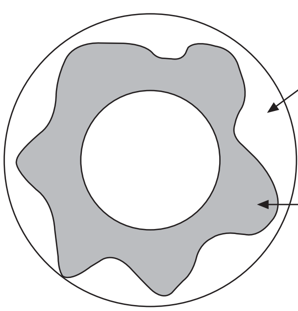
7
Fabric complex deformation analysis and simulation

7.1 Introduction

Drape can be generally classified into two categories, namely two-dimensional drape and three-dimensional drape. A two-dimensional drape means that a fabric bends under its own weight in one plane while three-dimensional drape allows a fabric to be deformed into folds in more than one plane under its own weight. The study of three-dimensional drape was begun by Chu *et al.* (1950) when they established a measuring method for fabric drape using the F.R.L. Drapemeter. Chu quantified the drapeability of a fabric into a dimensionless value termed the drape coefficient which is defined as the percentage of the area from an angular ring of fabric covered by a vertical projection of the draped fabric. The apparatus was further studied by Kaswell (1953) and later revised by Chu *et al.* (1960, 1962). Finally, Cusick (1968) re-investigated the experimental method by using a parallel light source which reflects the drape shadow of a circular specimen from a hanging disc onto a paper ring (Fig. 7.1). He also modified the calibration of Chu's drape coefficient in terms of paper-weighing method. In recent years, the emphasis has been on improving the efficiency and accuracy of Cusick's drapemeter by using digital readout of the drape shadow from photovoltaic cells (Collier,



7.1 Measurement of the drape coefficient using image analysis.

1991), as well as computerised image analysis (Vangheluwe and Kiekens, 1993).

Both subjective and objective evaluations can be found in the literature on fabric drape study. Objective evaluation of fabric drape involves the measurement of the drapeability in terms of drape coefficient, drape profile and node analysis from Cusick's drapemeter (1962, 1965, 1968), and simulating fabric drape by various mechanical methods such as finite-element analysis (1962, 1965, 1968). On the other hand, fabric drape is also affected by psychological factors which relate to human perceptions and fashion. Subjective evaluation of the drape of a fabric involves the rating of drapeability on a garment such as a skirt, and image analysis on circular fabrics (Dowlen, 1976). Generally, subjective evaluation of fabric drape can provide understanding which relates to person, place, custom and fashion trends. Thus, subjective evaluation of fabric drape is an investigation aimed at understanding the human perception of drape of fabrics.

Basically, fabric drape is not an independent fabric property. It relates to fabric bending, shear, tensile, fabric thickness and fabric weight (Niwa and Seto, 1986; Collier, 1991; Hu and Chan, 1998). A fabric bends under its own weight during draping. Fabrics bend differently according to different fabric directions. Peirce (1930) also termed fabric bending under its own weight as drape stiffness. Since drape behaviour in two dimensions can be evaluated by a cantilever test in which bending length and bending rigidity are the measurable objective values for describing the two-dimensional drapeability of fabrics, the use of bending length and bending rigidity as the indices to trace the drape properties is important.

7.2 Drape categories and fabric cantilever

7.2.1 Three-dimensional drape

7.2.1.1 Objective measurement

Chu *et al*. (1950) had quantified the drapeability of a fabric into a dimensionless value termed the drape coefficient (*DC*%). The apparatus was further studied by Kaswell (1953) and later revised by Chu *et al*. (1960, 1962). At last, Cusick (1965, 1968) investigated again the experimental method by using a parallel light source which reflects the drape shadow of a circular specimen from a hanging disc onto a paper ring. In Cusick's modified formula, the drape coefficient is defined as the ratio of the paper weight from the drape shadow W_2 to the paper weight of the full specimen W_1. The formula is shown in dimensionless quantities in equation 7.1. The quantitative value of *DC*% can represent the drapeability of fabrics in three dimensions. *DC*% is high on stiff fabrics but *DC*% is low on limp fabrics.

$$DC\% = \frac{W_2}{W_1} \times 100\ (\%) \qquad [7.1]$$

Cusick's experimental method consists of hanging a 15 cm radius fabric specimen over a 9 cm radius supporting disc, a parallel light source inside the drapemeter will then form a shadow from the draping specimen on a piece of paper. The shadow pattern on the paper can be traced out and (*DC*%) can then be calculated. Alternative specimen sizes can be adopted according to different fabric properties. An 18 cm radius specimen may be used for a stiff fabric if its *DC*% on a 15 cm radius specimen is greater than 85 %. In another case, a 12 cm specimen may be used for a very limp fabric if its *DC*% on a 15 cm radius specimen is smaller than 30 %.

More recently Collier *et al*. (1991) designed a digital drapemeter to evaluate drape coefficient by using photovoltaic cells. Cusick's experimental drapemeter was used but photovoltaic cells were applied to the bottom surface of the Cusick paper to determine the amount of light blocked by a fabric specimen draped on a pedestal. A digital display gives the amount of light being absorbed by the photovoltaic cells, which is related to the amount of drape of the fabric specimen. The method is more convenient and accurate than the paper tracing method.

Vangheluwe and Kiekens (1993) measured the drape coefficient using image analysis. A charge coupled device (CCD) camera was mounted centrally above the drapemeter. This camera sent the image to a monitor and a frame grabber in a personal computer, and the frame grabber digitised the image. Calibration of the drape coefficient was preceded by recording the image from the drape tester in terms of area. The image analysis system saves both time and paper. The drape coefficient can be evaluated accurately within a few seconds. Because the measuring system is more time-efficient, change of drape can be measured and comparisons made within a short time.

Stylios *et al*. (1996) developed a new generation of drapemeter which measured the drape of any fabric both statically and dynamically in three dimensions by using a CCD camera as a vision sensor. This system, called the Marlin Monroe Meter (M^3), was used to measure the drape behaviour of fabric without being restricted to small circular fabric specimens, and to verify the theoretical prediction model. The draped profile of the specimen was taken and presented on a computer. In addition to this, evaluation of three-dimensional drape on a real garment can also be carried out using the Moiré Camera System (Iwasaki and Niwa, 1983; Niwa and Suda, 1984). The system can convert images into digital data; for example the three-dimensional drape image of a flared skirt can be successfully predicted and presented on paper.

7.2.1.2 Subjective measurement

The numerical value from the drape coefficient is not sufficient to represent drape behaviour. Drape is differentiated even when fabrics have the same value of *DC*%. In practice, using only the numerical value of *DC*% drape appearance cannot be fully described. Thus, Cusick's drape study involves not only objective measurement through a numerical value of drape coefficient, but also subjective evaluation. Rating of drape profile is a very typical example of subjective measurement of fabric drape; the rating result depends on person, place, custom, fashion trends, etc. The node analysis will usually involve the counting of node number, the measurement of the node length, as well as the observation of drape behaviour (Hearle, 1969).

Cusick (1962) mounted semi-circular fabrics with various cottons and rayons in the shape of a skirt on a model. The model was rated to see which skirt could drape most. The results indicated that a good drape as assessed by objective measurement almost matches one assessed by subjective selection. The subjective rating of fabric drape is rather inconsistent. However, the fabric with the most drape may not be the preferred one. The subjective study pointed out that the drape of fabric is also a psychological phenomenon which is related to human perceptions and fashion trends.

Collier (1991) reported that subjective drape is affected by the length of draping fabric on the pedestal. He carried out experiments comparing the subjective rating of drape as 'not preferred' with the objective experimental results. He found that results can be accurately predicted by garment professionals; however, he also pointed out that subjective measurement is closely related to the fashion trends in certain time periods.

Ayada and Niwa (1991) found that fabric mechanical properties are highly related to fabric drape. They made 24 skirts for subjective evaluation of total quality and visual beauty of skirts. It was found that bending, shear and fabric weight are the important factors influencing the garment appearance. In addition, dynamic drape of fabrics is also related to the mechanical properties. Subjective evaluation of dynamic drape (Izumi and Niwa, 1985; Mamiya and Kanayama, 1985; Niwa and Seto, 1986) is found to be highly correlated with dynamic bending and shear properties, as well as the hand feel. The results of the investigation are important in targeting and responding to customer demand.

7.2.2 Two-dimensional drape

7.2.2.1 Evaluation methods of fabric cantilever

Peirce (1937) initiated the study of fabric drape using the fabric cantilever in 1930. In this section, fabric drape can be evaluated using the cantilever test in which bending length, a numerical term in equation 7.2 for evaluating fabric stiffness and drape of the cantilever, can be obtained. Bending property can also be quantified into a series of mathematical functions such as flexural rigidity and bending modulus in equations 7.3 and 7.4. In theory, the easier the fabric is to drape, the shorter is the bending length. Thus, Peirce termed the bending length drape stiffness. Peirce's mathematical expressions of bending length could not be solved analytically; thus Peirce used Hummel and Morton's (1927) approximation method to evaluate bending length. In Peirce's study, evaluation methods can be adopted for fabrics in the two extreme categories – very stiff and very limp. For very stiff fabrics, a weight can be added to the free-end of the specimen; the evaluation of bending length for stiff fabric can be modified into equation 7.5. For very limp fabrics, bending length can be obtained from equation 7.6 from a heart loop test. Pierce assumed a general fabric cantilever, which deformed under its own distributed weight, and a stiff fabric cantilever deformed by the concentrated weight at the tip end.

Postle and Postle (1992) also provided a very detailed explanation for the weight effect on drape of a fabric cantilever. They used bending length in the drape study, and taking advantage of the wide availability of computers, solved the differential equation by the finite-difference method.

Grosberg and Swani found that drape of a fabric cantilever is the combined effect of both the distributed and concentrated weight (Grosberg, 1966; Grosberg and Swani, 1966). A draped cantilever is divided into two sections. The first section near the hanging edge bends under its own distributed weight and a concentrated weight from the second section. They assumed that the second section of the fabric cantilever is straight and will not bend during draping. Also, fabric weight of the second section exists as a concentrated point load at the centre of this section. The total deflection of the fabric cantilever is the combined deflections of these two sections. The point O is the junction of these two sections at which bending moment is equal to M_o. If an applied moment M is greater than M_o, the fabric will bend. If an applied moment M is smaller than M_o, the fabric will remain straight. The analytical solution is obtained by Bickey's approximated methods (1936). His frictional couple theory is one of the non-linear models which can explain the bending property in terms of bending rigidity, frictional couple and curvature of cloth. The model can specify the real situation existing on the cantilever.

However, Peirce's beam theory assumed a linear bending behaviour for fabrics and is known as the classical linear model. In fact, most fabrics bend in a non-linear way. Besides, Peirce's evaluation method only provides an average value for the fabric drape and bending behaviour. Therefore, other non-linear models, including bilinear bending theory, indirect measurement of moment–curvature and large deformation (Clapp *et al.*, 1990; Grosberg and Swani, 1966; Huang, 1979; Leaf and Anandjiwala, 1985; Potluri *et al.*, 1996), have been developed. They are all non-linear studies of bending behaviour. Equations for bending length C, bending rigidity B and bending modulus q are given by:

$$c = l\left(\frac{\cos 0.5\theta}{8\tan\theta}\right)^{1/3} \qquad [7.2]$$

and $$B = wc^3 \qquad [7.3]$$

$$q = \frac{12B}{t^2} \qquad [7.4]$$

where l is fabric length, θ is bending angle, t is fabric thickness and W is distributed weight. Hence

$$c = l\left(\frac{W}{2wbl} + 0.13\right)^{\frac{1}{3}}\left(\frac{\cos 0.93\theta}{\tan\theta}\right)^{\frac{1}{3}} \qquad [7.5]$$

and

$$c = 0.1337L \cdot f_2(\theta) \qquad [7.6]$$

where

$$f_2(\theta) = \left(\frac{\cos\theta}{\tan\theta}\right)^{\frac{1}{3}},\ \theta = 32.85^\circ\ \frac{l - 0.1337L}{0.1337L}$$

and b is the width of the fabric strip, L is the length of the beam and f_2 denotes a function of θ.

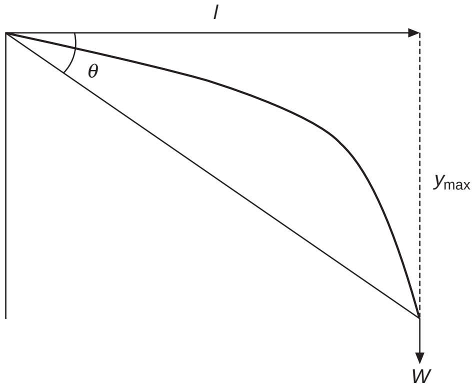
7.2.2.2 Theories of fabric cantilever with different weight distributions

Classical beam theory

Potluri *et al*. (1996) conducted differential equations to describe the drape profile of the fabric cantilevers having distributed weight and concentrated weight at the tip. They reported that Peirce's cantilever study is based on the concept of the classical beam theory from which fabric beam is assumed to satisfy the Bernolli–Euler law. The Euler law states that the bending moment of a beam is proportional to the radius of curvature of the beam R caused by that moment, as shown in equation 7.7. Two assumptions are made when the theory is applied to a cantilever. It is assumed that the curvature is evaluated by the approximate equation and change in length of moment arm during beam deflection is ignored. Since $1/R \cong d^2y/dx^2$

$$M = B\frac{d^2y}{dx^2} \qquad [7.7]$$

By simple mechanical theory, the applied bending moment of the beam is also equal to the product of the applied load on the cantilever to the perpendicular distance of the line of action x. Two cases of applied loading are studied: one with weight and one with distributed weight.



7.2 Cantilever beam with concentrated load *W*.

Fabric cantilever with concentrated weight

In this case the applied load *W* is acting on the free tip end of the cantilever as shown in Fig. 7.2, and equation 7.8 is developed:

$$M = B\frac{d^2y}{dx^2} = -Wx \quad [7.8]$$

By double integrating equation 7.8 and applying the boundary condition, equation 7.9 is obtained where bending rigidity of the beam can be found from the deflection angle.

$$\tan\theta = \frac{Wl^2}{3B} \quad [7.9]$$

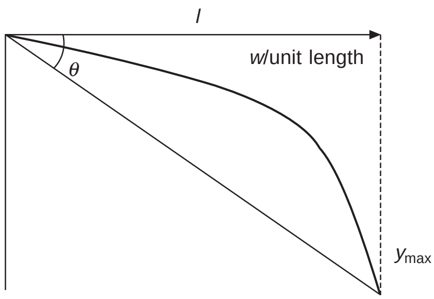
Peirce developed an empirical relation from his experimental results by multiplying the right side of equation 7.9 by a factor of cos 0.93θ. As a result, the Peirce bending equation for a concentrated weight at the tip end of the cantilever is formed in equation 7.10.

$$\frac{B}{Wl^2} = \frac{\cos 0.93\theta}{3\tan\theta} \quad [7.10]$$

Fabric cantilever with distributed weight

The deflection of a cantilever due to the distributed load from its own weight can be seen in Fig. 7.3. A uniformly distributed weight *w* is applied along the length of the cantilever and thus equation 7.9 can be rewritten to form equation 7.11.

$$M = B\frac{d^2y}{dx^2} = -\frac{wx^2}{2} \quad [7.11]$$



7.3 Cantilever beam with uniformly distributed load *w*.

Again, by double integrating equation 7.11 and applying the boundary conditions, equation 7.12 is obtained where bending rigidity of the beam can be found from the deflection angle.

$$\tan\theta = \frac{wl^3}{8B} \qquad [7.12]$$

Peirce developed an empirical relation from his experimental studies by multiplying the right-hand side of equation 7.12 by a factor of cos 0.5θ. As a result, Peirce's bending equation for the distributed weight is formed in equation 7.13.

$$\frac{B}{wl^3} = \frac{\cos 0.5\theta}{8\tan\theta} \qquad [7.13]$$

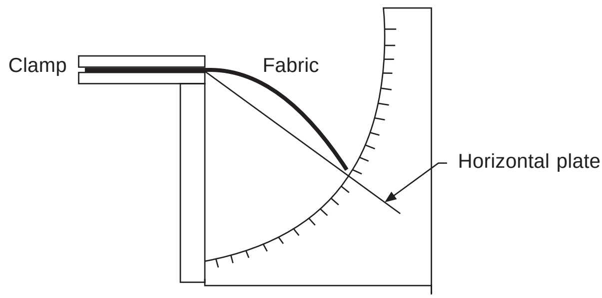
In Peirce's paper (1930), he defined the term B/w as equal to the cube of the bending length c where bending length is a quantitative value to measure a strip's drapeability in two dimensions. Equation 7.13 can be rewritten as equation 7.14 from which bending length can be evaluated from the extended fabric length l that bends to an angle θ under its own weight. Peirce's cantilever formula as shown in equation 7.14 is extensively adopted to describe the characteristics of fabric stiffness and fabric drape in two dimensions.

Since $c^3 = B/w$

$$c^3 = l^3\,\frac{\cos 0.5\theta}{8\tan\theta} \qquad [7.14]$$

7.2.2.3 Testing methods of fabric cantilever

In Peirce's theory, bending length c of the fabric cantilever can be evaluated either by measuring the extended fabric length (l) under a fixed angle or by measuring an angle from the extension of a fixed length l. The Flexometer shown in Fig. 7.4 can be used as a testing instrument for measuring the



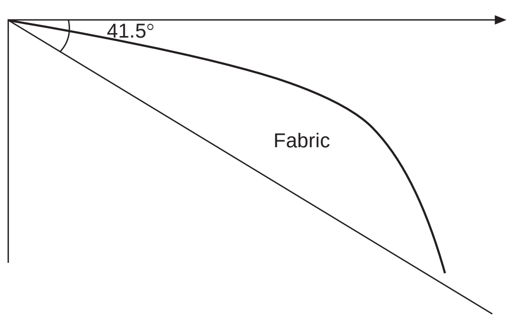
7.4 Flexometer.

bending angle θ of a draped cantilever with a constant length l. Bending length c can be evaluated from this bending angle by the mathematical formula shown in equation 7.14.

A bending tester from the Shirley Institute (Booth, 1968; Feather, 1970) is specially designed for measuring an extended length l with a fixed angle. The extended fabric bends under its own weight until the free end intercepts a plane at an angle of 41.5^{o} from the horizon. Figure 7.5 shows the concept of Shirley's bending tester. With this fixed angle, the expression $(\cos 0.5\theta/8 \tan \theta)^{1/3}$ in equation 7.14 will be equal to 0.5. Thus, the bending length is calculated by a simple formula from equation 7.15. If $\theta = 41.5°$,

$$c = 0.5l \qquad [7.15]$$

In recent years, the experimental process has been simplified more. The Fabric Assurance by Simple Testing (FAST) system consists of cantilever bending meter. The FAST-2 Bending meter can be used to measure the bending length using the same concept as the Shirley Stiffness Tester. A photocell detector for detecting the free end is used. The extended fabric l bends under its own weight until the free end intercepts at an angle of 41.5°



7.5 Concept of Shirley's and FAST bending meters.

from the horizon. Then, a photocell detector inside the measuring cavity detects the length of *l*. Experimental results are recorded directly in the computer. Bending length evaluated from equation 7.15 can be displayed digitally.

Clapp *et al*. (1990) developed an indirect method of measuring the moment–curvature relationship for fabrics. At the same time, they developed a method to measure the draped profile of the fabric cantilever. Deformed co-ordinates were recorded as a fabric sample was cantilevered under its own weight from a fixed support. The advantage of this method is that fabric non-linear bending behaviour, inherent in most fabrics, is readily obtained, unlike in the traditional cantilever beam test. The draped image obtained by using a laser sensor can be used to verify the numerical simulation results.

Potluri *et al*. (1996) also developed an experimental technique to verify their numerical method for the capability to simulate in general situations. A laser triangulation sensor, attached to a robot arm, was used to measure the cantilever profile of the fabric samples. A manipulating device positions the fabric sample as a fabric cantilever of specified length. The laser scans along the centre line of the fabric cantilever. The *x* co-ordinates are obtained from the robot position and the *y* co-ordinates from the output signal of the triangulation sensor.

7.2.3 Relationship between fabric drape and mechanical properties

The drape coefficient provides an objective description of drape deformation in three dimensions, but the study of three-dimensional fabric drape is not independent. In general, fabric drape is closely related to fabric stiffness (Hearle and Amirbayat, 1986a,b,c). Very stiff fabrics have drape coefficients approaching 100 %; very limp, loose, or open-weave rayon fabrics have *DC*% about 30 %. *DC*% is about 90 % for a starched cotton gingham. The drape coefficient provides an objective description of drape deformation in three dimensions, but the study of three-dimensional fabric drape is not independent. In other words, the study of three-dimensional drape in terms of *DC*% is empirically related to two-dimensional drape in terms of bending properties.

Chu *et al*. (1960) found that drapeability is dependent on three basic fabric parameters: Young's modulus *Y*, the cross-sectional moment of inertia *I*, and weight *W*. From their study, an equation was generated in which drape coefficient is equal to $f(YI/W)$. Later, Yamada *et al*. (1995) also reported that the drape area changes positively to $(EI/W)^{1/3}$ with a scale factor. When bending rigidity per weight (*EI*/*W*) of fabric is similar to each other, *DC*% and deflection angle obtain similar values.

Cusick (1965) proved by statistical evidence the hypothesis that fabric drape involves curvature in more than one direction, and that the deformation is dependent on the shear angle *A* in addition to bending length *c*. He used 130 fabrics for his multiple regressions. Regression equations were formulated for the relationship between drape coefficient, bending length and shear angle:

$$DC = 35.6c - 3.61c^2 - 2.59A + 0.0461A^2 + 17 \qquad [7.16]$$

For this equation, residual sum of squares of the regression is the smallest when *c* and *A* are both considered to be the main factors influencing the *DC*%.

Mooraka and Niwa (1976) generated an equation to predict fabric drape using data from the KES system and concluded that fabric weight and bending rigidity were the most important factors. In their study, *DC*% is found to be determined by $(B/W)^{1/3}$. The correlation coefficient *r* between *DC*% and $(B/W)^{1/3}$ is 0.767 which is greater than the value of 0.686 for *DC*% and *B* only. The use of bending rigidity from the warp, weft and bias on a regression equation allows for better prediction of *DC*% than by using a mean bending rigidity. Physical properties which contribute greatly to the *DC*% are bending properties followed by weight and thickness, and then the shear properties. When bending and shearing hysteresis is large, *DC*% would be large and unstable.

Collier (1991) authored a paper in which six parameters were measured: shear stiffness, bending hysteresis, bending stiffness, shear hysteresis at 0.5°, shear hysteresis at 5°, from the KES testers, and bending rigidity from cantilever. He found that both bending stiffness from the KES and bending rigidity from the cantilever, as well as shear hysteresis and thickness, were significant in the model predicting the drape coefficient. However, shear hysteresis and bending stiffness from the KES explained most of the variation, with the other two variables being less important. They concluded that shear hysteresis is more important.

Niwa and Seto (1986) published a paper concerned with the relationship between drapeability and mechanical properties of fabrics. They used mechanical parameters $(B/W)^{1/3}$, $(2HB/W)^{1/3}$, $(G/W)^{1/3}$ and $(2HG/W)^{1/3}$ as independent variables, where *B*, 2*HB*, *W*, *G* and 2*HG* are bending rigidity, bending hysteresis, weight per unit area, shear stiffness and shear respectively. These parameters were derived from the analysis of the bending of a cantilever of fabric having hysteresis in bending and shear by applying the heavy elastica theory. An equation to describe drape coefficient was then introduced.

From the above studies, three-dimensional drape in terms of *DC*% is closely associated with two-dimensional drape study in terms of bending length and bending rigidity. Nevertheless, *DC*% from three-dimensional drape study is also influenced by other fabric physical properties which include shear and tensile properties as well as fabric weight and fabric thickness (Hu and Chan, 1998; Hu *et al*., 2000; Suda *et al*., 1984a,b; Tanabe *et al*., 1975). In addition, mechanical fabric properties also proved to be correlated to subjective drape evaluation (Okabe and Akami, 1984; Yamakawa and Akiyama, 1996). Although two-dimensional drape study is only a partial measure of drape behaviour, it is the most important index for predicting three-dimensional drape behaviour. Many numerical and theoretical investigations of fabric drape used the two-dimensional drape of a fabric cantilever to verify their mechanics models or the accuracy of their software programs (Gan and Steven, 1995).

7.3 Modelling of fabric drape profile

7.3.1 Background

Drape profile (*DP*) of a fabric is a projected two-dimensional image taken from the Cusick Drapemeter. It is characterised in terms of drape coefficient, node locations and node numbers of the projected image of a fabric. This section will introduce an attempt made to develop a model for the prediction of *DP* of fabrics using polar co-ordinates directly measured from the drapemeter. Drape coefficient, node locations and number of the drape profile of a fabric can all be determined by this model. Polar diagrams of the *DP* model will also be provided. The constants in the *DP* model can be either estimated using the polar co-ordinate fitting technique, or directly calculated from fabric bending and shear properties using regression analysis.

7.3.2 Modelling

A fabric drape profile can be captured in a two-dimensional image projected from a three-dimensionally draped fabric sample on the so-called Cusick Drapemeter by digital camera. From this image, node locations and numbers and the detailed shape of the drape profile can be observed from the computer screen, and the fabric drape coefficient can be accurately and automatically calculated by Leica QWin image analysis software. Although the nodes are not uniform, the drape profile exhibits a cyclic change in polar co-ordinates. Some assumptions, which have to be made to establish a mathematical model for the description/prediction of fabric drape profile measured by the above method using polar co-ordinates, are listed as follows:

(1) the fabric freely hangs under its own weight;
(2) nodes are evenly distributed around the plate and all node shapes are identical;
(3) the average value of node numbers of one fabric sample is a positive integer.

A trigonometric function is selected for the modelling,

$$r = p + q \sin (k\theta + \alpha) \quad [7.17]$$

where p is the average radial length taken between the peaks and troughs of the draped profile, q is the half depth of the draped node, r is the radius of the projected drape profile, k is the number of nodes (peaks) in the drape profile while α is a constant which represents an angle between the fabric warp direction and its neighbour peak. The details are demonstrated in Fig. 7.6b. Figure 7.6a illustrates the image analysis system used for the measurement of fabric drape profile, in which a digital camera connected to a personal computer is used to capture the projected two-dimensional draped image directly from the drapemeter while the printer and digitiser are used to print out the drape profile results. Computer software, Leica QWin image analyser, serves the function of automatically calculating the drape coefficient from the captured image.

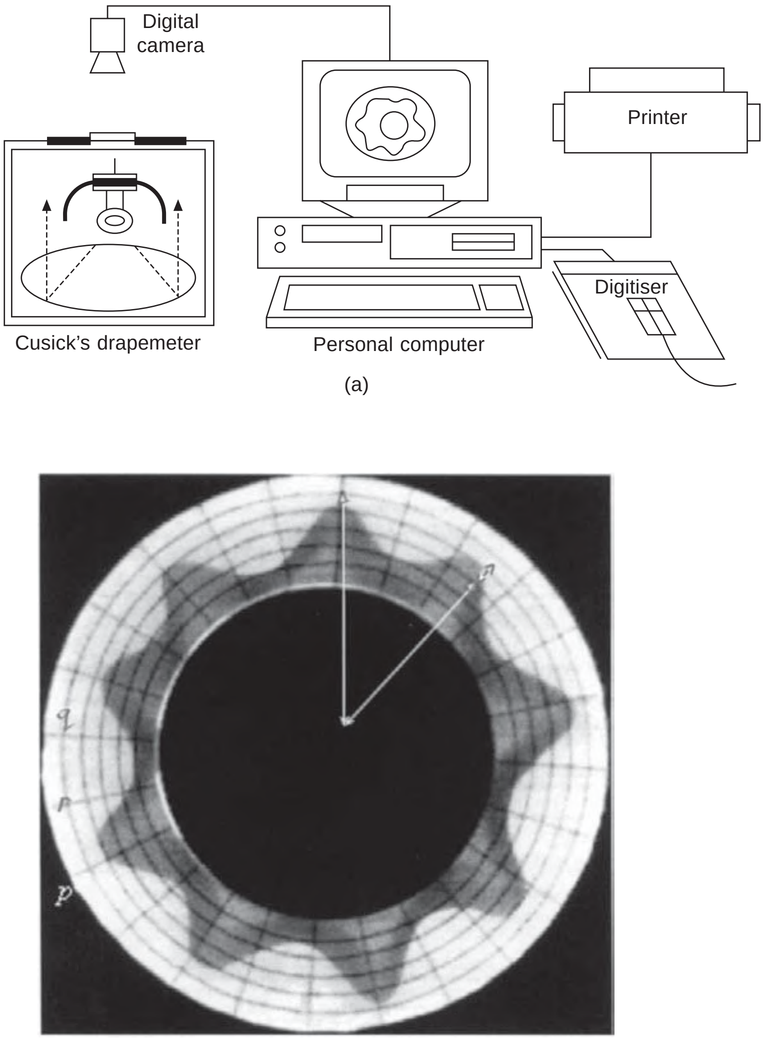
The constants p, q and k in the model can be either estimated by polar co-ordinate fitting technique or determined using multiple and stepwise regression analysis from SPSS based on the relationship between fabric mechanical properties and fabric drape. With the values of the constants known, the drape coefficient, node locations, node numbers and node shape of the drape profile of a fabric can be automatically predicted by this model. In particular, the projected area A_2 under the fabric drape profile is calculated in the following:

$$\begin{aligned} A_2 &= \int_0^{2\pi} \frac{1}{2} r^2 \,d\theta \\ &= \frac{1}{2}\int_0^{2\pi} [p + q \sin (k\theta)]^2 \,d\theta \\ &= \pi\left(p^2 + \frac{q^2}{2}\right) \end{aligned} \quad [7.18]$$

Drape coefficient ($DC\%$) is defined as the ratio of the projected area of draped fabric to the original non-draped area A_1 multiplied by 100:

$$DC\% = \frac{A_2}{A_1} \times 100\ \% \quad [7.19]$$

Node location is defined as the position of a peak found in the drape profile (polar diagram) expressed in degrees. Node number is the number of nodes (peaks) in the drape profile while node profile is defined as the shape of each draped node.



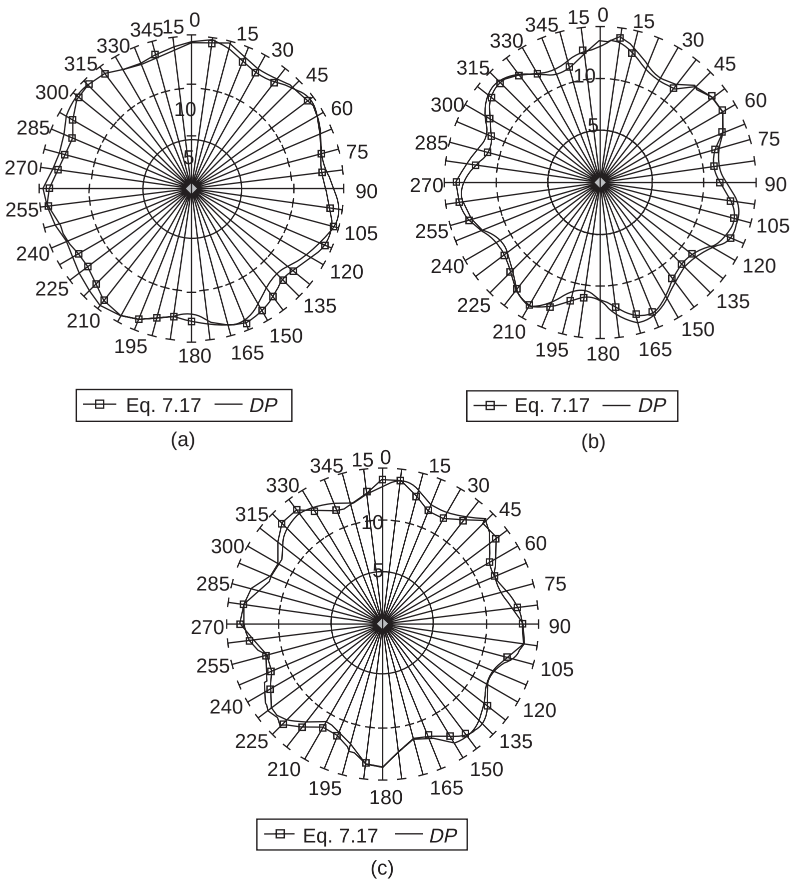
7.6 The set up for the measurement of fabric drape profile: (a) image analysis system; (b) captured image on the drapemeter.

7.3.3 Prediction of *DP* using constants from polar co-ordinate fitting

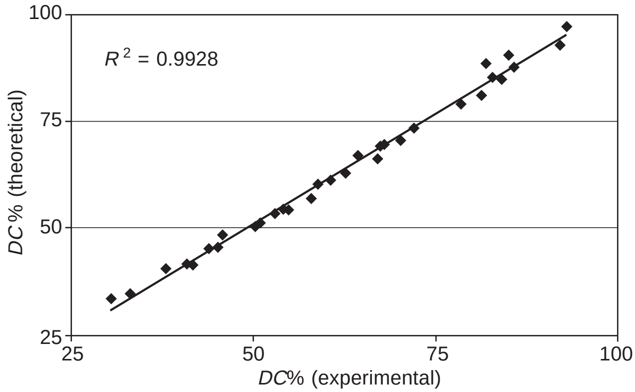
The three constants *p*, *q* and *k* in equation 7.17 can be determined by the polar co-ordinate fitting technique using a computer program written in the MATLAB software package. The input parameters of the computer program are the co-ordinates (r, θ) of the draped profile with θ from 0–352.5° at every 7.5°. The predicted graphical drape profile is presented in the form of a polar diagram.

7.3.3.1 Drape profile

The drape profiles (*DP*) of plain, twill and satin woven fabrics are illustrated in Figs 7.7a–c. It can be seen that the theoretical model gives good agreement with the experimental data with some deviations in the node numbers and locations in the drape profile. The deviation between the theoretical and experimental *DP* of different woven fabrics is not more than 10 %.



7.7 Theoretical and experimental results of drape profile of woven fabrics: (a) plain weave; (b) twill weave; (c) satin weave.



7.8 Relationship between theoretical and experimental *DC*%.

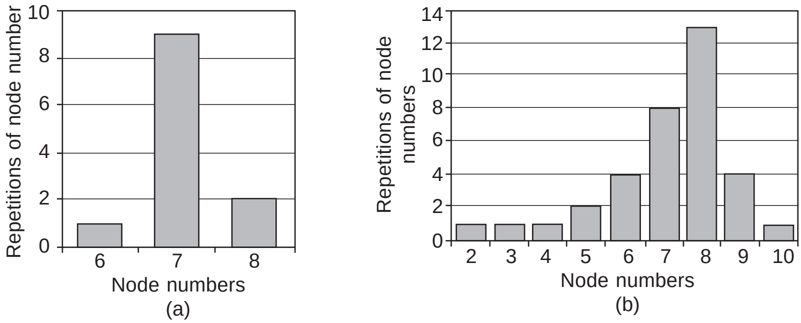
7.3.3.2 Drape coefficient

The validity of the model described above for the prediction of fabric drape profile can be further verified using excellent agreement between the theoretical and experimental results for drape coefficient (*DC*%) of 35 different types of fabrics exemplified in Fig. 7.8. That is, the experimental and the theoretical *DC*% have high coefficient of determination (R^2 = 0.9928). This means that over 99 % of experimental *DC*% can be explained by the theoretical *DC*%. The deviation between the theoretical *DC*% predicted from the *DP* model and the experimental *DC*% is smaller than 8.3 %.

7.3.3.3 Node number and location

As can be seen from Fig. 7.8, the theoretical model gives good agreement with some of the experimental data with some deviations in the node numbers and locations in the drape profile. This section shows that the model is applicable in average terms. This is because, although node numbers and their locations may vary from time to time, perhaps, on average a certain fabric should have a certain number of nodes and node locations. Some evidence is presented below.

The repetitions of the node numbers of one draped fabric sample under different drape tests are shown in Figs 7.9a and b. The results obtained from Fig. 7.9a imply that the drape node numbers of one fabric sample are 6, 7 and 8. The repetitions of 6, 7 and 8 nodes within 12 trials are 1, 9 and 2 respectively while 7 nodes give the majority in this sample. Therefore, in this case, the mean value of node number calculated from 12 trials is equal to 7.08. As the number of nodes in the fabric drape test must be a positive integer, we round off the mean value of the node number to get 7 nodes for this fabric sample. This result is very close to the mean value of node number, 7.08, with deviation 1.14 % and proves that the mean value obtained from



7.9 The repetitions of the node numbers within (a) one fabric sample and (b) 35 woven fabrics.

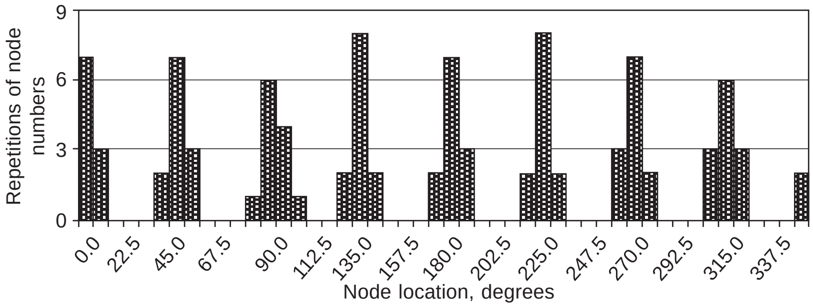
constant *k* in the *DP* model is acceptable in the prediction of draped node numbers.

If the same test is extended to a total of 35 woven fabrics, it is found that 8 nodes is the most frequent number to appear in the 35 woven fabrics, as shown in Fig. 7.9b. Selecting those fabrics having 5–10 nodes for analysis, a comparison is presented in Table 7.1 of their theoretical and experimental node locations, where the peaks are found in the polar diagram, which indicates

Table 7.1 Correlation coefficient between each constant in *DP* model and all selected fabric mechanical properties

Mechanical properties	**Average of mechanical property in the warp and weft directions**			**Average of mechanical property in the warp, weft and ±45° directions**		
	p	***q***	***k***	***p***	***q***	***k***
B	0.497*	0.474*	0.556*	0.617*	0.604*	0.652*
2*HB*	0.542*	0.529*	0.551*	0.682*	0.632*	0.672*
G	0.672*	0.679*	0.678*	0.723*	0.723*	0.612*
2*HG*	0.715*	0.724*	0.625*	0.740*	0.724*	0.676*
2*HG5*	0.730*	0.721*	0.690*	0.780*	0.750*	0.682*
LT	0.451*	0.407	0.456*	0.408*	0.343	0.450*
WT	0.429*	0.482*	0.291*	0.388	0.444*	0.225
RT	0.206	0.239	0.159	0.258	0.298	0.172
EMT	0.040	0.107	0.085	0.085	0.159	0.067
W	0.415*	0.344	0.435*	0.415*	0.344	0.435*
T	0.265	0.321	0.236	0.265	0.321	0.236
$\sqrt[3]{B/W}$	0.370	0.290	0.481	0.444*	0.376	0.539*
$\sqrt{2HB/W}$	0.600*	0.540*	0.615*	0.634*	0.582*	0.638*
$\sqrt[3]{G/W}$	0.487*	0.435*	0.470*	0.627*	0.583*	0.600*
$\sqrt{2H/W}$	0.523*	0.474*	0.471*	0.663*	0.664*	0.511*
$\sqrt{2HG5/W}$	0.636*	0.555*	0.616*	0.684*	0.636*	0.651*
Stepwise regression	0.684	0.664	0.700	0.847	0.750	0.782

*Significant value at $p < 0.005$



7.10 Node locations of 8 nodes in various directions.

a close relationship with deviation as low as 0.9°. Figure 7.10 illustrates the node location of each respective node for a fabric with 8 nodes, which indicates clearly that the probability of node repetition is comparatively high at 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° for 8 node numbers. Undoubtedly, the above facts also indicate that constant *k* in the *DP* model is not applicable only in predicting the node numbers, but also in determining the node locations.

Another conclusion which can be reached is that the higher the value of *DC*%, the lower the number of nodes: for stiffer or heavy fabrics with a *DC*% value larger than 85 %, 2–5 node numbers are recorded; for those medium fabrics whose *DC*% values fall in the range 50–85 %, they exhibit 6–8 node numbers; while for loose or light woven fabrics with a *DC*% value between 30 % and 50%, 9 or 10 node numbers can be observed. These facts confirm the findings of Cusick (1962) that the number of nodes is governed by the fabric stiffness.

7.3.3.4 Node profile

Since a woven fabric is anisotropic and exhibits different values of mechanical properties in different directions, each draped node may exhibit different shape. However, it is found that the agreement between the theoretical and experimental node profile has only minor deviations as demonstrated in Fig. 7.8. This may reveal that all node shapes in the drape profile can be assumed to be similar to each other and the mean value of node profile assumed in the *DP* model is acceptable in predicting the fabric drape profile.

7.3.4 Prediction of *DP* using fabric mechanical properties from regression analysis

In addition to polar co-ordinate fitting, the fabric drape profile can also be predicted from fabric mechanical properties using regression analysis. In addition, stepwise regression can be adopted to determine which combination of mechanical properties gives the best description in predicting the fabric drape profile.

7.3.4.1 Drape profile

Sixteen mechanical properties are used in regression analysis, including bending (*B* and 2*HB*), shear (*G*, 2*HG* and 2*HG*5) and tensile (*WT*, *EMT*, *LT* and *RT*) properties, fabric weight (*W*) and fabric thickness (*T*). Among the selected mechanical properties, bending and shear properties give significant correlations with the constants *p*, *q* and *k* in the drape profile (*DP*) model while bending hysteresis and shear hysteresis have higher correlation coefficient, *r*, than their rigidities. In addition, the results indicate that the values of mechanical properties taken in the warp, weft and ± 45° directions have higher *r* than those taken only in the warp and weft directions. With all correlation coefficients between the constants in the *DP* model and the mechanical properties, the best combination in predicting the fabric profile can be found by using stepwise regression. The criterion of stepwise regression for entering a parameter was $p = 0.05$ and that for removal was 0.1.

After the removal of all variables that correlated with each other and were within the same mechanical property group, the most important properties are entered into the final equations given below:

$$p = 10.795 + 7.458(2HB_T) + 0.1087(2HG5_T) \qquad [7.20]$$

$$q = 0.5116 + 1.861(2HB_T) - 0.122(2HG_T) \qquad [7.21]$$

and

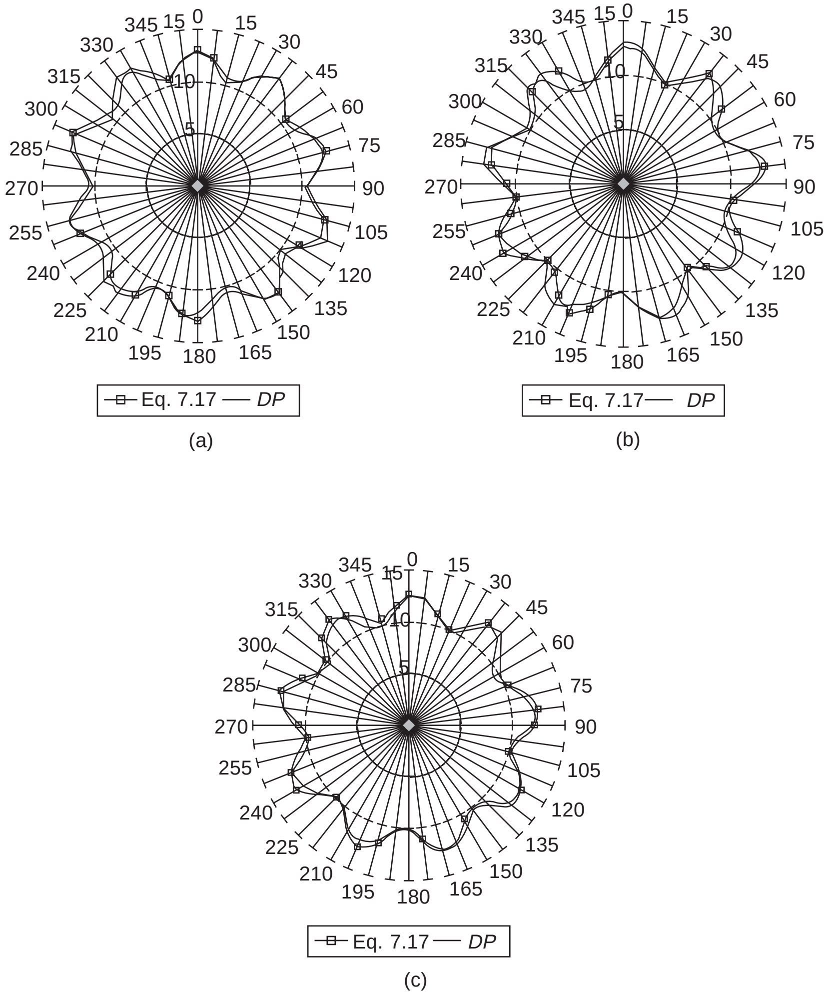
$$k = 2.753 + 0.8153(2HB_T) - 0.469(2HG5_T) \qquad [7.22]$$

where 2*HB*, 2*HG* and 2*HG*5 are the bending hysteresis, shear hysteresis at 0.5° and shear hysteresis at 5° respectively. Suffix *T* is the mean value of its property obtained in the warp, weft and ± 45° directions. Equations 7.20–7.22 show that these constants can be directly calculated from the bending hysteresis and shear hysteresis along different directions.

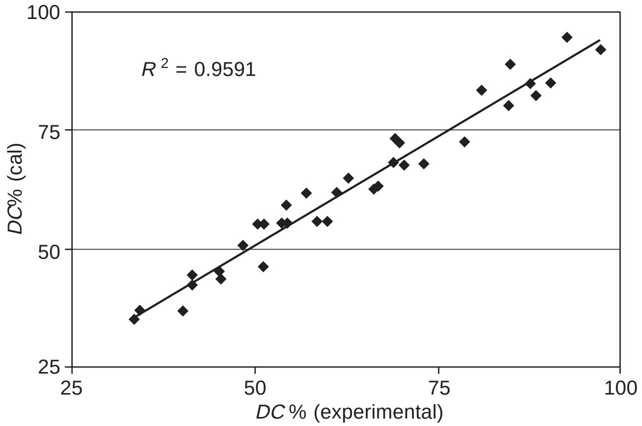
As indicated by Fig. 7.11a–c, the constants *p*, *q* and *k* in the *DP* model can be determined from bending hysteresis and shear hysteresis in various directions. This indicates that draped nodes and locations of a fabric are affected by these properties not only in the warp and weft directions but also in other directions.

7.3.4.2 Drape coefficient

Substituting the experimental data of bending and shear hysteresis into equations 7.20–22, constants *p*, *q* and *k* can be identified and thus the drape



7.11 Theoretical and experimental results of drape profile of woven fabrics: (a) plain weave; (b) twill weave; (c) satin weave.



7.12 Comparison between theoretical *DC*% value and experimental *DC*%.

profile and drape coefficient can be predicted from the *DP* model. Figure 7.12 illustrates a comparison between the theoretical output of the *DP* model and the experimental drape coefficient (*DC*%), which indicates a high correlation between them (R^2 = 0.9591). It further implies that the *DP* models are applicable for the prediction of fabric drape profile from the values of fabric bending and shear hysteresis in various directions using the regression method.

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