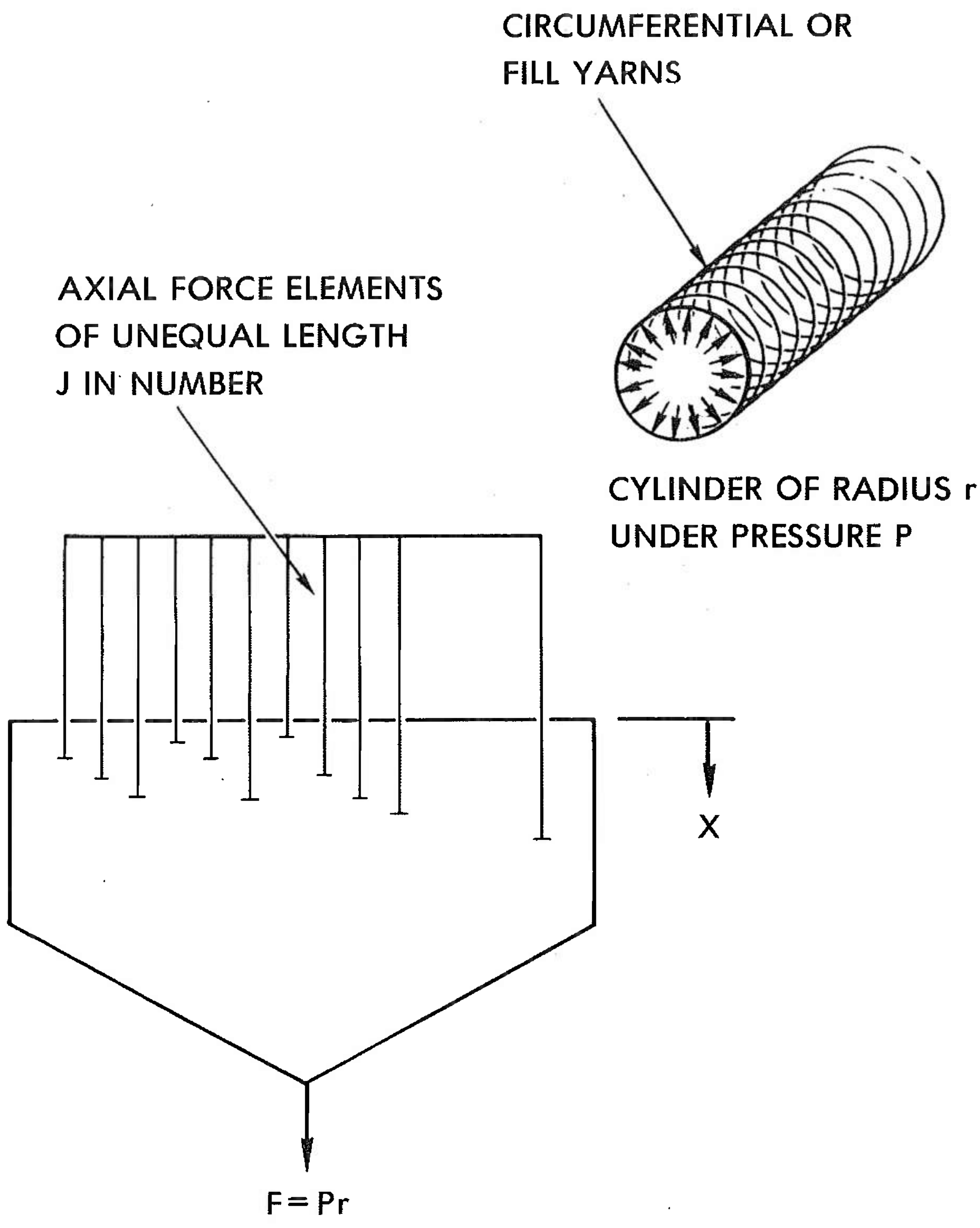

FIGURE 1. REPRESENTATION OF THE LOAD DEFORMATION BEHAVIOR OF A PRESSURIZED WOVEN CYLINDER HAVING CIRCUMFERENTIAL YARNS OF UNEQUAL LENGTH

As the deformation x becomes larger than $(l_2 - l_1)$ the second yarn becomes stressed and supports part of the load, so for

$$(l_2 - l_1) \leq x < (l_3 - l_1)$$

$$F = f_1 + f_2$$

$$f_1 = Kx$$

$$f_2 = K\,[x - (l_2 - l_1)]$$

$$x = F/2K + 1/2\,(l_2 - l_1)$$

When the deformation becomes greater than $(l_3 - l_1)$ the third yarn becomes stressed and it too supports part of the load, so for

$$(l_3 - l_1) \leq x < (l_4 - l_1)$$

$$F = f_1 + f_2 + f_3$$

$$f_1 = Kx$$

$$f_2 = K\,[x - (l_2 - l_1)]$$

$$f_3 = K\,[x - (l_3 - l_1)]$$

$$x = F/3K + 1/3\,(l_2 - l_1) + 1/3\,(l_3 - l_1)$$

Continuation of this analysis leads to the following general relations when L yarns are effective in supporting load:

$$(l_L - l_1) \leq x < (l_{L+1} - l_1)$$

$$F = \sum_{j=1}^{L} f_j \tag{3a}$$

$$f_j = K\,[x - (l_j - l_1)] \tag{3b}$$

$$x = F/LK + \frac{1}{L} \sum_{j=1}^{L} (l_j - l_1) \tag{3c}$$

This process is then continued until $L = J$. Equations (3) appear deceivingly simple in that it seems that if the total force F is specified then x and the f_j are computable. This however is not the case because the limit on the summation, L, in equation (3c) is not known and is in fact dependent on x, the total deformation, which in turn is dependent on F; thus equation (3c) in nonlinear. An example of the load-deformation curve associated with equations (3) is shown graphically in figure 2 for the case of $J = 7$. On the deformation axis the value at which each of the yarns begins to support load, refered to hereafter as yarn take-up points, are noted since these are known if the lengths are known. On the force axis the values corresponding to the yarn take-up points are shown. These forces can be computed from equation (3c) since the magnitude of x is known at the take-up points. Also shown on the figure are the load-deformation curves for each of the yarns.

These all have the same slope but differ in the magnitude of x for which they begin to support load. For any value of x the magnitude of the force F can be found by summing the yarn forces for the value of x. This then gives a complete description of the load-deformation behavior of a fabric cylinder under pressure with circumferential yarns of unequal length.

We now address the question of using this analysis of the load-deformation behavior to estimate the breaking strength so that its reduction due to variations in length of fill yarns in the fabric can be determined. To do this it is necessary to adopt a failure criteria, and we chose the initiation of failure, that is, the breaking of the most highly loaded yarn which is the shortest yarn, the one with length l_1. Using this failure criteria, the failure load F can be found by computing the magnitude of x for which $f_1 = f_b$, the breaking load of the yarn. This computation is accomplished using equation (3b) with $j = 1$ and $f_1 = f_b$. Given this magnitude of deformation for breakage of the first yarn, x_b, it is possible to determine the number of yarns supporting the load by comparison of x_b with the yarn take-up values $(l_j - l_1)$. The number of yarns supporting load is set equal to L and the force causing breakage is given by

$$F_b = LKx_b - K \sum_{j=1}^{L} (l_j - l_1) \tag{4}$$

which is obtained from equation (3c).

In order to provide some basis for comparison, the strength of the ideal fabric is assumed to be the product of the yarn breaking strength and the number of yarns per unit of width.

$$\tilde{F} = f_b J \tag{5}$$

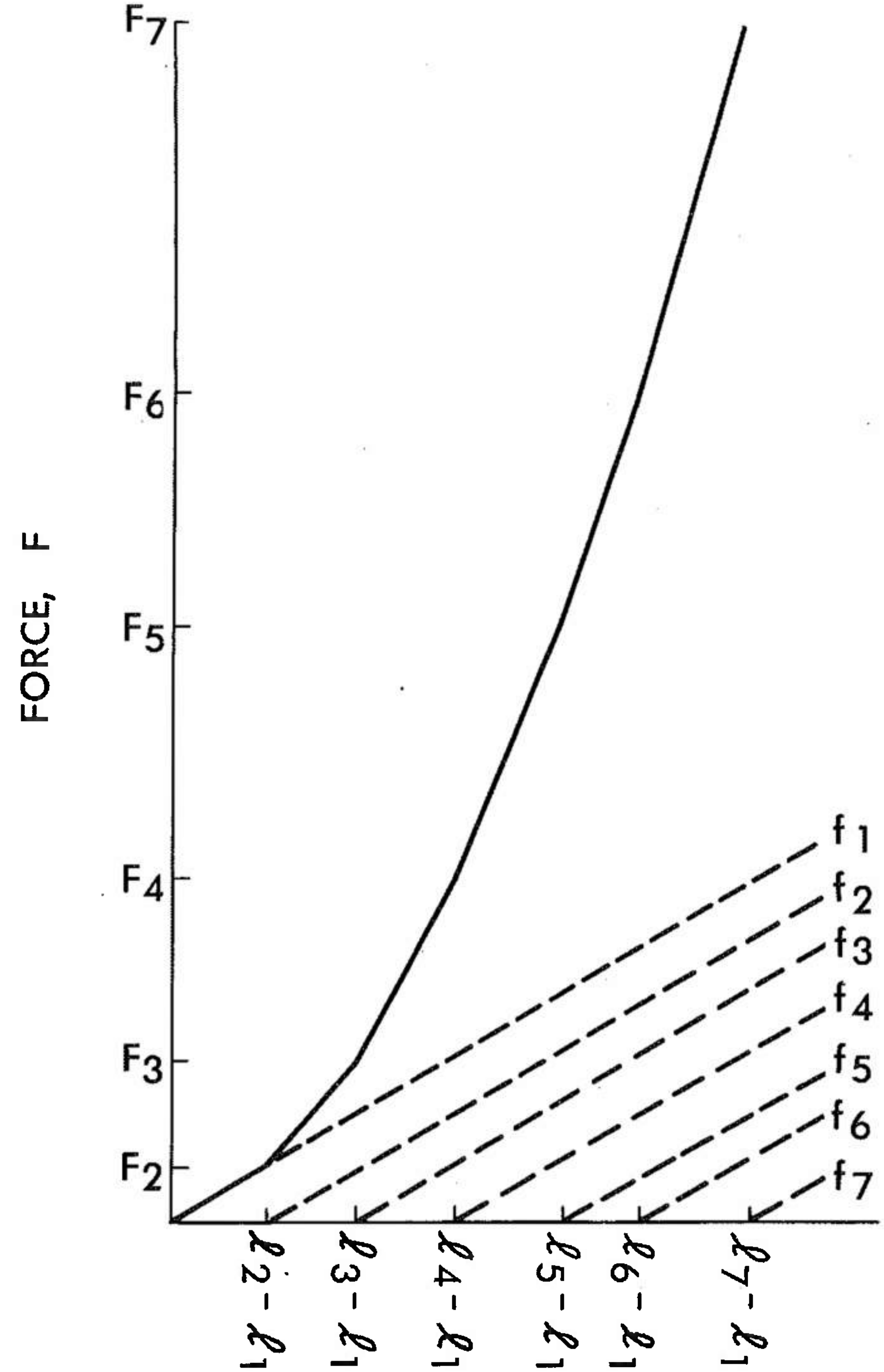

FIGURE 2 . LOAD-DEFORMATION BEHAVIOR OF FABRIC HAVING YARNS OF UNEQUAL LENGTH

A measure of the reduction in strength caused by the unequal length yarns will then be taken as the ratio of this ideal fabric strength and the strength given by equation (4).

As can be seen, this analysis requires some knowledge of the fill yarn lengths. This information is not generally known in advance or even after the fact in any exact sense, so the lengths are here taken as some nominal length plus a random variation about this nominal length. This random variation is assumed to be normally distributed. Instead of attempting to carry out a formal analysis of the strength reduction using this model of the length variation, a computer simulation will be used. In this simulation the statistics of the length variation, the mean and standard deviation, will be specified, and statistic of the strength will be computed.

For carrying out such a simulation is is convenient to write equations (3) in nondimensional form. Adopting the yarn breaking load, f_b, and the nominal or average fill yarn length, l, as the characteristic force and length parameters the equations become

$$\bar{F} = \sum_{j=1}^{L} \bar{f}_j \tag{6a}$$

$$\bar{f}_j = \bar{K} \left[\xi - (e_j - e_1) \right] \tag{6b}$$

$$\xi = \bar{F}/L\bar{K} + \frac{1}{L} \sum_{j=1}^{L} (e_j - e_1) \tag{6c}$$

where

$$\begin{aligned} \bar{f}_j &= f_j/f_b \\ \xi &= x/l \\ \bar{F} &= F/f_b \\ e_j &= l_j/l \\ \bar{K} &= KL/f_b \end{aligned} \tag{7}$$

Examination of these nondimensional equations and parameter definitions reveals that breakage of the shortest yarn occurs when $\bar{f}_1 = 1$ and that the strength of the ideal fabric, see equation (5), has a magnitude equal to the number of yarns per unit length, J. In addition, if the distribution of random lengths is to be centered about the nominal length, then the nondimensional lengths, e_j, will have a unit mean.

A copy of the Fortran program used to carry out this simulation is presented in the Appendix. The program has liberal use of comments defining all the parameters. The subroutines used to generate the normally distributed lengths and to compute the mean and standard deviation of the failure load are Univac 1108 Math-Pac subroutines.

The simulation is carried out in the following fashion. A sequence of IS sets of random numbers are computed, each of the sets contains J elements and represent the randomly distributed yarn lengths the mean and standard deviation of which are read as input. For each set of yarn lengths the load-deformation curve is computed as is the breaking strength of the fabric. Once these calculations have been carried out for all of the sets of yarn lengths we have a sequence of fabric breaking strengths which are used to compute the average and standard deviation of the fabric breaking strength. This average breaking strength is then taken as the measure of the reduction in strength resulting from the variation in yarn length.

DISCUSSION

In this section we examine the results of this simulation beginning with the convergence of the process. In Table 1 the behavior of the average and standard deviation of the failure load with the number of sequences of yarn lengths used in the simulation is shown. The process appears to converge quite rapidly as the number of sequences is increased. With eight and greater sequences the average breaking strength changes very little in comparison with the standard deviation of the breaking strength which remains fairly constant over this range of number of sequences. There is no uniform trend in the average breaking strength so it is difficult to say the result has converged or is converging in any classical sense, but it is believed that the data in Table 1 shows that the simulation process is stable and that useful results can be obtained. The remainder of results presented were computed using 10 sequences of lengths.

An additional check on the behavior of the process is provided by examining the behavior of the average breaking strength as the standard deviation of the yarn lengths becomes small as shown in Table 2. As the standard deviation becomes very small the fabric approaches perfection, and it is expected that the breaking strength will approach that of the ideal fabric which in nondimensional form is equal to the number of yarns per unit length. Examination of the data in Table 2 reveals that the process is well behaved with respect to decreasing yarn length standard deviation. In addition to the average breaking strength approaching the ideal fabric strength, the standard deviation of the breaking strength becomes very small. These results are exhibited for both values of stiffness and yarn densities shown. All results in Table 2 are for average nondimensional yarn lengths of unity.

The effect of variation in yarn length within a fabric on the breaking strength of the fabric is shown graphically in figure 3. Results are shown for fabrics with yarn densities of 10, 16, and 18 yarns per unit width all having nondimensional yarn stiffness of 22.0 and with a yarn density of 16 yarns per unit width having a stiffness of 11.0. As the independent variable which is the standard deviation of the yarn length approaches zero the fabric approaches perfection, and it can be seen that the breaking strengths approach that of a perfect fabric which in nondimensional form has the value of the yarn density. The other limiting case is for large values of the independent variable, and examination of the results in figure 3 reveals that the breaking strengths of all fabrics approach a common value. To understand this result it must be realized that as the standard deviation becomes large it is possible for the most highly stressed yarn to reach its breaking strength, which is here defined as fabric failure, before sufficient deformation has taken place so that all yarns are supporting load. Thus, what is seen in figure 3 for large values of the standard deviation is that all the fabrics have nearly the same number of yarns supporting load, thus they are nearly identical fabrics with respect to their ability to support load. The average number of yarns supporting load at failure are shown in Table 3 for each of the fabrics considered in figure 3. The independent variable in this table is again

TABLE 1

Behavior of Simulation Process with Number of Yarn Length Sequences

No. of Yarn Length Sequences	Fabric Breaking Strength Nondimensional: Average	Fabric Breaking Strength Nondimensional: Standard Deviation
1	13.54	
2	13.54	0.00
5	12.70	1.28
8	12.74	1.11
10	12.92	1.05
15	12.86	1.09
20	12.80	0.99
25	12.76	0.94
30	12.74	0.94

Number of Yarns/unit width = 16
Yarn lengths (nondimensional)
Average = 1.0
Standard Deviation = 0.005
Nondimensional Yarn stiffness = 22.0

TABLE 2

Behavior of Breaking Strength Simulation with Yarn Length Standard Deviation

Nondimensional Fabric Breaking Strength

Yarn Length Standard Deviation	Yarn Density = 16				Yarn Density = 10			
	Nondimensional Stiffness = 22.0		Nondimensional Stiffness = 11.0		Nondimensional Stiffness = 22.0		Nondimensional Stiffness = 11.0	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
0.05	2.18	0.99	4.27	1.99	2.18	1.26	3.45	1.92
0.01	9.84	2.09	12.92	1.05	6.55	1.62	8.27	0.81
0.005	12.92	1.05	14.46	0.53	8.27	0.81	9.14	0.41
0.001	15.38	0.21	15.69	0.11	9.65	0.16	9.82	0.08
0.0005	15.69	0.11	15.84	0.05	9.82	0.08	9.91	0.04
0.0001	15.94	0.02	15.97	0.01	9.96	0.02	9.98	0.01
0.00005	15.97	0.01	15.98	0.00	9.98	0.01	9.99	0.00
0.00001	15.99	0.00	15.99	0.00	9.99	0.00	10.00	0.00

Average nondimensional yarn length = 1.0

TABLE 3

Average Number of Yarns Supporting Load at Failure

Yarn Length Standard Deviation	Yarns Supporting Load N = 18 K = 22.0	N = 16 K = 22.0	N = 16 K = 11.0	N = 10 K = 22.0
0.001	18	16	16	10
0.0025	18	16	16	10
0.005	18	16	16	10
0.0075	18	16	16	10
0.01	18	15	16	10
0.0125	16	14	16	9
0.015	16	13	16	8
0.0175	14	12	16	8
0.02	12	11	15	7
0.025	10	9	14	6
0.03	8	7	13	5
0.04	6	5	11	5
0.05	5	4	9	3

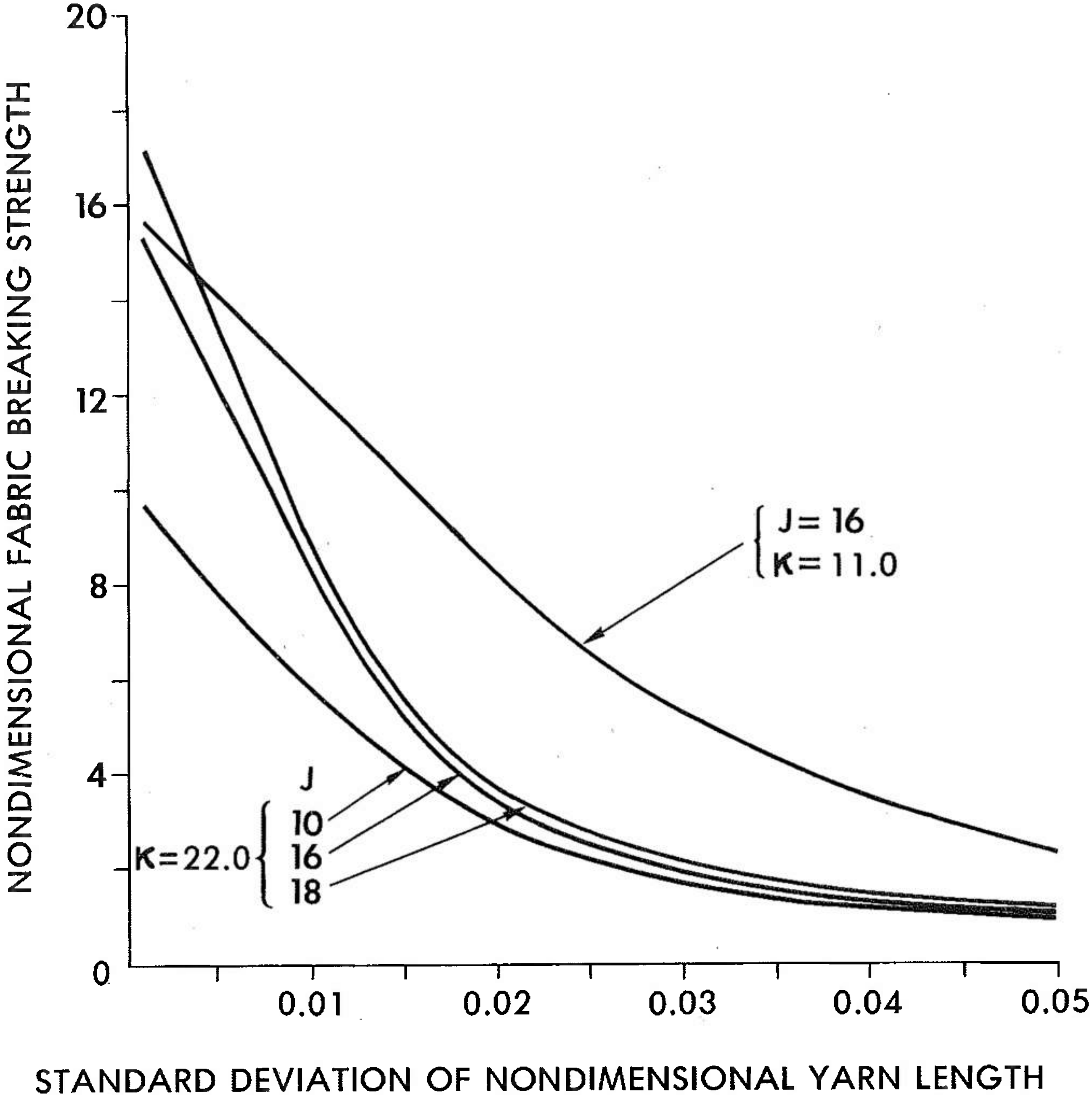

FIGURE 3. BEHAVIOR OF FABRIC BREAKING STRENGTH WITH VARIATION IN YARN LENGTH

the standard deviation of the yarn length and for large values of this parameter it is seen that the number of yarns supporting load at failure approaches a common value. This reasoning leads to the conclusion that the limiting value of the breaking strength for large standard deviation is unity, meaning that only one yarn is supporting load at failure. This limit is in all likelihood way beyond the situations which arise in actual fabrics.

The data presented in figure 3 also reveals that the reduction in breaking strength is much less severe for the fabric woven with yarns having lower stiffness. This result is not unexpected because the lower stiffness provides for more deformation and thus a more uniform distribution of the load among the yarns.

In addition to the fabric strength the analysis carried out also gives the load-deflection behavior of the fabric, a typical example of which is given in figure 4. Although it is difficult to discern from the figure, this curve is piecewise linear. The general character which can be described as stiffening with increasing deformation is typical of stress-strain behavior obtained for most fabrics. This stiffening effect in fabric is usually attributed to crimp interchange or to a transfer from the relatively low stiffness bending mode of deformation to the high stiffness axial mode of deformation of the yarns in the fabric. While this crimp interchange or take-up is a likely mechanism, the results presented here suggest another possible mechanism based on unevenness of the load distribution among the yarns. Experimentally observed behavior may be a combination of these mechanisms.

This analysis was prompted by our experience with some woven Kevlar tubes which failed at a pressure far below their design pressure and nonuniformity of the length of the circumferential yarns was suggested as a possible cause of the premature failure. The tubes woven with 44 tex Kevlar 29 yarn and a circumferential yarn count of 18 yarns per cm were 0.163 m in diameter. This yarn material has a breaking strength of 1.94 N/tex and a modulus of 42 N/tex. Based on these numbers, the breaking pressure should have been 1861 KPa, but in tests one tube failed at 310 KPa and another at 330 KPa. Thus, a strength reduction on the order of 1/6 was observed. The nondimensional yarn stiffness for the yarns used is 22, and since the yarn count is 18, we can use the result on figure 3 to determine the likelihood of nonuniformity of yarn lengths in causing the premature failure. The failures occured at 1/6 of that of the ideal or perfect fabric. The nondimensional breaking strength for the pefect fabric is 18 so failure occured at 3 and data given in figure 3 indicates that a yarn length standard deviation of about 0.025 is required to cause that reduction in breaking strength.

In using this nondimensional result to interpret the physical behavior we first examine the complete tube assuming that the variability is distributed throughout the tube circumference. Recalling that the tube diameter was 0.163 m, we have a nominal yarn length, l, of 0.51 m, the tube circumference. Thus the yarn length standard deviation required to cause the observed strength reduction is 0.013 m, or 2.5% of the nominal or average length. A visual examination was made of yarns taken from the woven tube

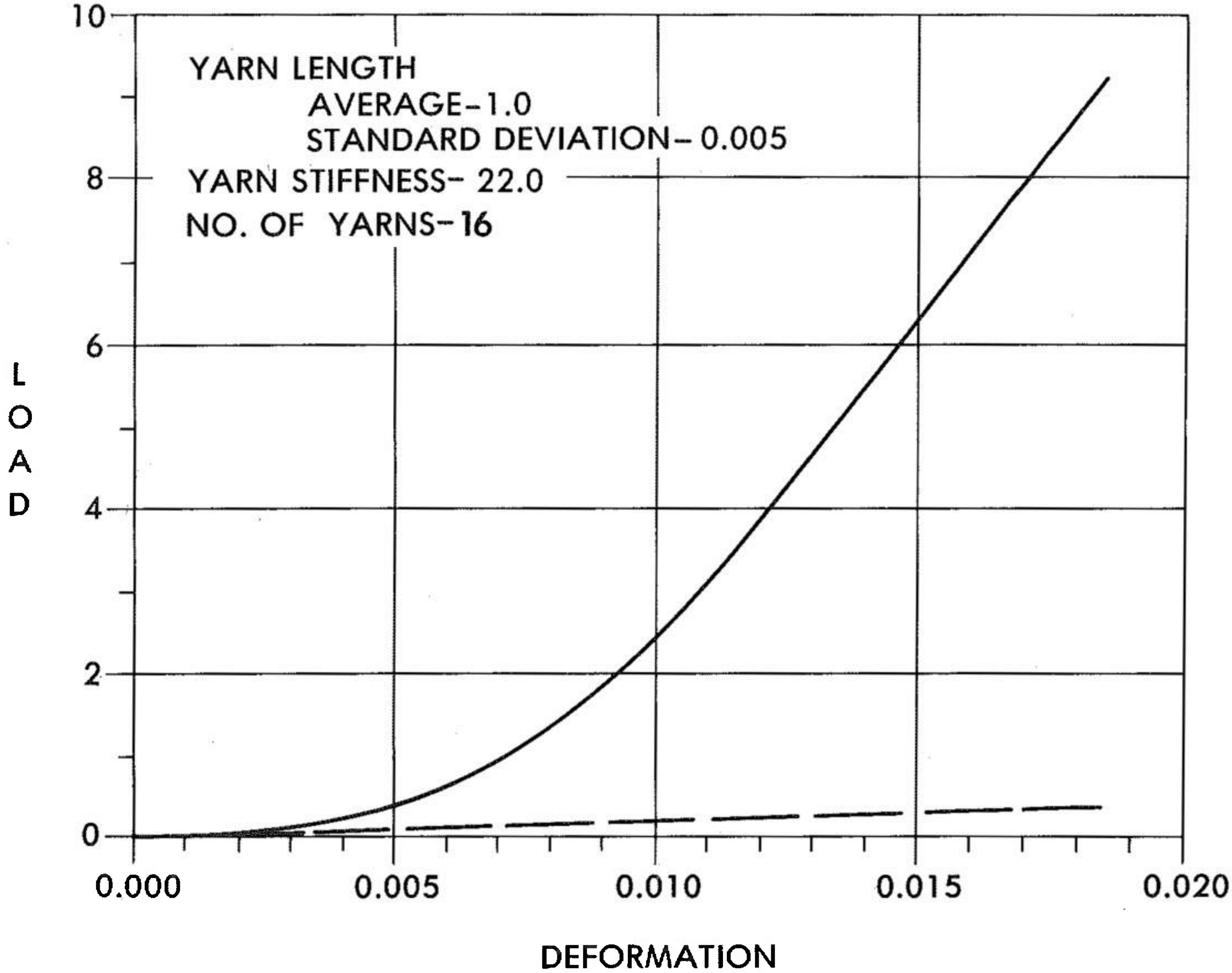

FIGURE 4. FABRIC LOAD-DEFORMATION CURVE RESULTING FROM THE COMPUTER SIMULATION .

and no variations in length approaching this magnitude were found. So it was concluded that this mechanism based on involvement of the full length of the circumferential yarn does not explain the observed premature failures. This analysis can also be used to examine the local behavior around the crease or fold line that results from weaving the tubes. The tubes are woven in a flat configuration as shown in figure 5a. A complete circumferential yarn requires two passes of the shuttle and a fold line or crease is generated where the yarn changes direction. It is speculated that, because of the difficulties in keeping yarn tension constant as the shuttle changes direction, the variations in yarn length may be concentrated in the fold region. If this is the case we can model the behavior as shown in figure 5b by treating a segment of fabric of width l centered about the crease line. Within this segment yarns have variable lengths because of the unequal amounts of slack in the yarns. Because of the slack and the resulting variable lengths, the stress in the fabric is not uniform. It is assumed, however, that this nonuniformity diffuses, and that at some distance from the crease line the stress becomes uniform. We take l to be twice that distance. The model shown in figure 5b then has a series of yarns having unequal lengths and loaded by a uniform load. In this model the number of yarns supporting the load depends on the magnitude of the load and is thus identical analytically with the model developed previously in this report. In examining the physical case with this model, even less is known since the average length l is not known. That is, the distance required for redistribution of the stress is not known. The best that can be done is to examine the behavior as a function of l and see if the results seem feasible. Using the nondimensional result above we find that the yarn length standard deviation must be 0.025 l for the observed strength reduction. Thus, if l is 10 cm, the stress redistribution would occur within 5 cm from the crease line, and the standard deviation in length would be 0.25 cm. Similarly for l = 5 cm the standard deviation would be 0.125 cm. Variations in length of this magnitude probably would not have been noticed in the visual examination of the yarns and, with a thread count of 18 yarns per cm, redistribution of the stress in distance of 5 to 10 cm seems possible. In addition, the premature failures occurred most frequently in tubes that had been coated with a latex material which would accelerate the redistribution of stress by increasing shear stiffness. These facts suggest that this local yarn length variation is responsible for the premature failure of these woven tubes.

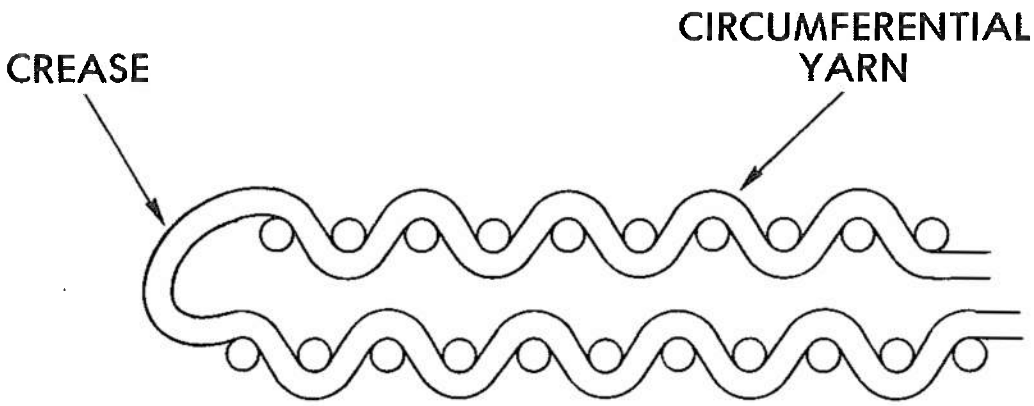

FIGURE 5a. LAY-FLAT WEAVING OF FABRIC TUBES

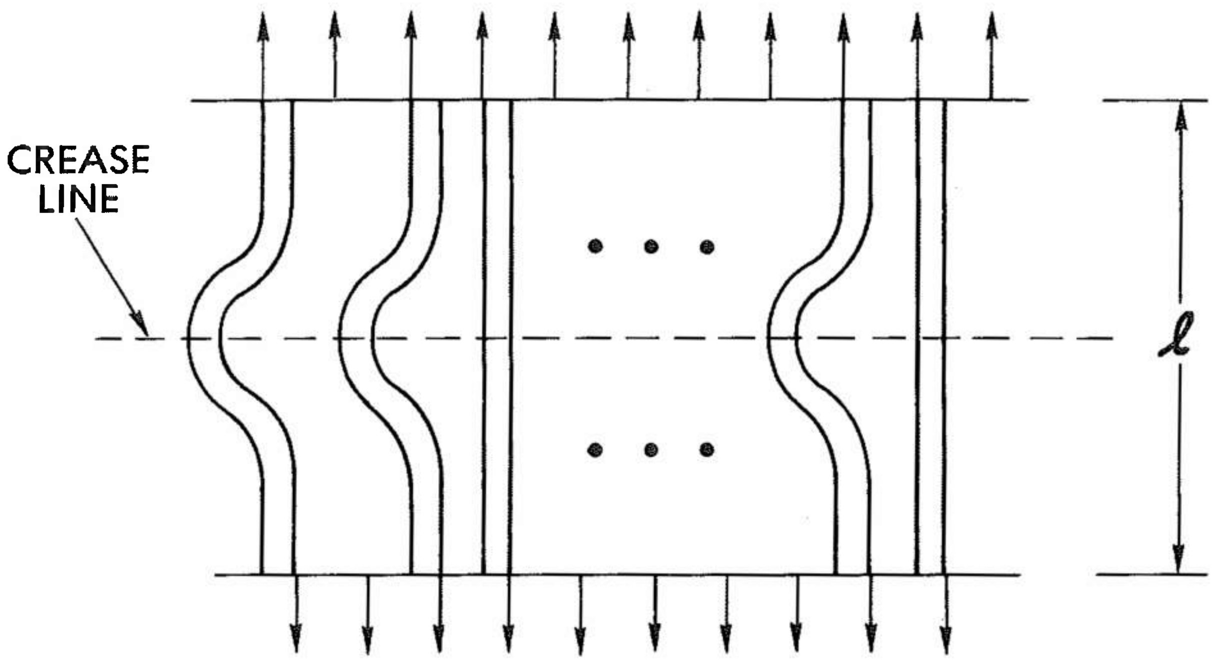

FIGURE 5b. SCHEMATIC OF THE MODEL FOR THE CREASE REGION

CONCLUDING REMARKS

An analysis of the load-deformation behavior and the failure of woven fabric tubes having circumferential yarns of unequal lengths has been presented. The results of the analysis shows that significant strength reductions can be caused by this phenomenon and that it may also be a mechanism in the deformation of fabrics which contributes to the stiffening of the stress-strain curve of fabrics as the deformation or elongation increases.

The results of the analysis were used to examine possible causes of failure of woven Kevlar tubes at pressure levels of 1/6 the design level. It was concluded that the presence of variable length yarns could not explain this premature failure if the variability was distributed throughout the circumference of the tubes. If, however, the variability is concentrated in the region of the crease line developed during weaving, then the results suggest that yarn length variation contributed to the premature failures.

APPENDIX

Fortran program for computer simulation of fabric strength reduction

ECS*JUNK(1).TUB

```
      DIMENSION RL(2000),QL(100),DQL(100),CFT(100),SFT(100)
      DIMENSION FL(100),XF(100),FS(100)
      DIMENSION YL(4),XL(11)
      DATA/YL/76,79,65,68/
      DATA/XL/68,69,70,79,82,77,65,84,73,79,78/
C
C    DEFINITIONS
C     N=NUMBER OF YARNS/UNIT LENGTH
C     RL=ARRAY OF RANDOM LENGTHS
C     IS=NUMBER OF SEQUENCES IN SIMULATION   N*IS<2000
C     QLM=MEAN LENGTH
C     QLSD=STD. DEV. OF LENGTH
C     QL=YARN LENGTHS
C     SKA=NONDIN. STIFFNESS
C     DQL= LENGTH DIFFERENCES,DEFORMATION AT YARN TAKE UPS
C     CFT=TOTAL FORCE AT YARN TAKE UPS
C     SFT=MAX. YARN FORCE AT TAKE UPS
C     XF=DEFORMATION AT FAILURE
C     FL=FAILURE LOAD
C     AFL=AVERAGE FAILURE LOAD
C     SDFL=FAILURE LOAD STD. DEV.
      READ(5,10) QLM,QLSD,SKA
      READ(5,10)N,IS
      READ(5,10)NPR,NPL
10    FORMAT()
      RL(1)=347.0
      IN=IS*N
C    GENERATE NORMALLY DISTRIBUTED LENGTHS
      CALL RANDN(RL,IN,QLM,QLSD)
      JM2S=0
C     PRINT INPUT DATA
      WRITE(6,1008) QLM,QLSD,SKA,N,IS
1008  FORMAT(1H1,4X,'FABRIC STRENGTH DUE TO YARN LENGTH VARIATION',//
     . 1X,'MEAN LENGTH OF YARNS='E16.8,/
     . 1X,'STD.DEV.OF YARN LENGTH=',E16.8,/
     . 1X,'YARN STIFFNESS PARAMETER=',E16.8,/
     . 1X,'NUMBER OF YARNS/UNIT WIDTH=',I4/
     . 1X,'NO. OF RUNS IN SIMULATION=',I4,/)
C    LOOP ON THE SIMULATION SEQUENCES
      DO 100 JS=1,IS
C    LOOP TO PICK UP THE NEXT SEQUENCE OF LENGTHS
      DO 101 J=1,N
      IB=(JS-1)*N
101   QL(J)=RL(IB+J)
C    ORDER LENGTHS IN ASCENDING ORDER
      CALL DESORD(QL,N)
C    INITIATION OF ARRAYS FOR PLOTTING
      DQL(1)=N
      DQL(2)=0.0
      CFT(1)=N
      CFT(2)=0.0
      SFT(1)=N
      SFT(2)=0.0
      JMAX=0
      NP=N+1
      LCK=0
```

```
C     LOOP ON YARN LENGTHS
C         COMPUTE DEFORMATION,DQL
C                 TOTAL FORCE,CFT
C                 MAX. YARN FORCE,SFT,  AT YARN TAKE UPS
       DO 102 JT=3,NP
       DQL(JT)=QL(JT-1)-QL(1)
       JQ=JT-2
       TF=0.0
       DO 103 K=1,JQ
       TFS=(QL(JQ+1)-QL(K))*SKA
  103  TF=TF+TFS
       CFT(JT)= TF
 1003  FORMAT(4X,'FORCESIN YARNS AT BREAK'/,(1X,6E16.8))
 1007  FORMAT (1X,'TAKE UP POINT NO.',I4)
 1000  FORMAT(1X,'DEFORMATIO TO TAKE UP POINT=',E16.8/
      . 1X,'TOTAL FORCE AT TAKE UP POINT=',E16.8/
      . 1X,'FORCE IN SHORTEST YARN AT TAKE UP=',E16.8/)
       SFT(JT)=SKA*(QL(JT-1)-QL(1))
       IF(NPR.NE.0)GO TO 106
       WRITE(6,1007)JQ
C     PRINT FORCE-DEFOR. AT YARN TAKE-UPS
       WRITE(6,1000) DQL(JT),CFT(JT),SFT(JT)
  106  CONTINUE
C     MONITOR MAX. YARN FORCE FOR BREAK
       IF((SFT(JT).GE.1.0).AND.(LCK.EQ.0)) GO TO 104
       GO TO 102
  104  JMAX=JT
       LCK=1
  102  CONTINUE
       IF(JMAX.EQ.0)JMAX=N+2
       JM2=JMAX-2
 1001  FORMAT(1X,'NUMBER OF YARNS SUPPORTING LOAD=',I4/)
       JM2S=JM2S+JM2
C     COMPUTE FAILURE LOAD AND DEFORMATION
       D1=1.0-SFT(JMAX-1)
       D2=DQL(JMAX)-DQL(JMAX-1)
       D3=SFT(JMAX)-SFT(JMAX-1)
       XF(JS)=DQL(JMAX-1)+D1*D2/D3
       TSL=0.0
       DO 105 NS=1,JM2
       TFS=SKA*(XF(JS)-(QL(NS)-QL(1)))
       FS(NS)=TFS
  105  TSL=TSL+TFS
       FL(JS)=TSL
       JM2A=JM2S/IS
       IF(NPR.EQ.2) GO TO 100
       IF(NPR.LT.2) GO TO 107
C     PRINT YARN FORCES AT FAILURE
       WRITE(6,1003) (FS(IP),IP=1,JM2)
C     PRINT DEF. &TOTAL FORCE AT FAILURE FOR CURRENT SEQUENCE
  107      WRITE(6,1002)XF(JS),FL(JS)
C     PRINT NO. OF YARNS CARRYING LOAD AT FAILURE
       WRITE(6,1001) JM2
  100  CONTINUE
       AFL=-1.0
C      COMPUTE AND PRINT STATICS OF FAILURE LOAD
       CALL STDEV(FL,IS,AFL,SDFL)
```

```
      WRITE(6,1004)AFL,SDFL
 1002 FORMAT( /1X,'DEFORMATION AT FAILURE=',E16.8,/
     . 1X,'FAILURE LOAD=',E16.8)
 1004 FORMAT(//2X,'FAILURE LOAD STATISTICS'/
     . 1X,'AVERAGE=',E16.8,/
     .1X,'STANDARD DEVIATION=',E16.8)
C     PRINT AVERAGE NO. OF YARNS SUPPORTING LOAD AT FAILURE
      WRITE(6,1005) JM2A
 1005 FORMAT(/1X,'AVERAGE NUMBER OF YARNS SUPPORTING LOAD=',I4/)
      IF(NPL.EQ.0)GO TO 110
C     PLOT LOAD-DEFORMATION BEHAVIOR
C       COMMENT NEXT 18 STATEMENTS TO REMOVE PLOTTING
      CALL INITT(30)
      CALL BINITT
      CALL CHECK(DQL,CFT)
      CALL DSPLAY(DQL,CFT)
      CALL MOVABS(025,400)
      CALL VLABEL(4,YL)
      CALL NOTATE(400,025,11,XL)
      CALL LINE(72)
      CALL CPLOT(DQL,SFT)
      CALL VCURSR(IA,XI,YI)
      CALL MOVEA(XI,YI)
C     CALL SCURSR(IA,IX,IY)
C     CALL MOVABS (IX,IY)
      WRITE(6,1010) QLM,QLSD,SKA,N
      CALL ANMODE
 1010 FORMAT(24X,'YARN LENGTH'/
     . 24X,'                    AVERAGE=',E16.8/
     . 24X,'   STANDARD DEVIATION=',E16.8/
     . 24X,          'YARN STIFFNESS=',E16.8/
     . 24X,           'NO. OF YARNS=',I4)
      CALL FINITT(0,700)
  110 STOP
      END

@PRT,S   ECS*JUNK.DESORD
```

```
ECS*JUNK(1).DESORD
            SUBROUTINE DESORD(A,N)
            DIMENSION A(N)
            LIM=N-1
      100   INT=1
            DO 101 I=1,LIM
            IF(A(I+1).GE.A(I)) GO TO 101
            TEMP=A(I+1)
            A(I+1)=A(I)
            A(I)=TEMP
            INT=I
      101   CONTINUE
            IF(INT.EQ.1) GO TO 102
            LIM=INT-1
            GO TO 100
      102   CONTINUE
            RETURN
            END

@FIN
```

LIST OF SYMBOLS

e_j	Nondimensional yarn lengths
f_j	Yarn forces
$\bar{f}_j$	Nondimensional yarn forces
f_b	Yarn breaking strength
F	Total force acting on the fabric
F_b	Total force on fabric at failure
$\bar{F}$	Nondimensional form of F
$\tilde{F}$	Breaking strength of ideal fabric
j	Subscript designating yarns
J	Number of yarns per unit width of fabric
K	Yarn stiffness
l_j	Yarn lengths
l	Average or mean yarn length
L	Number of yarns supporting load
N_θ	Circumferential stress resultant
P	Pressure
γ	Tube radius
U_j	Yarn deformation
x	Fabric deformation
x_b	Fabric deformation at failure
ξ	Nondimensional fabric deformation
K	Nondimensional yarn stiffness