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DEVELOPMENT OF TRIAXIALLY WOVEN FABRICS

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Fabric Research Laboratories, Inc.
Dedham, Mass.

TECHNICAL REPORT AFML-TR-70-222
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FOREWORD

This report was prepared by Fabric Research Laboratories, Inc., Dedham, Mass., under U. S. Contract No. F33615-69-C-1292. This contract was initiated under Project 7320, "Fibrous Materials for Decelerators and Structures," Task 732002, "Fibrous Structural Materials," The work was administered under the direction of the Nonmetallic Materials Division (LNF), Air Force Materials Laboratory, with Capt. Robert Stanton as project engineer.

This report covers work conducted from August 1969 through June 1970.

The program was directed by Dr. W. D. Freeston, Jr. The development of the prototype loom was carried out under the supervision of Mr. J. Skelton and Mr. R. E. Sebring.

The authors wish to express their appreciation to Mrs. K. D. Cragan for weaving the experimental fabrics and to Dr. M. M. Platt for handling the contractual matters and reviewing this report.

The report was released by the authors July 1970.

This technical report has been reviewed and is approved.

Jack H. Ross

JACK H. ROSS, Chief
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ABSTRACT

An experimental loom was devised for the development of small samples of triaxially woven fabrics and was used to weave experimental amounts of fabric from coarse string, 3-ply, 840-denier nylon yarn, and from graphite yarn. The shedding and warp yarn indexing motions are controlled by a series of cams mounted on a cam roll. The sequence of cams can be changed to produce various weave patterns; changes in weave pattern can also be produced for any particular cam roll by varying the sequence of shedding and indexing motions.

The nylon traixial fabric and a range of square orthogonal fabrics woven from the same yarn were evaluated for various structural and mechanical properties. The stability of the traixial fabric is much greater than that of an orthogonal fabric with the same percentage open area. The triaxial fabric exhibits greater isotropy in its bending behavior and a greater shear resistance than a comparable orthogonal fabric.

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SUMMARY

A. PROGRAM OBJECTIVE AND SCOPE

Triaxially woven fabrics, formed by the intersections of three sets of yarn elements, have mechanical properties that are significantly different from those of conventional orthogonal fabric produced from two intersecting perpendicular sets of yarns. In particular, the variation of mechanical properties with fabric orientation is expected to be smaller for triaxial fabrics than for orthogonal fabrics: that is, the triaxially woven fabrics are more closely isotropic. This program is concerned with the development of triaxial fabrics, and the preliminary evaluation of their mechanical behavior.

B. CONCLUSIONS

A loom was developed for producing small samples of traixially woven fabrics and was used to weave experimental amounts of fabric from coarse string, 3-ply, 840-denier nylon yarn and from graphite yarn. The shedding and warp yarn indexing motions are controlled by a series of cams mounted on a cam roll. The sequence of cams can be changed to produce various weave patterns; changes in weave pattern can also be produced for any particular cam roll by varying the sequence of shedding and indexing motions.

The nylon triaxial fabric and a range of square orthogonal fabrics woven from the same yarn were evaluated for various structural and mechanical properties. The stability of the triaxial fabric is much greater than that of an orthogonal fabric with the same percentage of open area. The triaxial fabric exhibits much greater isotropy in its bending behavior and a greater shear resistance than a comparable orthogonal fabric.

C. RECOMMENDATIONS FOR FUTURE WORK

The scope of the current program limited the work to the construction of only very short, narrow samples of plain weave fabric. As a result the characterization of the mechanical properties of the fabrics was also very limited. However, sufficient evidence was obtained to show that the triaxially woven structures have interesting and potentially valuable charactersitics. In order to explore in greater detail the structural features and mechanical behavior of triaxial fabrics it is necessary that fabric be made available in greater quantities, and in a wider variety of weave patterns. The investigation has demonstrated the viability of the present loom design, and shows its capability to produce triaxial fabric from a broad range of materials, including graphite. This loom could be readily enlarged and modified to produce the range of fabrics necessary for a complete investigation; it is suggested that this further development and the subsequent characterization of the fabrics would form a logical continuation of the present study.

SECTION II

INTRODUCTION

Woven fabrics are conventionally produced from two sets of intersecting perpendicular yarns; however, analogous structures have been produced historically in basketwork from the intersection of three and four sets of elements, and the extension to even higher numbers of sets can be conceived. Triaxially woven structures corresponding to the perpendicular plain weave are encountered occasionally: snow-shoes are traditionally produced in this construction, as are some styles of straw hat. However, the exploration and possible exploitation of the vast range of possible triaxial weaves has only recently been carried out [1] and it appears that triaxial structures might offer advantageous properties in certain applications. In particular, the variations of fabric mechanical properties with orientation are known to be significantly different from those found in orthogonal fabrics. While such properties as stiffness can probably be adequately predicted on a theoretical basis, it is not possible to make predictions for a property such as tearing strength or shear resistance and there is, therefore, a need for a comprehensive experimental evaluation of triaxially woven fabrics in order to establish for design pruposes the behavior characteristics of the fabrics.

The need for such an evaluation establishes in turn the need for a supply of triaxial fabrics with controlled, uniform properties. This requirement can be adequately met only with a loom specifically designed for use in development of the fabrics. A preliminary study of a triaxial loom has been carried out [2], but no satisfactory device for the production of triaxial fabric from regular textile yarns has been described hitherto. This report describes such a device, its mode of operation, and its use to produce experimental quantities of fabric which were subsequently evaluated for a limited range of mechanical properties. The properties of the triaxial fabric were compared to the properties of equivalent orthogonal fabrics, and the comparisons are discussed in detail. Finally, as an indication of the capability of the loom to handle materials with low abrasion resistance, a sample of fabric was produced from graphite yarn.

SECTION III

DEVELOPMENT OF LOOM FOR TRIAXIAL FABRIC

In order to weave a triaxial fabric the standard weaving procedure can be modified in one of two ways: a single set of warp yarns can be interlaced with two sets of filling yarns; or two sets of warp yarns can be interlaced with a single set of filling yarns. The latter approach appears to be the more simple of the two and is embodied in the loom concept described below. One advantage of this method is that the line of cloth production is perpendicular to the length of the fabric, which simplifies the design of the beat-up mechanism.

There are three basic requirements of a loom for producing triaxial fabric from two sets of warp yarns and one set of filling yarns:

(a) In addition to the shedding motion found in conventional looms, it is necessary to provide a means of indexing the two sets of warp yarns in opposite directions across the width of the fabric.

(b) When a warp yarn reaches the cloth selvedge it must be transferred from one set of warp yarns to the other set.

(c) In order to avoid interweaving of the warp yarns behind the heddles it is necessary that the warp yarn supply move in step with the shedding mechanism during the indexing motion.

Several experimental arrangements were evaluated, and the loom was continually modified during the development work; the final form of the loom satisfying the three requirements is described below.

An overall view of the loom is shown in figure 1. For ease of operation and mechanical convenience the loom was mounted vertically; however, this is not an indispensible feature of the design and in subsequent development work the more conventional horizontal orientation would probably be adopted. The ratchet-controlled fabric take-up roll A is at the upper end of the loom. In normal use the fabric is wound-on this roll at every pick and the filling yarns are beaten-up against the edge of the roll.

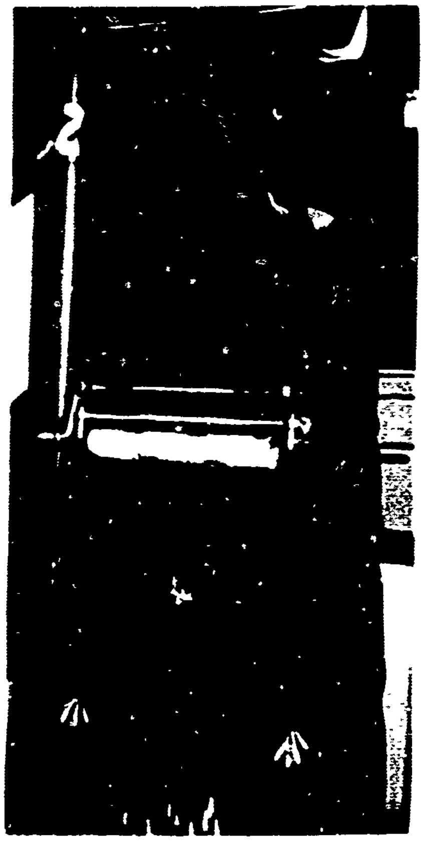


Figure 1. General View of Loom

In the photograph the fabric was not wound-on and the line of fabric production was allowed to move down the loom. The width of the woven fabric is controlled by the catch cords B, which apply an outward component of tension to balance the inward component of tension in the angled warp yarns and the filling yarns. The region of maximum opening of the shed is at C, where the filling yarn is inserted by means of a hand-held rapier arrangement, which is also subsequently used to beat-up the pick to the fell of the cloth. The shedding and indexing mechanisms are combined in the cam roll D; the two counter-rotating indexing screws E are also part of the indexing mechanism. Roll F serves a double purpose: it separates the warp yarns into two distinct warp sheets; and holds the individual yarns in close contact with the appropriate indexing screw. The double warp sheets G hang down below the roll under the influence of the individual tension weights H.

Figure 2 shows a close-up of the indexing and shedding mechanisms and illustrates in greater detail the positional relationship between the various components, and the structure of the cam roll. In order to simplify the discussion of the weaving process the shedding and indexing mechanisms will be described separately. The cam roll consists of an assembly of the three individual components shown in figure 3. These components are pressed from 1/16 inch thick aluminum sheet; components A are 2-1/2 inches in diameter and the smaller components B and C are 1-1/2 inches in diameter. Components A and C have a coaxial hole 1/2 inch in diameter, while component B has a 1/2 inch diameter hole positioned 1/2 inch off center. All components have keyways and are assembled on a 1/2 inch diameter keyed shaft in the order ABACABAC----. This order of assembly yields a cam roll in which small and large diameter cams alternate to give a series of separated slots into which individual yarns can be positioned. If the yarns are under longitudinal tension they bear on the outer surface of the small cams and are separated from each other by the larger cams. Since alternate yarns bear on concentric and eccentric cams, rotation of the shaft produces a differential movement of these yarns, the yarns on the eccentric cams being moved alternately above and below the

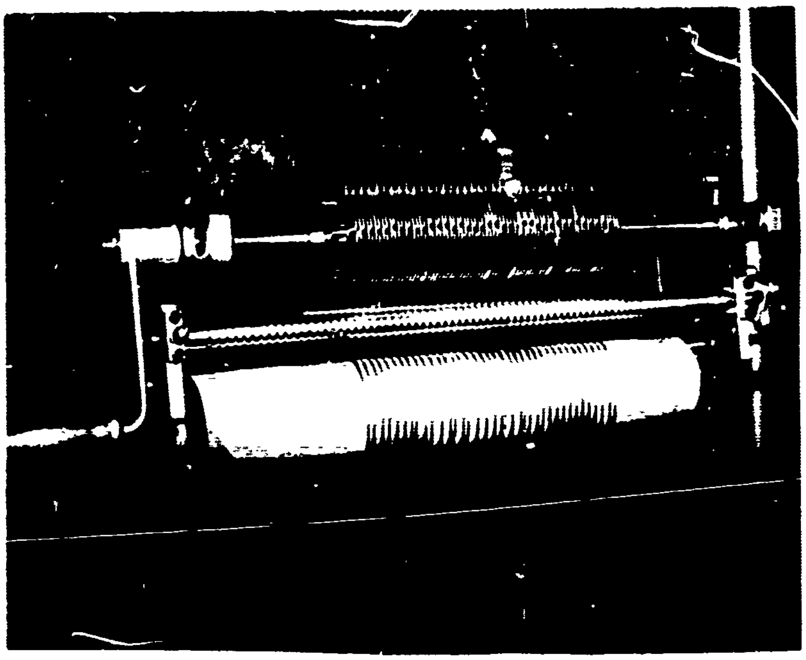


Figure 2. Close-up of Indexing and Shedding Mechanisms

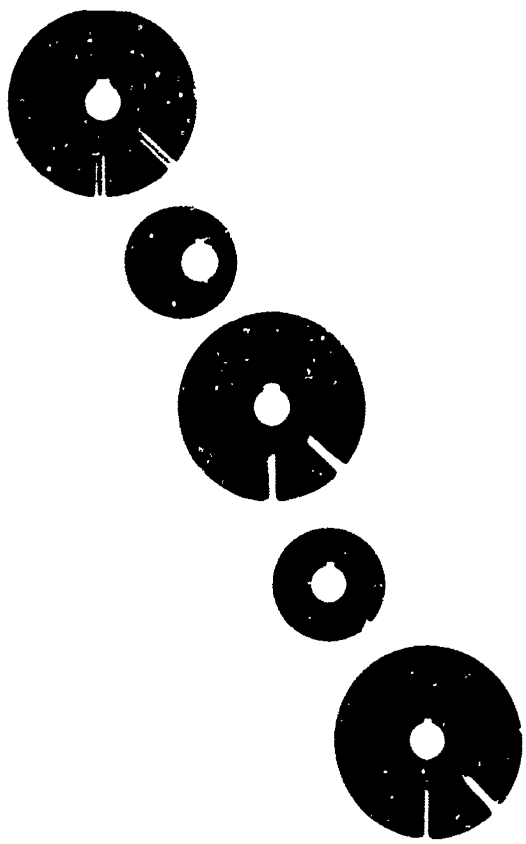
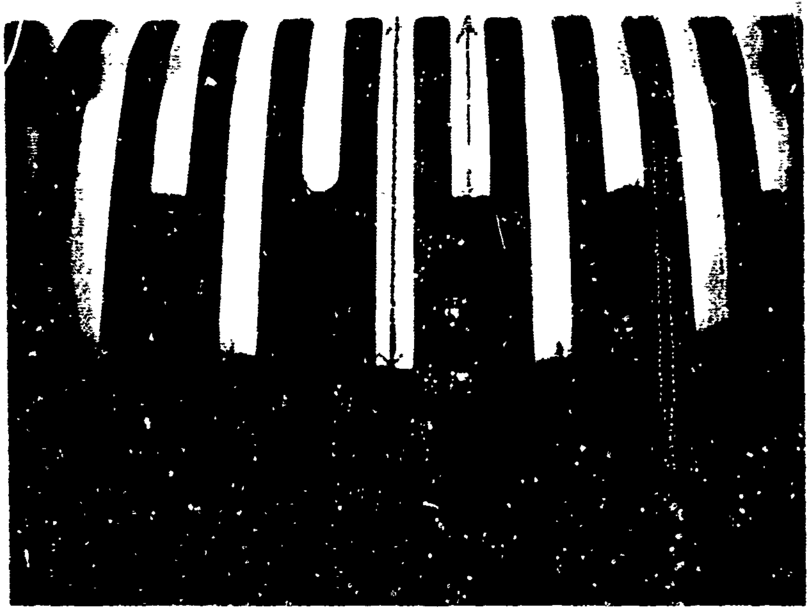


Figure 3. Components of Cam Roll

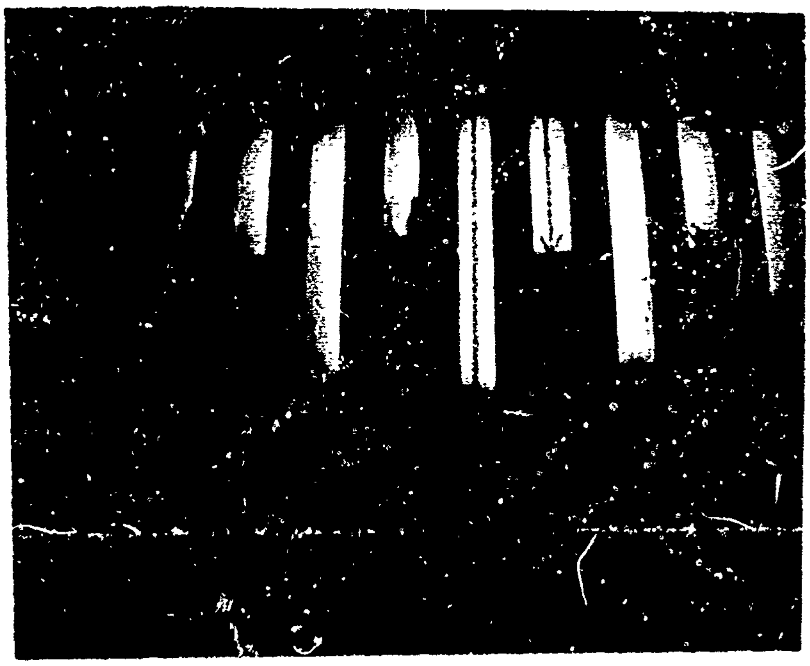
stationary yarns on the concentric cams. This relative displacement creates a shed into which a filling yarn can be inserted during the weaving process. Figure 4 is a sequence of photographs of the profile of the cam roll at every 30° of rotation through a half turn; this sequence illustrates clearly the operation of the shedding mechanism.

In order to produce triaxial fabric each warp yarn must be moved over to the next adjacent similar cam after each pick insertion. This simultaneous transfer of the assembly of warp yarns is accomplished by means of the angled slots in the large cams which can be seen in figures 2 and 3, and which are shown in close-up in figure 5. If the sheet of yarns to be transferred are pulled sideways below the cam roll so that they are in contact with the sides of the large cams, then they will pass through the pairs of angled slots as the cams rotate and, thus, each yarn will be transferred from one small cam to the next similar small cam. There are two sets of angled slots in the large cams, one for each sheet of warp yarns; these two sets of slots transfer their respective yarns in opposite directions. The slots are spaced on the perimeter of the large cams such that no interference of the transferring sets is possible. By suitably positioning the slots of the keyways it is possible to achieve the ideal transfer characteristics with a single version of the large cam. In the current design one of the slots is diametrically opposite the keyway and the second slot subtends an angle of 45° to the first slot.

The warp sheets are pulled sideways by means of the indexing screws shown in detail in figure 2. The pitch of these screws is the same as the spacing of the small cams of the same type, so that all the yarns make contact with corresponding identical sections on the screw groove. By rotation of the screw the assembly of warp yarns may be moved sideways sufficiently to initiate the index transfer as the cam roll rotates. The two index screws must rotate in opposite directions since the two sheets of warp yarns must move in opposite directions.



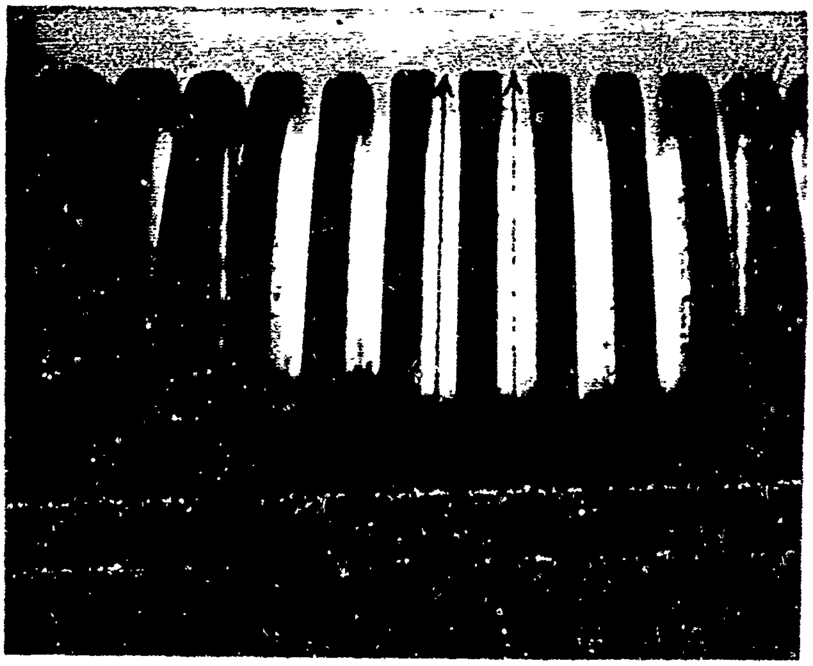
0°



30°

Figure 4. Sequence of Cam Profiles at Various Angles of Rotation During a Half-turn (Sheet 1 of 4)

60°



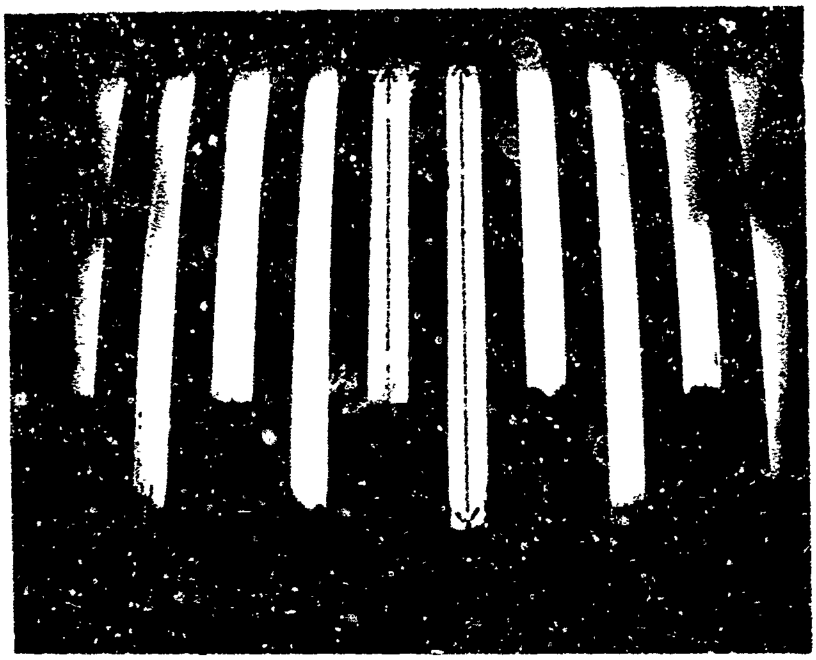
90°

Figure 4. Sequence of Cam Profiles at Various Angles of Rotation During a Half-turn (Sheet 2 of 4)

120°

150°

Figure 4. Sequence of Cam Profiles at Various Angles of Rotation During a Half-turn (Sheet 3 of 4)



180°

Figure 4. Sequence of Cam Profiles at Various Angles of Rotation During a Half-turn (Sheet 4 of 4)

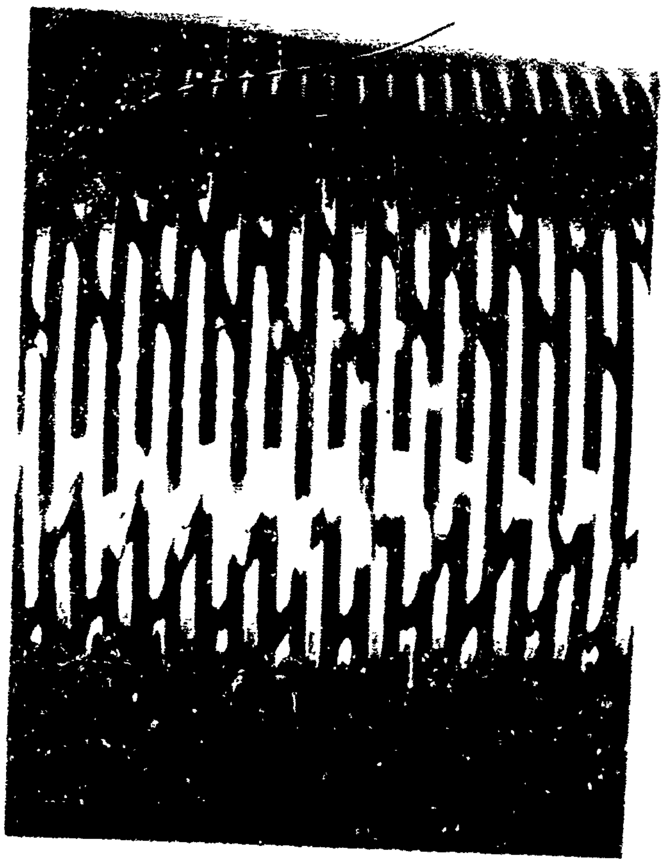


Figure 5. Close-up of Yarn Transfer Slots

The two sheets of warp yarns are separated by the large roll mounted below the index screws As each warp yarn reaches the selvedge it must pass from the upper to the lower sheet and must, therefore be transferred from the front of the roll to the back. In the current design this transfer is carried out by hand by passing each warp yarn in turn around the end of the roll with the other end of the roll supported by the bearing. This mechanism is facilitated by the provision of a loose, sliding shaft for the separating roll. In any mechanized version of the loom it is anticipated that the separating roll would have no axle but would be suspended by a thin band of material from a restraining bar resting above the indexing screws. In this way the ends of the roll would be free and the yarn transfer would be much easier to perform, and could be performed automatically by a suitable mechanism

Warp tension is applied by means of small tension weights tied to individual warp yarns. These weights form a cluster some distance below the separating roll and are indexed automatically along with the warp yarns as the weaving proceeds. In earlier designs a rotating creel was used as a warp yarn supply, but problems were encountered with maintaining proper yarn tension and the current, simpler method was adopted. There is no doubt, however, that a rotating creel would be preferred in a full scale loom; it is anticipated that a suitable design would not present serious problems

The weaving of fabric with the above-described loom is very simple; it differs from the weaving of plain weave orthogonal fabric only in that the sheets of warp yarns are indexed in turn between pick insertions, and in that yarns must be transferred from one warp sheet to the other at the appropriate times When the routine is learned, fabric production is quite rapid At the present time all the motions are carried out by hand, but it should be reasonably simple to arrange for the separate motions to be power driven in the correct sequence in order to increase the production rate and the fabric uniformity in subsequent versions of the loom. The loom in its final form had sufficient cam spaces for two sheets of warp each containing 38 yarns, giving a total of 76 warp yarns. This array of cams was 8 inches in width; no difficulty is foreseen in extending this width by a factor of 10, if necessary.

SECTION IV

DEVELOPMENT OF TRIAXIAL FABRICS

For ease of manipulation and identification of the various components, initial weaving trials were carried out using colored string approximately 1/16 inch in diameter. The weaving and yarn handling routines were worked out using this material and various samples of fabric were produced; photographs of two of the samples are shown in figures 6 and 7. Figure 6 shows the "plain weave" triaxial fabric with its symmetrical locked intersections. Figure 7 shows another triaxial structure that is produced by indexing both sets of the warp yarns one space between pick insertions. This structure has the nature of an unbalanced twill, and appears to be less stable than the plain weave, though it can be woven more tightly; it illustrates some of the complexities that can quickly arise in other than the most simple triaxial weaves.

Following development of the weaving routine a length of plain weave fabric was woven from 3 ply, 840 denier nylon yarn with 2 turns per inch Z twist. The yarn in general processed well and the woven fabric was very good in appearance. The high degree of uniformity in the fabric is evident in the photograph shown in figure 8. However, the yarn was rather susceptible to abrasion because of its low twist and the yarns became hairy as the weaving proceeded. This is a common feature of low twist continuous filament yarns, which must be sized before weaving on conventional looms. The yarns used in the triaxial loom were not prepared in any way; it is very likely that the amount of abrasion could be significantly reduced by suitable sizing treatment. It is also probable that the abrasion would be lessened by the use of higher twist yarns; however, this poses certain difficulties since each warp yarn is tensioned by means of a freely hanging weight, which rotates and lets the yarn twist run out. This aspect of the loom would require modification in any subsequent development. The use of yarns with high singles twist and high ply twist in a balanced structure would perhaps give the best results with the present loom.

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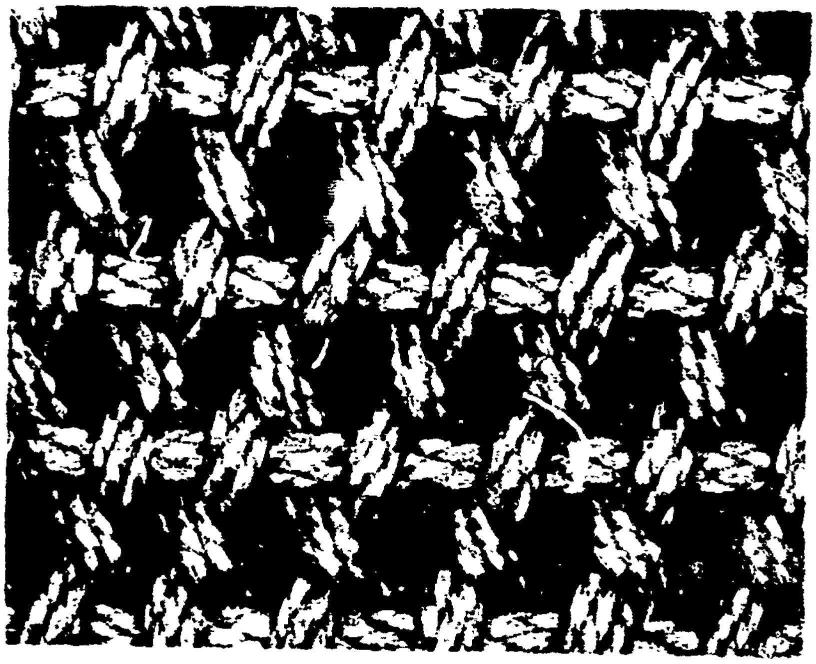

Figure 6. Plain-weave Triaxial Fabric

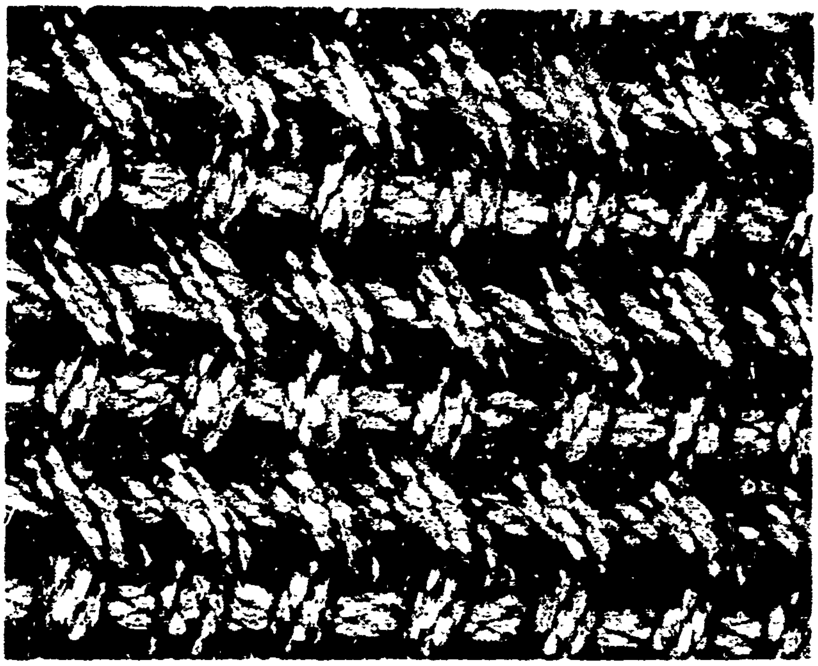

Figure 7. Unbalanced Twill Triaxial Fabric

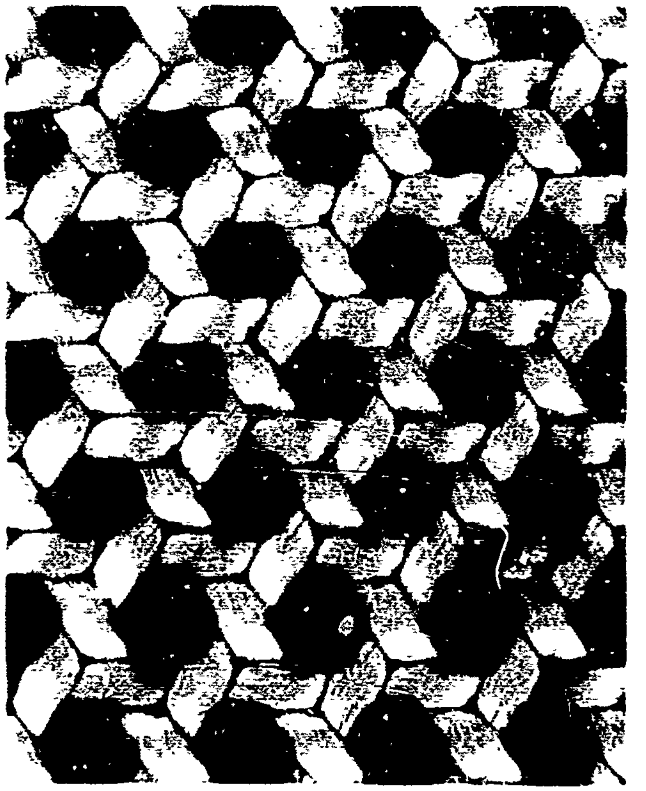

Figure 8. Plain-weave Triaxial Fabric
3-Ply, 840-Denier Nylon Yarn

Since one of the potential uses of triaxial fabric is as reinforcement in composite structures, it was of interest to attempt to weave fabric from a currently used reinforcing material. After a series of trials in which such matters as yarn anchoring, warp tension, and beat-up techniques were modified slightly a length of fabric was woven from low modulus graphite yarn. The yarn was triple-coated with AF-F101 (a Viton and paraffin emulsion) [3] before weaving to reduce the possibility of abrasive damage. A photograph of the graphite fabric is shown in figure 9. The projecting broken fibers give evidence of yarn damage, though considering the rigors of the weaving process and the poor abrasion resistance of the graphite yarn the amount of damage is remarkably small. It should be noted that the graphite fabric is more open than the nylon fabric. This is due to the much greater bending rigidity of the graphite yarn which prevents the complete closing up of the triangular intersections. This particular structure is, of course, much too open to be considered as a reinforcing material, but it demonstrates that the loom is capable of processing materials that are known to give difficulty on conventional weaving equipment.

Several points of interest emerged during the weaving of the experimental fabrics. The first point concerns the width of the woven fabric, and is well illustrated by the nylon fabric shown in figure 8. If successive filling yarns are beaten up to the maximum extent, the fabric unit cell takes up the symmetrical close-packed structure evident in the nylon fabric. The size of this unit cell and, hence, the fabric width, is determined principally by the yarn diameter as it lies in the fabric. Thus, in the jammed condition the fabric width is independent of the warp yarn spacing at the shedding cam roll and the same shedding cam roll can be used to weave a wide range of yarns into the close-packed structure. As was seen for the graphite yarn, stiffness can have a modifying effect on the closeness of the close-packed structure, but this is an effect that will only be found with extremely stiff materials.

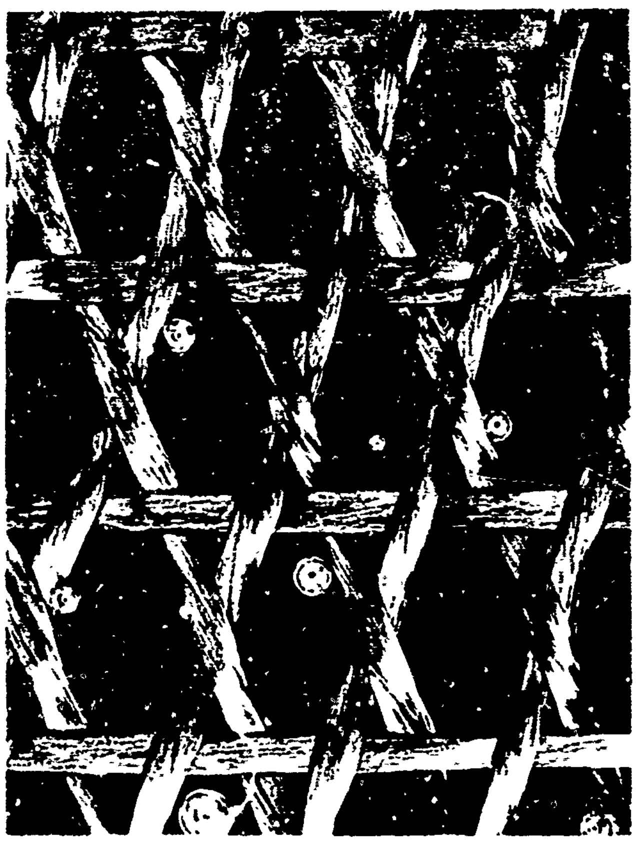

Figure 9. Plain-weave Triaxial Fabric Graphite Yarn

The considerations described above do not necessarily apply to other than plain-weave structures. In the unbalanced twill structure produced from the string the maximum beat-up does not define the width in the same way, and, if unrestrained, this structure degenerates into a more compact, thicker fabric with both sets of warp yarns almost parallel to each other locally. The triaxial fabrics differ fundamentally from conventional woven fabrics in respect to the parameters which define fabric width. In an orthogonal fabric the insertion of each filling yarn displaces the outermost warp yarns toward the center of the fabric, and the fabric width is controlled by the equilibrium of the triangle of forces set up by the tensions in filling and the displaced warp yarns. In triaxial fabrics, however, the tension in each warp yarn as it rounds the selvedge is always directed toward the center of the fabric and the filling tension only adds to the existing inward force, thus tending to make the fabric narrower. Only if the fabric on beat-up reaches a jammed configuration that is geometrically defined, as in the plain weave, will a fabric of stable width be produced without the aid of auxiliary selvedge yarns as in the current loom design.

The second point is a general observation concerning the nature of twill-type triaxial weaves. As was discussed previously, a non-plain weave structure was produced early in the program by indexing both sets of warp yarns one space between pick insertions to give the structure shown in figure 7. Each warp yarn passes alternately under three other yarns and over one other yarn, while the filling yarns pass alternately over and under single warp yarns to give an unsymmetrical twill weave. There exists also another class of twill weaves discussed by Dow [1,2] in which each set of yarns has the same weave pattern. The triaxial fabrics are clearly different in this respect from orthogonal fabrics and it would be interesting to explore the difference in detail. The difference is more than academic since the unbalanced twills can be produced on the present loom without modification, while the balanced twills require a modification to the cam roll to give the appropriate shedding sequence. It is anticipated that subsequent development looms would have a different cam roll for each weave pattern, to avoid the inconvenience of restacking a single cam roll.

SECTION V

MECHANICAL BEHAVIOR OF TRIAXIAL FABRIC

A. INTRODUCTION

An investigation of the mechanical properties of the nylon plain weave triaxial fabric was carried out. The loom in its current form produces samples approximately 4-1/2 inches wide x 15 inches long, and the scope of the program precluded the manufacture of repeat samples. Accordingly, the investigation was very limited, though as much information as possible was obtained from the small amount of material available.

In order to compare the properties of the triaxial fabric with those of equivalent orthogonal fabric, short length of narrow (approximately 3-1/2 inches wide) plain weave fabrics were woven from the same yarn in three different constructions. The triaxial fabric and the three orthogonal fabrics are shown in figure 10 and constructional details are given in Table I.

TABLE I

CONSTRUCTIONAL DETAILS OF FABRICS

Fabric		Threads per Inch[1]	Threads per Inch[2]	Weight (oz/sq yd)	Open Area (%)
Triaxial		9x9x9	16x16x16	9.98	40
Orthogonal	#1	10x10	10x10	6.77	40
	#2	13x13	13x13	9.26	10
	#3	18x18	18x18	12.80	2

[1]Measurement along line perpendicular to each set of yarns.
[2]Measurement along line parallel to each set of yarns.

Fabric #1 was designed to have the same inter-yarn spacing within each set of yarns as in the triaxial fabric, while fabric #3 is designed to have the same density of crossing yarns along any particular yarn as in triaxial fabric. Figure 10 and Table I show that these aims were quite closely achieved. Fabric 2 was designed to have t : same weight per unit area as the triaxial fabric. Thus, the three orthogonal fabrics represent three different, but equally valid, "equivalent" orthogonal fabrics.

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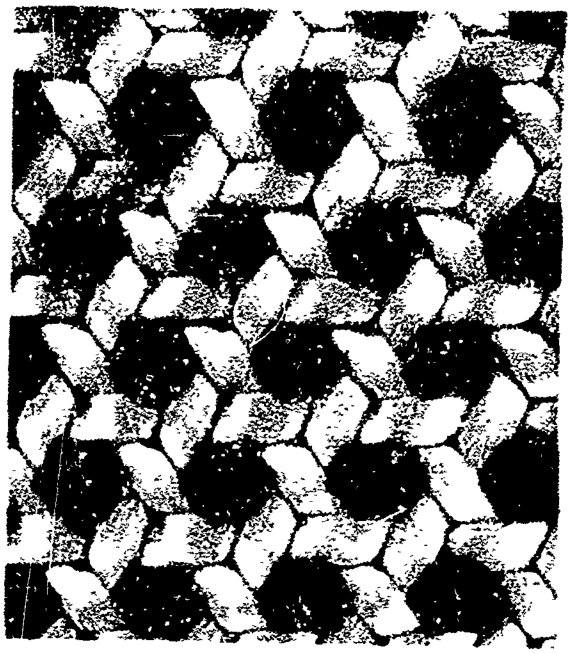
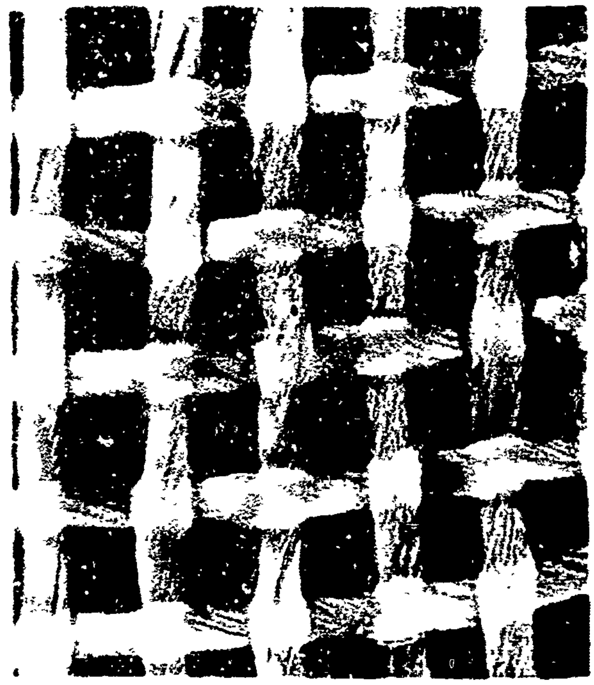
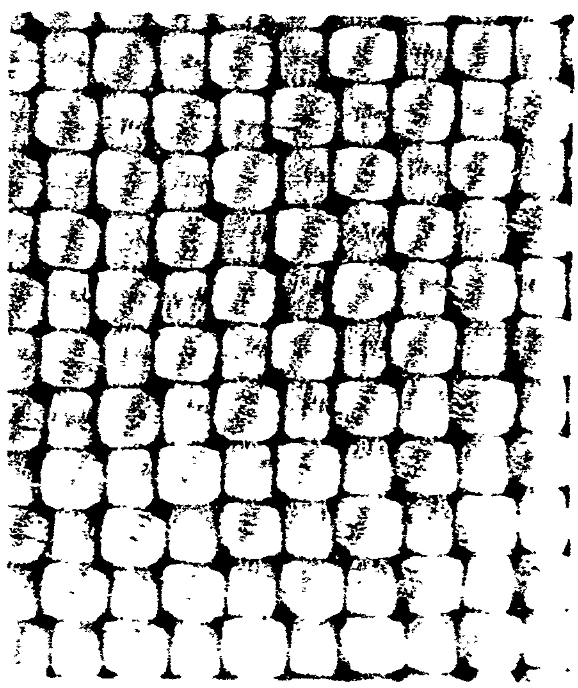


TRIAXIAL



ORTHOGONAL #1

ORTHOGONAL #2



ORTHOGONAL #3

Figure 10. Plain-weave Triaxial Fabric and Equivalent Orthogonal Fabrics

Study of the fabrics immediately yields an interesting feature of the triaxial fabric. Each yarn has a high density of crossing yarns along its length -- in fact, the maximum possible number, since the fabric was beaten up to the limiting configuration -- and thus technically can be considered as tightly woven as fabric #3. In spite of the closeness of the weave the triaxial fabric has an open area of approximately 40% which is identical with that of the most open orthogonal fabric, #1. Orthogonal fabric #1, however, is completely lacking in weave stability and is very prone to skewing distortion and yarn shifting, almost to the point of being unweavable. It could certainly never be considered as a suitable fabric for any practical end use. The triaxial plain weave structure, therefore, could possibly find use in situations where open, mechanically stable fabrics are required.

B. FLEXURAL RIGIDITY

In view of the differing structures of the triaxial and orthogonal weaves, it is of interest to examine the way in which the properties of the fabrics vary with orientation. The variation of stiffness with orientation in orthogonal fabrics has been explored in some detail [4,5] and for open fabrics can be predicted with reasonable accuracy. No theoretical complexities are introduced by the triaxial weave, and predictions of the bending behavior of these fabrics can also be made. The measurement of fabric stiffness is nondestructive and thus a study of bending behavior forms an ideal starting point, on both theoretical and experimental grounds, in an investigation of the mechanical properties of the fabrics.

The most commonly used method for the measurement of fabric stiffness is the cantilever test [6]. However, in view of the limited amounts of fabric available, this method could not be used and measurements were made using a variant of the compressed cylinder technique first used by Steel [7]. The test is fully described in Appendix IA.

Experimental results are shown in figures 11 through 14, which show for the various fabrics the variations of compressive force P

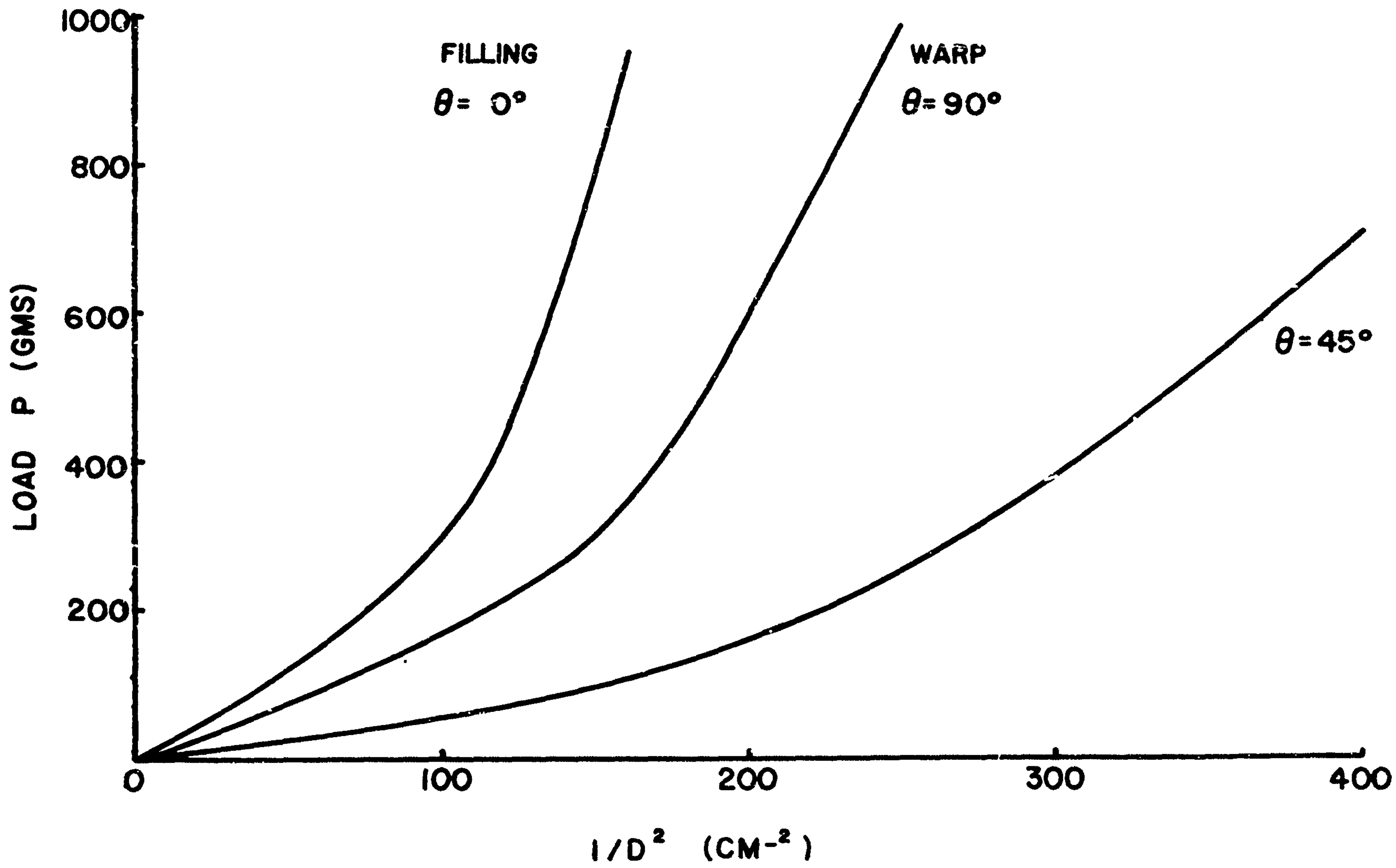


Figure 11 Variation of P with $1/D^2$ for Orthogonal Fabric #1

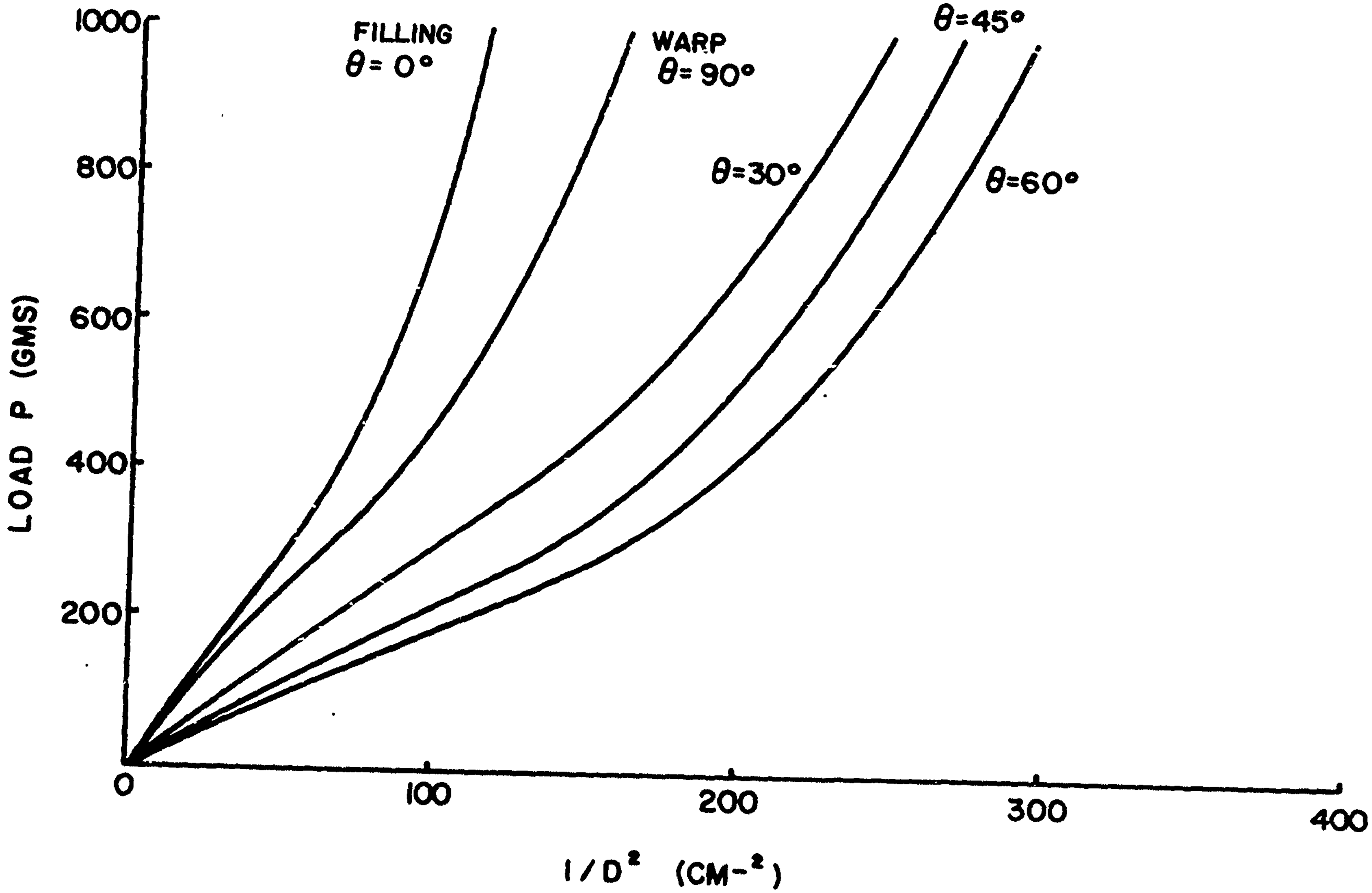


Figure 12. Variation of P with $1/D^2$ for Orthogonal Fabric 2

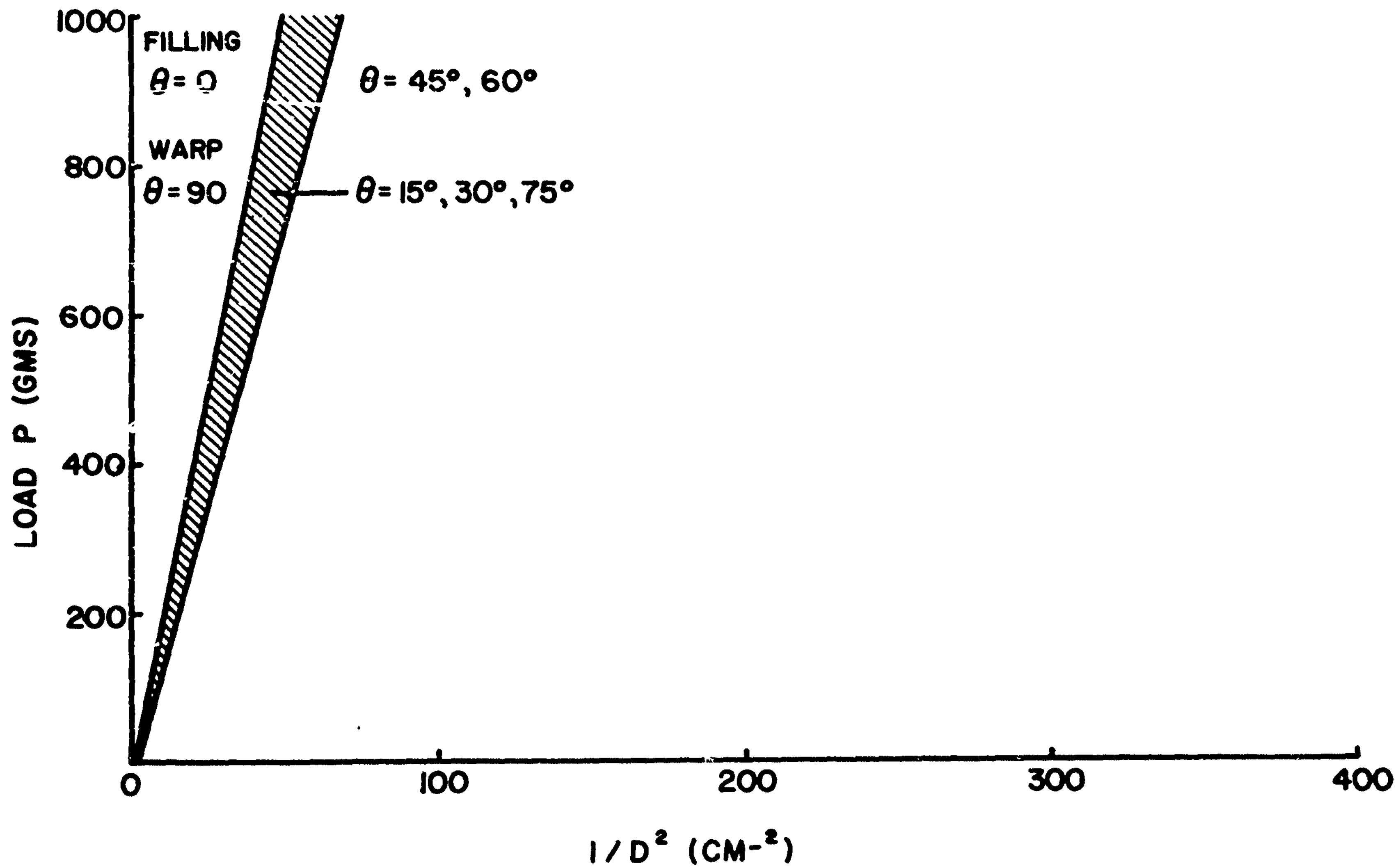


Figure 13. Variation of P with $1/D^2$ for Orthogonal Fabric #3

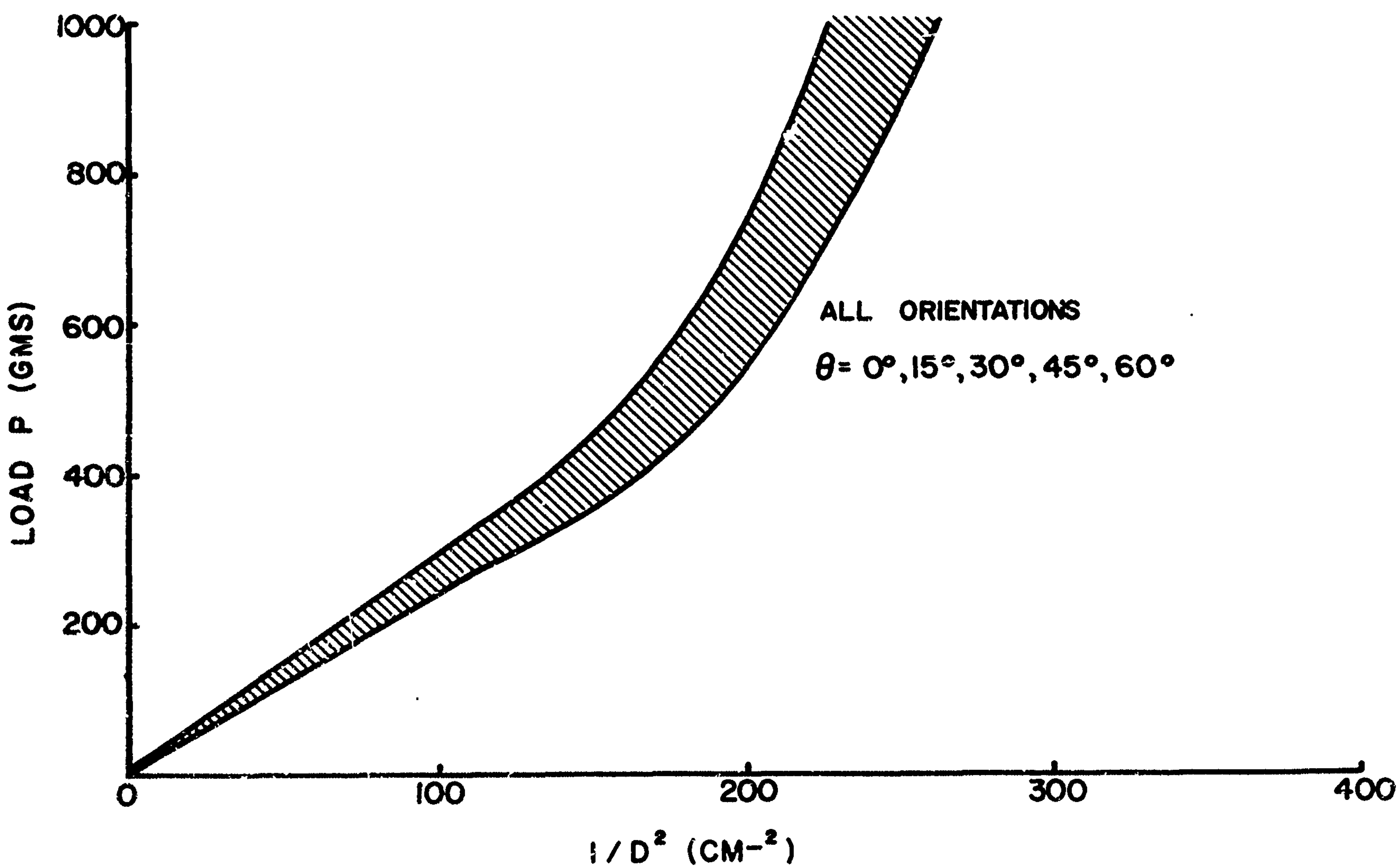


Figure 14. Variation of P with $1/D^2$ for Triaxial Fabric

with $1/D^2$ where D is the separation of the compression plates; all results are plotted to the same scale to facilitate comparisons between fabrics. Figure 11 shows the results for fabric #1. Because of the difficulty of handling the specimens, results were only obtained for orientations of 0° (filling direction), 45° and 90° (warp direction). The curves are not straight lines, and the results indicate an increase in flexural rigidity at high curvatures (high values of $1/D^2$). However, the trends are clear. The fabric is stiffest in the filling direction, with the warp being somewhat less stiff and the stiffness in the bias direction (45° to the filling direction) is much less than that in the thread direction. Similar trends are seen for fabric #2 (figure 12) though in this case the stiffness is smallest at $\theta = 60°$ to the filling yarns. The fact that the nominally square fabrics are stiffer in the filling direction than in the warp direction is probably a result of the greater crimp in the warp yarns. The results for fabric #3 (figure 13) show very little change of stiffness with orientation, and the overall level of stiffness is much higher than for fabrics #1 and #2. Both these effects are a consequence of the high frictional restraints operating in the closely woven fabric, which contribute a considerable proportion of the fabric stiffness. Since the frictional component of the stiffness is not very dependent on fabric orientation, it tends to override the marked variation of stiffness found for the more open fabrics. The results for the triaxial fabric are shown in figure 14. There is no systematic variation of stiffness with orientation and the overall level of stiffness is similar to that found for the thread directions in fabric #1.

A single representative value of flexural rigidity at moderate curvatures may be found from the initial slopes of the curves relating P and $1/D^2$. These values are tabulated in Table II and are plotted on a polar graph in figure 15. This plot illustrates diagramatically the relationships described above and clearly demonstrates the isotropy of the triaxial fabrics compared to orthogonal fabrics. This difference has a sound theroetical basis. The

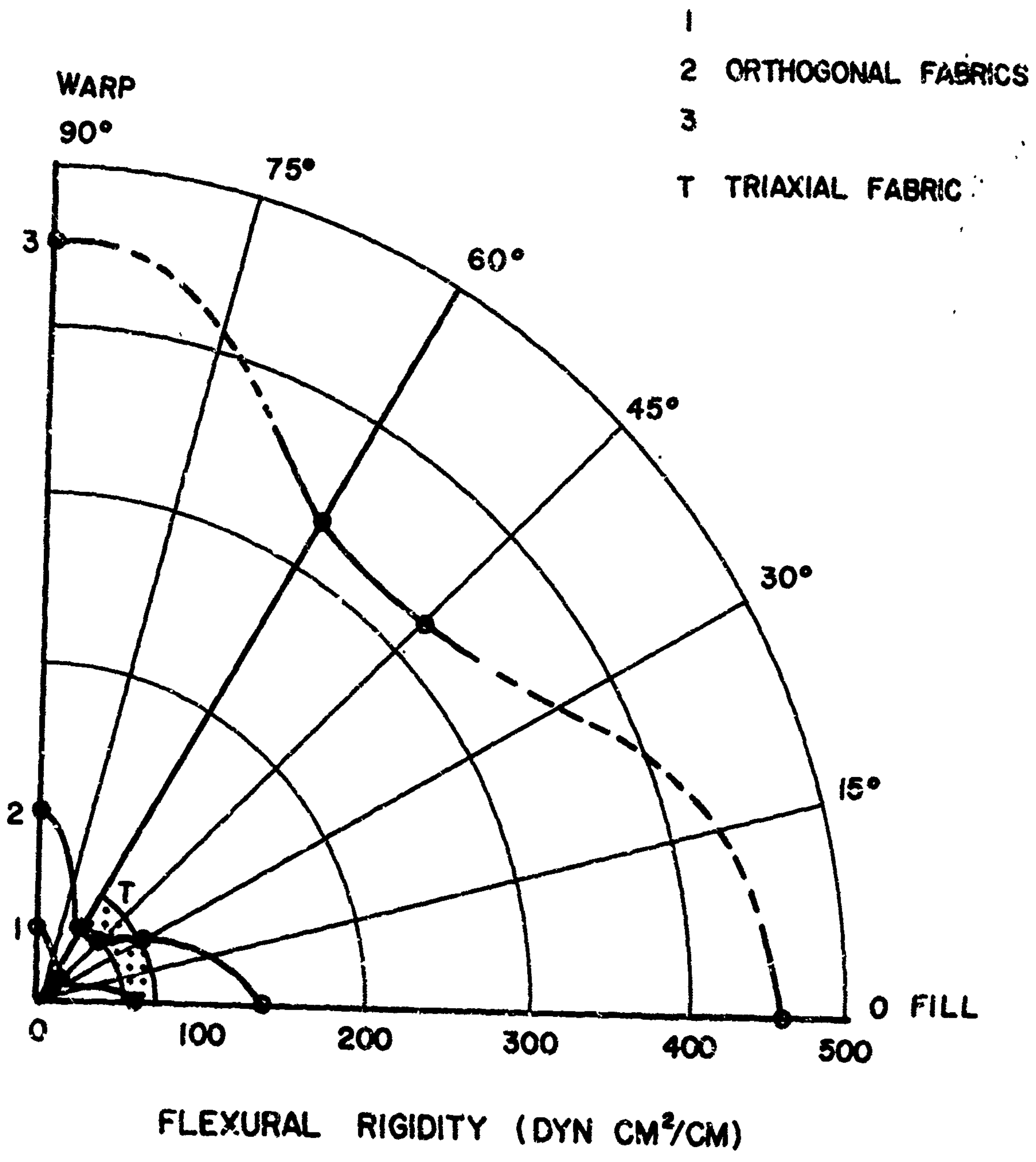


Figure 15. Polar Variation of Flexural Rigidity for Various Fabrics

bending rigidity per unit width $G(\alpha)$ of a sheet of yarns, in a direction making an angle α to the direction of the yarns can be shown [4,5] to be given by:

$$G(\alpha) = G_1 \sin^4\alpha + J_1 \sin^2 \alpha \cos^2 \alpha$$

where G_1 and J_1 are respectively the flexural and torsional rigidities of the yarn assembly. For an orthogonally woven fabric, which may be idealized as two sheets of yarns at right angles, the fabric stiffness in any direction α is given by:

$$\begin{aligned} G(\alpha) &= G_1 \sin^4\alpha + J_1 \sin^2\alpha \cos^2\alpha + G_2 \sin^4(\alpha+90) \\ &\quad + J_2 \sin^2(\alpha+90) \cos^2 (\alpha+90) \\ &= G_1 \sin^4\alpha + G_2 \cos^4\alpha + (J_1+J_1) \sin^2\alpha\cos^2 a \end{aligned}$$

where subscripts 1 and 2 refer to the two sets of yarns. For a triaxial fabric the expression becomes:

$$\begin{aligned} G(\alpha) &= G_1 \sin^4\alpha + J_1 \sin^2\alpha \cos^2\alpha \\ &\quad +G_2 \sin^4(\alpha+60) + J_2 \sin^2(\alpha+60) \cos^2 (\alpha+60) \\ &\quad +G_3 \sin^4(\alpha+120) + J_3 \sin^2(\alpha+120) \cos^2 (\alpha+120) \end{aligned}$$

where the subscripts 1, 2 and 3 refer to the three sets of yarns.

TABLE II

FLEXURAL RIGIDITY OF FABRICS AT VARIOUS ORIENTATIONS

	Fabric Stiffness (dyne cm^2/cm)						
Fabric	Filling 0°	15°	30°	45°	60°	75°	Warp 90°
#1	64.9	---	---	13.9	---	---	37.1
#2	132.2	---	70.7	51.0	42.9	---	104.2
#3	Range 324.7 to 463.9						
Triaxial	Range 55.6 to 68.4						

Figure 16 shows the theoretical polar variation of bending rigidity for a triaxial assembly of yarns compared with that for the same total number of yarns in two arrays aligned 90° apart - that is for an orthogonal fabric of the same weight per unit area; a ratio of (yarn flexural rigidity/yarn torsional rigidity) = 3 was used for the calculation. The theoretical plots are clearly very similar to the experimentally determined variations shown in figure 15.

C. SHEAR RESISTANCE

The shear resistance of fabric is a deceptively simple concept which requires very careful definition before comparisons can be made between fabrics as different in structure as orthogonal and traixial fabrics. A discussion of test methods and the difficulties involved in the interpretation of results is given in Appendix IB.

Measurements were made of the shear resistance of the various fabrics using an apparatus of the type shown in figure 21. A specimen 1-1/2 inches long and 1 inch wide was used, and the lower movable clamp weighed 203 grams. Results are given in figure 17 which show the variation of shear resistance with shear angle for the fabrics. The shear stiffness of the fabrics, calculated according to the expression previously derived are given in Table III; for convenience all values are calculated for a shear angle of 20°. The shear stiffness of orthogonal fabric #1 is very low; it is sufficiently open to be considered as an assembly or parallel yarns with essentially no interactions at the crossover points. Fabric #2 has greater shear stiffness and fabric #3 is very much stiffer than fabric #1.

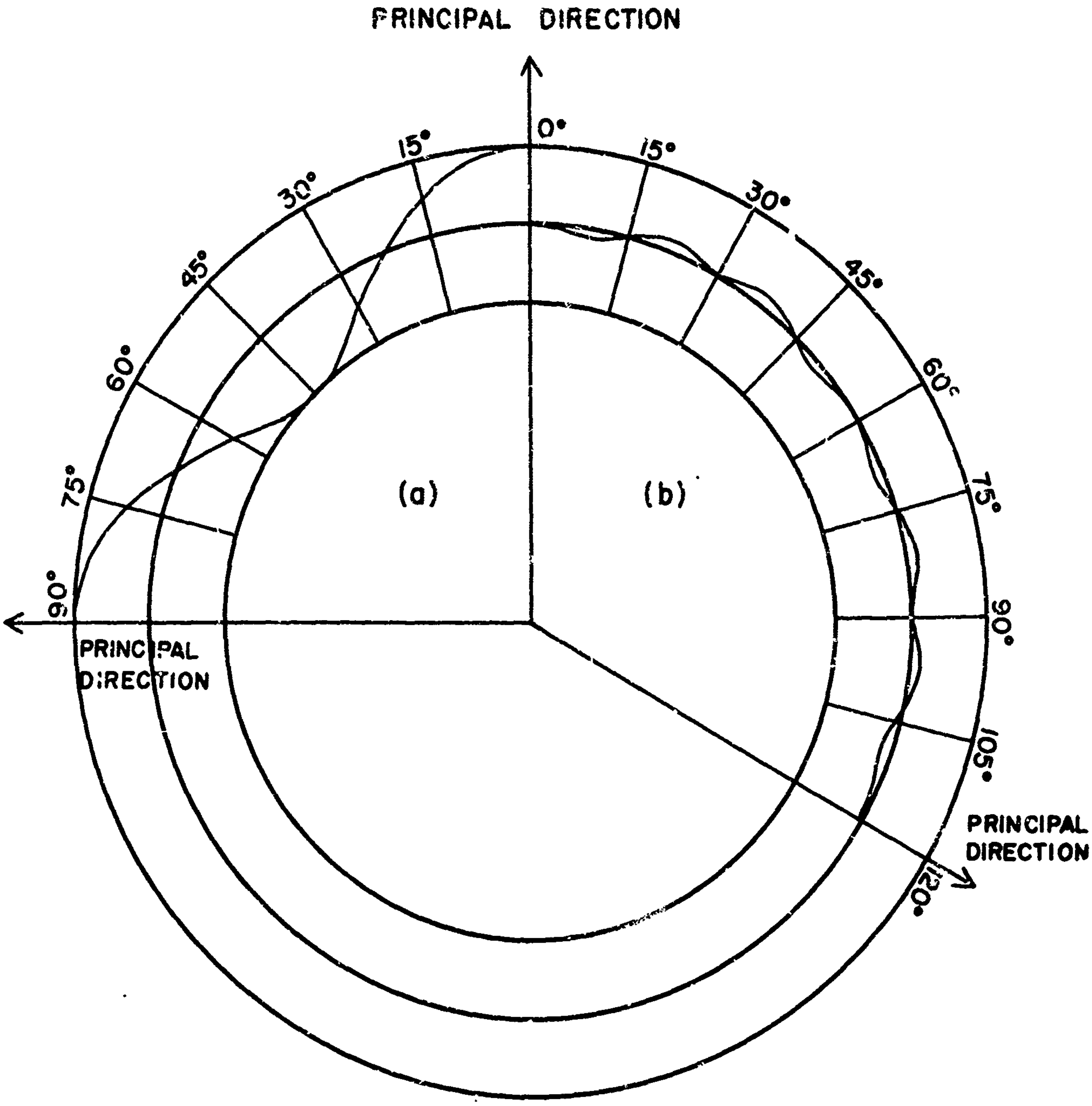


Figure 16. Fabric Flexural Rigidity as a Function of Yarn Orientation for

(a) Two Parallel Arrays of Yarns Aligned 90° Apart
(b) Three Parallel Arrays of Yarns Aligned 120° Apart

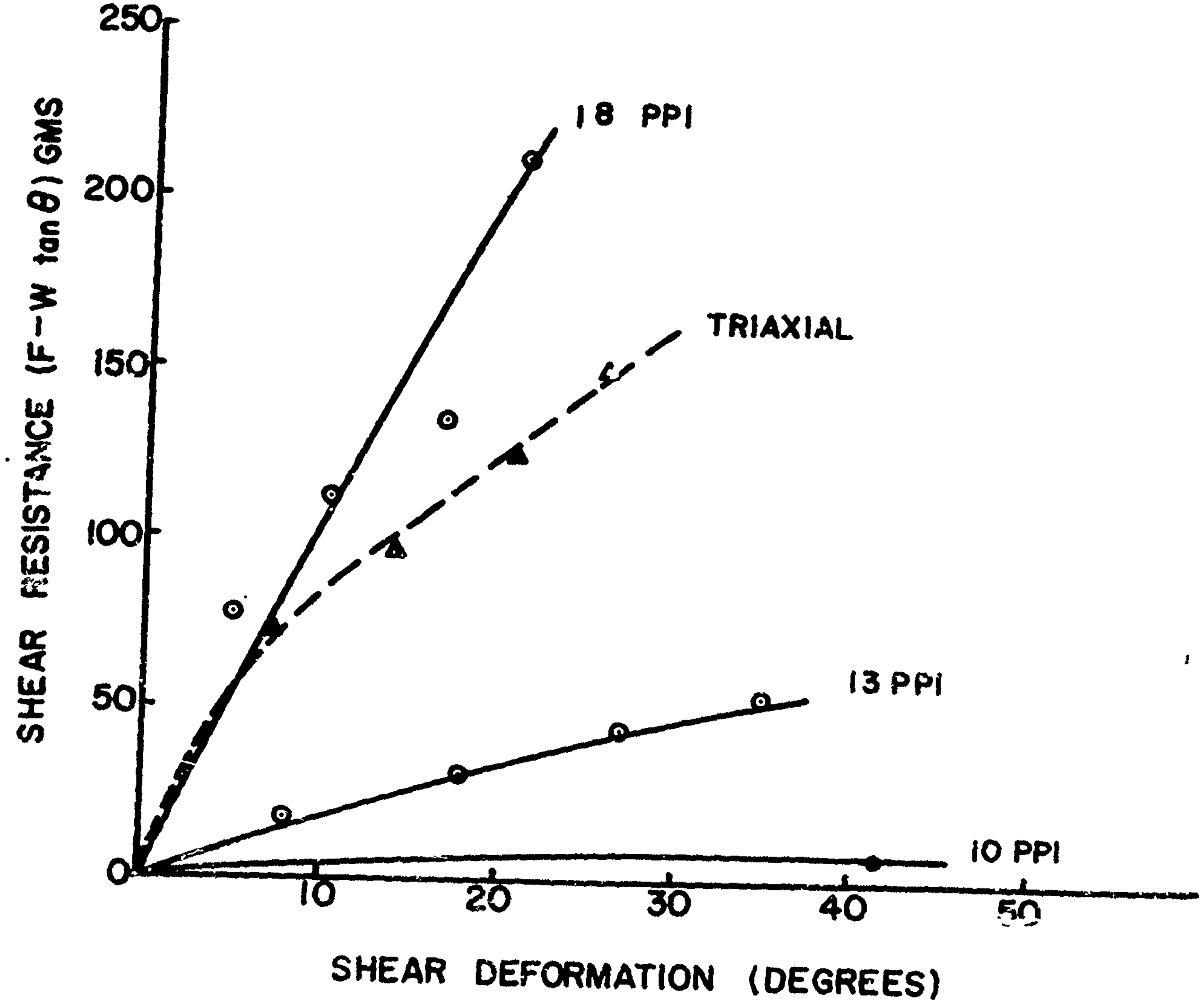


Figure 17. Variation of Shear Resistance with Shear Deformation of Various Fabrics

TABLE III

SHEAR STIFFNESS OF FABRICS

Fabric	Shear Stiffness (gm cm/sq cm/radian)
#1	4
#2	25
#3	150
Triaxial	90

The triaxial fabric has a resistance to shear intermediate between fabrics #2 and #3, and despite its extreme openness behaves like a tightly woven orthogonal fabric. If the buckling of the third set of yarns could be prevented, either by external constraint to prevent the out-of-plane displacement, or by increasing the tension in the yarns, the shear resistance would be increased. It would be of interest to investigate the shear behavior of the triaxial fabric in greater detail when larger fabric samples become available.

D. OTHER MECHANICAL PROPERTIES

Because of the very limited availability of fabric no other mechanical properties were evaluated. If the triaxially woven material were available in greater quantities it would be of great interest to measure such properties as tensile and tearing strength, seam strength, ball-burst strength, and abrasion resistance. In particular the tearing behavior would be very much complicated by the presence of three sets of yarns and the triaxial fabric should show tearing characteristics very different from those of orthogonal fabrics. The tensile strength of the triaxial fabric would depend markedly on the amount of shear distortion sustained by the fabric at rupture, but it seems probable that the variation of strength with direction would be less than the variation found in orthogonal fabrics.

SECTION VI

CONCLUSIONS

A loom was developed for weaving triaxial fabric and was used to weave samples of fabric from coarse string, 3-ply, 840-denier nylon yarn, and graphite yarn. All the various mechanisms and movements are hand powered and operated in the current loom, but the mechanization of the entire weaving process does not appear to present any insuperable difficulty. The current loom is about 8 inches wide and produces a fabric approximately 3 inches in width. It should be possible to increase the width of woven fabric up to 30 inches without difficulty.

The shedding and warp yarn indexing motion in the loom are controlled by a set of cams oriented in a cam roll. In its present form the loom can be used to weave plain weave and unbalanced twill weave fabrics; the weaving of balanced twills requires either a change in cam stacking sequence or a multiplicity of cam rolls. It appears that the latter possibility is more attractive for future development.

The nylon triaxial fabric and a range of square orthogonal fabrics woven from the same yarns were evaluated for various structural and mechanical properties. The stability of the triaxial fabric is much greater than that of an orthogonal fabric with the same percentage open area. The triaxial fabric exhibits much greater isotropy in its bending behavior than comparable orthogonal fabrics, in accord with theoretical expectation. The shear resistance of the triaxial fabric is greater than that of comparable orthogonal fabrics, and could be made even greater if the out-of-plane buckling of one of the sets of threads could be prevented. In general the plain weave triaxial fabric exhibits all the characteristics of a very closely woven orthogonal fabric, while at the same time maintaining a very large (approximately 40%) open area, a value that is hardly attainable in orthogonal fabrics. Presumably, it is this combination of stability and openness that has led to the historical uses in basketry, straw-work, and snowshoes previously mentioned; other, similar uses would no doubt be found for the fabric if it were available in large quantities.

There are other aspects of the triaxially woven materials that are as yet completely unexplored. A great range of weave structures are possible that have no analogue in orthogonal fabrics. In particular the various balanced and unbalanced twills, and double plain weaves in which the open areas of one layer of fabric are filled by the intersections of a second layer are of interest. These structures would have densities and stability unobtainable in conventional woven fabrics, and in view of their mechanical isotropy should have considerable application in the field of composite reinforcement. The full exploration of the possibilities of these materials can only be carried out if adequate supplies of fabric are available. The present investigation has demonstrated the feasibility of machine forming of simple structures, and the viability of a particular loom design, which could be upgraded to semiautomatic production of full width (approximately 30 inches) fabric without great difficulty. There is no doubt that both the intrinsic scientific interest of the unusual triaxial structures and the importance of their possible areas of utilization warrant further effort in the field of development and fabric characterization.

APPENDIX I

MEASUREMENT OF FLEXURAL RIGIDITY AND SHEAR RESISTANCE OF TRIAXIAL FABRICS

A. FLEXURAL RIGIDITY

In the usual version of the compressed cylinder test for the measurement of flexural rigidity a strip of fabric is formed into a cylinder and is compressed between two parallel plates; the experimental arrangement is shown in figure 18. At plate separations smaller than 1.44R, where R is the undeformed radius of the specimen, the fabric takes up an elastica configuration which is invariant in shape, and the plate separation D, the force P required to maintain the configuration and the flexural rigidity of the specimen G are related through the equation:

$$P = 5.73\ G/D^2$$

and a graph of P against $1/D^2$ for an ideal elastic material should be a straight line through the origin. In the present experiments the measurements were made on circular specimens cut from the various fabric samples. Two diametrically opposite points of the flat discs were joined together with a small tab of adhesive tape, and the tubular specimens so formed were compressed as described above, with the joint positioned to be in the center of the portion of the specimen in contact with the top plate. The width of material traversing the bend is not constant in this arrangement, but is greatest at the bottom and least at the top plate. However, at small values of plate separation the variation in fabric width becomes insignificant, and, as can be seen from figure 19, the test can be considered to take place on a uniform specimen of width d' = 0.866d, where d is the diameter of the disc. After testing of the specimen, it can be opened out and allowed to recover for some time, and tested again at a different orientation; in this way, a complete investigation of the polar variation of stiffness can be made.

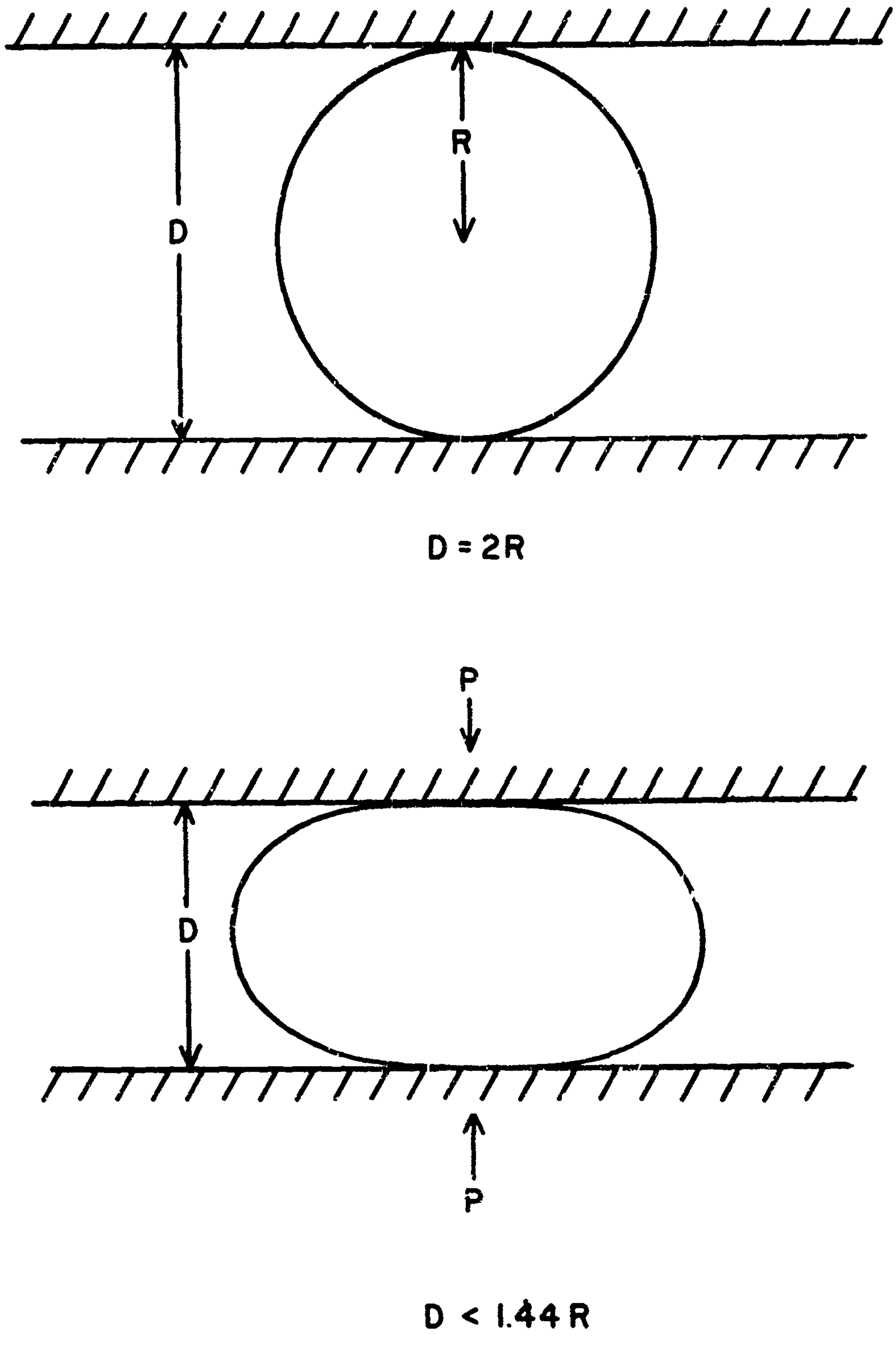


Figure 18. Experimental Arrangement and Nomenclature for Compressed Cylinder Test

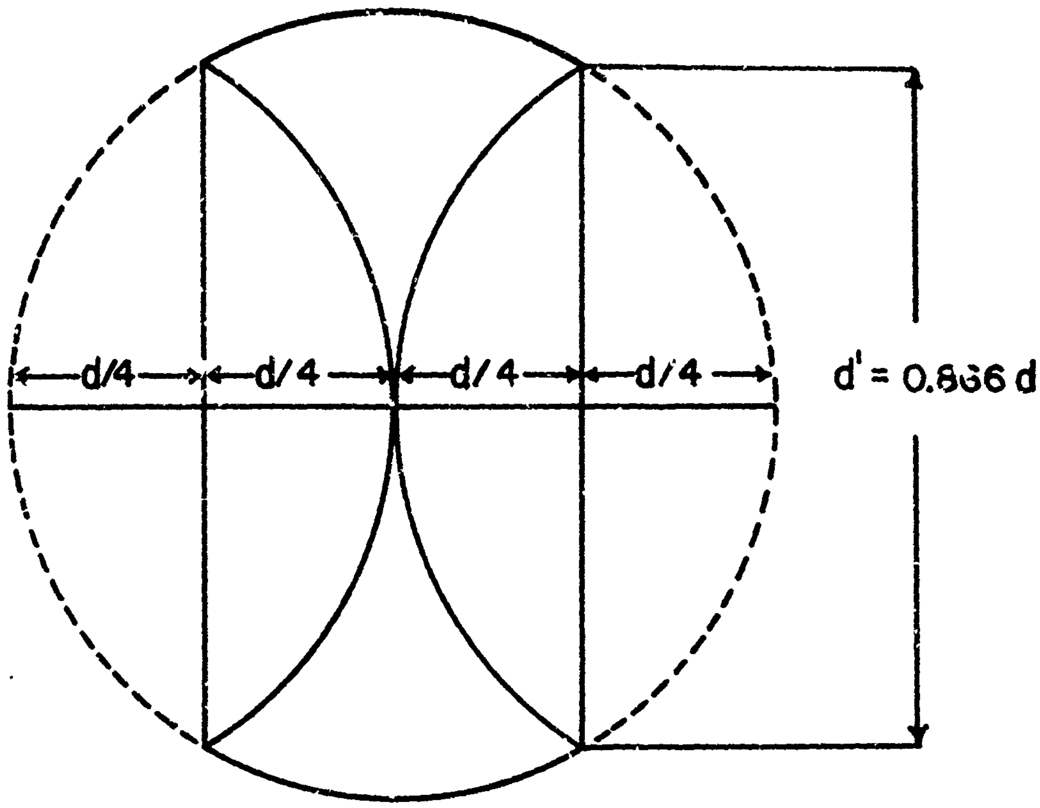


Figure 19. Effective Width of Circular Specimen in Compressed Cylinder Test

The tests were carried out using 3.4 inch diameter specimens giving an effective specimen width of 2.94 inches (7.47 cm), using an Instron tensile tester equipped with a compression cell. A crosshead speed of 1 inch per minute was used. The specimens were compressed to a load of 1000 grams, at which point the upper and lower inside faces of the specimens were almost in contact. The value of D appropriate for the calculations is that for the central plane of the fabric, and hence a correction for fabric thickness must be made. This was done by maintaining the positional relationship between the crosshead and chart during the removal of the cylinder and carrying out a second compression test on a single layer of the appropriate flat fabric. In this way an estimate of the fabric thickness under a particular load is obtained, and an approximate correction can be made. The procedure is illustrated in figure 20.

B. SHEAR RESISTANCE

Several methods for the measurement of shear resistance of orthogonal fabrics have been described in the literature [8, 9, 10] many of them based on variants of the method shown in figure 21. A rectangular fabric specimen of length ℓ and width d is held in a fixed clamp at AB along the line of threads and in a movable clamp at CD. A load W is applied to the bottom edge of the fabric via the clamp and a sideways force F is applied to draw the clamp to one side and to set up within the fabric a shear distortion θ. If the fabric has zero resistance to shear, the magnitude of the force F_0 is given by:

$$F_0 = W \tan \theta$$

If the fabric has resistance to the shear deformation an additional force is required. If the total force applied is F, then the force associated with the shear of the fabric is given by:

$$F - F_0 = F - W \tan \theta$$

and the shearing couple is

$$(F - W \tan \theta)d..$$

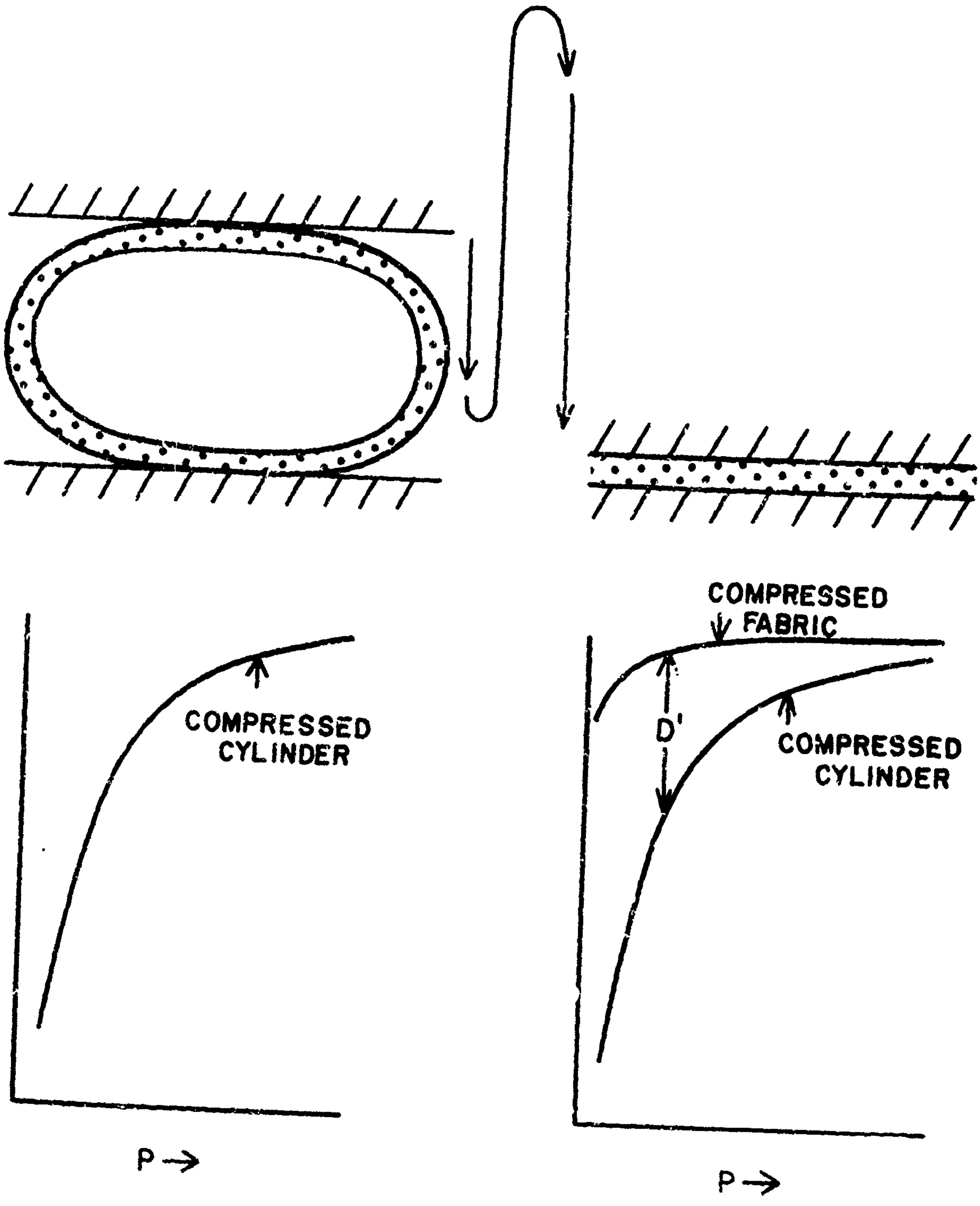


Figure 20. Compressed Cylinder Test

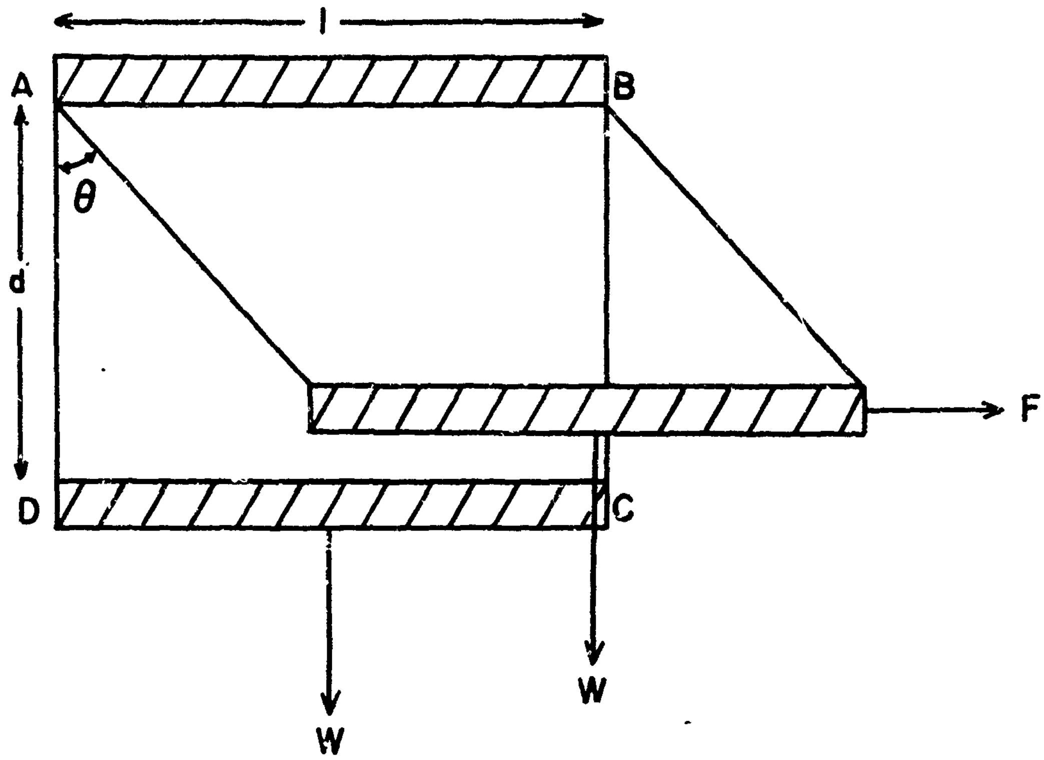


Figure 21. Principle of Fabric Shear Tester

The shearing couple per unit area is given for small angles of shear by

$$C = (F - W \tan \theta)\, d/\ell d$$

$$= (F - W \tan \theta)/\ell,$$

and the shear stiffness of the fabric S, the couple per unit area required to produce unit angular deformation is:

$$S = (F - W \tan \theta/\ell\theta.$$

A simple variant of this test is the "picture-frame" test in which a square or rectangular specimen of fabric under test is held along each edge in a pin jointed frame and the force required to shear the frame is measured. There is no difficulty in interpreting either of these tests so long as the rigid edges of the frame or clamps coincide with thread directions. However, if the line of clamping does not coincide with the thread directions the two types of test do not yield the same result as for orthogonal fabrics, and care must be taken in interpreting the results. Consider the fabric clamped as shown in figure 22a. The two triangular areas AJC and ELG cannot be deformed in shear, but can change their configuration only by extension of the yarns. However, if a force is applied to the clamp GFE the area ADEH can shear and the clamp can move in the direction of the force, giving a measurable shear deformation.

If the fabric is also clamped along the edges CDE and GHA, as in a picture-frame test, then (figure 22b) the triangular areas ACJ, CEK, ELS, and SIA cannot be deformed without yarn extension and the entire area ACEG is effectively undeformable and the measured shear resistance is very high.

If a rectangular sample of triaxial fabric is clamped along all four edges, then the restraints on the fabric are similar to those discussed above for the orthogonal fabric and no shear deformation is possible without yarn extension. However, if the triaxial fabric is held by two clamps aligned parallel to one set

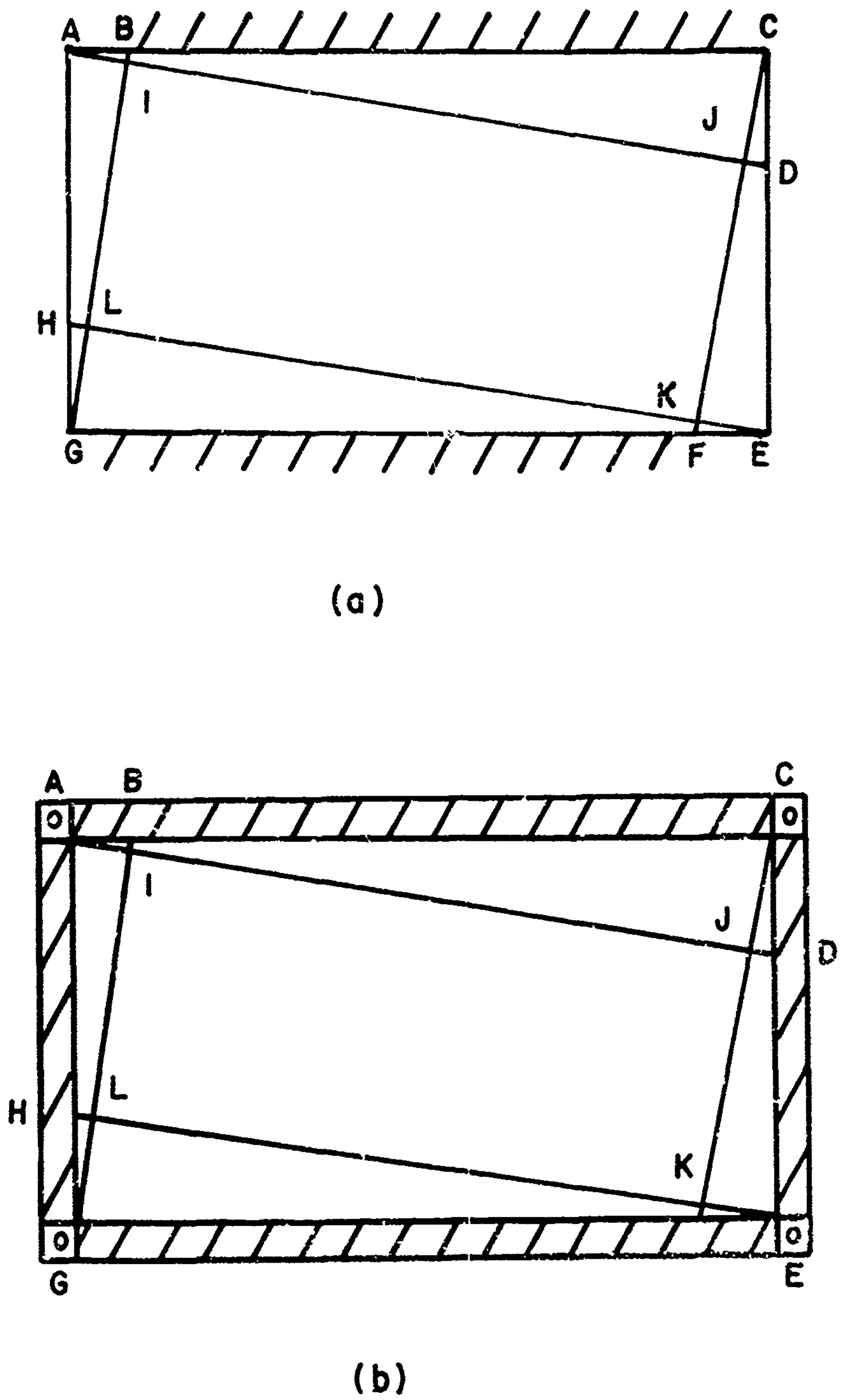


Figure 22. Shear Tests (a) Double Clamps, (b) Picture Frame

of threads then a shear deformation is possible, and the shear stiffness can be measured. Figure 23 shows the relationship between the geometries of orthogonal and triaxial fabrics in a typical test. Two sets of threads in the triaxial fabric at the start of the deformation are in a condition similar to the threads in the orthogonal fabric at large deformation. In addition, the third set of threads in the triaxial fabrics suffer a buckling deformation because of the contraction of the fabrics in the direction of the third set of threads. This buckling can be seen in figure 24. It is observed experimentally that the shear stiffness of orthogonal fabrics increases with increasing shear deformation as a result of increasing yarn bending deformation at the crossover points in the fabric; accordingly, the shear stiffness of the triaxial fabrics is expected to be greater than that of the orthogonal fabric with the same number of crossover points per unit area. In addition, the buckling of the third set of yarns requires an additional shear stress, which also increases the shear resistance of the triaxial fabrics compared with that of the equivalent orthogonal fabric. The ratio of the shear stiffness of the triaxial fabrics to that of the orthogonal fabrics is probably close to unity for very open fabrics and is expected to rise with increasing fabric closeness.

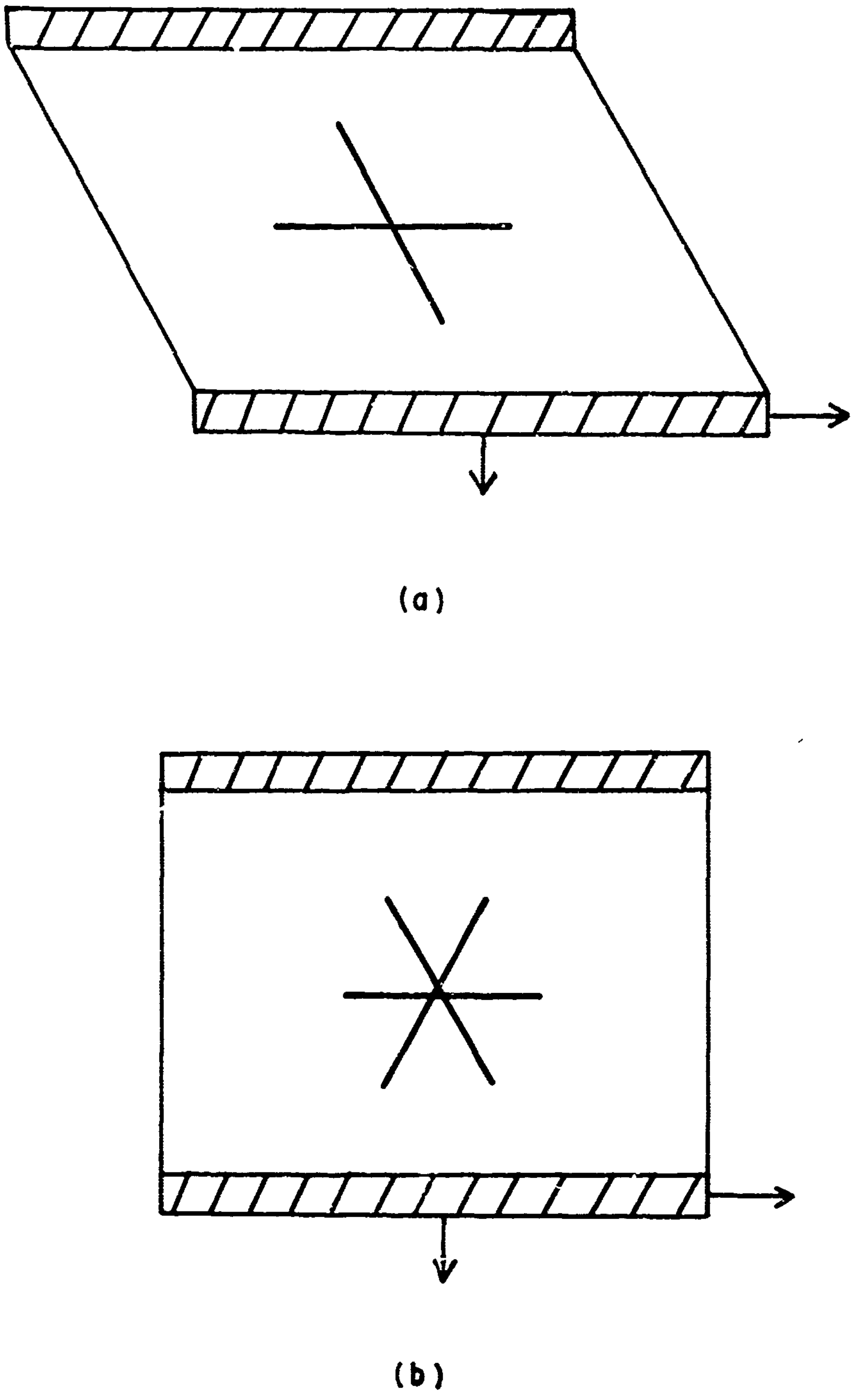


Figure 23. Shear of (a) Orthogonal and (b) Triaxial Fabrics

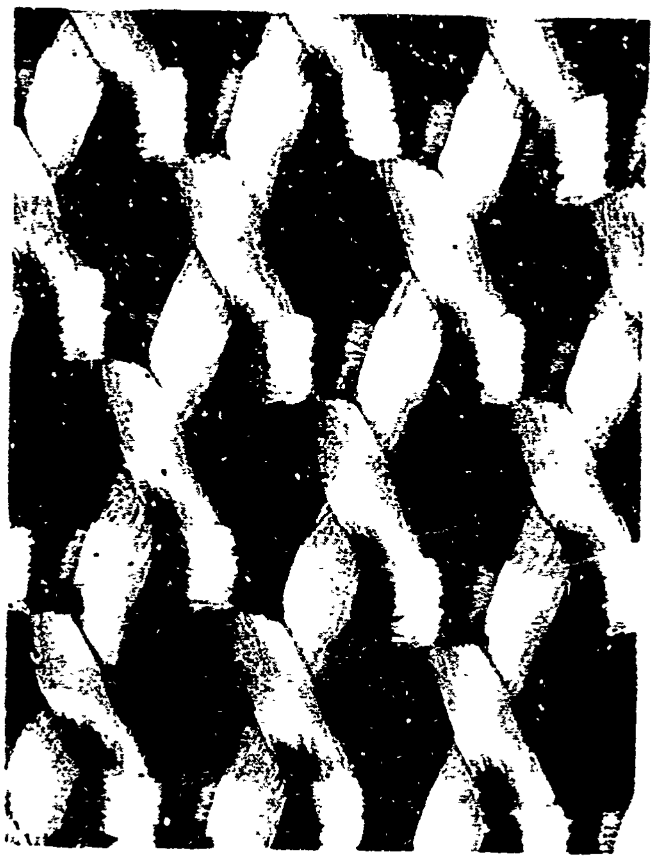


Figure 24. Buckling of Yarns in Shear Deformation of Triaxial Fabrics

REFERENCES

[1] Dow, N. F., U. S. Patent No. 3,446,251.

[2] Dow, N. F., Final Report under National Aeronautics and Space Administration Contract NAS 9-8026.

[3] Ross, J. H., AFML-TR-67-182 (1967).

[4] Cooper, D. N. E., J. Text. Inst. 1960, 51, T317.

[5] Skelton, J., J. Text. Inst., 1966, 57, T505.

[6] ASTM D 1388-64 (Option A) - ASTM Standards, Part 24.

[7] Steel, R., Text. Res. J., 1957, 27, 695.

[8] Mörner, B and Eeg-Olofsson, T., Text. Res. J., 1957, 27, 611.

[9] Behre, B., Text. Res. J., 1961, 31, 87.

[10] Treloar, L. R. G., J. Text. Inst., 1965, 56, 533.

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13. ABSTRACT

An experimental loom was devised for the development of small samples of triaxially woven fabrics and was used to weave experimental amounts of fabric from coarse string, 3-ply, 840-denier nylon yarn, and from graphite yarn. The shedding and warp yarn indexing motions are controlled by a series of cams mounted on a cam roll. The sequence of cams can be changed to produce various weave patterns; changes in weave pattern can also be produced for any particular cam roll by varying the sequence of shedding and indexing motions.

The nylon triaxial fabric and a range of square orthogonal fabrics woven from the same yarn were evaluated for various structural and mechanical properties. The stability of the triaxial fabric is much greater than that of an orthogonal fabric with the same percentage open area. The triaxial fabric exhibits greater isotropy in its bending behavior and a greater shear resistance than a comparable orthogonal fabric.

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