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FINAL REPORT

PRELIMINARY INVESTIGATION OF FEASIBILITY OF WEAVING TRIAXIAL FABRICS

CASE FILE COPY

by

Norris F. Dow

Space Sciences Laboratory

January 1969

Prepared for the
National Aeronautics and Space Administration
under Contract NAS 9-8026

General Electric Company
Valley Forge Space Technology Center
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SUMMARY

Studies were carried out to determine the feasibility of weaving triaxial fabrics (Doweave), in tight, low porosity configurations, and to investigate the stability and isotropy of triaxially woven fabrics. Detailed analyses of yarn motions required in triaxial weaving cycles disclosed no fundamental problems to prevent the achievement of tight fabrics woven of fine yarns. A breadboard loom, assembled to produce samples, to a degree confirmed analytic predictions of loom configuration precision required to yield quality triaxial fabrics. Guidelines were generated for extending weaving capabilities for full-scale production.

INTRODUCTION

Weaving of fabrics, one of the oldest of the arts, has always been done with only two sets of yarns, the warp and the woof. In consequence, all fabrics have been weak on the bias so that they can be pulled out of shape readily at 45° to the yarn directions.

Doweave fabrics, invented (patent applied for) by Norris F. Dow of the General Electric Company, are woven with three sets of yarns (usually at 60° to each other). They have no bias direction. With equal sizes and numbers of yarns in the three directions, they approach isotropy, i. e., equal strength and stiffness in all directions. Further, the addition of a third set of yarns opens up an entirely new range of textile possibilities heretofore inaccessible, such as:

1. Structural Properties - With three yarn elements, for the first time the design of desired strength/stiffness characteristics in a single ply fabric is possible. Properties may be made equal in all directions, or a maximum in some preferred direction to suit the requirements, and always with no weakness on the bias.

2. Stability of Weave - The third yarn set may be employed to lock in place the yarn courses, even for an open weave like a scrim, if desired, providing a stable weave pattern resistant to abrasion or pulling. This "locked intersection" nature of the triaxial fabric is illustrated in Figure 1, being

characterized by the "twisted pair" likeness of the adjacent intersecting yarns as shown in Figure 1a. Employment of locked intersections on both sides of a yarn element as in Figure 1b effectively locks it in place against transverse sliding. Weave patterns which thus lock the yarn courses in place as in Figure 1c are the essence of the Doweave triaxial fabrics.

3. Additional New Characteristics - Various weaving patterns of three elements can yield combinations of various densities and porosities, with one set of elements straight and uncrimped, if desired, or with one set of elements concealed from one or both sides of the fabric, ad libatum.

For the particularly demanding requirements for structural space fabrics, the Doweave triaxial approach appears to offer a number of advantages over ordinary weaves. As yet, however, Doweave triaxial fabrics have not been woven to the low porosities, high numbers of yarns per inch, or of the generally non-compliant materials desirable for space applications. Consequently their characteristics in these configurations and materials have not been measured or assessed. Accordingly, a program was initiated for the evaluation of Doweave for space fabric applications. This report is concerned with the first, preliminary phases of this program, namely:

(1) Studies of the feasibility of weaving triaxial fabrics in tight, low porosity configurations.

(2) Studies to investigate the stability and isotropy of triaxially woven fabrics.

(3) Generation of guidelines for extension to full-scale production.

WEAVING OF TRIAXIAL FABRICS

Weaving triaxial fabrics like the basic weave (Fig. 2), and the 1st and the 2nd Variants (Fig. 3 and 4) in which one set of yarns (those at 11 o'clock) are at all points over one other set (those at 1 o'clock) may be done with apparatus which is generically related to that described in U. S. patent 550,068 or U. S. patent 1,368,215 (Refs. 1 and 2). In essence two sets of transversely traversing warps, hereinafter designated the "A-warps" (for "Above-warps") and "B-warps" (for "Below-warps") are used, together with an ordinary pick-insertion system, to create the three-yarn fabric. Various weave patterns are created by proper programming of the shed-forming heddles during pick insertion.

The loom sub-contractor, Prodesco, Inc., with a view toward the simplification of loom design, elected to separate the warp-advance function from the heddle mechanism, using hooked-needle heddles at a fixed location transversely for insertion among the warp yarns to catch selected yarns and pull them back past one another for shed formation. Accordingly supporting, detailed studies were undertaken to evaluate this approach to the weaving process. While the results of these studies are not especially favorable to the hook-type heddle, they do describe many aspects of the general weaving problem fairly definitively, and provide the basis for the generation of guidelines which appear both necessary and sufficient for successful loom development. The essence of these studies is presented here, and the guidelines derived therefrom are presented in a subsequent section of this report.

The Basic Weave

Weaving analysis for the triaxial fabrics naturally begins with that of the simple, Basic Weave (in which the 11 o'clock yarns are over the 1 o'clock yarns and under the wefts, and the wefts in turn are under the 1 o'clock yarns.) Because the weaving of the basic pattern involves most of the operations required for any of the related, more complicated weaves, its analysis will first be considered in detail and then the variations from the basic procedures necessary for other variants will be discussed.

The weaving cycle, for the Basic Weave utilizing hooked-needle heddles, is made up of 14 steps as follows:

(1) The First Basic Position

The weaving cycle starts with the warp yarns aligned parallel, perpendicular to the weft, and uniformly spaced over and under one another as shown in cross section at the top of Figure 5, and in plan view in Figure 6. In this position, hereinafter referred to as the "First Basic Position", one of the sets of beaters (designated here the "B_1" beaters) is in position between each "A" (above) warp and its adjacent "B" (below) warp as shown in the plan view, and the "B" warps are positioned midway between adjacent "A" warps. For nominal density of the basic weave, the spacing between adjacent "A" warps (and likewise between adjacent "B" warps is $2\sqrt{3}$ d, where d = yarn diameter,- and the distance is measured between yarn centerlines. Thus the open distance between adjacent "A" and between adajcent "B" yarns is 2.464 d, and the nominal beater diameter to achieve the parallelism desired is 0.732 d. These dimensions are shown on the cross-sectional elevation diagrams of Figure 5.

(2) Shed Formation. (Fig. 7) From the First Basic Position the lower warps may be raised and the upper warps lowered vertically to form the shed for pick insertion. Using the hooked-needles the following sequence of motions is required to take advantage of the space available for needle insertion (see Fig. 8): (A) to insert the needles part way through the warps in their First Basic Position, (B) then to traverse back a half-space with both upper and lower warps before completing full needle insertion (C), and return of the warps (D) to position for shed formation (E). During these various warp traverse motions the maintaining of the B_1 beaters in position near the work is desirable to keep the completed work stable.

(3) - (5) Pick Insertion and Beat-Up. (Figures 9-11). Pick insertion and beat up is essentially a three stage process. During insertion (3) the "A" and "B" warps are traversed ahead a quarter space to make room for the insertion of the A_1 beaters and then traversed back a half space to make room for the insertion of the B_2 beaters. Both A_1 and B_2 beaters beat against the pick to beat it up in similar fashion to ordinary

weaving. After beat-up by B_2 the warps are advanced to the same position they occupied in step (2) immediately after shed formation, and in plan view the warps are once more parallel, and perpendicular to the weft.

Of importance is the fact that the advance/retreat traverse motions of the warps in steps (3) and (4) need to take place between the shed-forming needles and the work; i. e., an additional mechanism is required to position the warps transversely after shed formation. This mechanism is not required to provide overall warp advance but only a back and forth positioning to insure room for proper beater insertion.

(6) - (7) Warp Advance. (Figures 11 and 12) - Warp advance is characterized by three separate motions: (1) un-making the shed ((6)) so that the A-warps are over the B-warps and can be advanced without tangling; (2) advancing the end A-warp ("c" on Fig. 5) from above to below; (3) advancing all the warps (except "c") 3/4 space ("c" advances only 1/4 space.) After the general advance, the yarns are in position for the insertion of the A_2 beaters.

(8) Warp Beat Up. (Fig. 13) - The A_2 beaters beat up the warps which were advanced in step (7) . This beat up, which has no counterpart in ordinary weaving, establishes the warps in the Second Basic Position for the start of the second half of the weaving cycle. The seven steps

in this part of the cycle will not be described in detail because they are in essence the same as those of the first half of the cycle. The differences are that the pick is inserted from right to left (steps (9) - (11)), the end bottom warp (warp "10") is advanced from the "B"'s to the "A"'s (step (13)), and it is the B_2 beaters which beat up the new warp advance of step (14) to re-establish the First Basic Position with all warps advanced one position.

As shown, there are an odd number of warps, total, starting with an odd and (one) greater number of "A" warps than "B" warps in step (1). Thus fabric having like selvages on each side is produced as shown in Fig. 14 and the end yarn advance motion alternates from side to side (left side in step (6), right side in step (13)).

The 2nd Variant Weave

As is to be expected, the weaving of the 2nd Variant Weave is a more complicated process than that of the Basic Weave, requiring in effect a doubling of all components to achieve the doubled nominal density compared to the Basic Weave. Thus double sets of A and B warps are required, and a double warp advance system. For hooked-needles, additionally, some sort of lateral positioning device is needed capable of moving the A and B heddles (independently) two yarn diameters left and right. Further, at one stage in the weaving cycle the hooked-needle heddles are in the way; warp advance should take place with the needles in place holding a shed. Indubitably there are several possible solutions to this problem. The one described is to un-make the shed without completing pick beat-up, then to accomplish the warp advance, re-make the shed and continue.

The description of the weaving cycle for the 2nd Variant Weave concentrates upon the stages which differ from those in the cycle for the Basic Weave, for beginning with the First Basic Position, as will be seen, the process is essentially the same.

◎ First Basic Position - In plan view (Fig. 15) the First Basic Position looks the same as the First Basic Position for the Basic Weave. The warp yarns are straight out from the work, perpendicular to the weft, parallel to each other, and (for the yarns in any one plane) spaced apart nominally $2\sqrt{3}$ yarn diameters. Two sets of beaters B_1 and A_2 are in place to position the yarns. The nominal beater diameter is 0.732 d.

In cross-sectional elevation (Fig. 16) the fact that there are twice as many yarns as for the Basic Weave becomes apparent. There are now two sets of A warps (designated hereafter A_A and A_B) and two sets of B warps (B_A and B_B). In the First Basic Position the A_A's are directly above the B_A's and the A_B's are directly above the B_B's, the latter being positioned midway between the A_A's and B_A's. As will be seen, the distance between the A_B layer and the B_A layer of yarns must be sufficient to allow pick insertion when a shed has been formed within this distance, as discussed below, - i. e., more room is required than for the basic weave.

1 <u>Shed Formation</u> - From the First Basic Position the B_B warps may be raised and the A_A warps may be lowered to form the shed for pick insertion. Using a hooked-needle-heddle system of the type shown in Figure 17 , a number of warp translations are required to permit needle insertion; as B_1 in the Figure, translation of A_B warps and B_B warps to the left to make spaces for the insertion of the A heddles, then C_1 translation of all warps to the right to make spaces for the insertion of the B heddles, and D_1 return to the basic position prefatory to shed formation E_1.

(2) - (4) Pick Insertion and Beat-Up - Pick insertion and beat-up is essentially the same as for the basic weave, involving two sets of beaters (B_2 and A_1), and involving the same warp traverse motions to make room for the insertion of those beaters. Because the A_B warps and the B_A warps are in their original position, with the B_A warps and A_A warps between them and the pick, the greater vertical separation between them than for the basic weave, previously noted to be required, must be provided.

(5) Shed Inversion - Shed inversion, - which has no counterpart in the basic weave, - with needle heddles involves (Fig. 17) (F_1) return to the First Basic Position, (G_1) interchange of lateral position of A_A and A_B, and of B_A and B_B warps, (H_1) shed inversion, and (I_1) lateral positioning.

(5) - (6) Pick Insertion and Beat-Up - Because of the double number of weft yarns compared to the Basic Weave, a second pick insertion and beat-up occurs before warp advance.

(7) - (12) Warp Advance and Beat-Up - Yarn positions for warp advance and beat-up are shown in steps (7) - (12) of the diagrams of Figure 16. Achievement of these positions with hooked needle heddles requires getting the needles out of the way. One possible method for doing this is by un-making the shed as in the sequence (K_1) - (M_1) shown in Fig. 17. Warp advance can then be accomplished and the shed remade, if desired. This unmaking and remaking of the shed, however, must be coordinated with the beating up of the pick, to insure against warp yarn entanglement near the work.

From this point on the weaving sequence is mostly repetitive and straightforward, and it will not be discussed in detail.

The 1st Variant Weave

The 1st Variant Weave (Fig. 3) intermediate in density between that of the Basic and 2nd Variant is the most difficult of the three to weave on a hooked-needle-heddle apparatus. The Basic Position is shown in Figure 18, and the yarn sequence position diagrams are given in Figure 19. The closer yarn spacings, - such that the beater diameters are nominally 0.54d, - are evident, and the fact that three sets of beaters are required to establish the Basic Position. Furthermore, because of the pairing of the B warps, the selvaging becomes more troublesome as evidenced in Figure 20. Because of these complications, the 1st Variant appears unattractive for early weaving studies, and it has not been investigated further.

The Loose Weave, and the Bread-Board Loom

The Loose Weave (Fig. 21) produced by Prodesco as the nearest approximation of the 1st Variant possible on the bread-board loom is essentially a variant of the Basic Weave which incorporates double wefts, alternate pairs of which pass over the one o'clock yarns and under the eleven o'clock yarns. These alternate weft pairs are not "locked" in place by the adjacent yarn intersections (as is evident in Fig. 21), and they give the weave a looseness and lack of stability. Further, the fact that there are twice as many yarns in the weft direction as in either of the other two directions makes the material non-isotropic.

The Loose Weave is relatively easy to weave on a hooked-needle heddle loom, and the operations involved are the closest possible to those of weaving ordinary fabrics, - i. e., the shed is made one way for pick insertion from left to right and inverted for returning the pick from right to left. Additionally, of course, advances must be made in the warp yarns transversely across the work after each pick insertion to provide the inclinations to the eleven o'clock and one o'clock yarns.

The bread-board loom used in making the loose-weave sample is shown in Figure 22. In the overall view are shown (A) the rotating creel, (B) the ball-chain warp advance mechanism, (C) the hooked-needle heddles, (D) the beaters, and (E) the take-up reel. A typical view of a formed shed is shown below the overall view, with the 11th and 12th yarns from the left on the lower half of the shed snagged on the same needle. No mechanical drive or locating mechanisms for warp advance were used; the operator positioned the warps as best he could by eye, raising and lowering heddles, and inserting picks and comb-like beaters by hand.

The bread-board loom was of necessity (because of budgetary limitations) of maximum simplicity. Thus for example, its heddles were made with needles having open hooks (the needles from a Mali-type loom were used) even though their liklihood to snag was recognized. Similarly the need for precision machine alignment was recognized, but not possible of achievement with the available funds. Despite the minimal character of the bread-board loom, it revealed no problems the solution of which appear beyond the scope of straight-forward engineering solution.

Summary of Studies of Weaving, and Guidelines for Extension to Full-Scale Production

The detailed studies of yarn motions reveal that weaving of the Basic, 1st, and 2nd Variant Doweave patterns is feasible using a pair of traversing warps and conventional pick-insertion equipment. Moreover, the space available between adjacent yarns for shed formation, and for beater insertion, is ample (see Figures 6 , 15 , and 18) even when weaving with fine diameter yarns if precision machinery is employed.

The key to successful extension to full scale production of these weaves is the use of precise equipment. In particular, mechanical stops must be used to position the warps in their required locations for each step of the weaving cycle. In this respect the use of heddles having closed eyes to trap the warps would appear to offer promise of more accurate positioning than an open system of hooked needles.

The use of multiple beaters, mechanically positioned, to maintain the work and warps in alignment at all times should lead to the most uniform quality fabrics. In future development the use of fewer beaters and the omission of some of the intermediate yarn positioning stages suggested in the analyses given here may be found satisfactory. Until experience so shows, no such short cuts appear desirable.

STABILITY AND ISOTROPY OF TRIAXIAL FABRICS

Stability

The "locked intersection" characteristic of Doweave fabrics (Fig. 1) can provide an inherent stability to the weave pattern. The forces required to displace a "locked" yarn, - that is, a yarn that is snugly compacted into the intersections, - are akin to those encountered in beating-up picks during ordinary weaving (see Ref. 3), but involve functions of the 60° angles between the yarns (probably something like $\cos^2 60^{\circ}$) and of the spacing between the locking intersections (probably a higher than first power of the spacing.)

Samples prepared under this contract and supplied with this report were made on a "best effort" basis on a tight budget. The resulting quality of the samples produced is not judged adequate so that quantitative measures of weave stability may be derived from them. In particular the sample made on the prototype loom is considered so unlike the "1st Variant" Doweave that it was intended to represent (in the sample every other weft pair is not held in place by locked intersections, but actually "floating") that it is considered unfit for using for experimental measurements. Even with the available samples, however, some qualitative measure of weave stability may be obtained by abrading the weaves between thumb and forefinger; such manipulation does suggest a modicum of stability increase for the loosely woven triaxial sample relative to the characteristically easily-pulled biaxial comparison sample.

Isotropy

Isotropy can be demonstrated in first approximation for triaxial weaves having rotational symmetry as in the Basic Doweave (Fig. 2) by analyses such as that of the Appendix. Such an analysis, which linearizes all of the non-linear responses of the fabric elements, is of course only a first approximation. In particular the effects of crimp interchange, evaluated for biaxially woven fabrics in Reference 4, need to be included in the determination of the directional stiffness evaluations of triaxial weaves.

The increased shear stiffness of the Basic Weave has been measured in a "picture-frame" test. (See Ref. 5, for example, for discussion of the "picture-frame" test. Actually for fabrics the test is much more appropriate than for composites, because the frame may readily be made much stiffer than the material being tested.) The results of these measurements are plotted in Figure 23. As can be seen, the triaxial fabric is between 8 and 9 times as stiff in shear as the equivalent biaxial fabric.

CONCLUDING DISCUSSION

Despite the lack of refinement of the bread-board loom (Fig. 22), the experience gained therewith and the confidence acquired through explorations of the details of the weaving process strengthen the conviction that triaxial fabric weaving is entirely feasible. The isotropic nature of the woven material has been supported by test and analysis, but suitable samples for quantitative test evaluations are still wanting. In view of the potential merit of the triaxial concept continued investigations and developments thereof are recommended.

APPENDIX - APPROXIMATE, LINEAR ANALYSIS OF ISOTROPY OF DOWEAVE TRIAXIAL FABRICS

Suppose a displacement ΔL_o applied at an angle θ to the perpendicular to the weft direction (i. e., down on Fig. 2) at any intersection of the Basic Weave. This displacement has components in the weft and warps

$$\begin{aligned} \Delta L_{Weft} &= \Delta L_o \sin\theta \\ \Delta L_{A-Warp} &= \Delta L_o \cos(30-\theta) \qquad (1) \\ \Delta L_{B-Warp} &= \Delta L_o \cos(30+\theta) \end{aligned}$$

and it does work W such that

$$W = \left[\frac{1}{2}\left(\Delta L_{Weft}\right) R_{Weft} + \frac{1}{2}\left(\Delta L_{A-Warp}\right) R_{A-Warp} + \frac{1}{2}\left(\Delta L_{B-warp}\right) R_{B-Warp}\right] \qquad (2)$$

where the R are the reacting forces induced in the yarns. Assuming these forces proportional to the displacements, as

$$R_{Weft} = K\left(\Delta L_{Weft}\right) \qquad (3)$$

and substituting (1) and (3) in (2)

$$W = \frac{1}{2} K \left(\Delta L_o \right)^2 \left[\sin^2 \theta + \cos^2 (30 - \theta) + \cos^2 (30 + \theta) \right] \qquad (4)$$

which reduces to

$$W = K' \left(\Delta L_o \right)^2 \left(\sin^2 \Delta + \cos^2 \theta \right) \qquad (5)$$

which indicates that the work done is independent of the angle of application of the displacement.

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3. Grosberg, P.: "The Beat-Up Forces During Weaving." Lecture No. 15 for M. I. T. Symposium on Dynamics of Textile Processing, Aug. 1968.

4. Freeston, W. D.; Platt, M. M.; and Schopee, M. M.: "Stress-Strain Response of Fabrics Under Two-Dimensional Loading." AFML-TR-67-44, July 1967.

5. Anon.: "Structural Design Guide for Advanced Composite Applications." Prepared under Contract AF 33(615)-68C1241 by Southwest Research Institute, Nov. 1968, p. 30, Div. VIII.

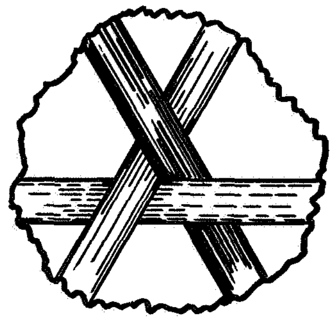


Fig. 1a.

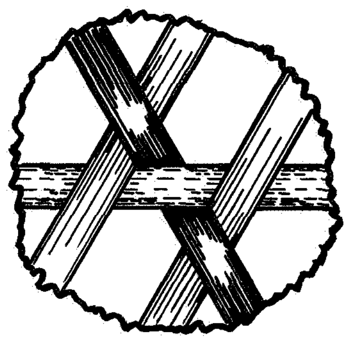


Fig. 1b.

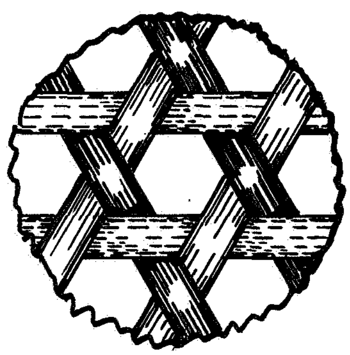
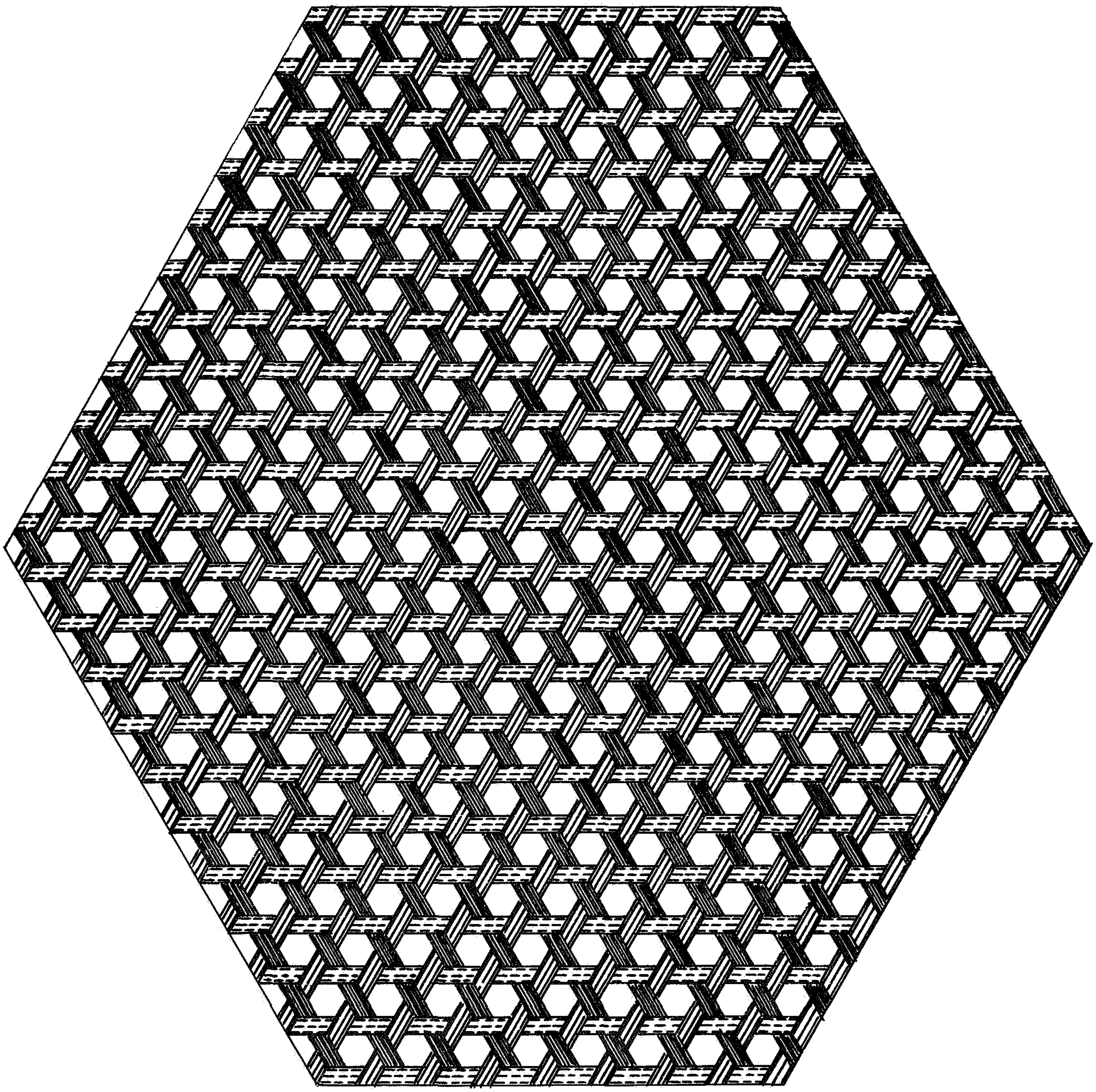


Fig. 1c.

Fig. 1 - Illustrations of "locked intersection" characteristics of Doweave triaxial fabrics.

DOWEAVE TRIAXIAL FABRICS-BASIC WEAVE

33 1/3% POROSITY

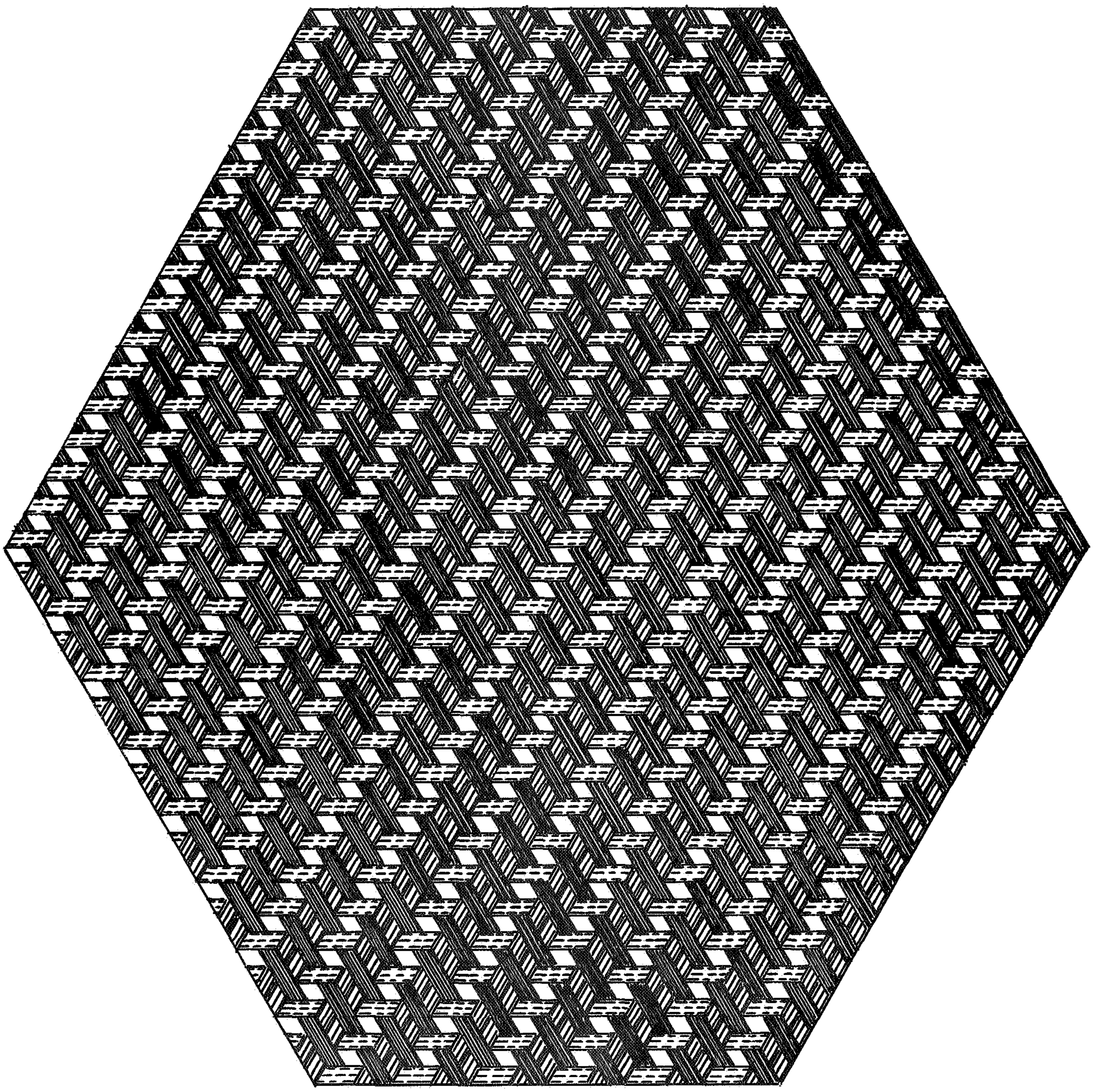


Obverse

Fig. 2 - Doweave triaxial fabrics - Basic Weave as seen from obverse side.

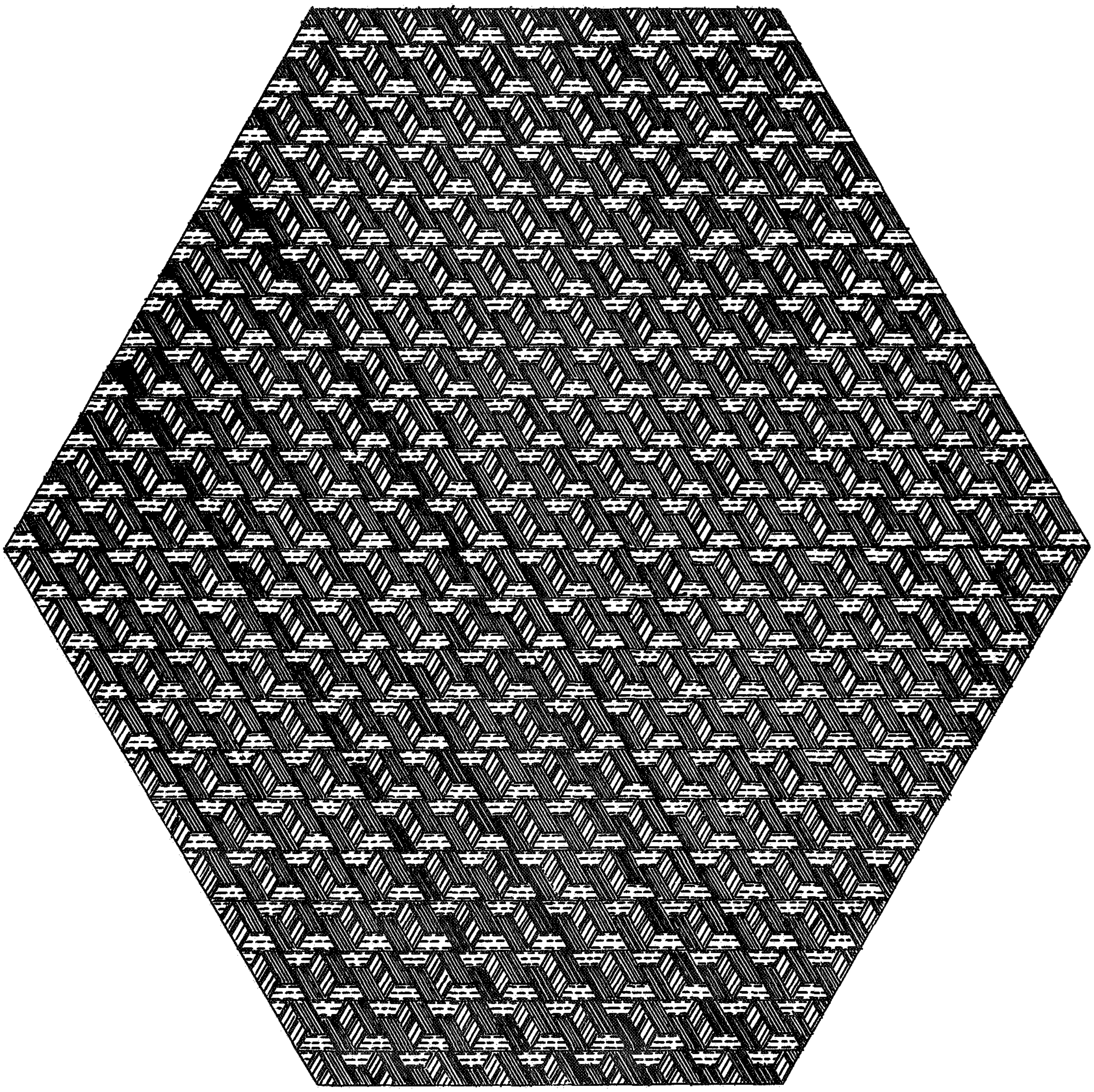
DOWEAVE TRIAXIAL FABRICS - FIRST VARIANT WEAVE

12 1/2% POROSITY



Obverse

Fig. 3 - First Variant weave pattern for Doweave triaxial fabrics as seen from obverse side.



Obverse

Fig. 4 - Second Variant weave pattern for Doweave triaxial fabrics as seen from obverse side.

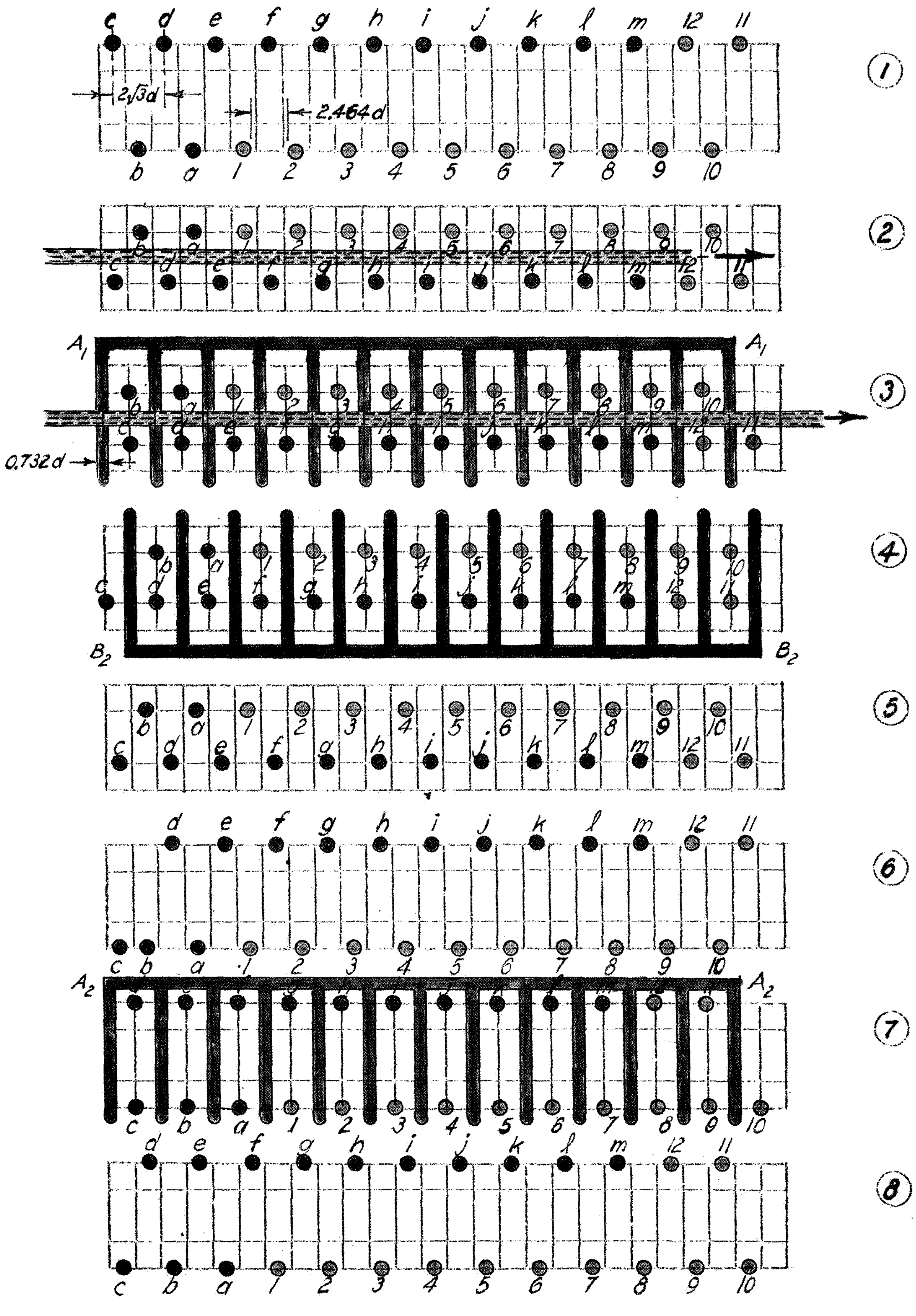


Fig. 5. - Cross-sectional elevation views of yarns and beaters near heddles for the Basic Weave.

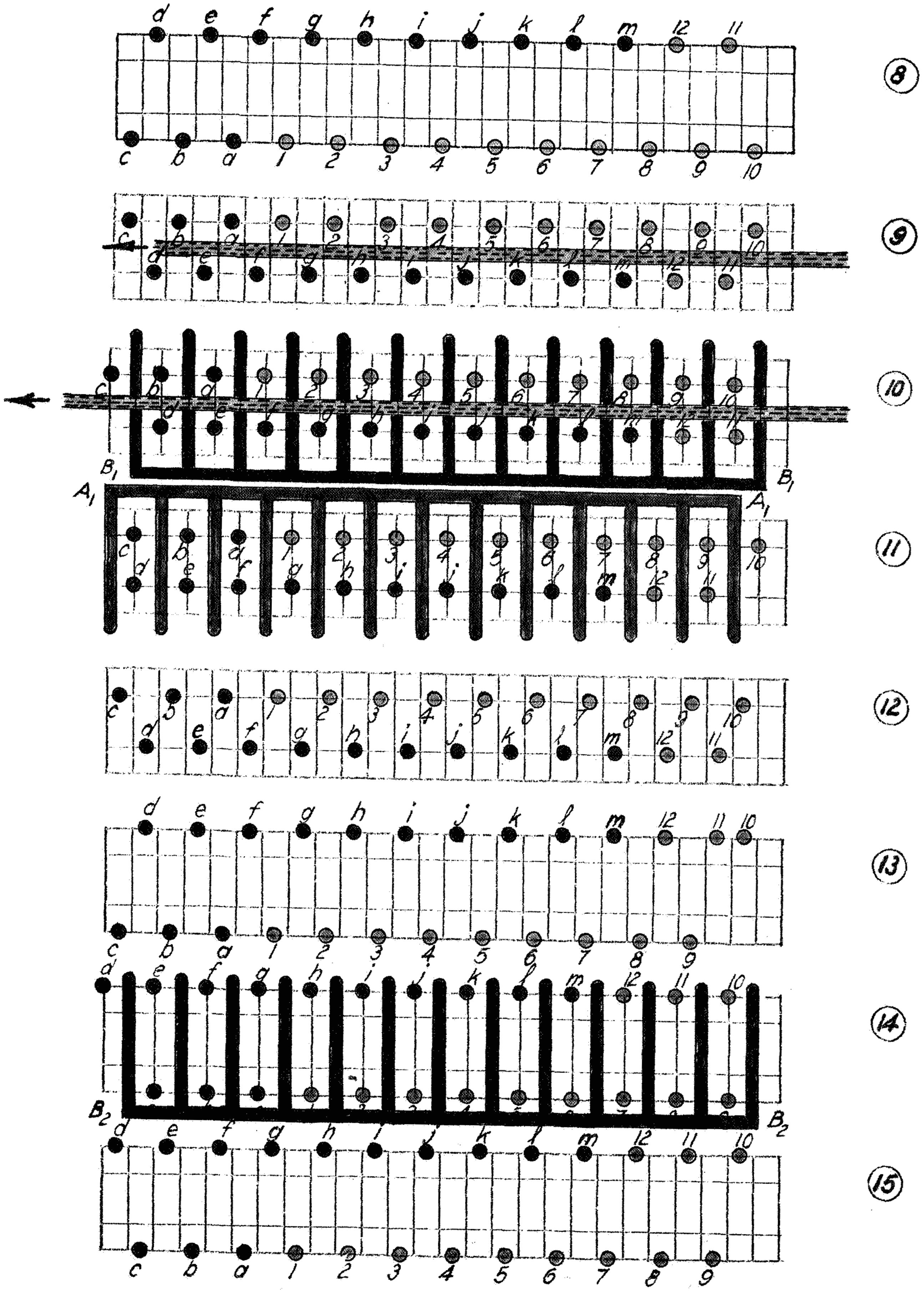


Fig. 5. - (Concluded)

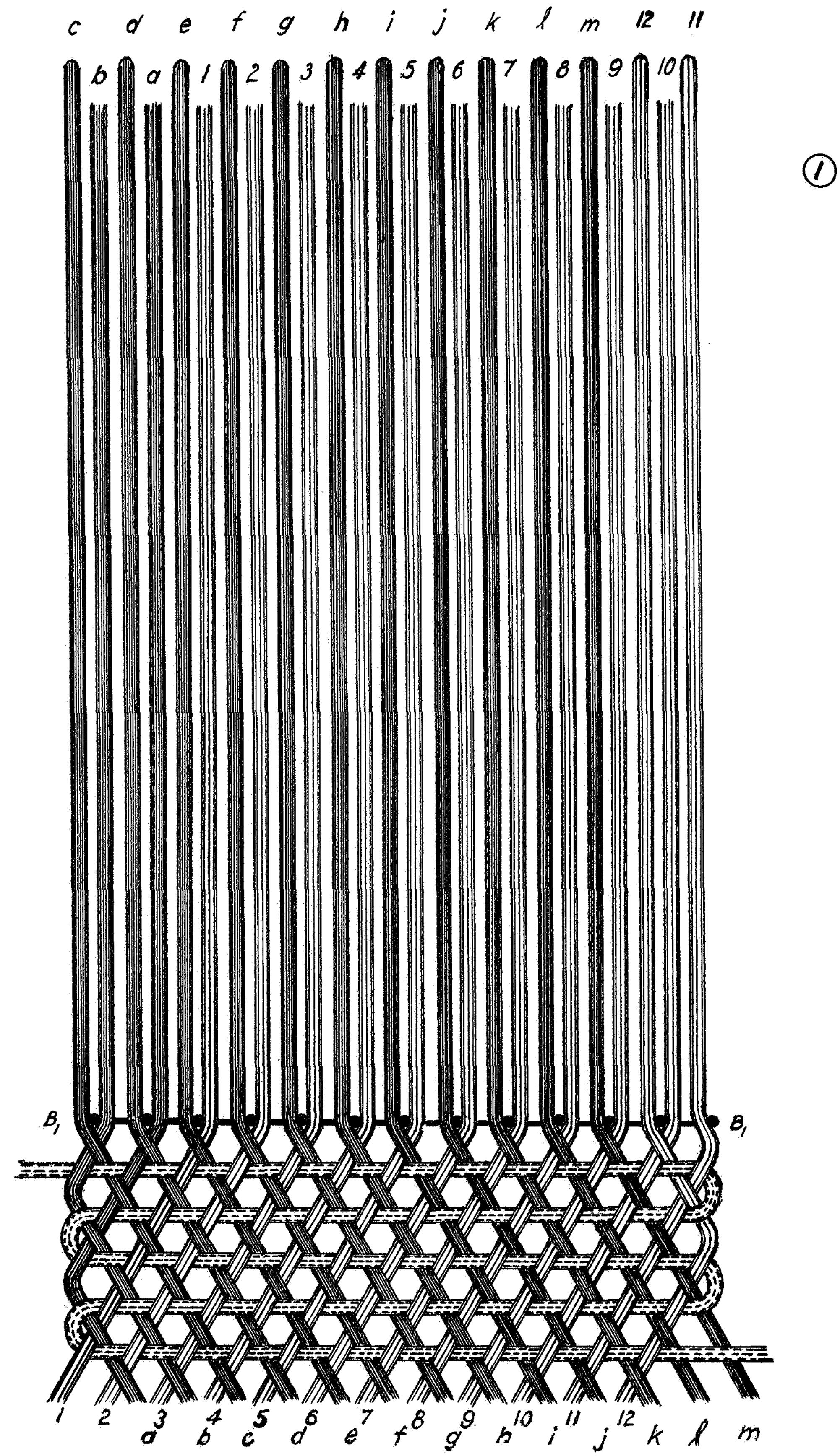


Fig. 6 - Plan View of First Basic Position for weaving Basic Weave.

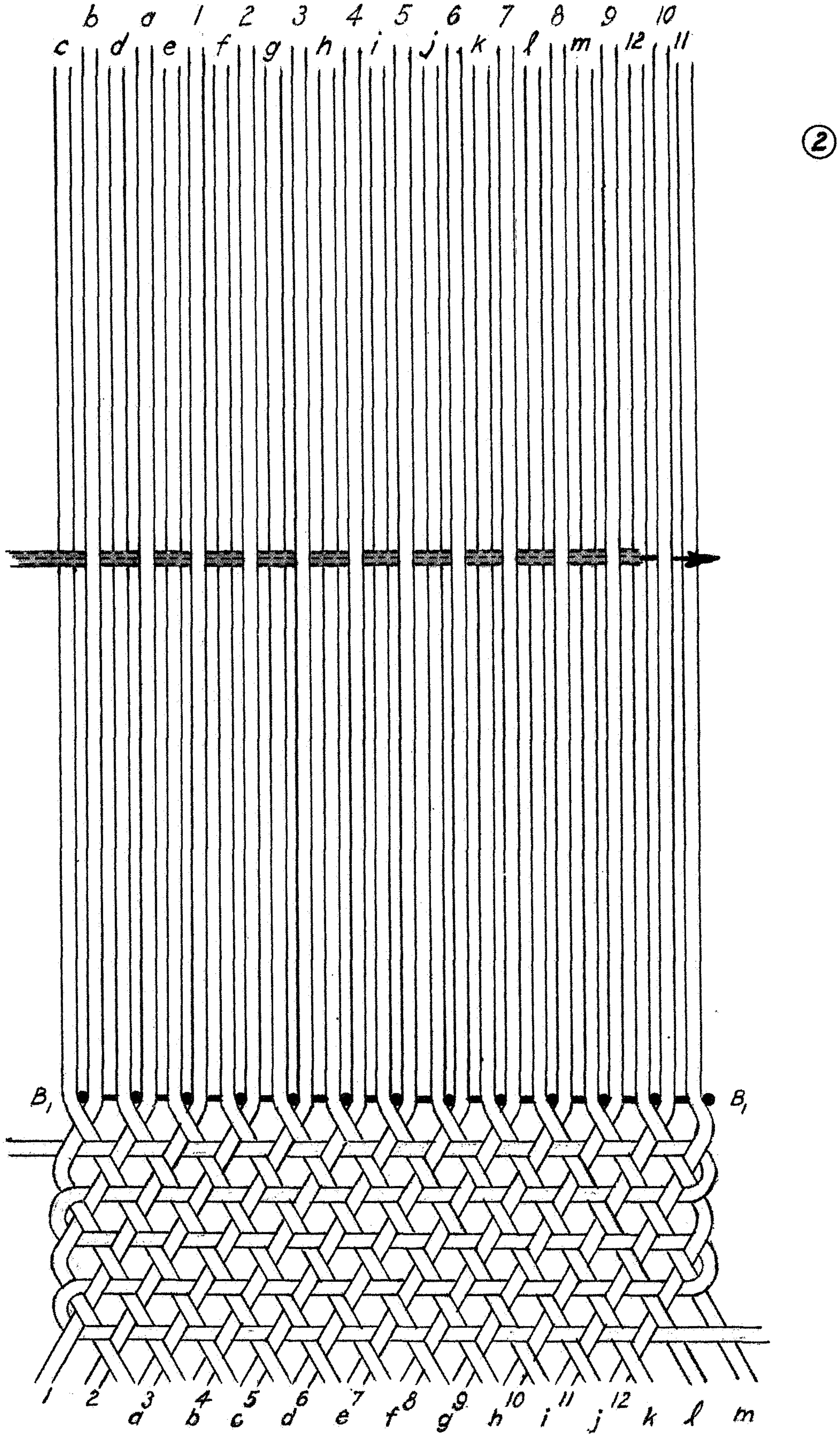


Fig. 7. - Plan view of second step in weaving cycle for Basic Weave: Shed Formation and Pick Insertion.

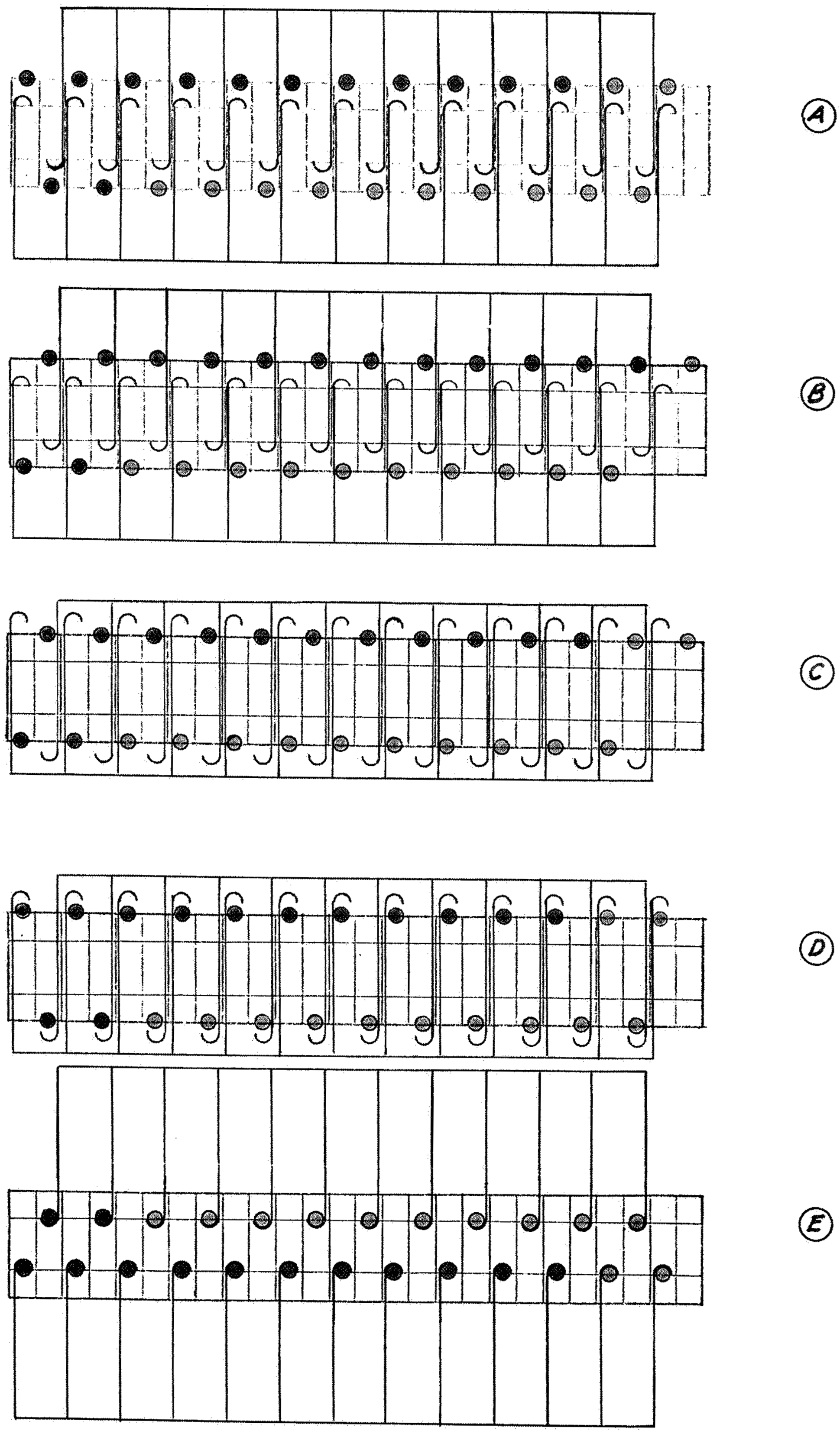


Fig. 8. - Schematic representation of transverse motions of warp yarns to make room for insertion of hooked-needle heddles for shed formation for the Basic Weave .

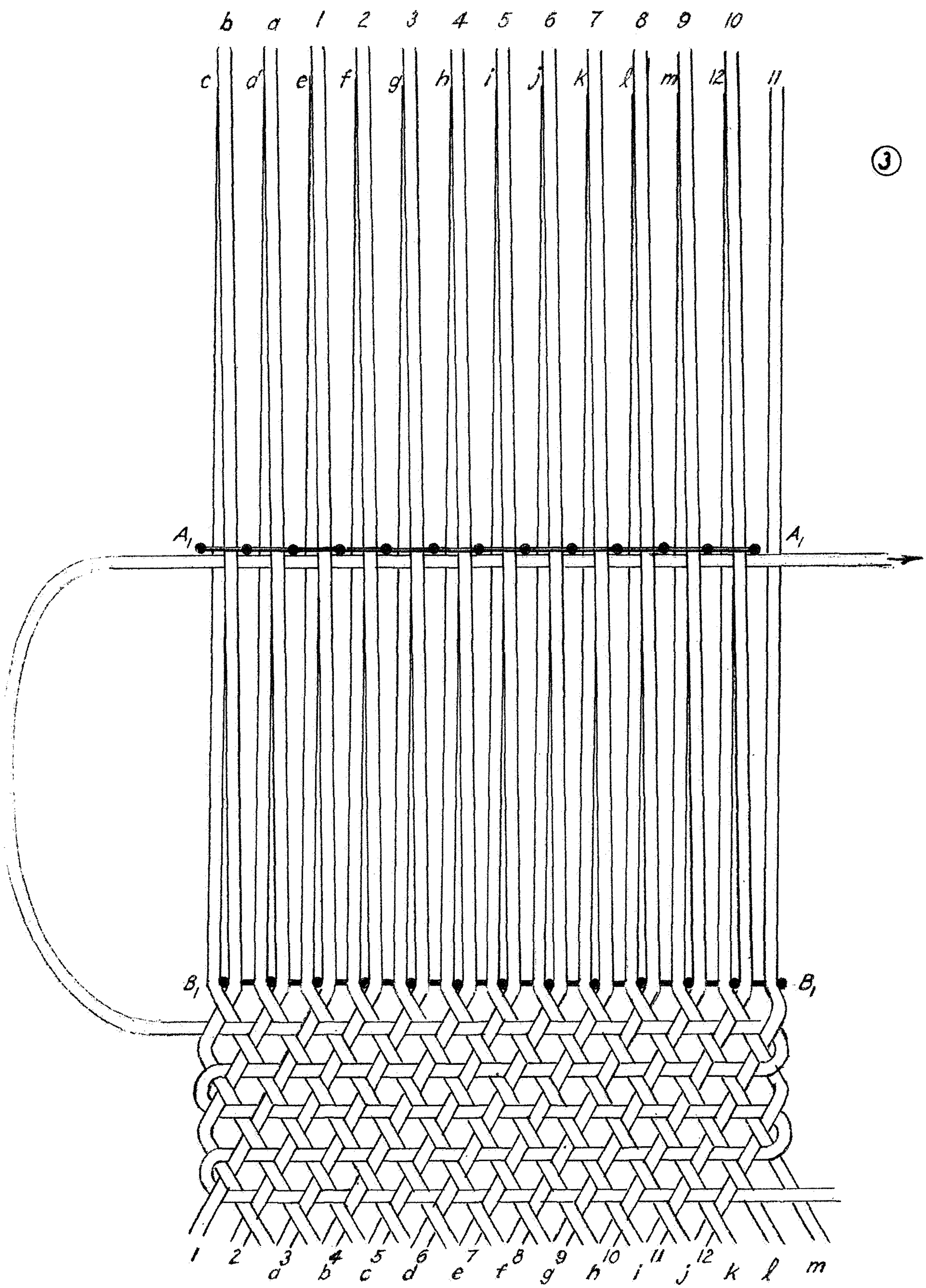


Fig. 9 - Plan view of third step in weaving cycle for Basic Weave: A_1 Beater Insertion and Pick Beat-Up.

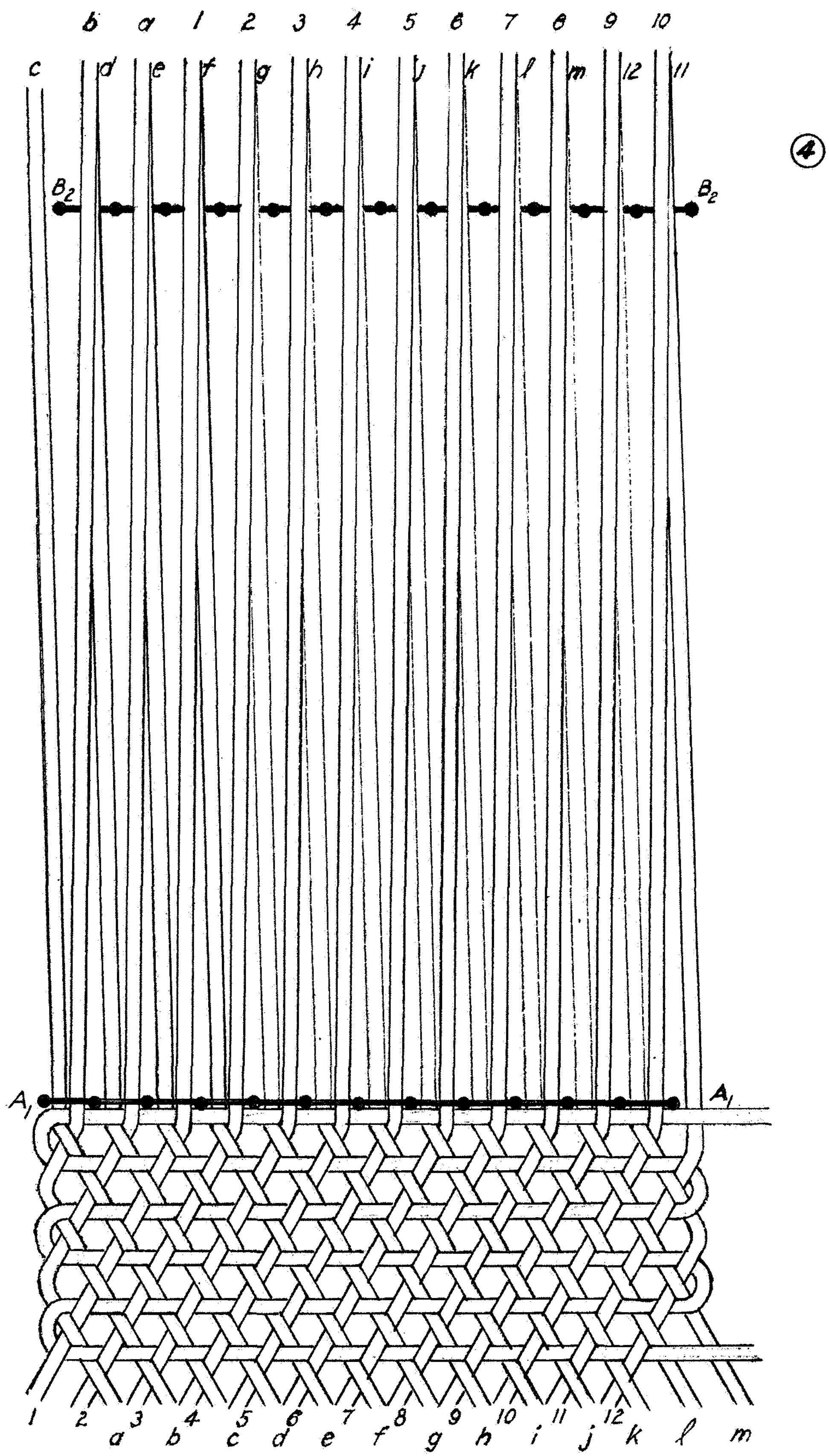


Fig. 10. - Plan view of fourth step in weaving cycle for Basic Weave: B_2 Beater Insertion and Continuation of Pick Beat Up.

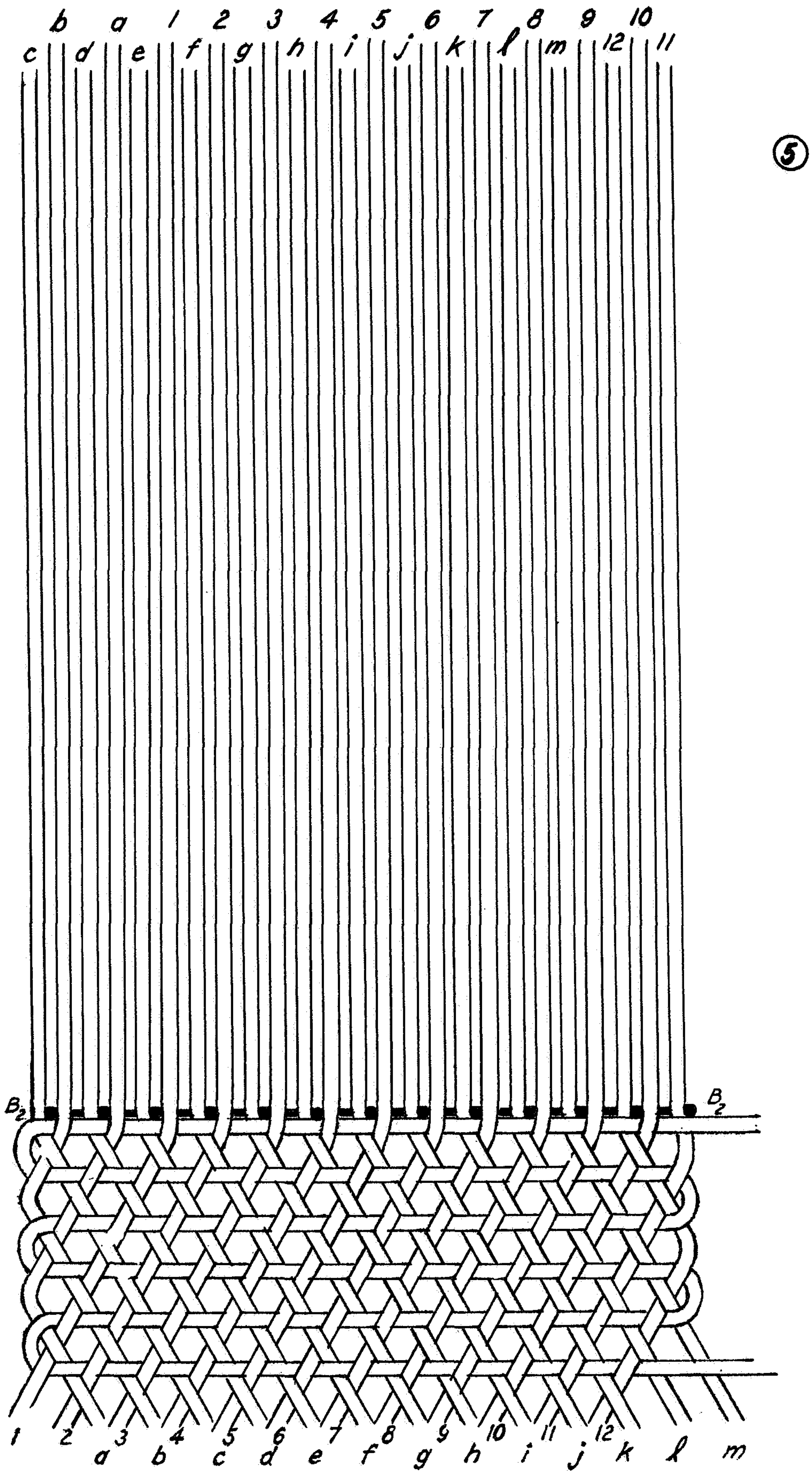


Fig. 11. - Plan view of fifth step in weaving cycle for Basic Weave: Conclusion of Pick Beat-Up.

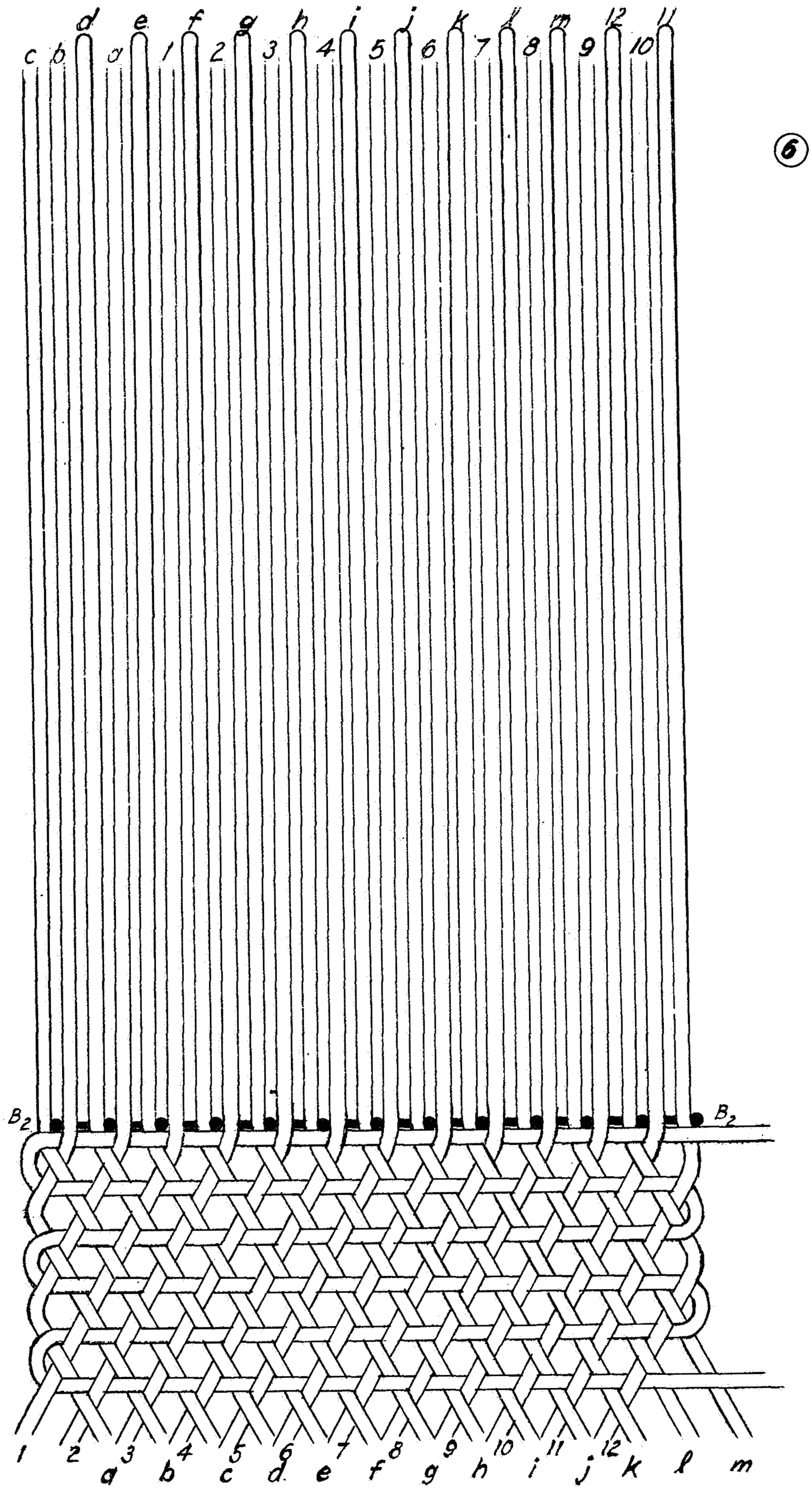


Fig. 11. - Plan view ot sixth step in weaving cycle for Basic Weave: Un-Making of Shed; Advance of Left-End Yarn.

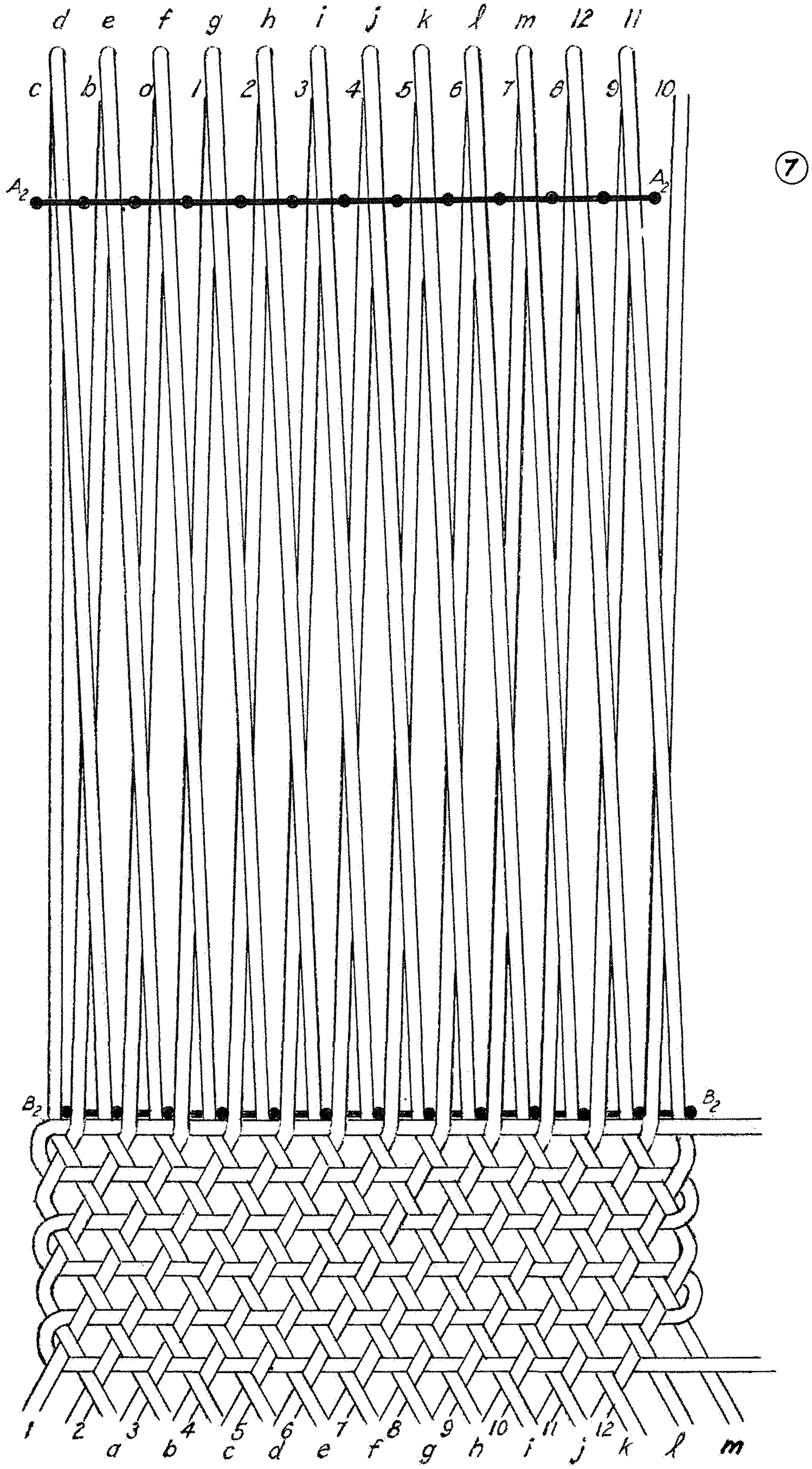


Fig. 12. - Plan view of seventh step in weaving cycle for Basic Weave: Warp Advance; A_2 Beater Insertion.

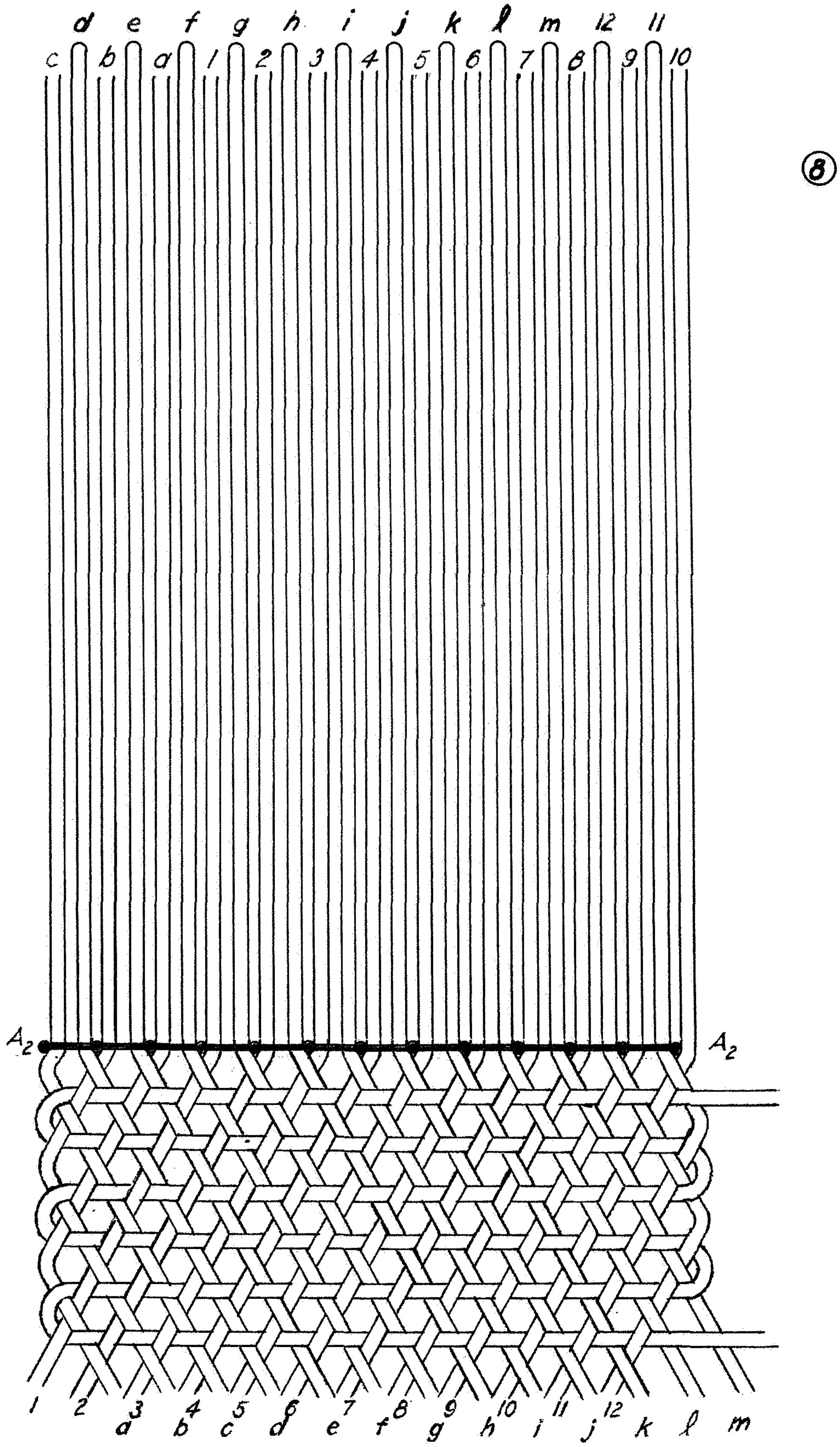


Fig. 13. - Plan view of eighth step in weaving cycle for Basic Weave: Warp Beat Up.

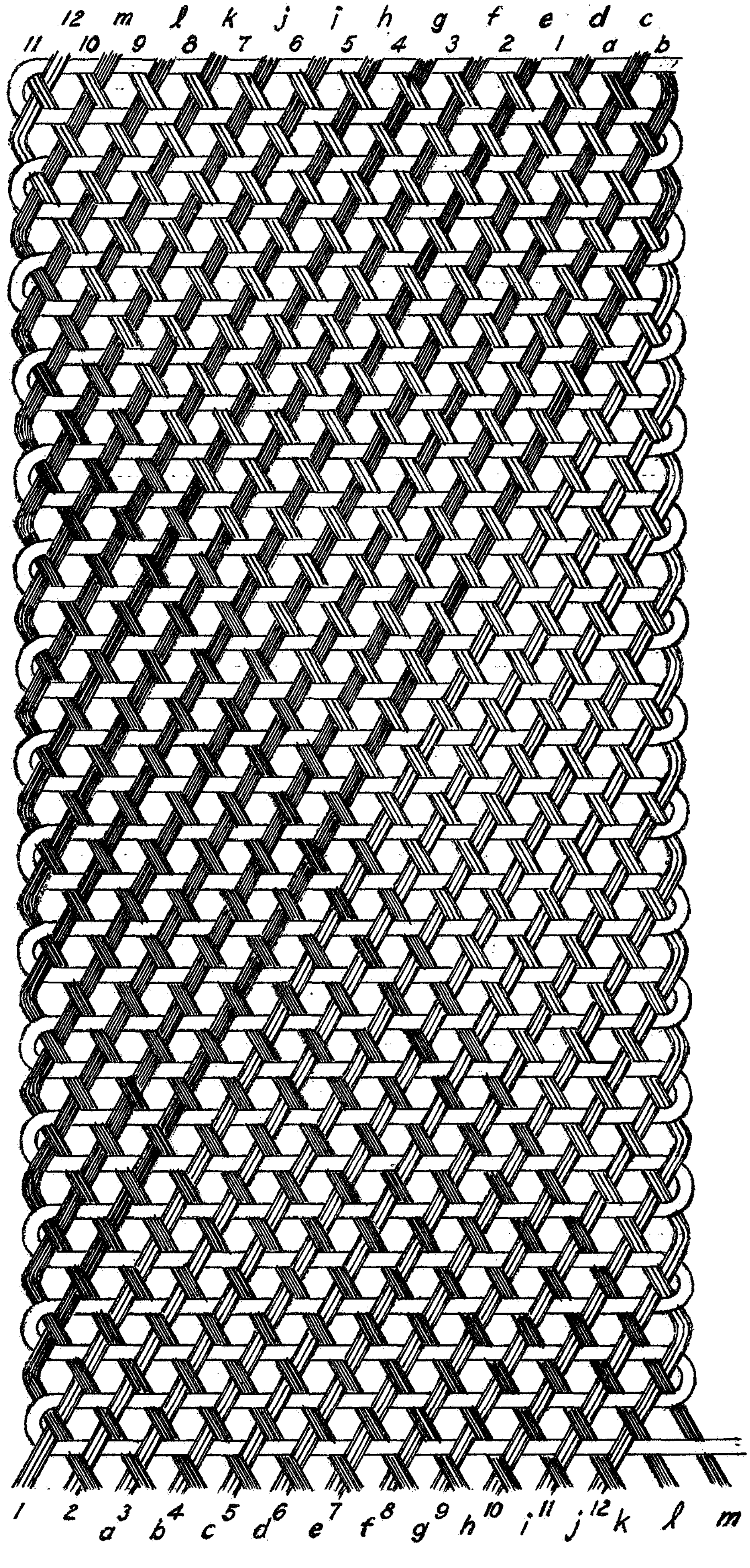


Fig. 14. - Plan view of Basic Weave with odd number of warp yarns showing like selvages on both sides of fabric.

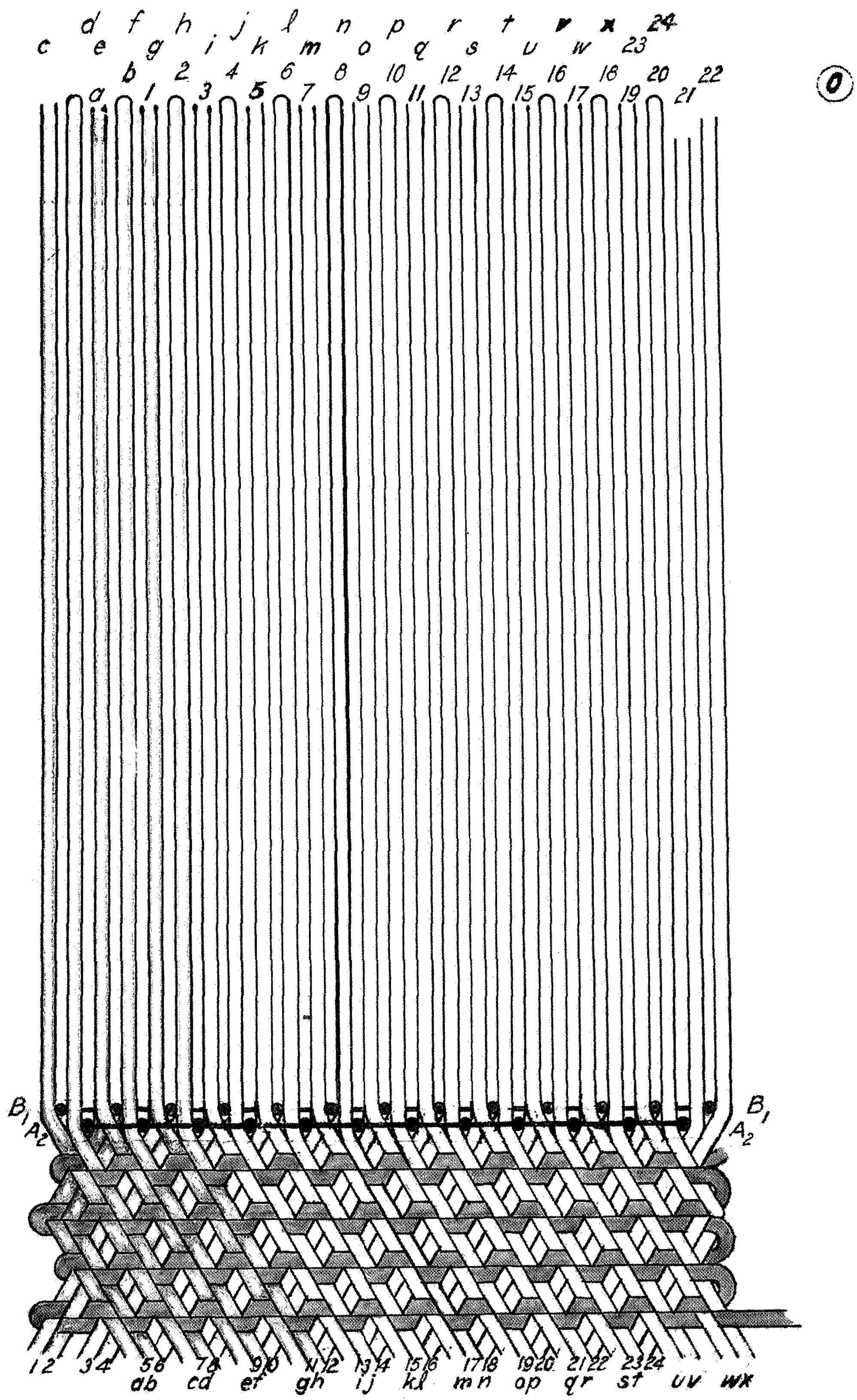


Fig. 15. - Plan View of First Basic Position for weaving 2nd Variant Weave.

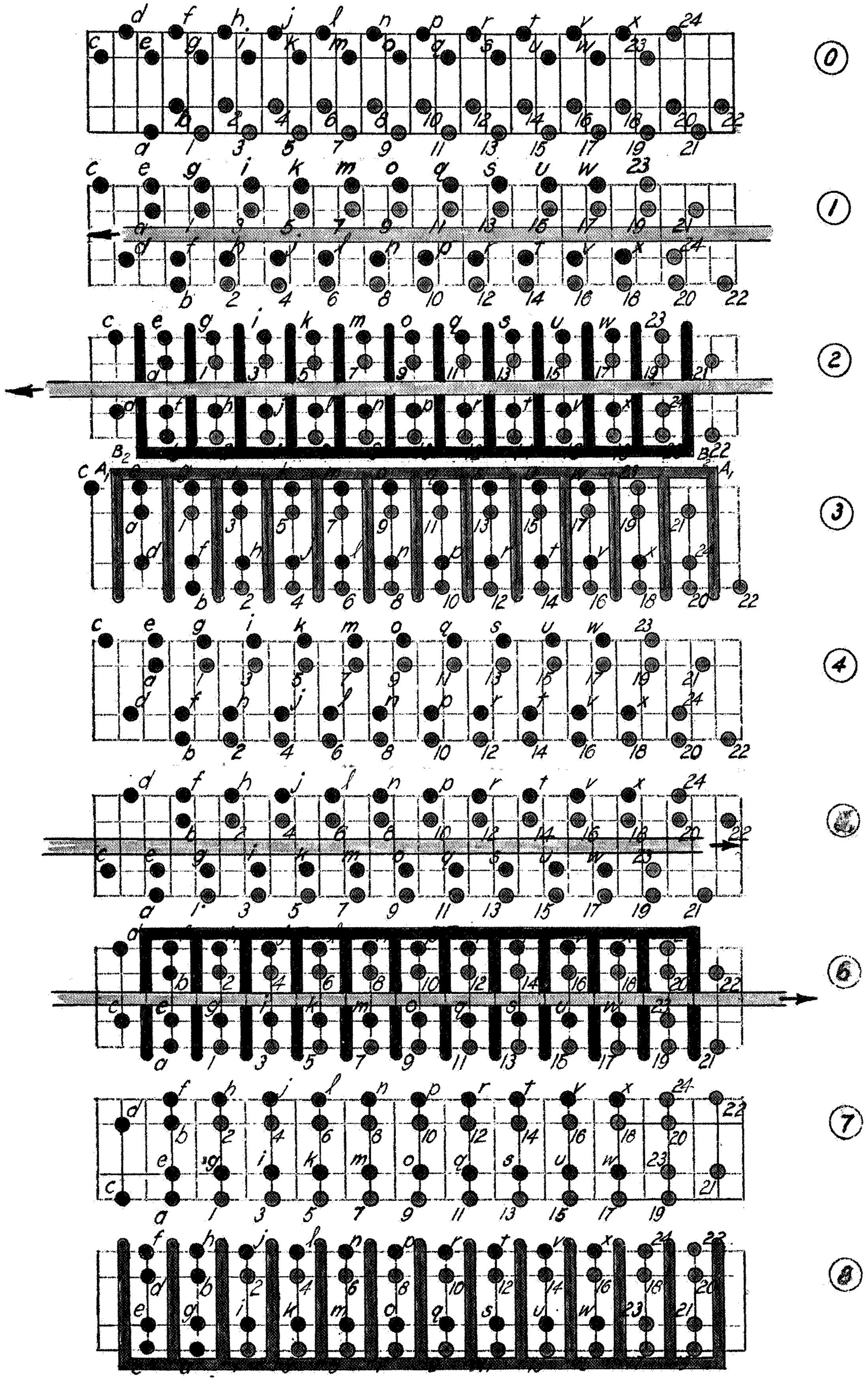


Fig. 16. - Cross-sectional elevation views of yarns and beaters near heddles for 2nd Variant Weave.

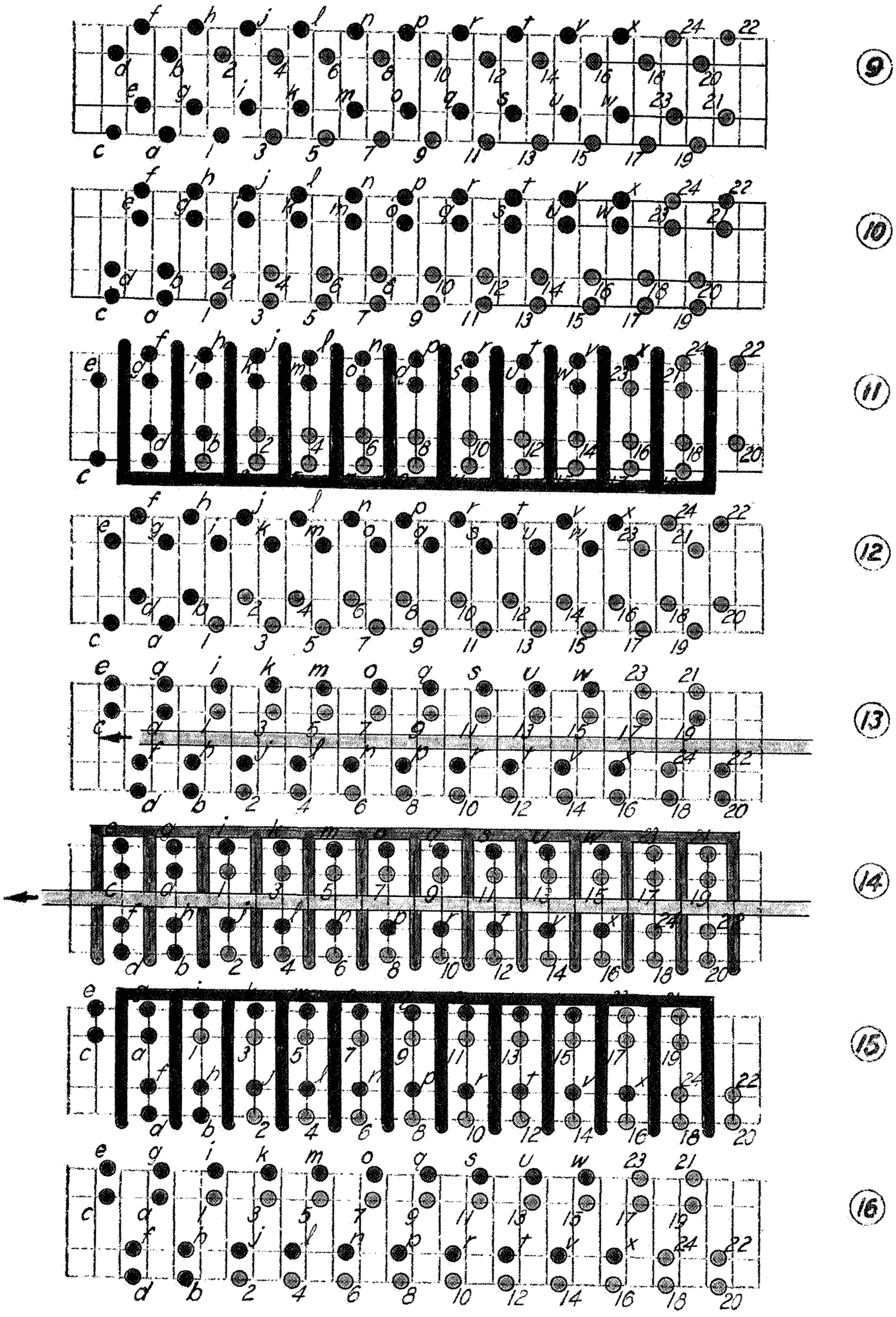


Fig. 16. - (continued)

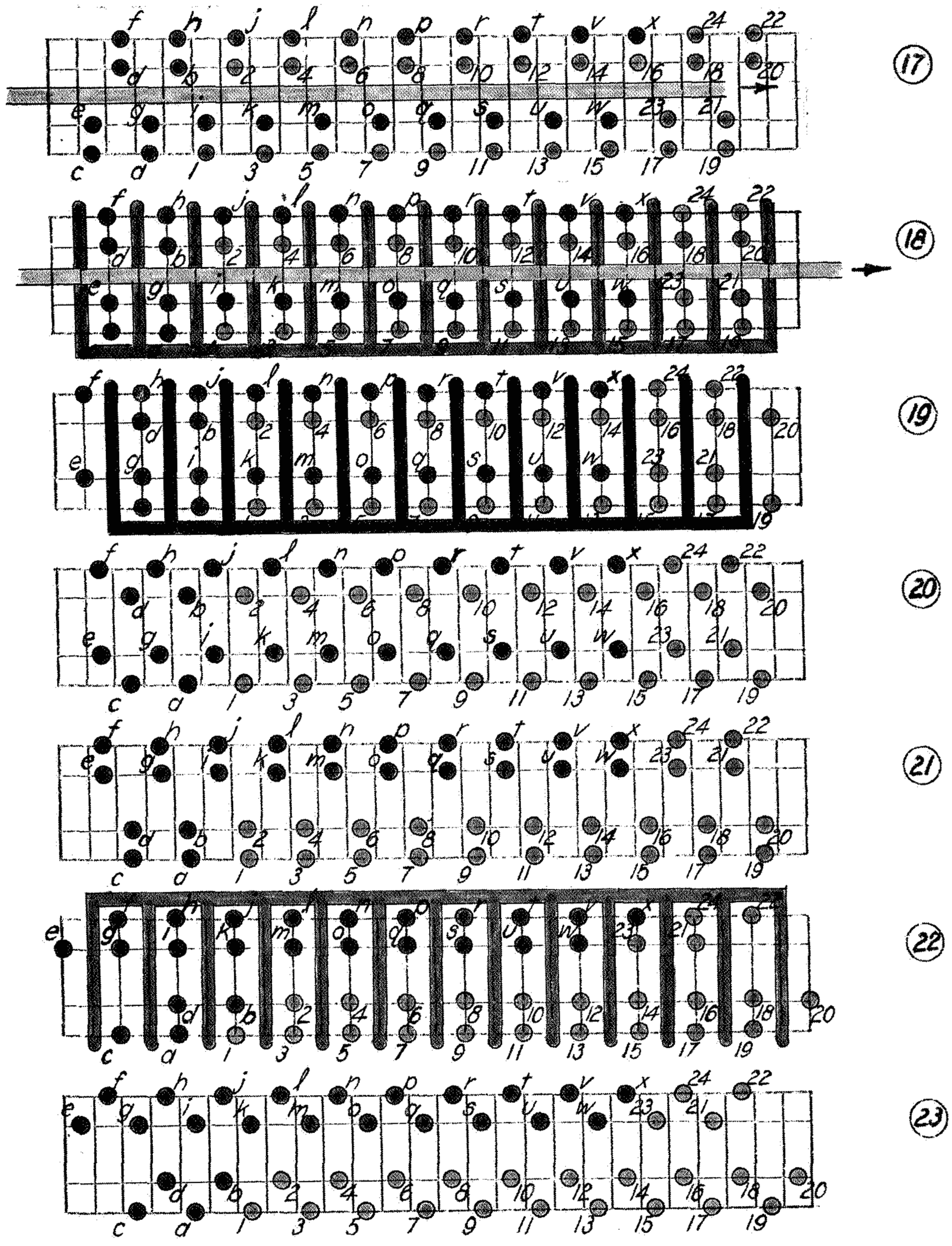


Fig. 16. - (concluded).

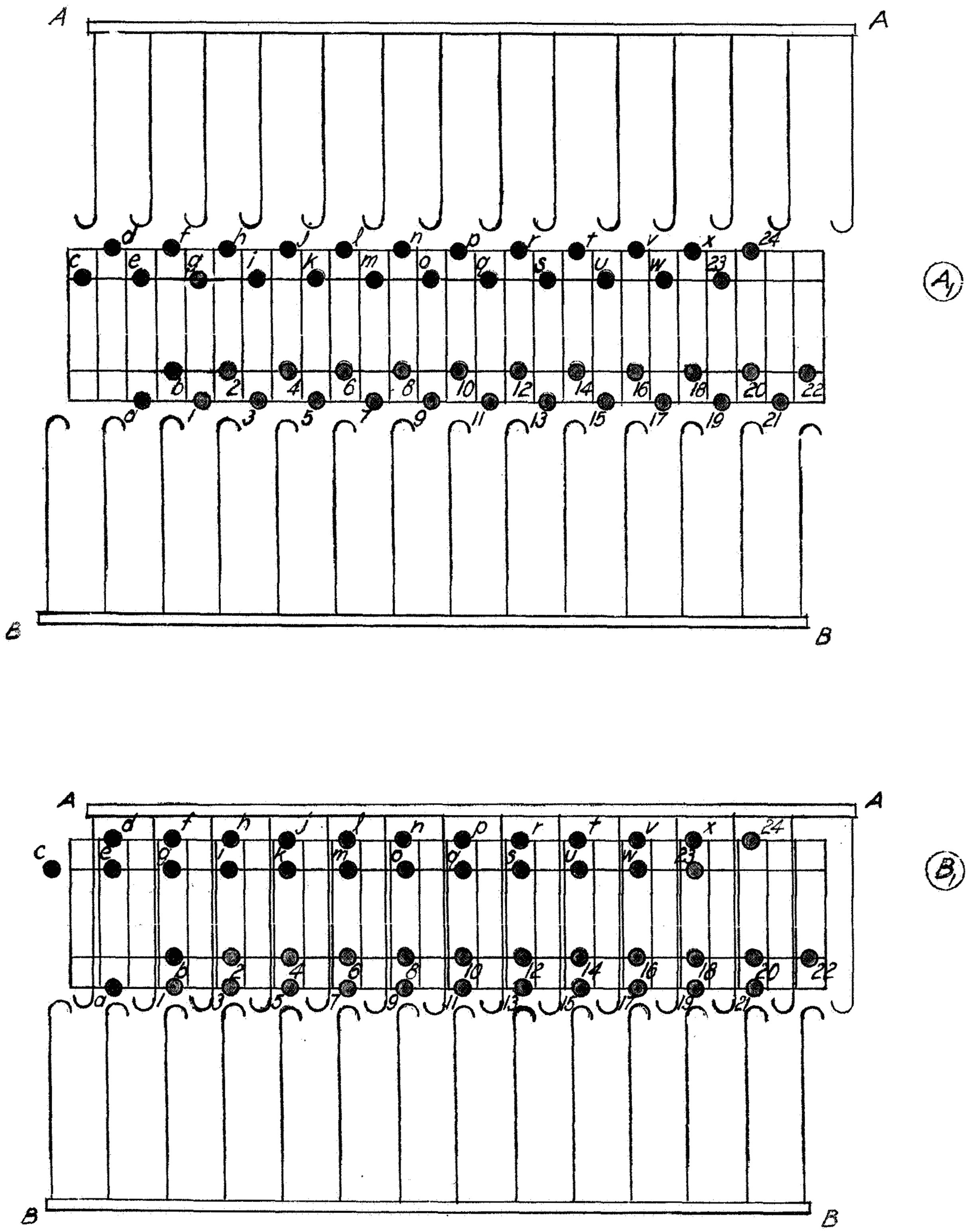
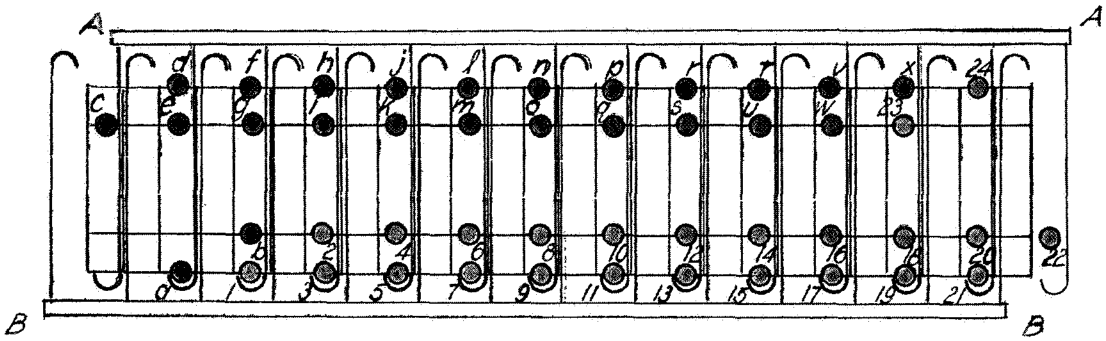
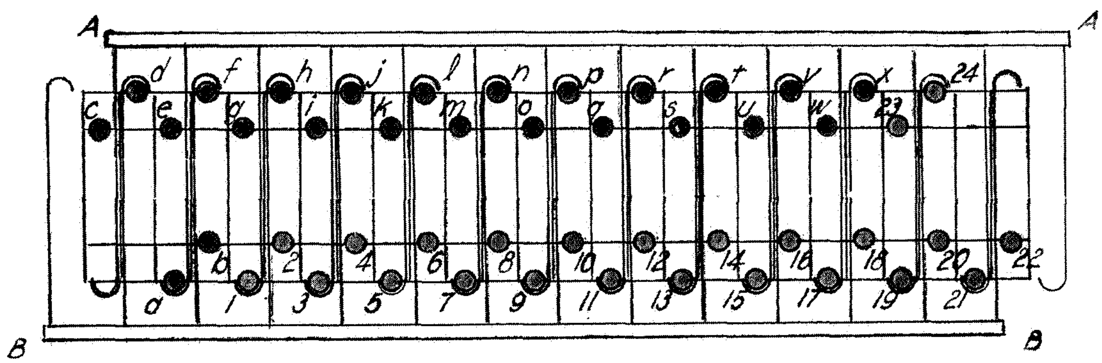


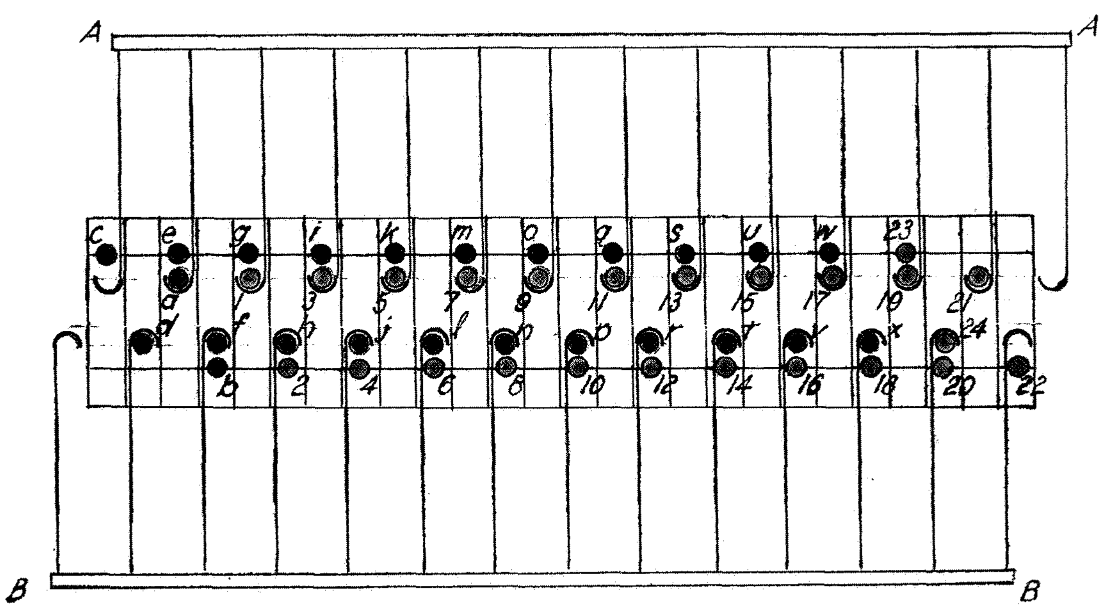
Fig. 17. - Schematic representation of transverse motions of warp yarns to make room for insertion of hooked-needle heddles for shed formation for the 2nd Variant Weave.



C_1



D_1



E_1

Fig. 17. - (Continued)

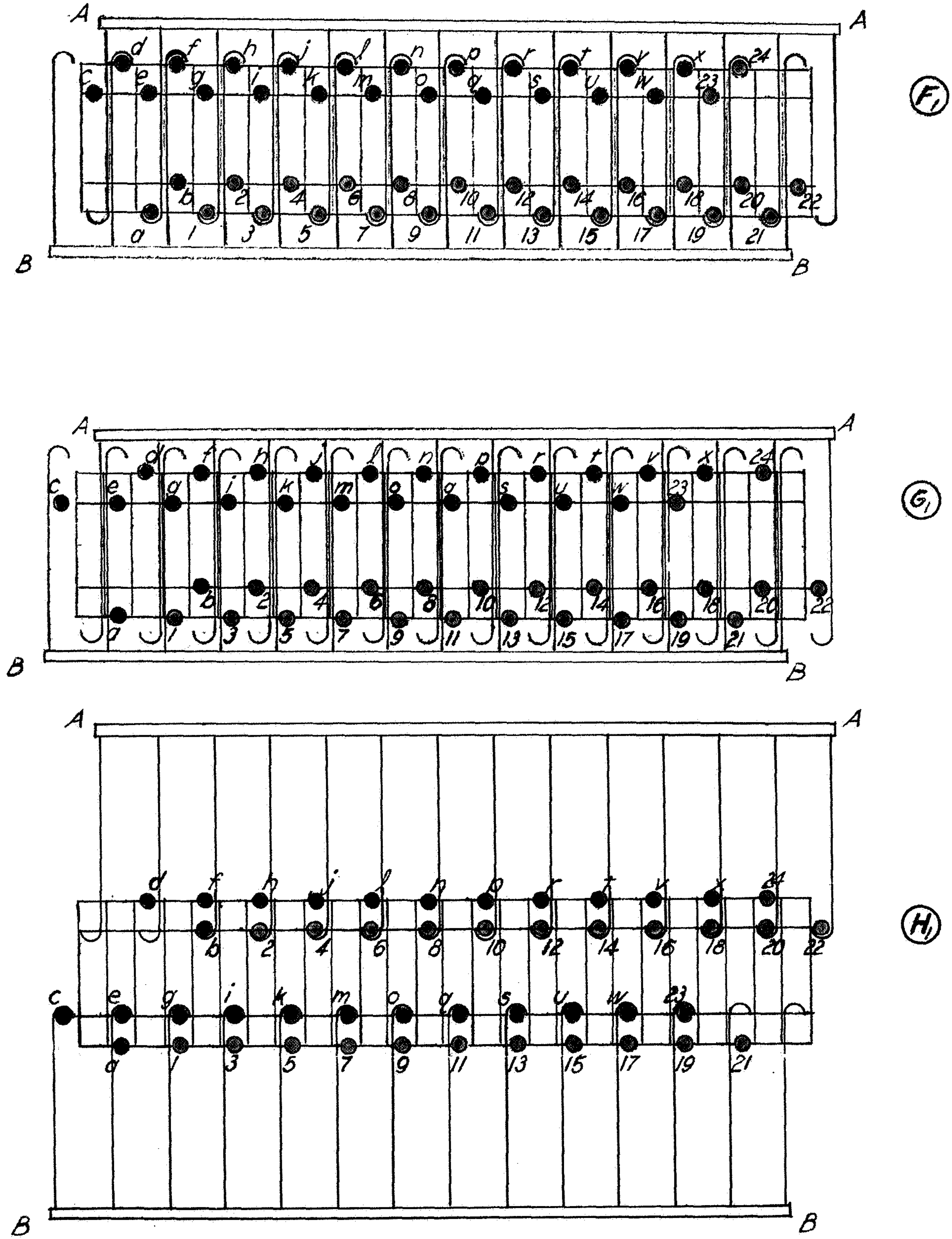
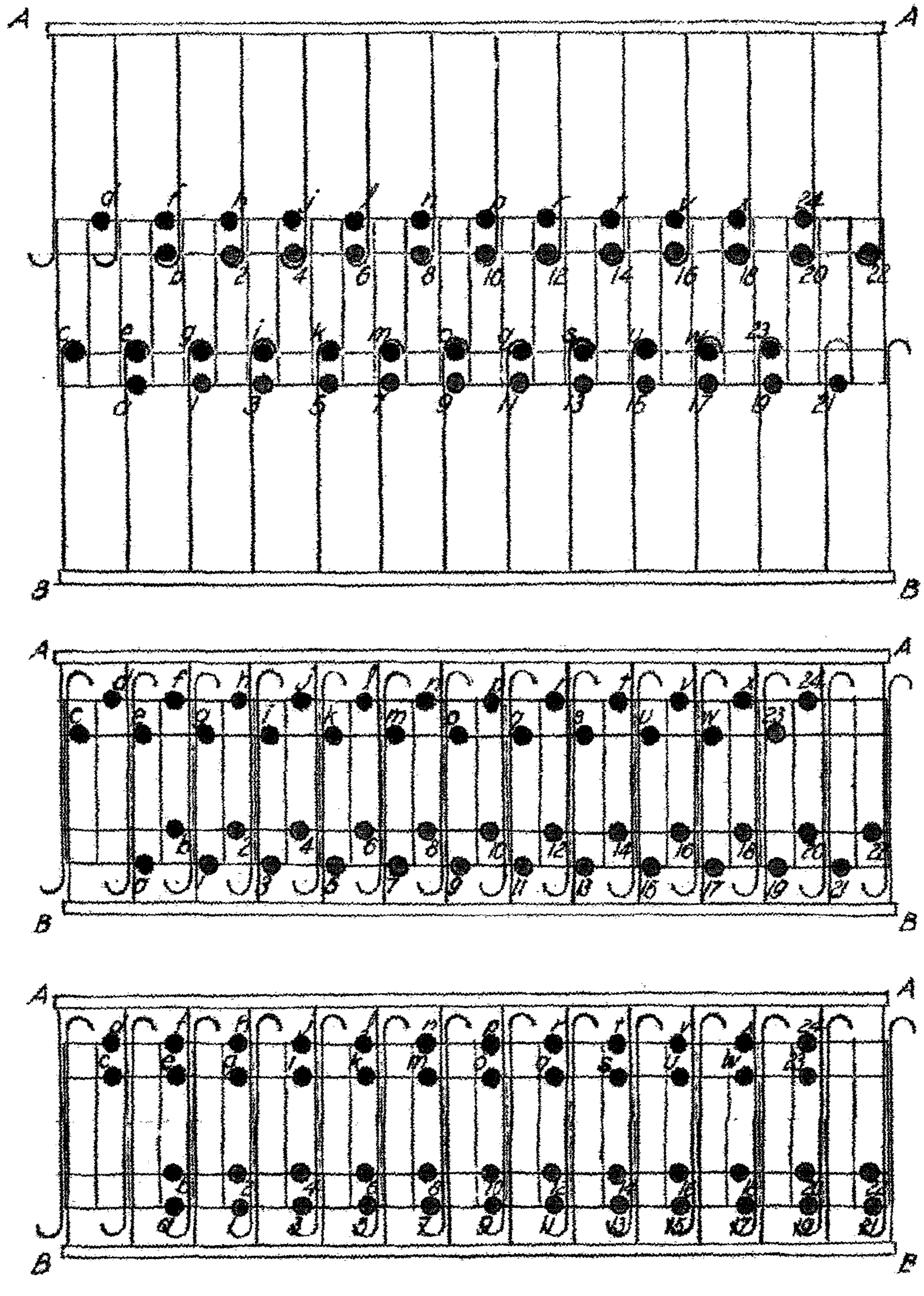


Fig. 17. - (Continued.)

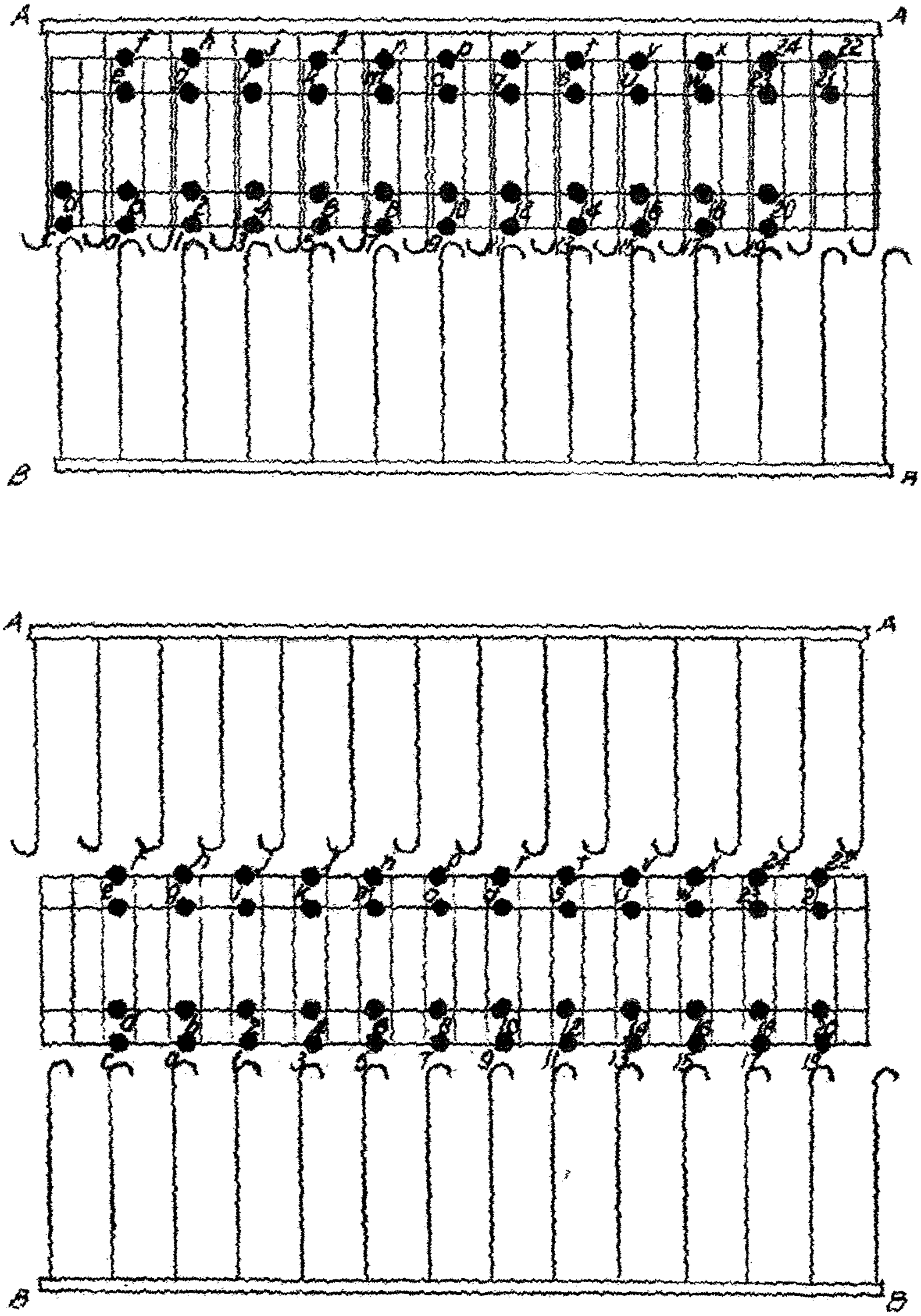


I_1

J_1

K_1

Fig. 17. - (Continued.)



L_1

M_1

Fig. 17. - (Concluded).

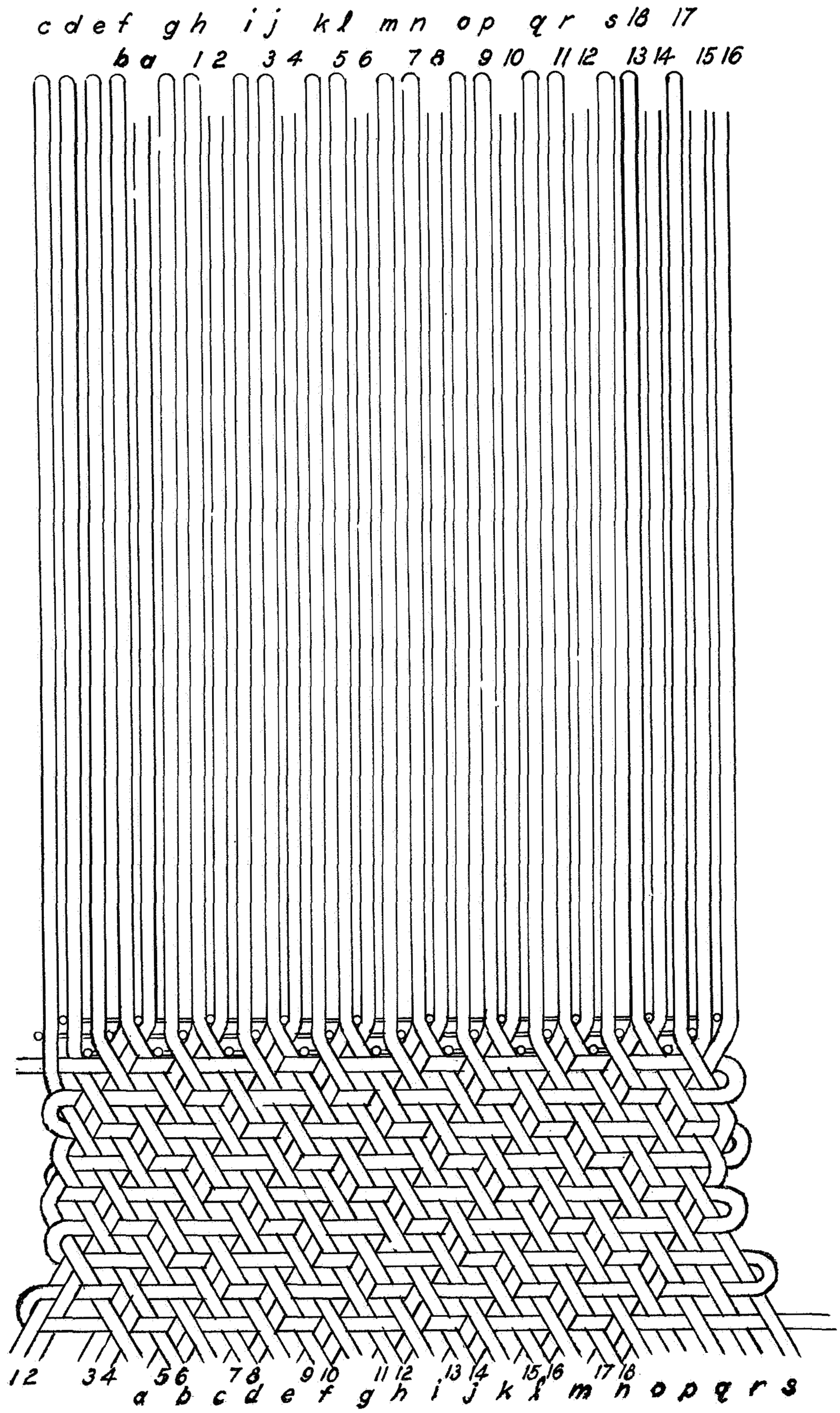


Fig. 18. - Plan View of First Basic Position for weaving 1st Variant Weave.

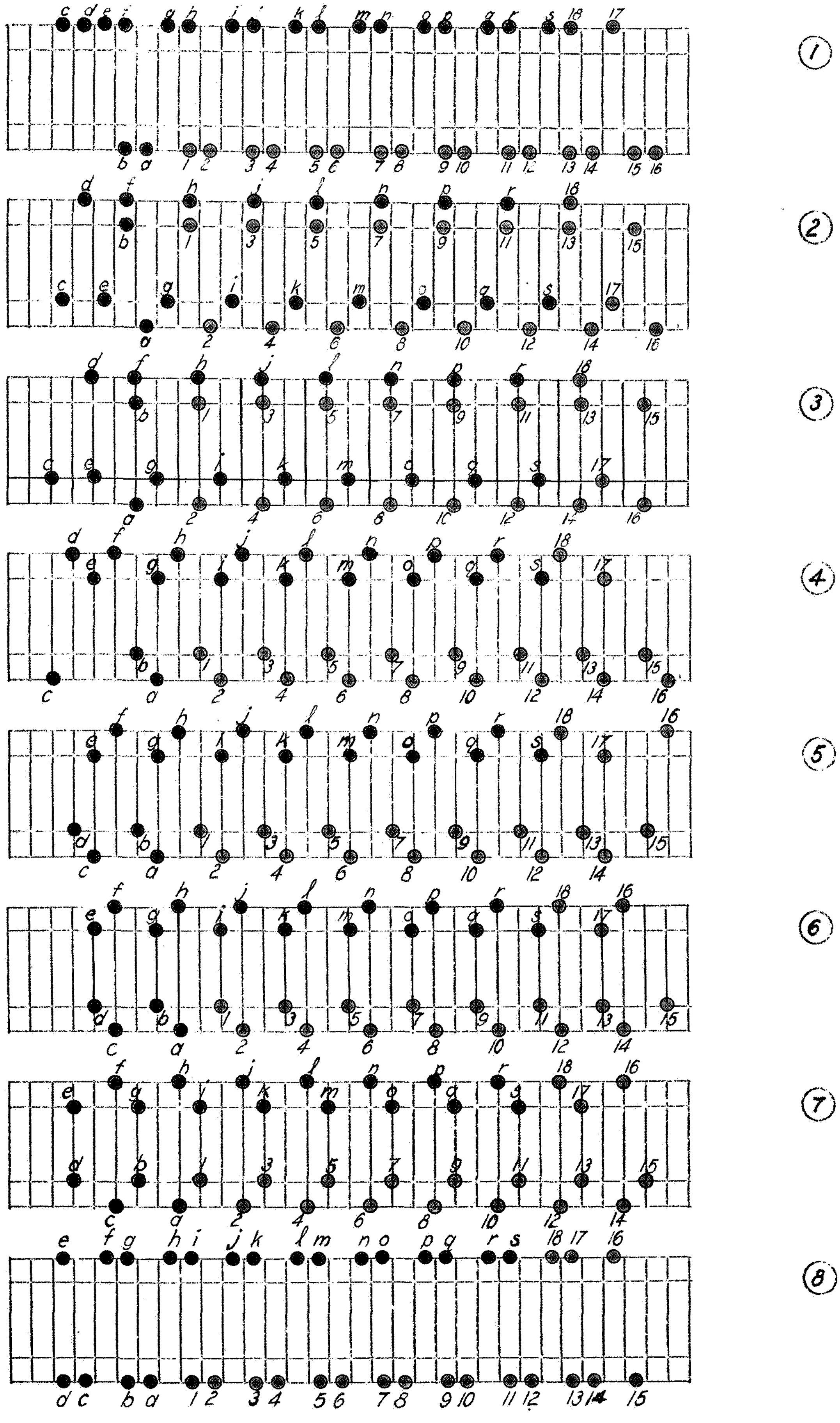


Fig. 19. - Cross-sectional elevation views of yarns near heddles for 1st Variant Weave.

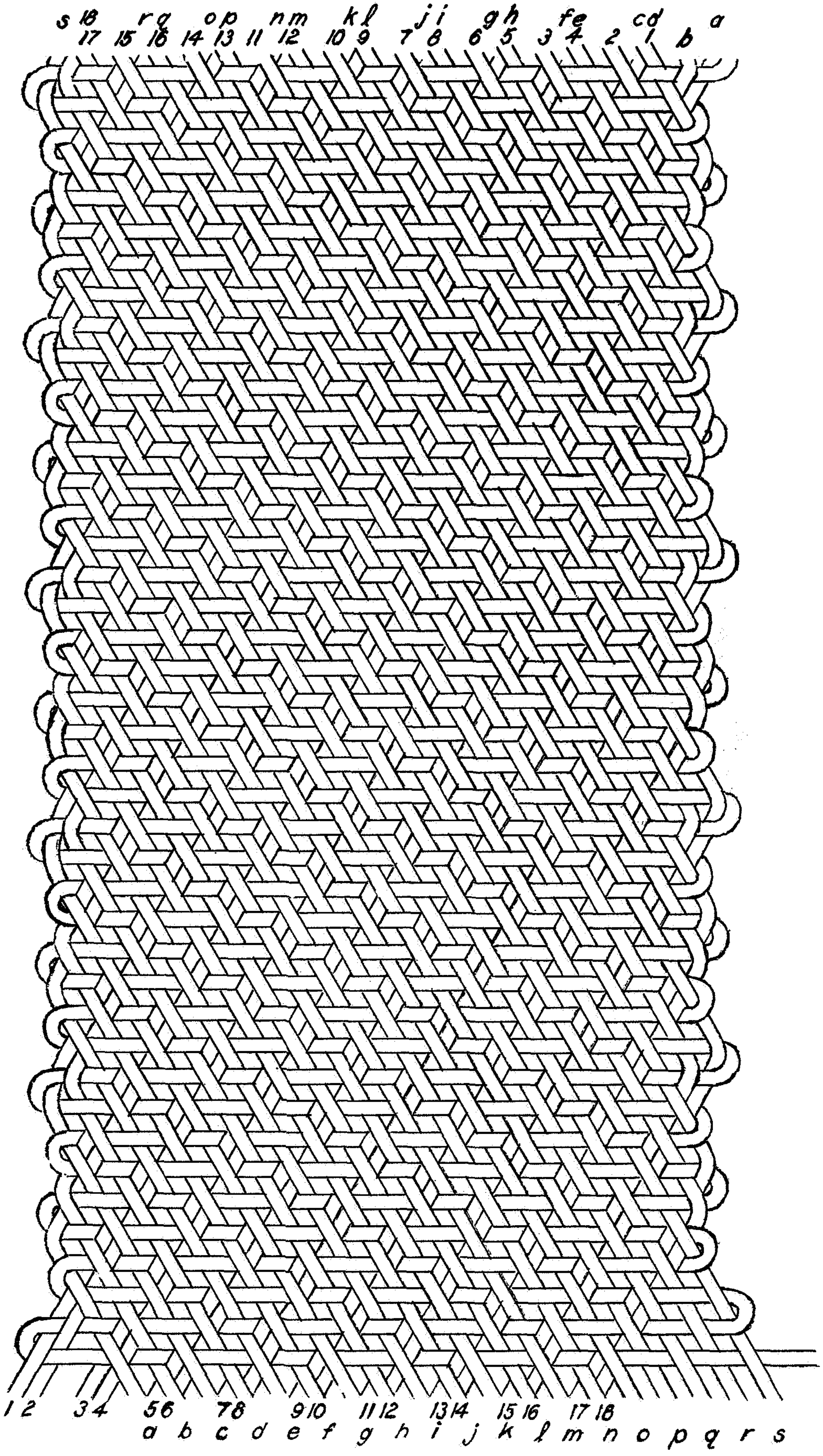
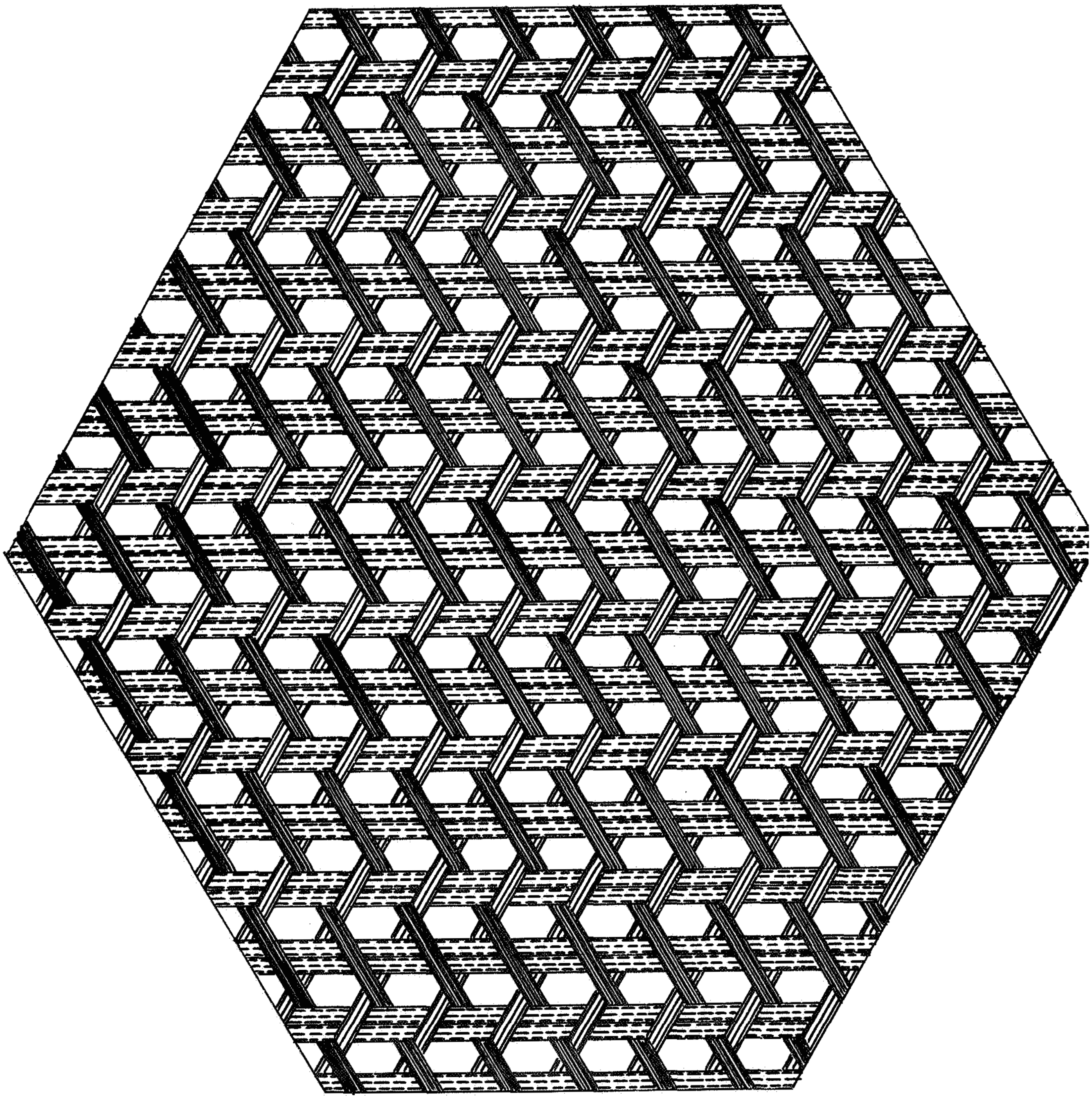


Fig. 20. - Plan view of 1st Variant Weave with even number of warp yarns showing varying selvages.

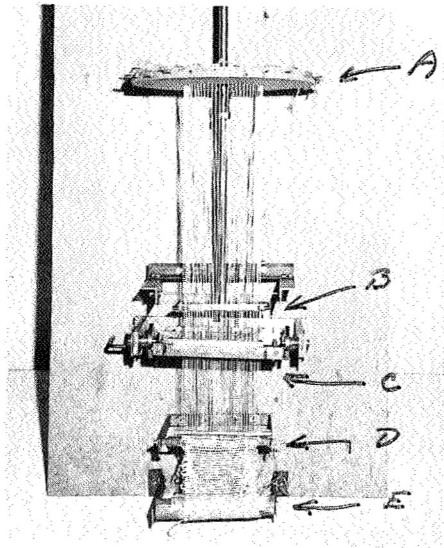
DOWEAVE TRIAXIAL FABRICS - LOOSE WEAVE

31 1/4% POROSITY

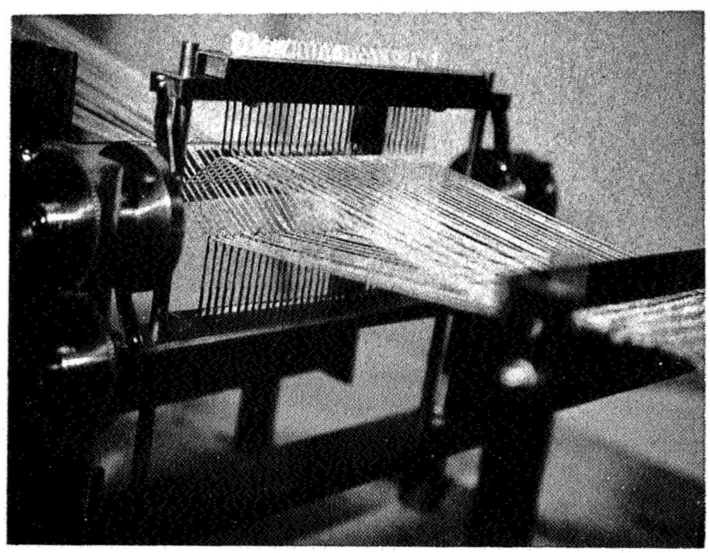


Obverse

Fig. 21 - Approximation to 1st Variant Weave achieved by weaving with hook-needle heddle loom.



Overall view



View showing shed formation

Fig. 22 . Bread-board loom for production of samples.

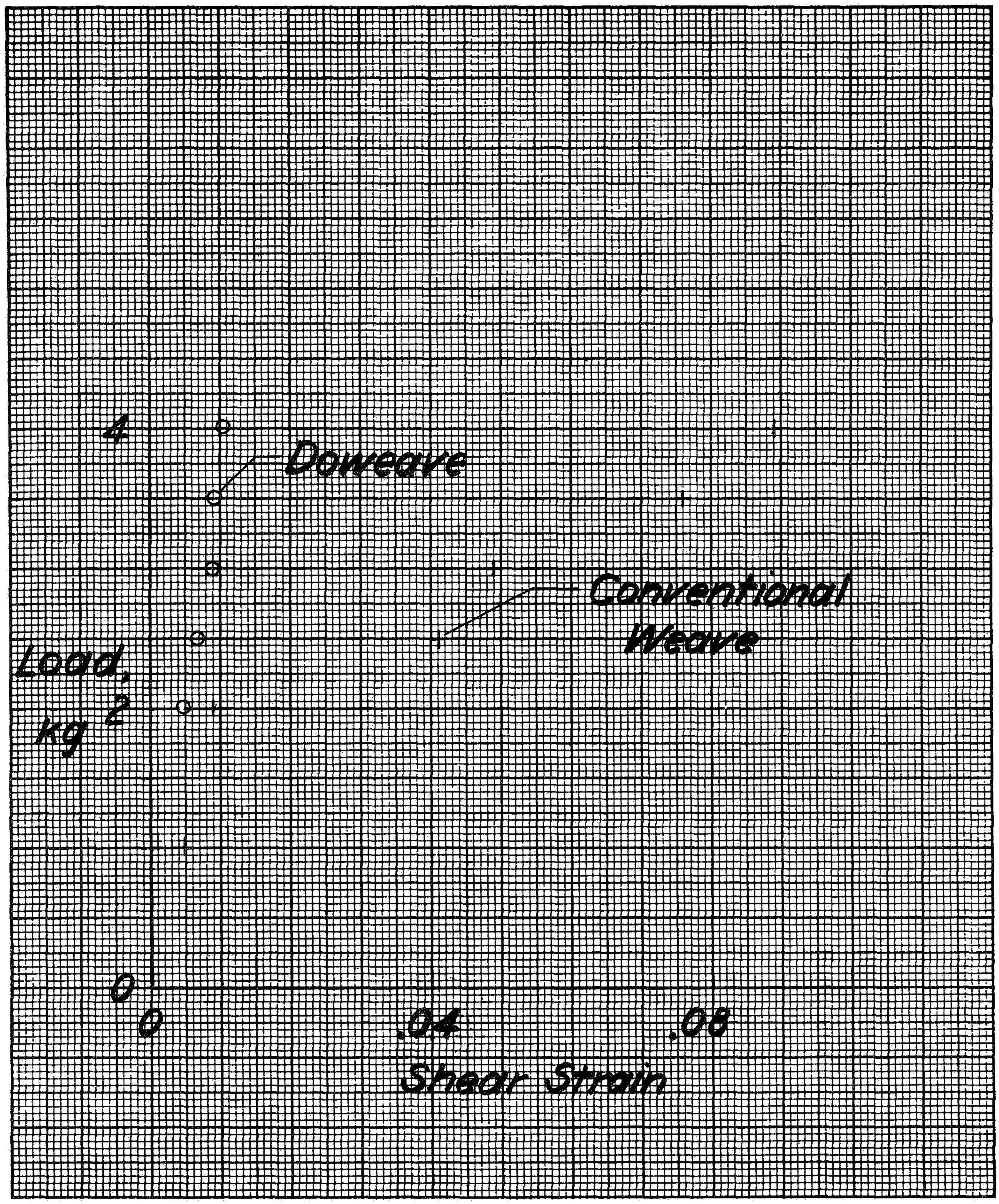


Fig. 23. - Experimental measurement of shear stiffness of Basic Doweave and comparable conventional fabric.