Characterization of Deformations of Multiaxial Warp Knitted Fabrics during Forming Process*

Hu Jinlian
Institute of Textiles and Clothing, The Hong Kong Polytechnic University
Jiang Yaming
Composites Research Institute, Tianjin Polytechnic University, Tianjin, 300191

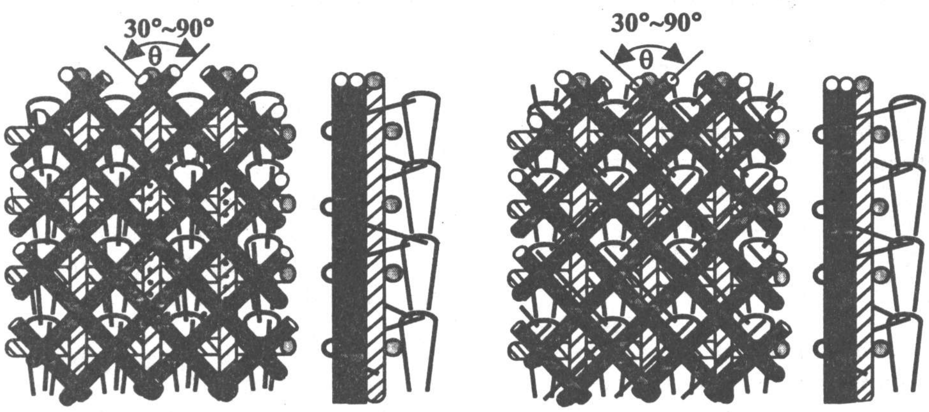
The typical structure (with four inserting yarn systems) of multi-axial warp knitted fabrics shows unsatisfactory conformability according to hemisphere pressing experiments. The structure containing only two bias inserting yarn systems (TBMWK fabric), however, proves to possess good conformability. This paper characterized in detail the forming behavior of TBMWK fabric. It was found that the two bias inserting yarn systems tend to gather always along the weft direction, and the angles between them along this direction are basically linear to the perpendicular distances from the measured points to the longitudinal axis of the hemisphere. And the trendline's slope of the above relation is not sensitive to the magnitude of diameter of the pressing hemisphere. The shape of flat TBMWK fabric that can yield the corresponding hemisphere is close to a rectangular, not to a square as presented by the woven fabric.

Keywords: MWK fabric, conformability, forming and characteristics.

Introduction

Multiaxial warp knitted (MWK) fabrics are a family of high technical fabrics, which was developed in the early of 1980's and entered into the field of structural composites in 1990's. MWK fabrics have a wide application scope ranging from geotextiles, pneumatic materials and construction materials to automobiles, aerospace-quality components as well as vessel-body parts due to its desired mechanical properties, flexibility in design and low production cost[1,2]. The typical structure of a MWK fabric is illustrated in Fig.1.

MWK fabrics obviously also belong to the scope of 2D reinforcements even though there is a stitching system (chain or tricot loops) which partly orients along the thickness direction and accordingly improves the through-the-thickness strength as well as the inter-laminar shear resistance. This means that a forming process must be carried out in advance in order to form the original flat fabric into the desired 3D preform. There have been many papers[3-14] published in the forming study of woven fabrics, most of which are based on the main and important assumption that the two intercrossed yarn systems in a plain weave are pin-jointed together at crossovers. As far as MWK fabrics are concerned, however, the detailed research work on the deformations during forming process as well as the subsequent simulation is still unavailable in the literature.



(a) Chain structure (b) Tricot structure
Fig.1 Typical structure of a MWK fabric

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In the 2D fabric forming process, the main deformation modes usually include in – plane tension, transverse compression, in – plane shear and out – of – plane bending (Fig.2), of which the in – plane shear is most important. And to some degree, it can be regarded as the dominant factor that dictates whether the desired 3D surface can be formed or not.

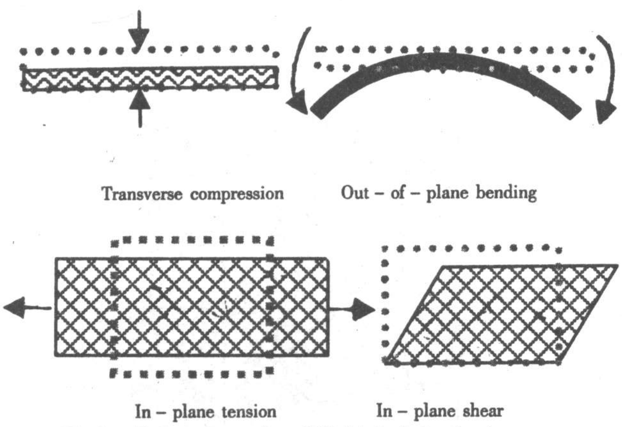
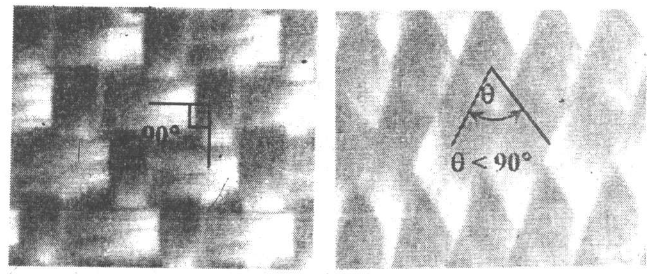


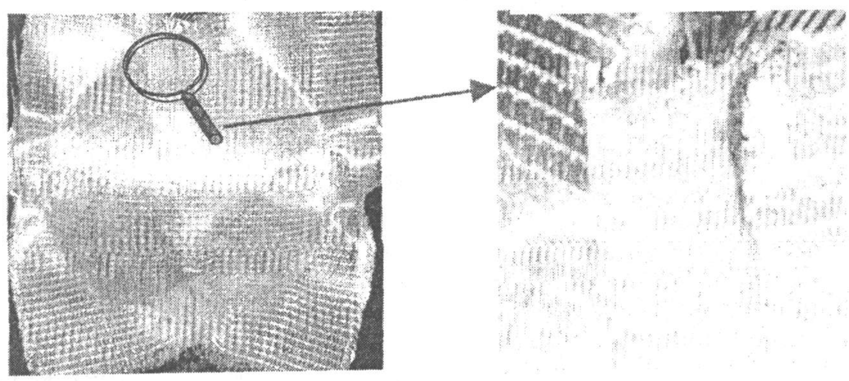
Fig.2 Deformation modes of 2D fabric during forming process

For woven fabrics, the in – plane shear deformation directly determines the magnitude of the locking angle[8], which will determine the jamming state during forming. It can be seen according to experiments that woven fabrics are formed into a 3D surface just through the changes of the original right angle between the warps and wefts, as illustrated in Fig.3 (a woven fabric with yarns of glass filament bundles). The research of many other authors[3-5] has also showed this. Actually, under the assumption of inextensibility of the constituent yarns, the in – plane shear deformation (trellis effect) really plays a leading role in the forming process. If the fabric can be sheared to a great degree, which means the locking angle

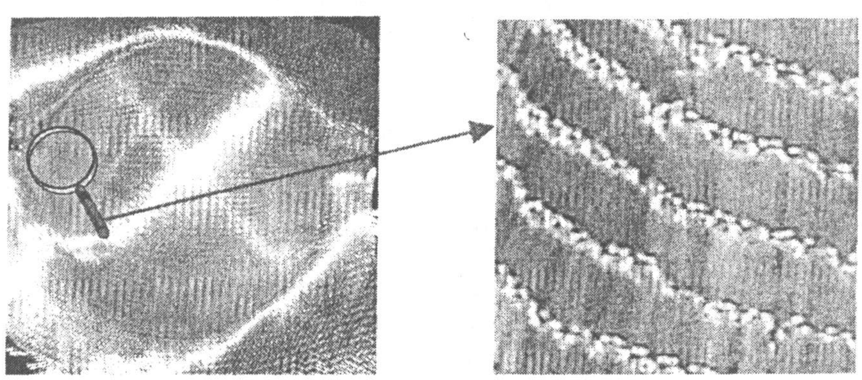


(a) Undeformed state (b) Deformed state

Fig.3 Trellis effect of the woven fabric



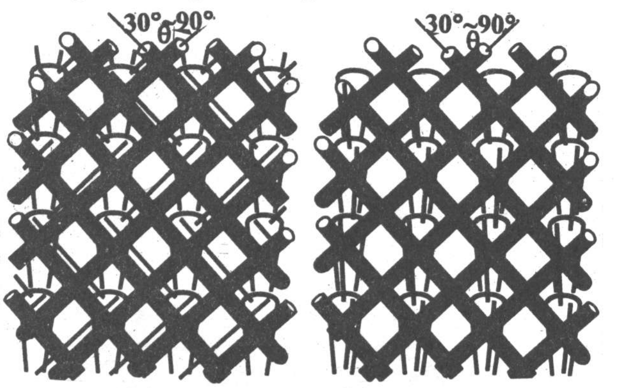
(a) Typical structure (as shown in Fig.1, inserting yarn are glass fiber bundles)



(b) MWK fabric with only two bias inserting systems (as shown in Fig.5)

Fig.4 Hemisphere pressing experiments of MWK fabrics is sufficiently small, a better forming will be resulted and more complex 3D surface may be formed. Once the locking angle is exceeded, wrinkles or buckling will occur.

As far as MWK fabrics are concerned, the situation is quite different due to the different geometrical structures. Our earlier study[14] suggests that the typical structure of a MWK fabric (Fig.1) present an isotropy in the in – plane tensile properties, which is the unique mechanical advantage of this kind of fabrics. However, this is at the same time a disadvantage as far as the deformation possibility during forming process is concerned. As the dotted square marked in Fig.1 (a), represents a unit cell, which can never be sheared easily no matter how the in – plane shear force is exerted since there will be in all situations one or more systems of inserting yarns stretched by the shear force. This means that the typical structure of the MWK fabric is more difficult to deform, i.e. to conform to a 3D surface. As illustrated in Fig.4 (a), the hemisphere pressing experiment gives a proof to this analysis. Fortunately, a variation structure of MWK fabric (as shown in Fig.5) shows quite good conformability, as suggested by Fig.4 (b), in which the inserting yarns come gathered together along the weft direction.



(a) Tricot structure (b) Chain structure

Fig.5 A variation structure of MWK fabric (Containing only two bias inserting yarn systems)

It can be inferred from Fig.4 that the typical structure of MWK fabric is more suitable for used as plate or low – curvature – shell composite material, and the structure as illustrated in Fig.5 (hereafter in this paper called TBMWK fabric) has great potential in forming 3D complex preforms. Another variation structure of MWK fabric also contains two inserting yarn systems – warps and wefts (Fig.6). However, it is just as difficult as the typical structure to deform during hemisphere pressing experiment not as expected to deform as easily as the TBMWK fabric does. Explanations will be given later in this paper. In the subsequent sections of this paper, discussions will be concentrated on deformations of TBMWK fabric.

Textile composite materials really offer an attractive alternative to metals in the automotive and aerospace industries. However, fiber and yarn movement during flat fabric forming can cause adverse effects such as wrinkling and thinning, which will lead to a decrease of the mechanical properties of the finished composite. In addition, the high level of waste generated by subsequent trimming operation is proving unacceptable. Accordingly, the aim of this paper is to study and characterize the deformation behavior of MWK fabrics during forming process in order to predict the possible defects in the design stage and make the waste – free design possible as well as to lay a foundation for establishing a related model.

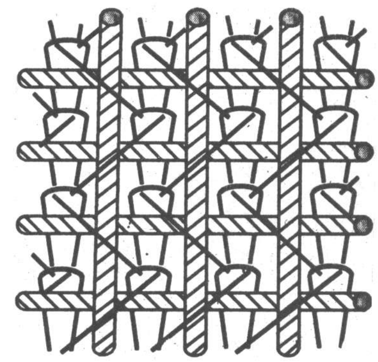


Fig.6 Another variation structure of MWK fabric (Containing only two inserting yarn systems – warps and wefts)

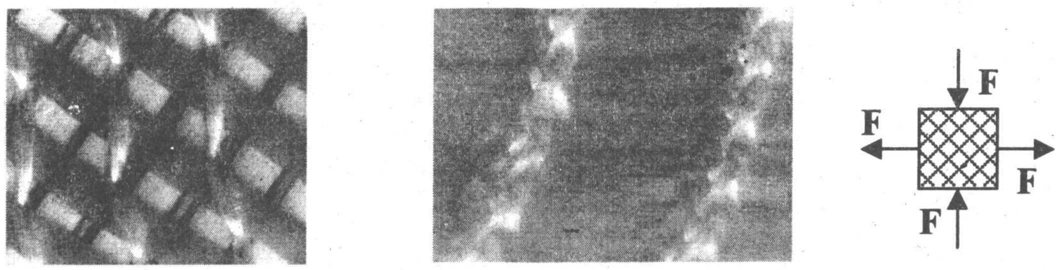
Deformation Behavior of TBMWK Fabric

As shown in Fig.5, the TBMWK fabric contains only two bias inserting yarn systems. Since the inserting systems are not interlaced as the woven fabric but overlapped together, there are obviously less frictional constraints at the contact area. This means that the relative movement between the two inserting systems will be easier. Actually, the angle between the two systems can nearly approach zero degree after deformation, as illustrated in Fig.7 (a), in which both of the two inserting yarn systems become nearly parallel to the weft direction. However, analogous phenomenon does not appear as expected that both of the two inserting yarn systems become nearly parallel to the warp direction when the exerted forces change directions as denoted in Fig.7 (b).

Fig.7 gives the deformations of the TBMWK fabric with tricot loops. The other structure, TBMWK fabric with chain loops, presents just similar deformation, as shown below.

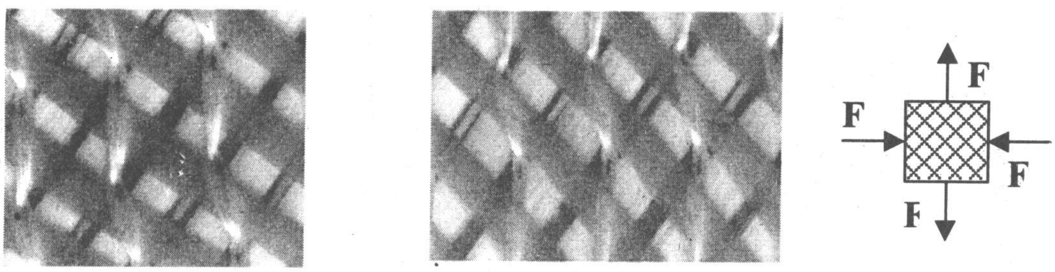
The inserting yarns always gathering along the weft direction is the unique deformation characteristic of TBMWK fabric, which is quite different from woven fabrics. As far as woven fabrics are concerned, the deformation of fabric should be similar under the exerted force conditions of Fig.7 (a) and (b), i.e. the yarns will tend to orient along the ± 45° directions (measured from the warp or weft direction). This has been proved by R.E. Robertson et al's experiment[4] of shaping the cotton cheesecloth around a bowling ball.

Apparently, this special deformation behavior of TB-MWK fabric must be resulted from the stitching system (tricot loops or chains). The microphotographs of deformations of these two kinds of stitches under stretching force can clearly explain this deformation characteristic of TBMWK fabric, as illustrated in Fig.9. Although the tricot fabric can extend in both of the weft and warp directions, the fabric's elongation along the warp direction is much smaller than that along the weft direction (Fig.9 (a)). The extensibility of the chain loops is also much smaller (3% or so for polyester filament yarn of 15 tex).



Undeformed state Deformed state

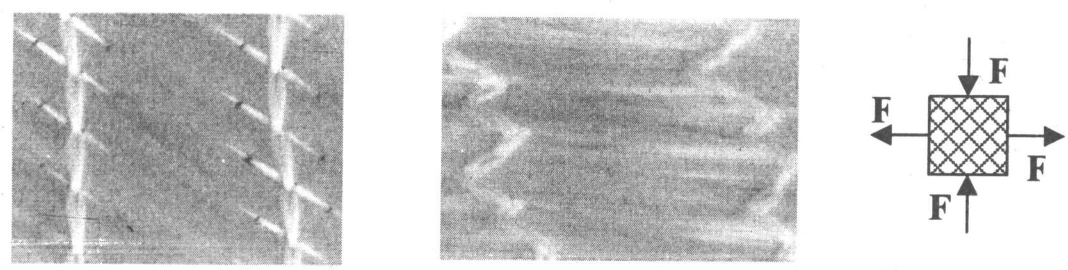
(a)



Undeformed state Deformed state

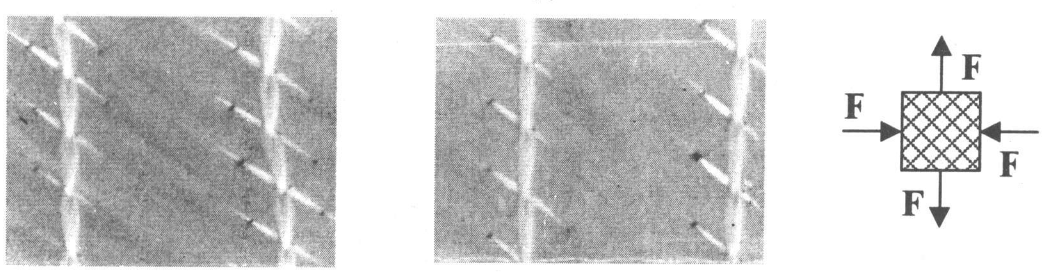
(b)

Fig.7 Deformations of a TBMWK fabric with tricot loops



Undeformed state Deformed state

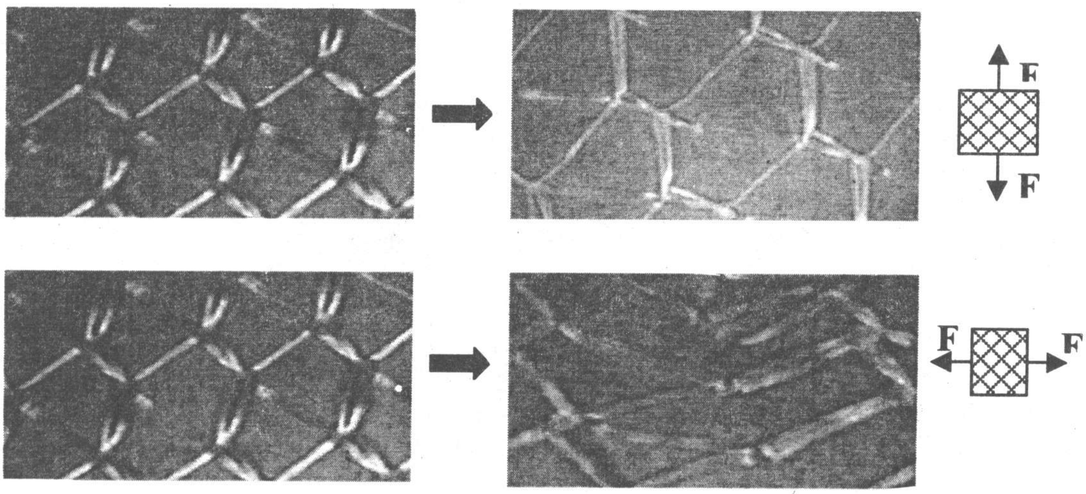
(a)



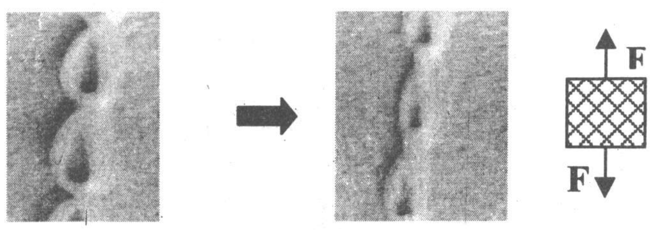
Undeformed state Deformed state

(b)

Fig.8 Deformations of a TBMWK fabric with chain loops



(a) Deformation of tricot loops



(b) Deformation of chain

Fig.9 Deformations of tricot loops and chains

As shown in Fig.7 (b) and Fig.8 (b), when the inserting yarns in the TBMWK fabric tends to orient along the warp direction, the stitching system is just being stretched in the same direction. From this point of view, when the TBMWK fabric conforms to a 3D surface, the quick and easy response of the inserting yarns is to orient along the weft direction, as justified by Fig.4 (b). This deformation behavior of TBMWK fabric is of great importance as far as the design of forming is concerned.

The structure shown in Fig.6 is not easy to deform since the shear deformation (the warps and wefts tend to orient along the ± 45° directions) will be constrained by the stitching system during forming process.

Experimental Arrangements

Hemisphere pressing experiments are made on three sample fabrics in order to study the forming behavior of TBMWK fabric. Specifications of the samples are listed below:

Sample 1 # : TBMWK fabric, consisting of two bias (± 45°) inserting yarn systems (glass filament bundles, count of 300 tex, density of 6.8 yarns per cm, yarn width of 0.98 mm), held by tricot loops (polyester filaments, count of 15 tex).

Sample 2 # : TBMWK fabric, consisting of two bias (± 45°) inserting yarn systems (glass filament bundles, count of 250 tex, density of 10.3 yarns per cm, yarn width of 0.96 mm), held by chain loops (polyester filaments, count of 15 tex).

Sample 3 # : plain – woven fabric, consisting of two interlaced yarn systems (glass filament bundles, count of 300 tex, density of 11 yarns per cm, yarn width of 0.86 mm).

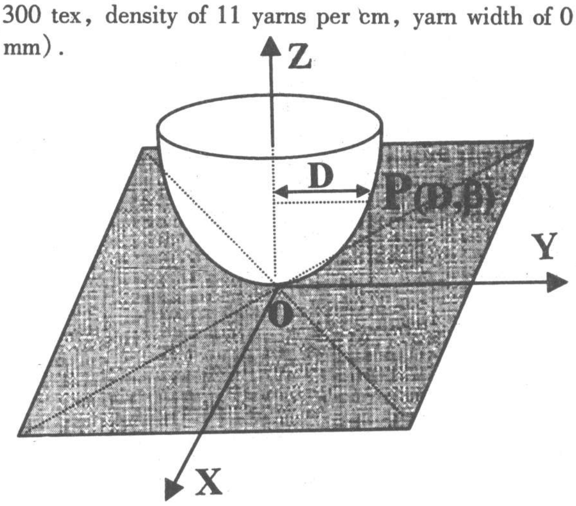


Fig. 10 Illustration of measurement

Two hemispheres in diameters of 75 mm (R_1) and 110 mm (R_2) are chosen in order to study whether the fabric deformation is sensitive to the size of the sphere or not. And the sample fabrics are cut into the sizes of 30×30 cm^2 for R_1 and 50×50 cm^2 for R_2. The angle changes between yarns are measured along the weft and warp direction for TBMWK fabrics or along the $\pm 45°$ directions for the plain - woven fabric. In addition, comparisons are also made between the patterns of flat TBMWK fabric and plain - woven fabric that can yield the corresponding hemisphere surface.

Experimental Results and Discussion

As shown in Fig. 10, we assume that the center point O (assumed to be some crossover point) of the original flat sample fabric happen to touch the pole of the pressing - hemisphere after forming. Measurements are made to angles (denoted as β in degree) as well as the corresponding distances (denoted as D in cm). β's are

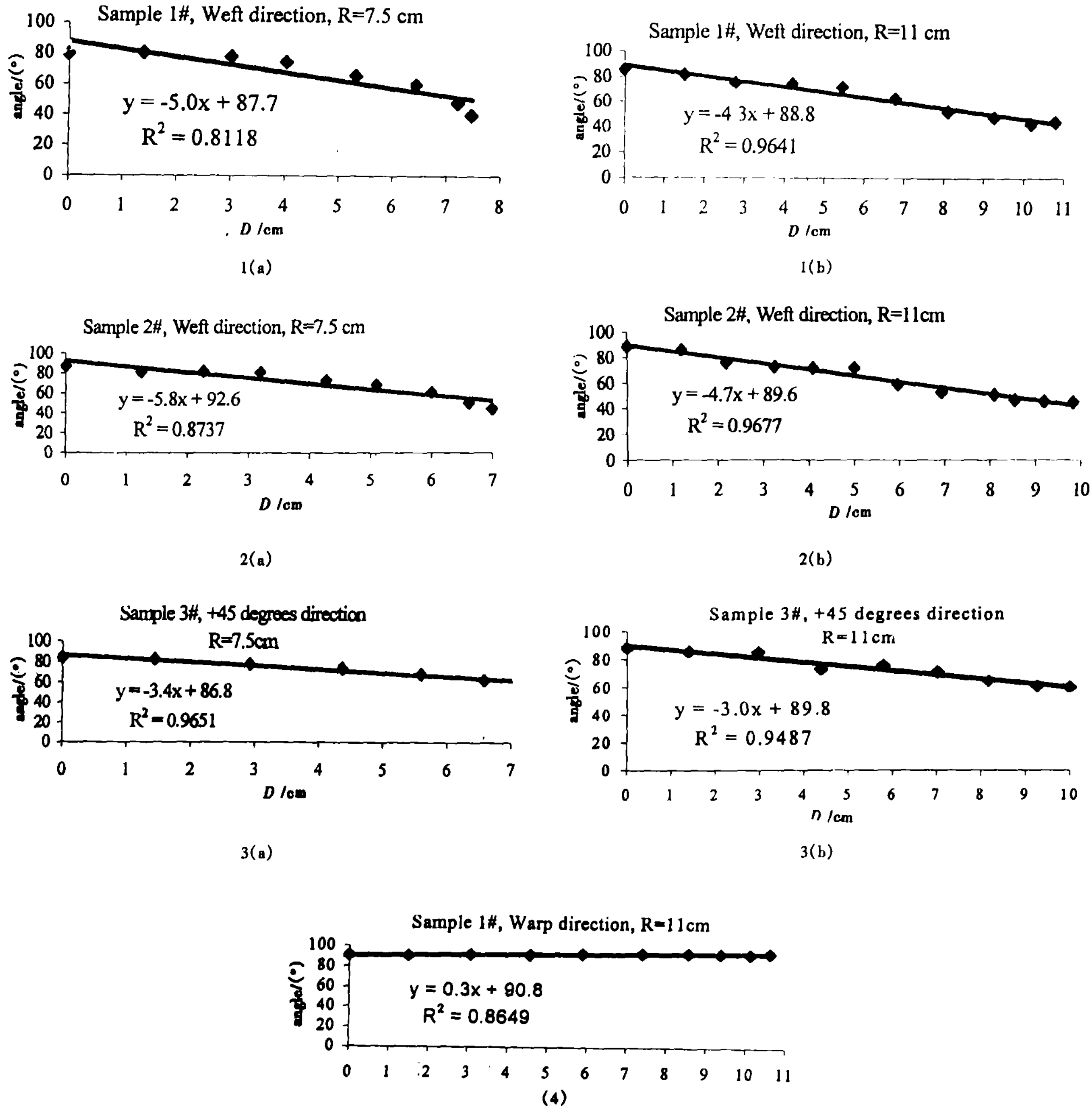


Fig. 11 The relation between D and β (angle)

between the two bias inserting yarn systems along the weft and warp directions for Sample 1 # and Sample 2 # , and between warps and wefts along the ± 45° directions for Sample 3 # . D is the distance from the measured point (such as P) to longitudinal axis of the hemisphere.

In Fig.11, the relation between D and β is presented. It can be inferred from Fig.11 that:

(1) The trendlines possess very good linearity (the correlation coefficients are close to unity);

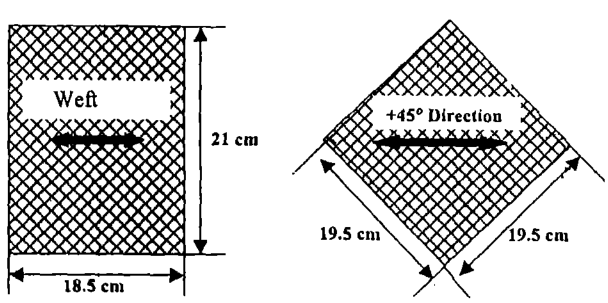
(2) The slopes of the trendlines are not sensitive to the diameter of the pressing – hemisphere;

(3) The inserting yarns of TBMWK fabrics tend to become gathered always along the weft direction of the fabric;

(4) The change of angles between the two inserting systems of a TBMWK fabric along the warp direction change is very small, as shown in Fig.11 (4) (here, only the curve for Sample 1 # is given, the other one for Sample 2 # is just similar);

(5) The curves for Sample 3 # along the – 45° direction are just analogous to those shown in Fig.11 (3a) and (3b).

These results just provide proofs to the foregoing analysis of the deformation behavior of TBMWK fabrics as well as the woven fabrics. In addition, it can also be seen from the schematic diagram in Fig. 12 that the two inserting yarn systems of a TBMWK fabric tend to become gathered along the weft direction during hemisphere – pressing process. Fig.12 gives the schematic flat patterns of both TBMWK fabric and woven fabric that can yield a hemisphere in diameter of 7.5 cm, in which pattern (a) is close to a rectangular while pattern (b) is close to a square.



(a) Sample 1 # , R = 7.5 cm (b) Sample 3 # , R = 7.5 cm

Fig.12 Schematic diagram of the flat patterns of both TBMWK fabric and woven fabric that can yield a hemisphere in diameter of 7.5 cm

Summary and Conclusions

Based on the hemisphere pressing experiments, the deformation behavior of MWK fabrics (especially the TB-MWK fabric) is characterized in detail. It was found that the typical structure of MWK fabric as well as the biaxial structure (only containing warp and weft inserting yarn systems) does not possess satisfactory conformability, which is suitable for used as plate or low – curvature shell materials. The TBMWK fabrics, however, turn out to possess much better conformability. It was noticed that the two bias inserting yarn systems tend to become gathered together always along the weft direction during hemisphere – forming process, which is quite different from that of woven fabrics – the yarns tend to orient along the ± 45° directions. In addition, the angle between the two bias inserting yarn systems can come to nearly zero degree during deformation; the woven fabrics, however, possess some locking angle, which is usually much larger than zero degree. An important phenomenon was found that the angles between the two bias inserting yarn systems in a TBMWK fabric along weft direction during hemisphere – forming process are basically linear to the perpendicular distances from the measured points to the longitudinal axis of the hemisphere. And the slope of the trendline is not sensitive to the magnitude of diameters of the pressing hemispheres. In addition, the shape of flat TBMWK fabric that can yield the corresponding hemisphere is close to a rectangular, not to a square as presented by the woven fabric.

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