b. Porous Properties Engineering

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Prediction of Elastic Properties of Plain Weave Fabric Using Geometrical Modeling

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1. Introduction

Fabrics are typical porous material and can be treated as mixtures of fibers and air. There is no clearly defined boundary and is different from a classical continuum for fabrics. It is complex to proceed with the theoretical analysis of fabric behavior. There are two main reasons (Hearle et al., 1969) for developing the geometrical structures of fabrics. One is to be able to calculate the resistance of the cloth to mechanical deformation such as initial extension, bending, or shear in terms of the resistance to deformation of individual fibers. The other is that the geometrical relationships can provide direct information on the relative resistance of cloths to the passage of air or light and similarly it can provide a guide to the maximum density of packing that can be achieved in a cloth. The most elaborate and detailed account of earlier work is contained in a classical paper by Peirce (Peirce, 1937). A purely geometrical model, which involves no consideration of internal forces, is set up by Peirce for the determination of the various parameters that were required. Beyond that, the geometrical structures of knits are another hot research issue, for instances, for plain-knitted fabric structure, Peirce (Peirce, 1947), Leaf and Glaskin (Leaf & Glaskin, 1955), Munden (Munden, 1961), Postle (Postle, 1971), DemirÖz and Dias (Demiröz & Dias, 2000), Kurbak (Kurbak, 1998), Semnani (Semnani et al., 2003), and Chamberlain (Chamberlain, 1949) et al. Lately, Kurbak & Alpyildiz propose a geometrical model for full (Kurbak & Alpyildiz, 2009) and half (Kurbak & Alpyildiz, 2009) cardigan structure. Both the knitted and woven fabrics are considered to be useful as a reinforcing material within composites. The geometrical structure of the plain woven fabric (WF) is considered in this study.

Woven fabric is a two-dimension (2-D) plane formation and represents the basic structural element of every item of clothing. Fabrics are involved to various levels of load in transforming them from 2-D form into 3-D one for an item of clothing. It is important to know the physical characteristics and mechanical properties of woven fabrics to predict possible behavior and eventual problems in clothing production processes. Therefore, the prediction of the elastic properties has received considerable attention. Fabric mechanics is described in mathematical form based on geometry. This philosophy was the main objective of Peirce's research on tensile deformation of weave fabrics. The load-extension behavior of woven fabrics has received attention from many researchers. The methods used to develop the models by the researches are quite varied. Some of the developed models are theory-based on strain-energy relationship e.g., the mode by Hearle and Shanahan (Hearle &

Shanahan, 1978), Grosberg and Kedia (Grosberg & Kedia, 1966), Huang (Huang, 1978), de Jong and Postle (Jong & Postle, 1977), Leaf and Kandil (Leaf & Kandil, 1980), and Womersley (Womersley, 1937). Some of them are based on AI-related technologies that have a rigorous, mathematical foundation, e.g., the model by Hadizadeh, Jeddi, and Tehran (Hadizadeh et al., 2009). Artificial neural network (ANN) is applied to learn some feature parameters of instance samples in training process. After the training process, the ANN model can proceed with the prediction of the load-extension behavior of woven fabrics. The others are based on digital image processing technology, e.g., the model by Hursa, Rotich and Ražić (Hursa et al., 2009). A digital image processing model is developed to discriminate the differences between the image of origin fabric and that of the deformed one after applying loading so as to determine pseudo Poisson's ratio of the woven fabric.

However, the above-mentioned methods have their limitations and shortcomings. The methods based on extension-energy relationship and system equilibrium need to use a computer to solve the basic equations in order to obtain numerical results that can be compared with experimental data. The methods based on AI-related technologies (i.e., ANN model) need to prepare a lot of feature data of samples for the model training before it can work on the prediction. Thus, the developed prediction models need quite a lot of tedious preparing works and large computation.

In this study, a unit cell model based on slice array model (SAM) (Naik & Ganesh, 1992) for plain weave is developed to predict the elastic behavior of a piece of woven fabric during extension. Because the thickness of a fabric is small, a piece of woven fabric can be regarded as a thin lamina. The plain weave fabric lamina model presented in this study is 2-D in the sense that considers the undulation and continuity of the strand in both the warp and weft directions. The model also accounts for the presence of the gap between adjacent yarns and different material and geometrical properties of the warp and weft yarns. This slice array model (i.e., SAM), the unit cell is divided into slices either along or across the loading direction, is applied to predict the mechanical properties of the fabric. Through the help of the prediction model, the mechanic properties (e.g., initial Young's modulus, surface shear modulus and Poisson's ratio) of the woven fabric can be obtained in advance without experimental testing. Before the developed model can be applied to prediction, there are parameters, e.g., the sizes of cross-section of the yarns, the undulation angles of the interlaced yarns, the Young's modulus and the bending rigidity of the yarns, and the unit repeat length of the fabric etc., needed to be obtained. In order to efficiently acquire these essential parameters, an innovative methodology proposed in this study to help eliminate the tedious measuring process for the parameters. Thus, the determination of the elastic properties for the woven fabric can be more efficient and effective through the help of the developed prediction model.

2. Innovative evaluation methodology for cross-sectional size of yarn

2.1 Definitions and notation for fundamental magnitudes of fabric surface

A full discussion of the geometrical model and its application to practical problems of woven fabric design has been given by Peirce (Peirce, 1937). The warp and weft yarns, which are perpendicular straight lines in the ideal form of the cloth, become curved under stress, and form a natural system of curvilinear co-ordinates for the description of its deformed state. The geometrical model of fabric is illustrated in Fig. 1. The basic parameters consist of two values of yarn lengths l, two crimp heights, h, two yarn spacings, P, and the sum of the diameters of the two yarns, D, give any four of these, the other three can be calculated from the model. There are three basic relationships as shown in equations 1~3 among theses parameters. The definitions of the parameters set in the structural model are denoted as follows.

$$h = (l - D\theta)\sin\theta + D(1 - \cos\theta) \tag{1}$$

$$p = (l - D\theta)\cos\theta + D\sin\theta \tag{2}$$

$$h_w + h_f = D \tag{3}$$

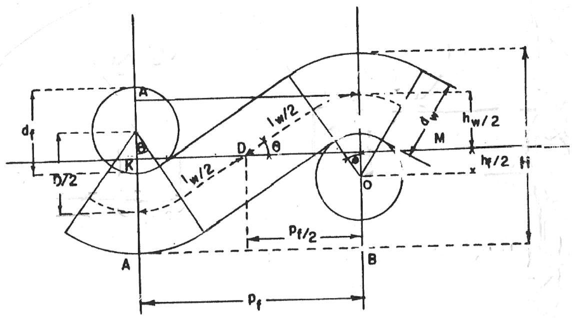


Fig. 1. Geometrical model (Hearle et al., 1969**)**

- Diameter of warp d_w, diameter of weft yarn d_f, and $d_w+d_f=D$.
- Distance between central plane of adjacent warp yarns P_w
- Distance between central plane of adjacent weft yarns P_f
- Distance of centers of warp yarns from center-line of fabric, $h_w/2$
- Distance of centers of weft yarns from center-line of fabric, $h_f/2$
- Inclination of warp yarns to center-line of fabbric, θ_w
- Inclination of weft yarns to center-line of fabbric, θ_f
- Length of warp between two adjacent weft yarns l_w
- Length of weft between two adjacent warp yarns l_f
- Warp crimp $C_w= l_w / P_f -1$
- Weft crimp $C_f= l_f/ P_w -1$

The woven fabric, which consists of warp and weft yarns interlaced one another, is an anisotropic material (Sun et al., 2005). In order to construct an evaluation model to help determine the size of the deformed shape (i.e., eye shape) of cross section, Peirce's plain weave geometrical structure model is applied in this study. Because both the warp and weft yarns of the woven fabric are subject to the stresses during weaving process by the shedding, picking and beating motions, the shapes of cross section for the yarns are not actually the idealized circular ones (Hearle et al., 1969). The geometrical relations, illustrated in equations 1 and 2, can be obtained by projection in and perpendicular to the plane of the fabric. From these fundamental relations between the constants of the fabrics, the shape and the size of the cross section of the yarns can be acquired. Through the assistance of the proposed evaluation model, the efficiency and effectiveness in acquiring the size of section for warp (weft) yarn can be improved.

2.2 Yarn crimp

The crimp (Lin, 2007)(i.e., C_w) of warp yarn and that (i.e., C_f) of weft yarn can be obtained by using equation 4. The measuring of yarn crimp is performed according to Chinese National Standard (C.N.S.). During measuring the length of the yarn unravelled from sample fabric (i.e., with a size of 20 cm × 20 cm), each yarn was hung with a loading of 346/N (g), where N is the yarn count (840 yds/1lb) of the yarn for testing.

$$C=(L-L')/L' \tag{4}$$

Where L denotes the measured length of the warp (weft) yarn, L′ denotes the length of the fabric in the warp (weft) direction.

2.3 Cross sectional shape and size

Both the warp and weft yarns of the woven fabric are subject to the stresses from weaving process during the shedding, picking and beating motions. Due to subjecting to stresses, the shapes of cross section for the yarns are not actually the idealized circular ones. Fig. 2 shows the deformed eye shape of the yarn with a long diameter "a" and a short diameter "h". The sizes of warp and weft yarn are of denoted as a_w, h_w and a_f, h_f, respectively.

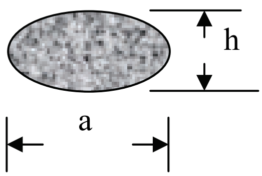


Fig. 2. Deformed shape of yarn

The Length of warp l_1 (weft l_2) between two adjacent weft (warp) yarns can be acquired using equation 5. The inclination of warp θ_1 (weft θ_2) yarns to center-line of fabric, can be obtained from equation 6, which is proposed by Grosberg (Hearle et al., 1969) and verified to be very close to the accurate inclination degree.

$$l = \frac{1 + 1/2nC}{N} \tag{5}$$

$$\theta = 106\sqrt{C} \tag{6}$$

where

C: Crimp

n: number of the warp and weft yarns in one weave repeat

N: Weaving density (ends/in; picks/in)

By Putting the measured values of l and θ into equations 1 and 2, the summation of the sizes of the short diameter for the warp and weft yarns (i.e., $D=h_w + h_f$ for the warp and weft in the thickness direction) and that of the sizes of the long diameter for the warp and weft yarns (i.e., $D_1=a_w^1 + a_f^1$ ($D_2=a_w^2 + a_f^2$) calculated from the known distance between central

plane of adjacent warp P_w (weft P_f) yarns). Because the obtained summation values calculated from the known distances between central plane of adjacent warp yarns P_w and weft yarns P_f are different, the average value $\overline{D}$ of them is calculated. The obtained $\overline{D}$ represents the sum of the long diameters of the warp and weft yarns. The larger the value of $\overline{D}$ is, the more flattened shape the warp and weft yarns are.
Although the summation for the diameter sizes of the warp and weft yarn in the length (thickness) direction of the woven fabric is obtained, the individual one for warp (weft) yarn is still uncertain. In order to estimate the individual diameters of warp and weft yarn, the theoretical diameter (Lai, 1985) is evaluated using equation 7 in the study. The diameter of the individual yarn can be estimated by the weigh ratios shown in equations 8~11.

$$d\ (\mu m)=11.89\sqrt{\frac{Denier}{\rho}} \tag{7}$$

where

Denier: denier of yarn
ρ: specific gravity of yarn

$$a_w=\overline{D}\times\frac{d_w}{d_w+d_f} \tag{8}$$

$$a_f=\overline{D}\times\frac{d_f}{d_w+d_f} \tag{9}$$

$$h_w=D\times\frac{d_w}{d_w+d_f} \tag{10}$$

$$h_f=D\times\frac{d_f}{d_w+d_f} \tag{11}$$

where

a_w: Long diameter of eye-shaped warp yarn
a_f: Long diameter of eye-shaped weft yarn
h_w: Short diameter of eye-shaped warp yarn
h_f: Short diameter of eye-shaped weft yarn
$D= h_w + h_f$
$\overline{D} =(D_1+D_2)/2$
d_w: Theoretical diameter of circular warp yarn
d_f: Theoretical diameter of circular weft yarn

3. Geometrical model and properties of spun yarn

The idealized staple fiber yarn is assumed to consist of a very large number of fibers of limited length, uniformly packed in a uniform circular yarn. The fibers are arranged in a helical assembly, following an idealized migration pattern. Each fiber follows a helical path, with a constant number of turns per unit length along the yarn, in which the radial distance from the yarn axis increases and decreases slowly and regularly between zero and the yarn radius. A fiber bundle illustrated in Fig. 3a, which is twisted along a helical path as shown in Fig. 3b, is manufactured into a twisted spun yarn.

In order to describe the distributed stresses on the body of yarn, a hypothetical rectangular element from is proposed and illustrated in Fig. 4. The stresses acting on the elemental volume dV are shown in Fig. 4. When the volume dV shrinks to a point, the stress tensor is represented by placing its components in a 3×3 symmetric matrix. However, a six-independent-component is applied as follows.

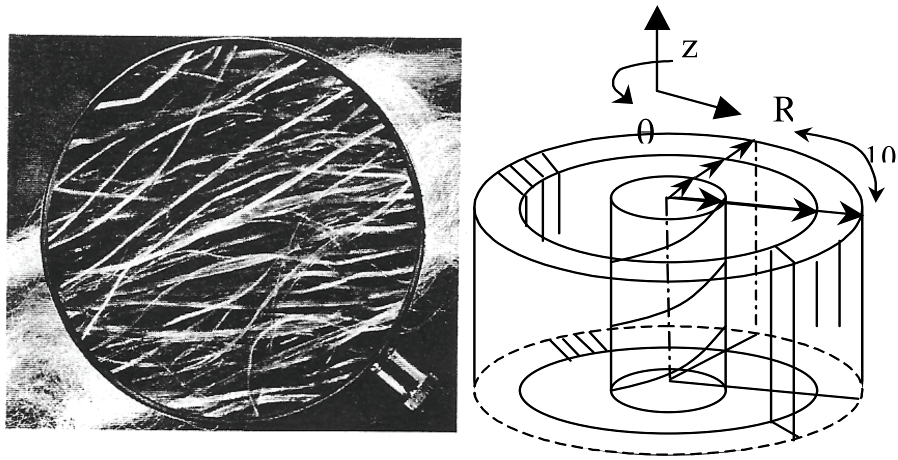
$$\sigma = \left[\sigma_x, \sigma_y, \sigma_z, \tau_{yz}, \tau_{zx}, \tau_{xy}\right]^T \tag{12}$$

Where $\sigma_x, \sigma_y, \sigma_z$ are normal stresses and $\tau_{yz}, \tau_{zx}, \tau_{xy}$ are shear stresses.

The strains corresponded to the acting stresses can be represented as follows.

$$\varepsilon = \left[\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{yz}, \gamma_{zx}, \gamma_{xy}\right]^T \tag{13}$$

Where $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are normal strains and $\gamma_{yz}, \gamma_{zx}, \gamma_{xy}$ are engineering shear strains.



(a) A fiber bundle as seen under a magnifying (Curiskis & Carnaby, 1985)

b) fiber bundle twisted along a helical path

Fig. 3. A fiber bundle

In the continuum mechanics of solids, constitutive relations are used to establish mathematical expressions among the variables that describe the mechanical behavior of a material when subjected to applied load. Thus, these equations define an ideal material response and can be extended for thermal, moisture, and other effects. In the case of a linear elastic material, the constitutive relations may be written in the form of a generalized Hooke's law:

$$\sigma = [S]\varepsilon \tag{14}$$

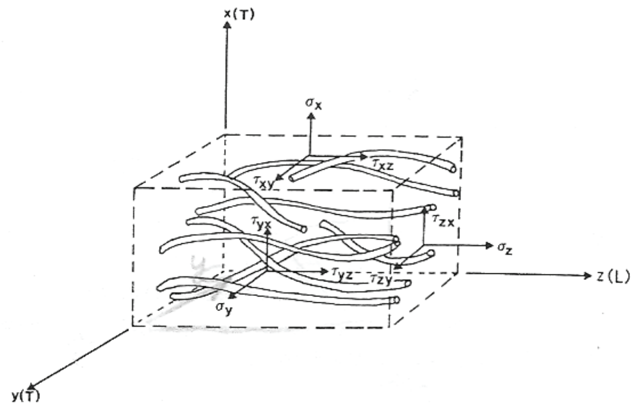


Fig. 4. A rectangular element of a fiber bundle (Curiskis & Carnaby, 1985)

That is

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} \tag{15}$$

$$\varepsilon = [C]\sigma \tag{16}$$

That is

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} \tag{17}$$

Where σ and ε are suitably defined stress and strain vectors (Carnaby 1976) (Lekkhnitskii , 1963), respectively, and [S] and [C] are stiffness and compliance matrices, respectively, reflecting the elastic mechanical properties of the material (i.e., moduli, Poission's ratios, etc.) There are four possible models (Curiskis & Carnaby, 1985) (Carnaby & Luijk, 1982) for the continuous fiber bundle, i.e., the general fiber bundle, Orthotropic material, square-symmetric material, and transversely isotropic material. The orthotropic material model is adopted in this study.

Thwaites (Thwaites, 1980) applied his equations subject to the further constrain of incompressibility of the continuum, that is,

$$\varepsilon_x + \varepsilon_y + \varepsilon_z = 0 \tag{18}$$

In which case the two Poisson's ratio terms are no longer independent：

$$G_{TT} = \frac{E_T}{2(1+v_{TT})} \tag{19}$$

$$v_{TT} = 1 - v_{TL} \tag{20}$$

And

$$v_{TL} = v_{LT} E_T / E_L \tag{21}$$

Thus, for the incompressible material of a spun yarn, whose elastic properties can be described using the seven elastic constants, i.e., G_{TT}, G_{LT}, E_T, E_L, v_{LT}, v_{TL}, and v_{TT}, an orthotropic material model is adopted to depict it in this study. The orthotropic material model as shown in Fig. 4, the fiber packing in the xy plane and along the z axis is such that the xz and yz planes are also planes of elastic symmetry. Furthermore, the continuum idealization then allows application of the various mathematical techniques of continuum mechanics to simplify the setting-up of physical problems in order to obtain useful results for various practical situations. For the study, the yarn (fiber bundle) is mechanically characterized as a degenerate square-symmetric homogeneous continuum. The elastic compliance relationship (Carnaby, 1980) can be described using the moduli and Poisson's ratio parameters illustrated as follows.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_T} & -\frac{V_{TT}}{E_T} & -\frac{V_{LT}}{E_L} & 0 & 0 & 0 \\ -\frac{V_{TT}}{E_T} & \frac{1}{E_T} & -\frac{V_{LT}}{E_L} & 0 & 0 & 0 \\ -\frac{V_{TL}}{E_T} & -\frac{V_{TL}}{E_T} & \frac{1}{E_L} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{TT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} \tag{22}$$

Where E_L is the longitudinal modulus governing uniaxial loading in the longitudinal (z) direction. v_{LT} is the associated Poisson ratio goving induced transverse strains, E_T is the transverse modulus goving uniaxial loading in the transverse (x or y) direction. v_{TT} is the associated Poisson ratio governing resultant strains in the remaining orthogonal transverse (y or x) direction. v_{TT} is the associated Poisson ratio governing the induced strain in the longitudinal direction, G_{LT} is the longitudinal shear modulus goving shear in the longitudinal direction, and G_{TT} is the transverse shear modulus governing shear in the transverse plane.

The theoretical equation for Young's modulus of the spun yarn developed by Hearle (Hearle et al., 1969) is adopted in the study. It is illustrated in equation 23. The fibers are assumed to have identical dimensions and properties, to be perfectly elastic, to have an axis of symmetry, and to follow Hooke's and Amonton's laws. The strains involved are assumed to be small. The transverse stresses between the fibers at any point are assumed to be the same in all directions perpendicular to the fiber axis. Beyond these, there are other assumptions for the developed equation. Thus, it can not expected to be numerically precise because of the severe approximations, can be expected to indicate the general form of the factors affecting staple fiber yarn modulus. However, despite the differences between the idealized model and actual yarns, it is useful to have a knowledge of how an idealized assembly would behave.

$$y_M = f_M \times \frac{1 - \dfrac{2}{3L_f}\left\{\dfrac{a\gamma W_y^{1/2}(1+4\pi v_f \varphi^{-1}\tau^2 10^{-5})^{1/2}}{4\tau\mu[1-(1+4\pi v_f \varphi^{-1}\tau^2 10^{-5})^{-1/2}}\right\}^{1/2}}{(1+4\pi v_f \varphi^{-1}\tau^2 10^{-5})} \quad (23)$$

Where

f_M: modulus of fiber
L_f: fiber length
a: fiber radius
γ : migration ratio (γ=4 for spun yarn)
W_y: yarn count (tex)
v_f: specific volume of fiber
ϕ: packing fraction
τ: twist factor (tex$^{1/2}$ turn/cm)
μ: coefficient of friction of fiber

The flexural rigidity of a filament yarns is the sum of the fiber flexural rigidities under the circumstance that the bending length of the yarn is equal to that of a single fiber. It has been confirmed experimentally by Carlen (Hearle et al., 1969) (Cooper, 1960). The spun yarn is regarded as a continuum fiber bundle in the study, so the flexural rigidity of it is approximately using the same prediction equation illustrated in equation 24.

$$G_y = N_f G_f \quad (24)$$

Where

N_f: cross-sectional fiber number
G_f: flexure rigidity of fiber

The change of yarn diameter and volume with extension has been investigated by Hearle etc. (Hearle et al., 1969) Through the experimental results for the percentage reductions in yarn diameter with yarn extension by Hearle, the Poisson's ratio v_{LT} in the extension direction can be estimated to be at the range of 0.6 ~ 1.1. The Poisson's ratio v_{LT} is set to be 0.7 for the spun yarn in the study.

Young's modulus E_L of the yarn in the (length) extension direction can be estimated using equation 23. Equation 24 can be applied to estimate the flexure rigidity G_{TL} of the yarn. Through putting the obtained E_L, G_{TL}, and the set value of 0.7 for the Poisson's ratio v_{LT} of the yarn into equations 19~21, the other four elastic properties (i.e., G_{TT}, E_T, v_{TL}, v_{TT}) can be acquired, respectively.

Now that the elastic properties of a spun yarn can be represented using the above-mentioned matrix. The simplification for the setting-up of physical problems using various mathematical techniques of continuum mechanics can thus be achieved. For the study, the yarn (fiber bundle) is mechanically characterized as a degenerate square-symmetric homogeneous continuum. The complex mechanic properties of the combination of the warp and weft yarns interlaced in woven fabric can be possible to be constructed as follows.

4. Construction of unit cell model

4.1 Mechanical properties of unit cell of fabric

Fig.5a illustrates a unit cell (Naik & Ganesh, 1992) of woven fabric lamina. There is only one quarter of the interlacing regin analysed due to the symmetry of the interlacing regin in plain weave fabric.

The analysis of the unit cell, i.e., slice array model (SAM), is performed by dividing the unit cell into a number of slices as illustrated in Fig. 5b. The sliced picess are idealized in the form of a four-layered laminate, i.e., an asymmetric crossply sandwiched between two pure matrix (if any) layers as shown in Fig. 5c. The effective properties of the individual layer considering the presence of undulation are used to evaluate the elastical constants of the idealized laminate. Because there is no matrix applied, the top and the bottom layer of the unit cell are not included in this study.

There are two shape functions proposed in the study, one as shown in Fig. 6a for the cross-section in the warp direction and the other as illustrated in Fig. 6b for the one in the weft direction.

Along the warp direction, i.e., in the Y-Z plane (Fig. 5(a))

$$z_{y_1}(y) = -\frac{h_f}{2}\cos\frac{\pi y}{a_{yt}} \tag{25}$$

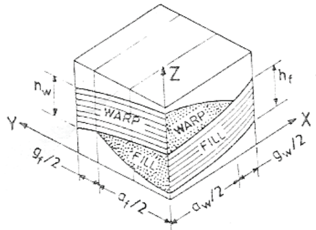
$$z_{y2}(y) = \frac{h_f}{2}\cos\frac{\pi y}{a_f + g_f} \tag{26}$$

Where

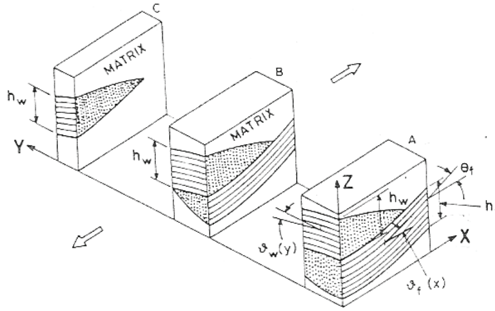
$$a_{yt} = \frac{\pi a_f}{2\left[\pi - \cos^{-1}\left(\frac{2z_{yt}}{h_f}\right)\right]}, \quad z_{yt} = \frac{h_f}{2}\cos\frac{\pi a_f}{2(a_f + g_f)}$$

and

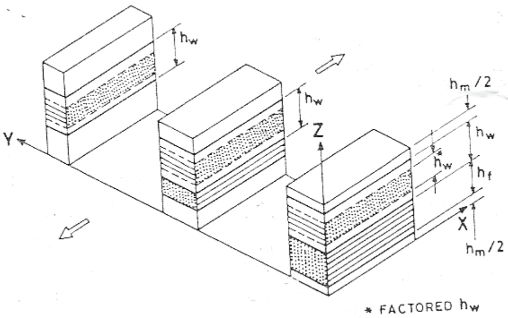
$$\left.\begin{aligned} hy_1(y) &= \frac{h_f + h_m}{2} - zy_2(y) \\ hy_2(y) &= h_w \\ hy_3(y) &= zy_2(y) - zy_1(y) \text{ (when } y = 0 \to a_f/2) \\ &= 0 \text{ (when } y = a_f/2 \to (a_f + g_f)/2) \\ hy_4(y) &= \frac{h_f + h_m}{2} - zy_1(y) \end{aligned}\right\} \tag{27}$$



(a) Unit Cell



(b) Actual Slice



(C) Idealized Slice

Fig. 5. Illustration for the slicing of unit cell and the idealized slice (Naik & Ganesh, 1992)

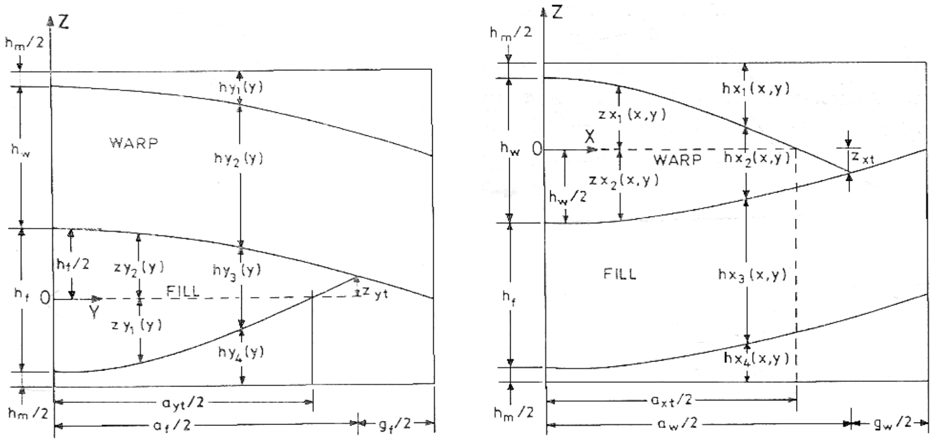
Along the weft (fill) direction, i.e., in the X-Z plane (Fig. 5(a))

$$zx_{1_1}(x,y) = \frac{h_w}{2}\cos\frac{\pi x}{a_{xt}} - hy_1(y) + \frac{h_m}{2} \tag{28}$$

$$zx_2(x,y) = -\frac{h_w}{2}\cos\frac{\pi x}{a_w + g_w} - hy_1(y) + \frac{h_m}{2} \tag{29}$$

where

$$a_{xt} = \frac{\pi a_w}{2\cos^{-1}(\frac{2z_{xt}}{h_w})},\ z_{xt} = -\frac{h_w}{2}\cos\frac{\pi a_w}{2(a_w + g_w)};$$



(a) Plain weave cross-section: warp (b) Plain weave cross-section: weft (fill)

Fig. 6. Illustration for the shape functions (Naik & Ganesh, 1992)

And

$$\left.\begin{aligned} hx_1(x,y) &= \frac{h_w + h_m}{2} - zx_1(x,y) \\ hx_2(x,y) &= zx_1(x,y) - zx_2(x,y) \text{ (when } x = 0 \to a_w / 2) \\ &= 0 \text{ (when } x = a_w / 2 \to (a_w + g_w)/2) \\ hx_3(x,y) &= hy_3(y) \\ hx_4(x,y) &= zx_2(x,y) - hx_3(x,y) + (h_w + h_m)/2 + h_f \end{aligned}\right\} \tag{30}$$

The local off-axis angles in the weft (i.e.,fill) and warp direction can be calculated using equations 31 and 32, respectively.

$$\vartheta_f(x) = \tan^{-1}\frac{d}{dx}[zx_2(x,y)] = \tan^{-1}\left(\frac{\pi h_w}{2(a_w + g_w)}\sin\frac{\pi x}{(a_w + g_w)}\right) \tag{31}$$

$$\vartheta_w(y) = \tan^{-1}\frac{d}{dy}[zy_2(y)] = \tan^{-1}\left(\frac{\pi h_f}{2(a_f + g_f)}\sin\frac{\pi y}{(a_f + g_f)}\right) \tag{32}$$

Because the woven fabric is manufactured by the interlacing of warp and weft yarn, there exists a certain amount of gap between two adjacent yarns. It is obvious that the presence of a gap between two the adjacent yarns would affect the stiffness of the WF lamina. Furthermore, the warp and weft yarns interlaced in fabric are undulated. It can be expected that the elastic properties of the yarn under the straight form and the undulated one are definitely different.

4.2 Mechanical properties of the undulated spun yarn

The respective off-axis angles reduce the effective elastic constants in the global X and Y directions. The increased compliance can be evatuated as follows. (Lekhnitskii, 1963).

$$C_{11}(\vartheta) = \frac{1}{E_L(\vartheta)} = \frac{m^4}{E_L} + (\frac{1}{G_{LT}} + \frac{2v_{LT}}{E_L})m^2n^2 + \frac{n^4}{E_T} \quad (33)$$

$$C_{22}(\vartheta) = \frac{1}{E_T(\vartheta)} = \frac{1}{E_T} \quad (34)$$

$$C_{12}(\vartheta) = \frac{v_{TL}(\vartheta)}{E_T(\vartheta)} = \frac{v_{TL}m^2}{E_T} + \frac{v_{TT}n^2}{E_T} \quad (35)$$

$$C_{66}(\vartheta) = \frac{1}{G_{LT}(\vartheta)} = \frac{m^2}{G_{LT}} + \frac{n^2}{G_{TT}} \quad (36)$$

Where $m = \cos\vartheta$, $n = \sin\vartheta$; E_L and E_T are Young's moduli of yarns in the length direction and the cross-sectional direction, respectively; G_{LT} and G_{TT} are the flexure rigidity and torsion one, respectively. The value of E_L is calculated by the theoretical equation 23 developed by Hearle (Hearle et al., 1969). Through the experimental results for the percentage reductions in yarn diameter with yarn extension by Hearle, the values of E_T , G_{LT} , and G_{TT} for the yarns are determined based on the orthotropic material model proposed by Curiskis and Carnaby (Curiskis & Carnaby, 1985).
The compliance of yarn is related to the angle of undulation of the yarn crimped in the fabric. The off-axis angle for each specific location at the warp and weft yarn can be acquired from equation 31 and 32. In order to precisely evaluate the changed compliances for the warp and weft yarn, the mean value of the compliance is applied and illustrated in equation 37.

$$\bar{C}_{ij} = \frac{1}{\theta}\int_0^{\theta} C_{ij}(\vartheta)d\vartheta \quad (37)$$

where θ is the angle of undulation for the yarn at $x=a_w/2+g_w/2$.

4.3 Evaluation of mechanical properties of slices and unit cell

After evaluating the changed elastic constants of the warp and weft yarn using equation 37, the extensional stiffness of the slice can be obtained from equation 38. The integration used in the equation is fulfilled by neumatic method in the study.

$$A_{ij}^{sl}(y) = \frac{1}{H}\sum_{k=1}^{2} hx_k(x,y)(\bar{S}_{ij})_k \quad (38)$$

Where, $hx_k(x,y)$ and $(\bar{S}_{ij})_k$ are the thickness and mean transformed stiffness of the kth layer in the nth slice.
The sliced pieces are idealized in the form of a two-layered lamina, i.e., warp and weft asymmetric crossply sandwiched between two pure matrix (if any) layers as shown in Fig. 5c. If there is no matrix applied on the fabric, i.e., the 1st and the 4th layers are vacant; the extensional stiffness of the slice consisting of a warp and a weft yarn can still be estimated from equation 38. The effective properties of the individual layer considering the presence of undulation are used to evaluate the elastical constants of the idealized woven fabric lamina.

Based on Fig. 5 and Fig. 6, $hx_k(x,y)$ is evaluated at constant x, for different values of y. The thickness of the warp yarn is maximum at x=0 and zero from $x=a_w/2$ to $x=(a_w+g_w)/2$. In order to acquire the mean thickness of each layer of different material, the coordinate of x is set to be at the middle (i.e., $x= (a_w/2+g_w/2)/2$) of the unit cell in the study. The extensional stiffness of the unit cell is evaluated from those of the slices by assembling the slices together under the isostrain condition in all the slices. In other words, the in-plane extensional stiffness of the unit cell is evaluated and can be expressed as follows.

$$A_{ij} = \frac{2}{(a_f + g_f)} \int_0^{(a_f+g_f)/2} A_{ij}^{sl}(y)dy \tag{39}$$

According to Fig. 5a, the unit cell is obviously not symmetric about its midplane, so there exist the coupling stiffness terms. However, the coupling terms in two adjacent unit cells of the woven fabric lamina would be opposite signs due to the nature of interlacing of yarns in the plain weave fabric. Thus, the elastic constants of the unit can be obtained and expressed as follows.

$$\left.\begin{aligned} E_x &= A_{11}\left(1 - \frac{A_{12}^2}{A_{11}A_{22}}\right) \\ G_{xy} &= A_{66} \\ v_{yx} &= \frac{A_{12}}{A_{22}} \end{aligned}\right\} \tag{40}$$

Where, E_x is the Young's modulus, G_{xy} is the flexure rigidity, and v_{yx} is the Poisson's ratio for the fabric, respectively.
Accordingly, the Young's modulus in the warp direction can be calculated using the above-mentioned steps as well.

5. Experiments

5.1 Characteristics of sample fabrics

The measured characteristics of the sample fabric are shown in table 1. The theoretically generalized elastic properties of cotton fiber are given in Table 2. Base on the data of the raw material cotton fiber, Young's modulus of the cotton spun yarn (i.e., y_M) is predicted to be 6694 (N/mm^2) using equation 23 developed by Hearle (Hearle et al., 1969). The flexure rigidity (i.e., G_{LT}) of the spun yarn can be acquired as 0.0031 (N/mm^2) using equation 24 as well.

Weave	Yarn count (warp×weft)	Yarn specific volume, cm^3/g	Density, yarns/inch (warp×weft)	Material (warp×weft)
plain	20'S × 20'S	1.22	60 × 60	C × C

Yarn count 'S=840 yd/ 1lb, Material: C=cotton

Table 1. Characteristics of woven fabric sample

5.2 Preprocessing and procedures

The sample fabrics are scoured at 30°C for one hour in sodium carbonate. Then they are washed and dried at room temperature. Static tensile test specimens are prepared according to Chinese National Standard (C.N.S.). The testing size is 25mm×100mm. The specimens are tested at room temperature (25°C) at a crosshead speed of 10 mm/min. A total of ten specimens are tested, five of which are the samples made for testing in warp direction and the other five are for testing in weft direction direction. An experimental program is designed by C language to calculate the elastic constants of the woven fabric lamina along the warp and weft directions in the study. The experiment is performed on cotton woven fabric lamina according to the essential requirements proposed by Bassett et al. (Bassett et al., 1999).

f_M (N/mm²)	L_f (mm)	a (mm)	γ	W_y (tex)	v_f	ϕ	τ (tex$^{1/2}$ turns/cm)	μ	E_L (N/mm²)	G_{LT} (Nmm²)
8000	40	0.0130	4	31.9200	0.6500	0.5300	33.36	0.22	6694	0.0031

f_M: Young's modulus of fiber, L_f: fiber length, a: fiber radius, γ:migration ratio, W_y: yarn count, v_f: specific volume of fiber, ϕ:packing fraction, τ:twist factor(tex$^{1/2}$turn/cm), μ:coefficient of friction

Table 2. Characteristics of the cotton fiber

6. Results and discussion

6.1 Cross-sectional size of yarn

Woven fabric, which consists of warp and weft yarns interlaced one another, is an anisotropic material. Peirce's plain weave geometrical structure model is used to set up a prediction model for the shapes and sizes of warp and weft yarn. Both the warp and weft yarns of woven fabric are subject to the stresses from weaving process during the shedding, picking, beating motions. Due to the occurred stresses, the shapes of section for yarns are not actually the idealized circular ones. It shows that the theoretically calculated results are pretty consistent to the experimental. Through the evaluation methodology for cross-sectional size of yarn based on Peirce's structure model, the efficiency and effectiveness in acquiring the sectional size for warp (weft) yarn can be improved.

The geometrical scales of the fabric are determined by means of an optical microscope at a magnification of 20. The obtained results are used to compare with the calculated ones for validation of the innovative evaluation methodology proposed in this study. The measured and calculated results are illustrated in Table 3 and Table 4, respectively. Table 5 shows there are errors less than 5% for each between the calculated and the tested results. It reveals that the proposed method is of good accuracy and can more efficiently acquire the geometrical sizes, i.e., the long and short diameters of the warp and weft yarns in the fabrics.

Crimp		Undulation angle (degree)		Length of repeat unit (mm)		Crimped length (mm)	
C_w	C_f	θ_w	θ_f	P_w	P_f	l_w	l_f
0.06	0.06	25.9646	25.9646	0.4305	0.4305	0.4487	0.4487

Table 3. Measured and induced results of the basic sizes for the fabric

Long diameter $p=(l-D\theta)\cos\theta+D\sin\theta$		Short diameter $h=(l-D\theta)\sin\theta+D(1-\cos\theta)$	Diameter (circular shape)		Diameter (actual eye shape)			
			warp	weft	warp		weft	
D_1(mm)	D_2(mm)	D (mm)	d_w (mm)	d_f (mm)	a_w (mm)	h_w (mm)	a_f (mm)	h_f (mm)
0.8856	0.8856	0.3288	0.2140	0.2140	0.4428	0.1644	0.4428	0.1644
$\overline{D}$ (mm)								
0.8856								

Table 4. Calculated results by evaluation methodology based on Peirce's model

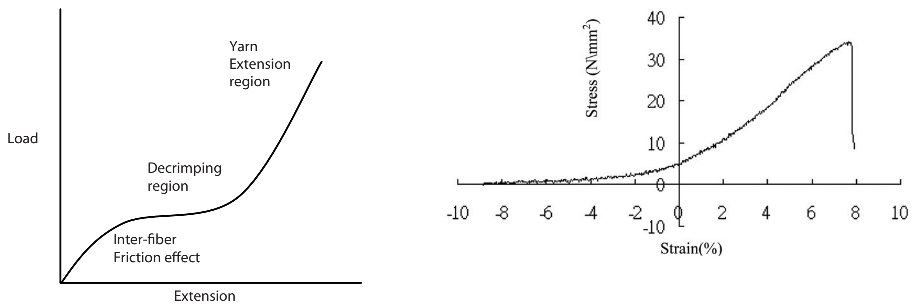
Predicted				Measured			
warp		weft		warp		weft	
a_w (mm)	h_w (mm)	a_f (mm)	h_f (mm)	a_w(mm)	h_w (mm)	a_f(mm)	h_f (mm)
0.4428	0.1644	0.4428	0.1644	0.4348	0.1625	0.4348	0.1625

Table 5. Comparison between the predicted and the measured sizes

6.2 Extensional behavior of fabric

The generalized load-extension curve as illustrated in Fig. 7 (Hearle et al., 1969) shows three actions, as in the initial decrimping region the load-extension curve possesses a point of inflexion. The initial high modulus of the fabric is probably due to frictional resistance to bending of the thread. Once the frictional restraint is overcome, a relatively low modulus is obtained which is mainly governed by the force needed to unbend the threads in the direction in which the force is being applied, and at the same time, the need to increase the curvature in the threads at the right angles to the direction of application of the force. As the crimp is decreased the size of this force rises very steeply and, as a result, the fibers themselves begin to be extended and in the final region, the load-extension properties of the cloth are almost entirely governed by the load-extension properties of the yarns themselves.

According to the description of the load-extension process, it can be concluded that the initial modulus of the fabric is determined by the first part. In other words, the resistance to bending of the thread (including frictional forces affected by the surface features of the warp (weft) yarns and the bending rigidity of the warp (weft) yarns) governs the initial modulus.



(a) Generalized load-extension curve (b) Sample fabric stress-strain curve

Fig. 7. Comparison between generalized and tested curve

This above-mentioned viewpoints on extension-load curve by Grosberg is quite in accordance with the equation deduced for Young's modulus by Leaf & Kandil (Leaf & Kandil, 1980). According to the deduced equation, the initial modulus is related to the bending rigidities of warp and weft yarns. However, the tested results for the sample fabric shown in Fig. 7b, in which there is a lack of level out appearance in the load-extension curve for the sample fabric, are different from the generalized load-extension curve. This is mainly because the sample fabric used in the study is of a small crimped angle of 26°. It brings about that once the resistances of the friction force occurred from the rough contact surfaces of the adjacent yarns and the bending rigidities of the warp and weft yarns are conquered, the second stage (i.e., lever out region) is skipped and directly move to the third region (i.e., the applied force used to extend the fibers themselves in the yarn).

6.3 Validation of slice array model

The slice array model (i.e., SAM) (Naik & Ganesh, 1992), which considers the actual yarn cross-sectional geometry and the presence of a gap between the adjant yarns, is presented for the elastic analysis of 2-D orthogonal plain weave fabric lamina. The shape functions agree well with the actual geometry of the woven fabric lamina. The assumption that the locally bending deformations are constrained is realistic considering the nature of interlacing of the plain weave fabrics.

In order to examine the micromechanical approaches for the prediction of the elastic constants of a woven fabric lamina, a plain woven fabric with warp and weft spun yarn of cotton fibers is selected. The elastic properties of the cotton fiber are given in Table 1. Based on the mechanical properties of the raw material cotton fiber, Young's modulus of the cotton spun yarn (i.e., y_M) is predicted to be 6694 (N/mm^2) using equation 23 developed by Hearle (Hearle et al., 1969). However, it is much higher than the actual measured value of 581 (N/mm^2). As Hearle (Hearle et al, 1969) said the prediction equation can not be expected to be numerically precise because of severe approximations.

E_T (N/mm^2)	G_{TT} (N/mm^2)	G_{LT} (N/mm^2)	v_{LT}	v_{TT}	v_{TL}
5592[a]	1969[a]	0.0031[a]	0.70[a]	0.42[a]	0.58[a]
484[b]	171[b]	0.0031[b]	0.70[b]	0.42[b]	0.58[b]

a: Calculated based on E_L=6694 (N/mm^2); b: Calculated based on E_L=581 (N/mm^2)

Table 6. Calculated elastic properties of the straight yarn based on Predicted and Measured E_L

E_x (N/mm^2)	G_{xy} (N/mm^2)	v_{yx}
3622[a]	669[a]	1.95×10^{-5} [a]
316[b]	58[b]	2.11×10^{-4} [b]
363[c]	---	---

a: Calculated based on E_L=6694 (N/mm^2); b: Calculated based on E_L=581 (N/mm^2); c: measured

Table 7. Elastic properties of plain weave fabric lamina: Comparison of predicted and experimental results

Once the value of E_L is determined and the value of v_{LT} is set at 0.7, those of E_T, G_{LT} and G_{TT} for the yarns can be calculated based on the orthotropic material model (Curiskis &

Carnaby, 1985) proposed by Curiskis and Carnaby. The obtained results of the mechanical properties of the yarn in straight form are illustrated in Table 6. Thus, the elastic properties (i.e. compliance coefficients) for the undulated warp and weft yarn in the fabric can be estimated by equations 33~36. The compliance matrix for each slice of the unit cell shown in Fig. 5b can thus be obtained and the one of the unit cell can be acquired from the summation of each of the slices as shown in Fig. 5c by equation 39. Furthermore, the stiffness matrix of the unit cell can be calculated from the inverse matrix of the obtained compliance matrix. Young's modulus of the woven fabric in the extension direction can be evaluated using equation 40. The predicted results are illustrated in Table 7, in which it reveals that the predicted Young's modulus E_x in the weft extension direction based on the actual measured E_L (= 581 N/mm^2) of yarn is much closer to the measured one than based on the predicted E_L (=6694 N/mm^2) of yarn.

7. Conclusions

In this study, a unit cell model for plain weave is developed to predict the elastic behavior of woven fabric during extension. A piece of woven fabric is regarded as a thin lamina because of its thickness is small. The plain weave fabric lamina model presented in this study is 2-D in the sense that considers the undulation and continuity of the strand in both the warp and weft directions. The model also accounts for the presence of the gap between adjacent yarns and different material and geometrical properties of the warp and weft yarns. This slice array model (i.e., SAM), which is used to predict the elastic properties of WF composites by Naik and Ganesh, is applied to evaluate the mechanical properties of woven fabric in this study. The applicability of SAM to prediction of the elastic properties of fabrics is as good as to that of the composites. However, it is necessary to have accurate elastic constants, i.e., Young's moduli of the warp and weft yarn, for the model in order to obtain a promising predicted result. It is found that the accuracy of a predicted Young's moduli of warp and weft yarn obtained from a deduced equation by Hearle is not as good as expected. In order to help eliminate the tedious measuring process but to obtain the exact sizes of the yarns in the fabric, an innovative methodology based on Peirce's geometrical model is developed in the study. It reveals that the proposed method is of good accuracy and can more efficiently acquire the geometrical sizes, i.e., the long and short diameters of the warp and weft yarns in the fabrics. Through the help of the modified SAM prediction model, the mechanic properties (e.g., initial Young's modulus, surface shear modulus and Poisson's ratio) of the woven fabric can be obtained in advance without being through experimental testing. Thus, the determination of the woven fabric can be more efficient and effective through the help of the modified SAM model. Another weave structure of woven fabrics, e.g., twill and satin, is to be selected to construct the geometrical model and a close examination into the stress-strain relations of the unit cell by using finite element analysis is interesting to be followed in our further study.

8. References

Bassett, R.J., Postle, R. & Pan, N. (1999). Experimental Methods for Measuring Fabric Mechanical Properties: A Review and Analysis, Textile Research Journal, Vol.69, No.11, pp. 866-875

Curiskis, J.I., Carnaby, G. A. (1985). Continuum Mechanics of the Fiber Bundle, Textile Research Journal, Vol.55, 334-344

Carlene, P.W. (1950). The Relation between Fiber and Yarn Flexural Rigidity in Continuous Filament Viscose Yarn, The Journal of The Textile Institute, Vol.41, T159-172.

Cooper, D.N.E. (1960). The Stiffness of Woven Textiles, The Journal of The Textile Institute, Vol.51, T317-335.

Carnaby, G. A. (1980). The Compression of Fibrous Assemblies, with Applications to Yarn Mechanics, in "Mechanics of Flexible Fiber Assemblies," J.W.S. Hearle, J.J. Thwaites, and J. Amirbayat, Eds., Sijthoff and Noordhoff, Alphen aan den Rijn, The Netherlands, , pp. 99-112.

Carnaby, G.A. & Luijk, C.J. Van (1982). The Mechanical Properties of Wool Yarns, in "Objective Specification of Fabric Quality, Mechanical Properties and Performance, S.Kawabata, R. Postle, & M. Niwa, Eds., Textile Machinery Society of Japan, Osaka, , 239-250.

Chamberlain, J. (1949). "Hosiery Yarns and Fabrics", Vol. 2., Leicester College of Technology and Commerence, Leicester, , pp. 107.

Curiskis, J.I., G. A. Carnaby (1985). Continuum Mechanics of the Fiber Bundle, Textile Research Journal, Vol.55, 334-344

Carnaby, G.A. (1976). The Structure & Mechanics of Wool Carpet Yarns, Doctoral thesis, University of Leeds,

De Jong, S. & Posite, R. (1977). Energy Analysis of Woven-Fabric Mechanics By Means of Optimal-Control Theory, Part I: Tensile Properties,Journal of Textile Institute, , Vol. 68, p350-362.

Demiröz, A., & Dias, T. (2000). A Study of the Graphical Representation of Plain-Knitted Structures, Part I: Stitch Model for the Graphical Representation of Plain-Knitted Structures, The Journal of The Textile Institute, Vol. 91 (4), No. 1, pp. 463-480.

Demiröz, A., & Dias, T. (2000). A Study of the Graphical Representation of Plain-Knitted Structures, Part II: Experimental Studies and Computer Generation of Plain-Knitted Structures, The Journal of The Textile Institute, Vol. 91 (4), No. 1, pp. 481-492.

Grosberg, P. and Kedia, S. (1966). The Mechanical Properties of Woven Fabrics, Part I: The Initial Load Extension Modulus of Woven Fabrics, Textile Research Journal, Vol.36 (1), pp71-79.

Hadizadeh, M., Jeddi, A.A.A. & Tehran, M. A. (2009). The Prediction of Initial Load-extension Behavior of woven Fabrics Using Artificial Neural Network, Textile Research Journal, vol.79, No.17, pp. 1599-1609.

Hearle, J.W.S., Grosberg, P., & S. Baker (1969). "Structural Mechanics of Fibers, Yarns, & Fabrics, " Vol. 1, John Wiley& Sons, New York, USA.

Hearle, J.W.S. & Shanahan, W.J. (1978). An Energy Method for Calculations in Fabric Mechanics, Part I: Principles of the Method, Journal of Textile Institute, , 69 (4), pp81-91.

Hearle, J.W.S. & Shanahan, W.J. (1978). An Energy Method for Calculations in Fabric Mechanics, Part II: Examples of Application of the Method to Woven Fabrics, Journal of Textile Institute, 69 (4), 92-100.

Huang, N.C. (1978). Technical Report SM7801, Solid Mechanics Group, Department of Aerospace and Mechanical Engineering, University of Notre Dame, U.S.A., Sep.,

Hursa, A., Rotich, T. & Ražić, S. E. (2009). Determining Pseudo Poisson's Ratio of Woven Fabric with a Digital Image Correlation Method, Textile Research Journal, vol.79, No.17, pp. 1588-1598.
Kurbak, A. (1998). Plain-Knitted Fabric Dimentions, Part II, Textile Asia, April, pp. 36-40, pp. 45-46.
Kurbak, A. & Alpyildiz, T. (2009). Geometrical Models for Cardigan Structures, Part I: Full Cardigan, Textile Research Journal, Vol. 79, No. 14, pp. 1281-1300.
Kurbak, A. & Alpyildiz, T. (2009). Geometrical Models for Cardigan Structures, Part II: Half Cardigan, Textile Research Journal, Vol. 79, No. 18, pp. 1635-1648.
Lekkhnitskii, S.G., Theory of Elasticity of an Anisotropic Elastic Body, Holden-Day, San Francisco,
Leaf, G.A.V., & Glaskin, A. (1955). Geometry of Plain-Knitted Loop, The Journal of The Textile Institute, Vol. 46, pp. 587-605.
Leaf, G.A.V. & Kandil, K.H. (1980). The Initial Load-extension Behaviour of Plain-woven Fabrics, Journal of Textile Institute, , Vol. 71, No. 1, pp. 1-7.
Lai, T.-P. (1985). "Practical Fiber Physical Chemistry", Tai-Long Publishing Co. Taipei, ROC,
Lekhnitskii, S.G. Theory of Elasticity of an Isotropic Body, Holden-Day, San Francisco, USA.
Lin, J. J. (2007), Prediction of Yarn Shrinkage Using Neural Nets, Textile Research Journal, Vol.77 (5), pp336-342,
Munden, D. L. (1961). The geometry of a Knitted Fabric in its Relaxed Condition, Hosiery Times, April, Vol. 43.
Naik, N.K. & Ganesh, V.K. (1992). Prediction of on-axes elastic properties of plain weave fabric composites, Composite Science and Technology, Vol. 45, 135-152.
Peirce, F.T. (1937), The Geometry of Cloth Structure, Journal of Textile Institute, Vol 28, T45-96.
Peirce, F.T. (1947). Geometrical Principles Applicable to the Design of Functional Fabrics, Textile Research Journal, Vol. 17, pp. 123-147.
Sun, H., Pan, N. & Postle, R. (2005). On the Poisson's ratios of a Woven fabric, Composite Structures Vol.68, pp. 505-510.
Postle, R. (1971). Structure Shape and Dimensions of Wool Knitted Fabrics, Applied Polymer Symposium, No. 18, John Wiley, Chichester, pp. 149.
Semnani, D., Latifi, M., Hamzeh, S., & Jeddi, A. A. A. (2003). A New Aspect of Geometrical and Physical Principles Applicable to the Estimation of Textile Structures: Ideal Model for Plain knitted Loop, The Journal of The Textile Institute, Vol. 99, No. 1, pp. 204-213.
Thwaites, J.J. (1980). A Continuum Model for Yarn Mechanics, in "Mechanics of Flexible Fiber Assemblies," J.W.S. Hearle, J.J. Thwaites, & J. Amirbayat, Eds., Sijthoff and Noordhoff, Alphen aan den Rijn, The Netherlands,, pp. 87-97.
Womersley, J.R. & D.I.C., B.Sc. (1937). The Application of Differential Geometry to the Study of the Deformation of Cloth under Stress, Journal of Textile Institute, , Vol. 28, T99-113.

8

Prediction of Fabric Tensile Strength by Modelling the Woven Fabric

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1. Introduction

The variety of fabric structures is divided into four parts as wovens, knitts, braids and nonwovens. Comparing with other fabrics, woven fabrics display both good dimensional stability in the warp and weft directions and highest cover yarn packing density. One of the most important features for the characterization of woven fabric quality and fabric performance is tensile properties of fabric strength. Even though the end products of spinning and weaving are woven fabrics, they are raw materials for clothing and other industries such as composites and medical textiles. Every piece of woven fabric is an integration of warp and weft yarns through intersection. The extent of this intersection is largely dependent on the friction between fibres and yarns.

The study of woven fabric mechanics is came across in a work reported by Haas in the German aerodynamic literature in 1912 during development of airships. In English literature, the paper by Peirce (1937) who is the pioneer in the investigation of tensile deformation of woven fabrics presented a geometrical and a mathematical force model of the plain-weave structure which is highly theoretical, both of which have been used extensively and modified by subsequent workers in the field. Many researchers modified his geometrical model to analyze tensile behaviour. Considerable progress has been made over the last century in the development of the theory of geometrical structure and mechanical properties of fabrics.

The mathematical modelling of fabric stress– strain relationships is a very tough topic. During the last 60 years, many outstanding textile scientists have dedicated to their talents to this field. The development of mathematical models for woven fabrics is an extremely complicated and difficult task due to the large numbers of factors on which the behaviour of the fabric depends. Usually, a mathematical model requires a large number of assumptions, covering missing knowledge or inability to express some of the relevant factors.

Mathematical models based on the fundamental mechanics of woven fabrics often fail to yield satisfactory results, as it is hardly possible to incorporate all the complexities in the model. Moreover, the application range of mathematical models is also very specific. Therefore, it is necessary to introduce a different approach for the mathematical modelling of fabric constitutive equations. With fabric, fundamental distinctions may be made between three kinds of modelling, namely: predictive, descriptive and numerical models. The predictive models which form most of the existing research into fabric mechanics are based on the consideration of at least the most important of the relevant factors, while the effect of the remaining ones is covered by suitable assumptions, defining the limits of validity and the accuracy of the resulting theories. Numerical models may ignore the exact mechanism taking place within the structure but emphasize the numerical relations of two variables such as stress– strain relations.

This method is based on statistical considerations; it needs fewer assumptions and provides, perhaps, an approach more relevant to real situations. There exist various methods for fitting a curve in many industrial or science fields. The descriptive models are largely empirical and reflect the need for simple mathematical relations, expressing the phenomenological behaviour of a fabric from the point of view of a particular property (Hu, 2004).

In addition to aforementioned models, in woven fabrics, parallel yarns are only in contact with each other over a fraction of their lengths, and crossover contact may act over relatively complex curved surfaces. Hence to produce an analytical model, a number of simplifications are required. Woven fabrics are well known to have non-linear mechanical properties. The tensile behaviour of woven fabrics is non-linear at low tensions, even if the yarn is linear in tension.

2. Importance of the study

Prediction of fabric mechanical properties such as strength, elongation, bending and shear is an intricate task, as it requires complete understanding of fabric structural mechanics and the interaction between warp and weft threads. Therefore, the solution of the fabric strength prediction problem could be performed by employing the empirical and computational models such as artificial neural network (ANN) or classical regression analysis (Majumdar et al, 2008).

In this study, the data obtained from Zeydan's paper (Zeydan, 2008) will be used for finding both the effect of some fibre, yarn and fabric parameters on the strength of jacquard woven mattress fabric and level configuration of parameters providing maximum fabric tensile strength. A new modelling methodology in the prediction of woven fabric strength will be introduced in this chapter and compared by using TDOE (Taguchi Design of Experiment), ANN, GA-ANN (Genetic Algorithm based Artificial Neural Network) Hybrid structure and multiple regression methodology. Initially, parameters affecting the fabric strength are chosen from experimental design perspective and then fabric strength is modelled based on the given parameters with TDOE, ANN, GA-ANN and multiple regression modelling approach. Besides, a hybrid model structure depending on GA-ANN is used to verify optimum woven fabrics manufacturing parameter configuration of TDOE. ANN and GA are two of the most important computational techniques of Artificial Intelligence. While ANN is a very powerful modelling method used in complex non-linear systems, GA can be suitable for parameter optimization. The performance criteria assessing appropriate model for the four approaches are root mean square error (RMSE) and MAE (Mean Absolute Error).

The following parameters collected from a Textile Factory producing jacquard woven bedding fabric have been identified as potentially important parameters affecting the strength of woven fabric as shown in the following Table 1.

While determining parameters of this study, parameters related to weaving process have been considered rather than yarn-based parameters. The firm that the research was carried out purchases the yarn from its suppliers. But, it performs all weaving and treatment processes in its plant. Because of this reason, production process parameters of the firm were adjusted according to desired conditions during the sample production. Thus, parameters significantly affecting fabric strength such as yarn strength and twist could not be taken into consideration. Consequently, it was not possible to manufacture additional (extra) samples that are suitable for the aforementioned parameters. Fabric strength was tested at Titan fabric strength tester machine according to the ASTM D5035 testing method.

Levels		
Factors	1	2
A: Number of warp yarns at fabric width	7040	8658
B: Weft density (weft/cm)	8	16
C: Weft yarn count(denier)	300	600
D: Fibre Type of weft yarn	PF	CF
E: Warp density(warp/cm)	33	38
F: Warp yarn count (denier)	150	354
G: Fibre type of warp yarn	PF	CF

Table 1. Factors and Levels

Strip method (ASTM D5035) was adopted for the evaluation of breaking force of narrow fabrics in Titan fabric strength tester. Any fabric slippage from the tester jaws was recorded. Breaking force was recorded for evaluation. Five samples were tested at each group, which were 20 cm in length and 25mm in ravelled width. Gage length was set to 75mm and none the samples were failed at or close to the grip region. Only warp-wise testing was performed. Testing machine was set for a loading rate of 300 mm/min. All tests were performed under standard atmospheric conditions (per cent 65 +-2 relative humidity and 20+- 28C temperature) and the samples were conditioned hours under such conditions for 24 before testing (Zeydan, 2008). Jacquard woven fabrics are widely used in various sections of upholstery industry, where mattress cover is one of them. Although Jacquard fabrics are most often used for upholstery, they are becoming more and more popular in the apparel trades. Strength of jacquard woven mattress fabric depends on several factors. The objective of this study is to model the relationship between fibre, yarn and fabric parameters on the strength of fabric using artificial neural network (ANN), Taguchi design of experiment (TDOE), Multiple Regression and ANN-GA modelling methodologies. There have been some studies in the literature of Textile about the usage of Fabrics and woven Fabrics modelling with ANN. Keshavaraj et al. (1996) modelled air permeability of woven fabrics for airbags. Ogulata et al. (2006) used regression and ANN models to predict elongation and recovery test results of woven stretch fabric for warp and weft direction using different test points. Behera and Muttagi (2004) reported the possibility of woven fabric engineering. Majumdar et al. (2008) employed ANN to forecast the tensile strength of a woven fabric. Hadizadeh et al. (2009) predicted initial load-extension behaviour of plain weave and plain weave derivative fabrics. Tilocca et al. (2009) detected fabric defects using two kinds of optical patterns. Gong and Chen (1999) predicted the performance of fabrics in garment manufacturing. Behera and Karthikeyan (2006) made a design of canopy fabrics. However, any research about comparing ANN, TDOE, multiple regression and ANN-GA in the literature hasn't been conducted on the strength prediction of woven fabric from fibre, yarn and fabric parameters using woven fabric modelling approaches with all together so far. Modelling the woven fabrics comes into existence in many forms.

In this study, traditional and computational modelling techniques are compared between each other. Compared the other classical modelling techniques, computational modelling methodology seems to have been more robust and appropriate. This study has many advantages to reduce the waste and scrap ratio before and during manufacturing. Therefore production planning will become more efficient in a textile plant. This study presents a new approach given in the following figure 1 about which woven fabric modelling is more efficient than the others.

2.1 Production cycle of weaving department at a textile factory

This study was made in a textile Factory in Turkey. The textile factory was founded in 2002. With over 1,000 employees, state of the art plants are made up of 120.000 m^2 open area of which 83.000 m^2 is closed area. It is a fully integrated facility consisting of weaving and knitting plants including narrow weaving crochet knitting, fabric finishing, chenille yarn and Bulk continuous filament polypropylene yarn manufacturing sections. The company is the world's largest upholstery fabric manufacturer. The Factory ships (delivers) the great bulk of its output (approximately 80 %) to world markets. Its plants are regarded as the Europe's most modern Jacquard weaving facility comprising 150 full automatic Jacquard weaving looms and composes of several departments related to woven and knitted upholstery and bedding fabrics. Annually weaving production capacity are 30.000.000 meters. Average scrap of production is 5/1000. The reason of returning the production back is generally originated from vision-based.

Textile Factory composes of several departments related to woven and knitted upholstery and bedding fabrics. Production cycle of woven bedding fabrics starts with warping process. Warp and weft yarns are sourced from external companies and stored at yarn warehouse at the factory. Warp yarns needs to be wound into beams in order to weave fabrics in order. Conic warping machine is used to arrange warp yarns in order at the beam. After that, warp yarns are drawn-in and the weaving machine is ready for weaving. Weft yarns are fed into weaving process in the cone form. Design office in the company is responsible for preparing the jacquard design of fabric according to the customer preferences. The fabric design is transferred into jacquard system of weaving machine via floppy disk. Woven fabrics are wound into larger beams at the greige fabric control section of the factory. This initial quality control enables to evaluate the quality of weaving process and checking for the weaving faults. Depending on the demands of the customers, chemicals and finishing additives are applied to the greige fabric at the finishing department. Some of the widely preferred finishing processes are bulkiness finish, fire retardancy, soil and oil repellency, and water resistance. Stenter is the next step before packaging and final quality control. Dimensional stability and skewness of fabric are adjusted at the stenter. Chemicals and additives are also applied to fabrics at stenter. Fabrics are dried and further stability is generated at the drying section of the stenter called calendaring. Finished fabric quality control and packaging is performed based on the customer specifications and instructions. Finally fabrics are shipped to the customer. This production lay-out is schematized at Figure 2.

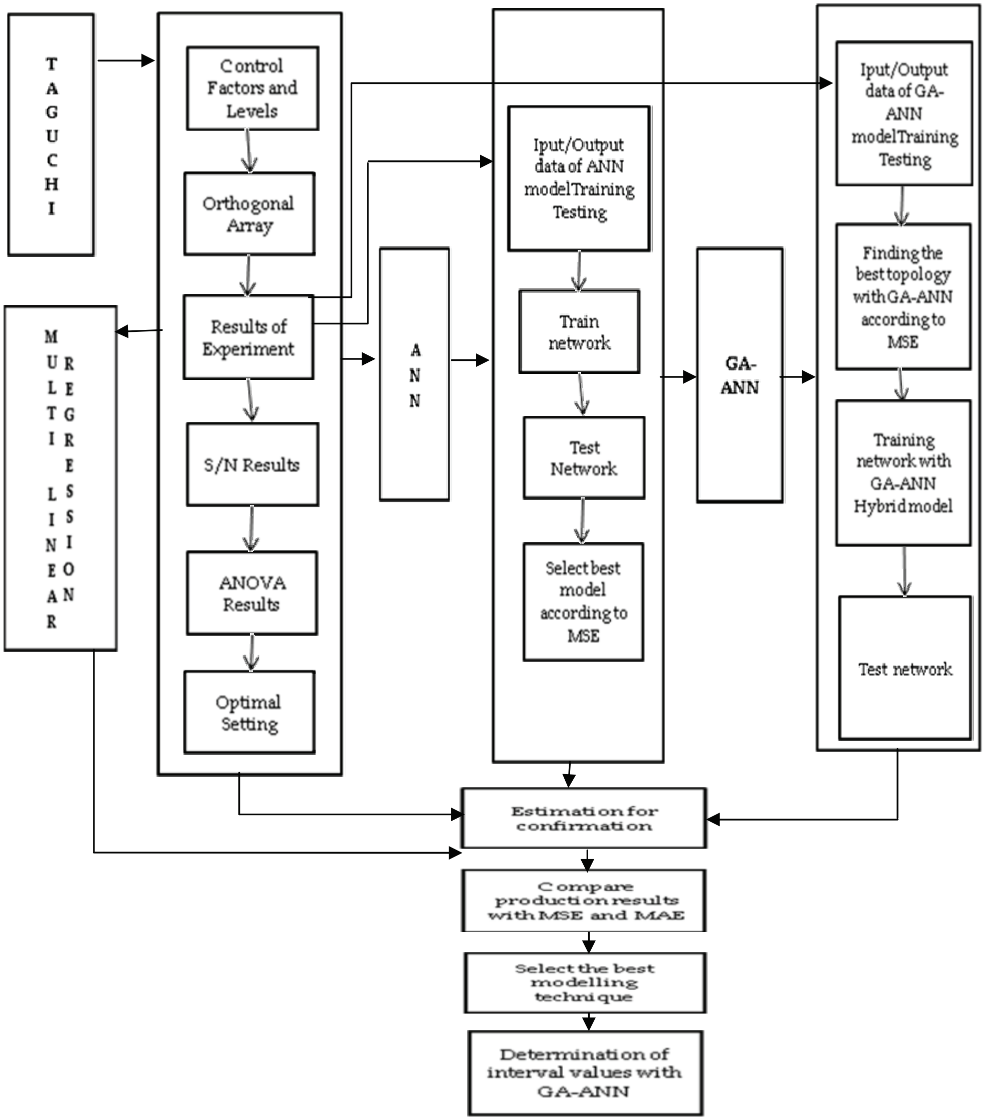

Fig. 1. Methodology of application

3. Modelling techniques

Here, Taguchi Design of Experiment Methodology will not be explained in detailed since this analyze was performed in Zeydan's paper (2008). Orthogonal matrix is given in Table 2. According to the result of this analyze, the most efficient parameter affecting the woven fabric strength was warp density in terms of S (signal) to N (Noise) Ratio. Optimal parameter setting is $A_2B_2C_1D_2E_2F_2G_1$ which means A (8658), B (16), C (300/DN), D (PF), E(38), F (30/2 DN), G (PF) the following stages will be considered according to the results obtained from TDOE.

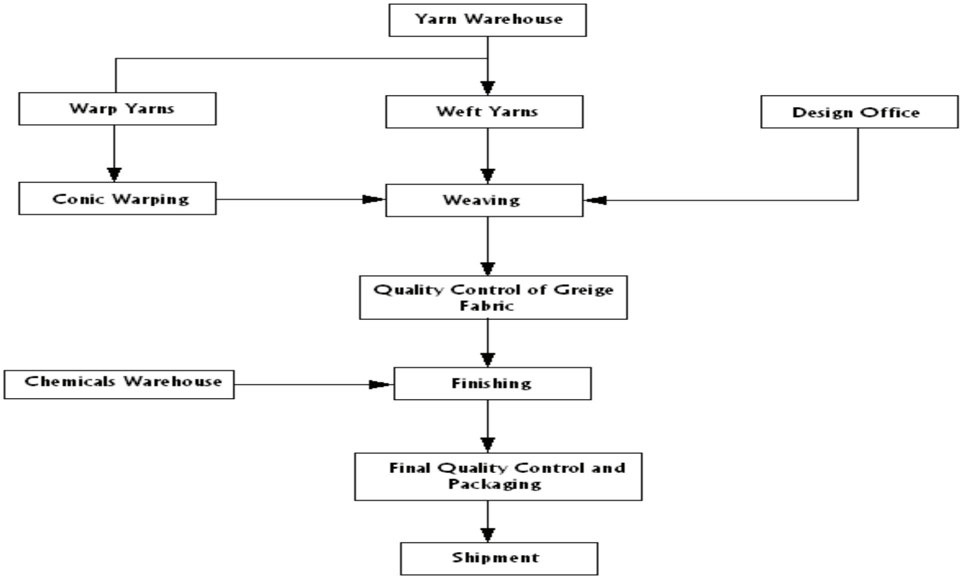

Fig. 2. Production work flow chart for jacquard woven bedding fabric

	Parameters							
Order	A	B	C	D	E	F	G	Average Fabric Strength (N/m)
1	7040	8	300	PF	33	150	PF	1026 (21.6)
2	7040	8	300	CF	38	354	CF	1313 (32.7)
3	7040	16	600	PF	33	354	CF	1057 (26.9)
4	7040	16	600	CF	38	150	PF	1350 (32.7)
5	8658	8	600	PF	38	150	CF	1148 (34.2)
6	8658	8	600	CF	33	354	PF	1161 (38.0)
7	8658	16	300	PF	38	354	PF	1669 (36.3)
8	8658	16	300	CF	33	150	CF	1117 (34.9)

Table 2. Orthogonal matrix

L8 experimental design orthogonal matrix formed related with fabric strength is given in table 2. Total amount of data about fabric strength collected from the factory is 120.

3.1 Multiple Linear Regression

Multiple Linear Regression (MLR) is a well known statistical procedure trying to find a linear relationship between two or more explanatory variables and a dependent variable by observing data. It can be used for forecasting output values. Dependent variable (y) can be explained by the equation below:

$$y = a + \sum_{i=1}^{n} b_i x_i + \varepsilon \qquad (1)$$

Before using ANN, multiple linear regression model is constructed. MLR is used as a verification and comparison model of ANN in the literature (Noori et al., 2010). It is claimed that ANN generally gives better results than MLR (Valvarde Ramirez et al., 2005). Fabric strength is defined as dependent variable and explanatory variables are; number of warp yarns at fabric width, weft density, weft yarn count, fiber type of weft, warp density, warp yarn count and fiber type of warp yarn. Multiple Linear Regression equation defined as below by considering the mean fabric strength data:

$$y = 618 + 87.2A + 136B - 102C + 10.2D + 280E + 140F - 143G \qquad (2)$$

3.2 Artificial Neural Network (ANN)

ANN is a nonlinear mapping system based on principles observed in nervous systems (Co, 2008). Complex nonlinear systems can be modelled efficiently by using ANN. In this study, multilayer perception is used for solving difficult predictive modelling problems. Multilayer perceptions networks consist of typically an input layer, single or more hidden layers, and one output layer. Hidden layers have one or more hidden neurons which performs nonlinear mapping between inputs and outputs (Lin and Choou, 2008). Activation functions are used to activate nodes. Here, sigmoid activation function is used, because generally MLP neural networks uses the logistic sigmoid function (Co, 2008) and using the sigmoid function in ANN topology provides a good nonlinear input–output mapping capability (Lo and Tsao, 2002). Choosing the proper learning algorithm is also very important while training the networks. For solving nonlinear optimization problems Levenberg–Marquardt algorithm is employed because of its efficient method (Sanjari et al., 2009). Besides, minimizing the MSE is the best known advantage of Levenberg-Marquardt (Purwanto et al., 2008). There is not a common sense about the number of the network layers, hidden nodes and generally a trial-and-error process approach is used for predetermining the optimal number of nodes in the hidden layer (Tu, 1996). Networks which contain different number of hidden layers and hidden neurons are being compared to find the best one (Wu et al., 2009). Mean square error (MSE) is generally used to judge the capability of networks while selecting the best one. Beside that, the simplest architecture is better than others (Didier, 2009). Therefore, the most important issue is to find the proper number of hidden neurons. Too much hidden neurons causes too much flexibility and this leads over fitting. But, too few hidden neurons prevent the learning capacity and decrease approximation performance of network (Haykin, 1994; and Xu and Chen, 2008). A single hidden layer can be chosen and it is sufficient for any continuous nonlinear mapping. But also, there have been many applications using two hidden layers (Behera and Karthikeyan, 2006). Recently, Artificial Neural Network became a popular modelling tool used in textile engineering area. It is commonly used in the applications of various types of fabrics. Defect detection and strength determination are some of the most known usage areas of ANN. In this study, ANN is also used to determine fabric strength. In Table 3, various options by comparing between 1 hidden layer and 2 hidden layers from one neuron to 10 neurons in terms of RMSE and MAE performance values, were tried to obtain the best ANN topology using trial and error method by considering literature claims. Results show that two hidden layers and three neurons are better than the other conditions. RMSE is used to compare topologies. Minimum RMSE is found for 7 (input)-2 (first hidden layer) – 3 (Second Hidden Layer) -1 (output) topology.

Performance						
	1 Hidden Layer			2 Hidden Layer		
Neuron	MSE	MAE	R	MSE	MAE	R
1	55939.1	1783289	0.558749	43301.66	1676.322	0.552495
2	15146.21	8729215	0.88216	12243.38	7986.922	0.871783
3	5953217,0	460774	0.956546	**4485.351**	5224.486	0.947723
4	8482484,0	6068052	0.94131	6852.638	6452.752	0.949635
5	12120.4	6657714	0.88593	12905.09	7121.598	0.887804
6	10212.87	5989459	0.900652	13256.95	7198.211	0.884492
7	11772.05	6277868	0.887777	24378.05	1187.689	0.808354
8	13014.74	7426107	0.871812	28423.24	1272.778	0.732697
9	11243.09	6145195	0.894136	16736.9	9074.597	0.852666
10	19056.53	9939427	0.856076	11566.42	653.403	0.896996

Table 3. Performance Values of 1-2 Hidden Layers

3.3 Genetic algorithm based artificial neural network

Genetic algorithm is a combinatorial optimization technique which models natural biologic evaluation process. GA searches for finding global optimal but cannot guarantee to find best solution (Núñez-Letamendia, 2007). It has a special terminology. Population includes alternative solutions set, genes mean variables which build up a solution, and chromosome is the name of all individual in population, so it represents an alternative solution. Generation means iteration. Also, fitness function represents an objective function.

To create a population, genetic algorithm chooses randomly a chromosome from search space. Populations are evolved until the best fitness value can be found. These evolutions are done by selection, crossover and mutation operators in which chromosomes will be used in reproduction process is decided in selection process. In this step, best chromosomes are tried to be chosen depending on the fitness function that is regarded as objective function. By this way, a decision can be made whether a solution is bad or not (Shopova and Vaklieva-Bancheva, 2006).

After selection process, recombination operator is applied to alter solutions. It combines two selected parent chromosomes' features with a probability to form new children. When recombination process finishes, mutation starts. The mutation refers creating of a new chromosome from an individual by changing some genes of chromosome with a predefined probability. After selection, crossover and mutation operators are applied, the newly created offspring is inserted into the population. Parent chromosomes in which they were derived from are replaced and so a new generation is created. Until the optimization criterion is met, this cycle is performed. Stopping criteria can be a generation number.

GA is used to determine the best network architecture and training parameters of ANN in this study. Trial and error method takes long time and sometimes cannot determine best topology. But genetic algorithm has become a popular tool in neural networks, recently. It is generally used in three ways in the literature of ANN. The first one is to optimize hidden neurons, learning rate and momentum rate (Mohebbi at al., 2008 ; Torres, 2005). By this way, time and effort required to find optimal architecture is minimized [Taheri, 2008; Kim et al., 2004; Saemi, 2007). The second usage of GA in ANN is to train parameters of neural networks (Liu et al., 2004; Heckerling, 2004; Versace, 200). And the final way is to set the weights in fixed architecture (Whitley, 1995). NeuroSolutions 5 is used to apply GA in ANN. It is an efficient software ANN optimization (Kim et al., 2004; Cheung et al., 2006).

In the first stage, GA is used to find best topology of ANN. Multilayer perception algorithm and 1 hidden layer is used. Sigmoid as an activation function and Levenberg Marquardt learning algorithm is chosen again, because of the mentioned advantages before. Under this circumstance, optimal processing element (PE) is determined by using GA which optimizes the architecture until the lowest error is found.

Results show that 1 hidden layer and four PEs are the best topology for our data. ANN-GA topology is 7-1-4-1. It was shown in Figure 3. After determining the optimal topology by using GA, next step is to perform genetic Training. Genetic training firstly creates an initial population of networks, randomly. All networks have different parameters. These are trained by considering minimum square error (MSE) that is defined as a threshold value. Threshold value is taken 0.01 for MSE. Properties of good networks are crossover and mutated to create better networks which include less MSE value than others. While selecting good chromosomes, Roulette wheel is used as selection operator. Selection depends on best fitness value.

The characteristics of the good networks are then combined and mutated to create a new population of networks. Again, the networks in this population are evaluated and the characteristics of the best networks are passed along to the next generations of networks. This process is stopped until the maximum generation is reached. Maximum generation number is 60 and maximum epoch is 1000 for this study. Population number is 50. Crossing over and mutation are done between 2 point with a probability of 0,9 and in uniform form with a probability of 0,01, respectively. Results show that GA-ANN gives better results than ANN.

Especially, testing MSE and correlation coefficiency (R) of GA-ANN has a significant difference rather than ANN. Especially, testing MSE and r of GA-ANN has a significant difference rather than ANN. According to the table 3, since all performance measurement values for GA-ANN topology are better than ANN topology, we will use the GA-ANN topology for modelling studies.

Performance	ANN topology	GA-ANN topology
MSE	5953.217	1906.985069
MAE	46.0774	29.96099284
R	0.956546	0.981429488

Table 4. Comparison of ANN and GA-ANN topologies

GA-ANN procedures generally gives better results rather than ANN. 10 experimental parameter sets collected from the production process are tested to compare the modelling performance of all methods that are used. Table 4 shows the production (forecasting) values of methods obtained from modelling. Experimental results for fabric strength are the real values. According to the experimental values, all forecasting values obtained from modelling is compared with each other. At the end of this process, Optimal modelling technique for the smallest RMSE and MAE value is determined as GA-ANN.

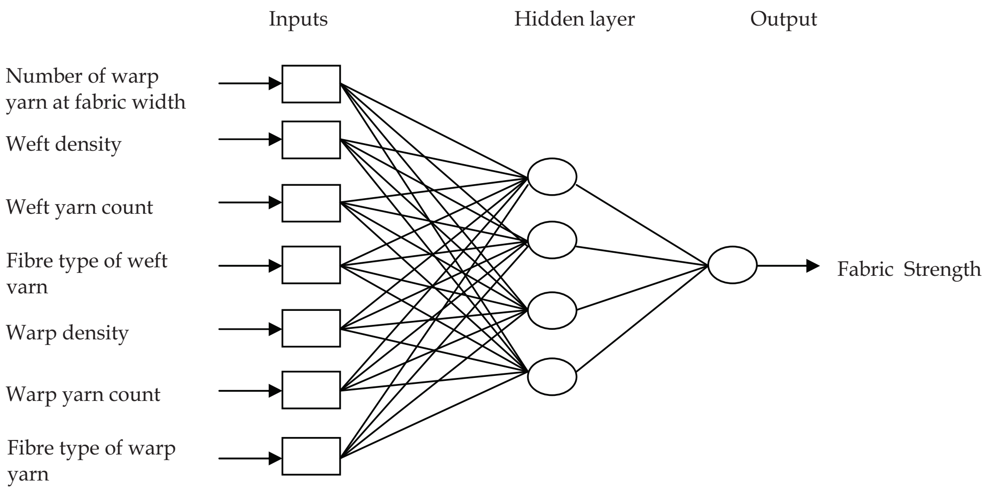

Fig. 3. ANN-GA Topology

Exp.	A	B	C	D	E	F	G	Experimental Results	Predicted Linear Regression	Predicted TDOE	Predicted ANN	Predicted GA-ANN
1	1	1	2	2	2	1	1	1250	1214.6	1213.75	1295879	1250
2	2	2	1	1	1	1	2	1098	1106.6	1106.75	1029.38	1098
3	1	1	2	1	1	2	2	1005	921.4	920.75	1035336	1005
4	2	2	1	2	2	2	2	1428	1536.8	1536.5	1518434	1428
5	1	1	2	2	2	1	2	1302	1071.6	1071	1252.7	1302
6	2	1	2	1	1	2	2	1052	1008.6	1008	1034977	1052
7	1	2	1	1	2	2	1	1637	1582.4	1581.75	1641925	1516912
8	2	1	1	1	2	1	2	1301	1250.6	1250.25	1294558	1224259
9	1	2	1	1	2	2	2	1544	1439.4	1439	1403969	1402.06
10	2	2	1	2	1	2	1	1498	1399.8	1399.5	1274407	1513988

Table 5. Comparison of experimental results with Linear Regression, TDOE, ANN and GA-ANN

RMSE and MAE values of linear regression, TDOE, ANN and GA-ANN are shown in Table 5. Also, Graphical representation of all modelling methods used is given by comparing with each other in figure 4 The best results are obtained with GA-ANN model.

	LINEAR REGRESSION	TDOE	ANN	GA-ANN
RMSE	100.6116	100.9521	93.97	63.80663
MAE	81.8	82.225	67.6584	35.47569

Table 6. RMSE and MAE values of modelling methods

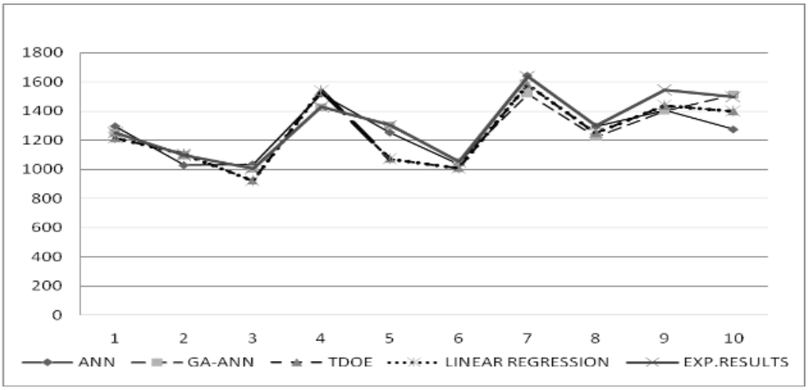

Fig. 4. Comparison of modelling methods

The final stage of the new modelling methodology is to make a verification of finding the optimum fabric strength with GA-ANN hybrid modelling technique as the best methodology. Warp density as the most important factor affecting the fabric strength is found with the Taguchi Design of Experiment Methodology and whether there have been in interval values of optimum parameter setting is tested by increasing from 33 to 38. The verification of TDOE results with GA-ANN hybrid modelling technique for interval values of warp density from 33 (warp/cm) to 38 (warp/cm) is shown in figure 5.

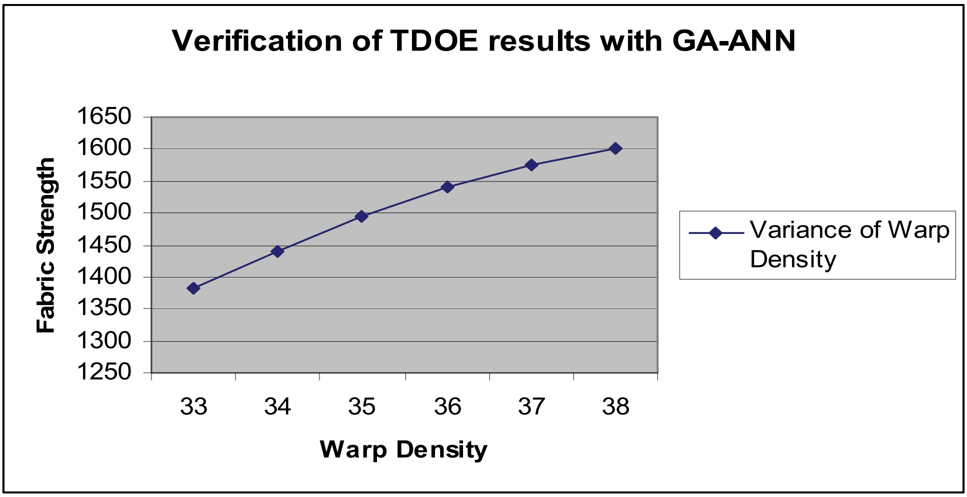

Fig. 5. Interval values of warp density

4. Conclusion

In this study, traditional and computational modelling techniques are compared between each other to predict woven fabric strength that is one of the main features for the characterization of woven fabric quality and fabric performance. Compared the other classical modelling techniques, computational modelling methodology seems to have been more robust and appropriate. This study made in a textile Factory producing jacquard woven bedding fabric in Turkey has many benefits for textile manufacturers to reduce waste and scrap ratio before and during manufacturing. Firstly, production planning function in the plant will be able to predict the woven fabric strength easily to be known optimal parameter setting before manufacturing. Secondly, The significant parameter in the manufacturing was found as Warp Density. Thirdly, after finding the optimum parameter setting with TDOE, interval values of the sensitive parameters in the production was found with ANN approach. According to the data collected from manufacturing Process of factory in Zeydan's paper (2008), Taguchi Design of Experiment methodology was applied to find the most significant parameters. Seven significant parameters affecting the Woven Fabric tensile strength was considered. Warp density was found the most important factor affecting the Fabric strength by using S/N Ratio. The main purpose of this study is modelling the woven fabric strength by comparing different modelling techniques. However, any research about comparing ANN, TDOE, multiple regression and ANN-GA in the literature hasn't been conducted on the strength prediction of woven fabric from fibre, yarn and fabric parameters using woven fabric modelling approaches with all together so far. ANN, GA-ANN hybrid approach, Multiple-Linear regression, TDOE based on RMSE and MAE modelling performance criteria which is frequently used, are compared with each other. Finally, GA-ANN hybrid methodology was found as a suitable modelling technique. At the last stage of modelling methodology, verification of TDOE results with GA-ANN hybrid modelling technique for interval values of warp density was performed by increasing from 33 (warp/cm) to 38 (warp/cm). Parameter value giving optimum fabric strength for Warp Density was determined as 38 (warp/cm).

5. References

Behera, B.K. & Muttagi, S.B.(2004). Performance of Error Back Propagation vis-á-vis Radial Basis Function Neural Network: Part I: Prediction of Properties for Design Engineering of Woven Suiting Fabric. Journal of the Textile Institute, Vol. 95, No 1, 283-300

Behera, B. K.& Karthikeyan, B.(2006). Artificial Neural Network-embedded Expert System for the Design of Canopy Fabrics. *Journal of Industrial Textiles*, Vol. 36, No. 2, 111-123

Cheung, S.O.; Wong, P.S.P.; Fung, A.S.Y. & Coffey, W.V. (2006). Predicting project performance through neural networks. *International Journal of Project Management*, Vol. 24, No. 3, 207–215

Co, H. C. (2008). Confirmation testing of the Taguchi methods by artificial neural-networks simulation, *International Journal of Production Research*, Vol. 46, No. 17, 4671 — 4685

Didier, C.; Forno, G.; Etcheverrigaray, M.; Kratje, R. & Goicoechea H. (2009). Novel chemometric strategy based on the application of artificial neural networks to crossed mixture design for the improvement of recombinant protein production in continuous culture. *Analytica Chimica Acta* , Vol. 650, 167–174

Geman, S.; Bienenstock, E. & Doursat, R. (1992). Neural networks and the bias/variance dilemma. *Neural Computation*, Vol.4, 1–58,

Gong, R.H. & Chen, Y. (1999).Predicting the Performance of Fabrics in Garment Manufacturing with Artificial Neural Networks. *Textile Research Journal*, Vol. 69, No.7, 477-482

Hadizadeh, M.; Jeddi, Ali A.A. & Tehran, M. A. (2009). The Prediction of Initial Load-extension Behavior of Woven Fabrics Using Artificial Neural Network. *Textile Research Journal*, Vol. 79, No. 17, 1599-1609

Haykin, S. (1994*). Neural networks-a comprehensive foundation*. Macmillan College Publishing, ISBN, New York

Heckerling, P. S.; Gerber, B. S.; Tape, T.G. & Wigton, R. S. (2004). Use of genetic algorithms for neural networks to predict community-acquired pneumonia. *Artificial Intelligence in Medicine*, Vol. 30, No. 1, 71-84

Hu, J. (2004). *Structure and Mechanics of Woven Fabrics*, Woodhead Publishing Limited, 1 85573 904 6 Cambridge

Keshavaraj, R. ; Tock, R.W. & Haycook, D. (1996). Airbag fabric material modeling of nylon and polyester fabrics using a very simple neural network architecture. *Journal of Applied Polymer Science*, Vol. 60, No 13, 2329-38

Kim, G.-H.; Yoon, J.-E.; An, S.-H.; Cho, H.-H. & Kang, K.-I. (2004). Neural network model incorporating a genetic algorithm in estimating construction costs, *Building and Environment*, Vol.39, 1333–1340

Majumdar, A.; Ghosh, A.; Saha, S.S.; Roy, A.; Barman, S.; Panigrahi, D.& Biswas, A. (2008). Empirical Modelling of Tensile Strength of Woven Fabrics. *Fibers and Polymers*, Vol.9, No.2, 240-245

Lin, H.L.; Chou, C.P.(2008). Modeling and optimization of Nd:YAG laser micro-weld process using Taguchi Method and a neural network. *International Journal of Advanced Manufacturing Technology,* Vol. 37, 513–522

Liu, Z.; Liu, A.; Wang, C.& Niu, Z.(2004) Evolving neural network using real coded genetic algorithm (GA) for multispectral image classification. *Future Generation Computer Systems*, Vol. 20, No. 7, 1119–1129

Lo, Y.L. & Tsao C.C. (2002). Integrated Taguchi Method and Neural Network Analysis of Physical Profiling in the Wirebonding Process*, IEEE Transactions On Components And Packaging* Technologies, Vol.25, No.2, 270-277

Mohebbi, A.; Taheri, M. & Soltani, A. (2008). A neural network for predicting saturated liquid density using genetic algorithm for pure and mixed refrigerants, *International Journal of Refrigeration,* Vol. 31, No. 8, 1317-1327

Noori, R. ; Khakpour A. ; Omidvar, B. ; Farokhnia, A. (2010). Comparison of ANN and principal component analysis-multivariate linear regression models for predicting the river flow based on developed discrepancy ratio statistic, *Expert Systems with Applications,* (article in press : doi:10.1016/j.eswa.2010.02.020)

Nunez-Letamendia, L. (2007). Fitting the control parameters of a genetic algorithm: An application to technical trading systems design. *European Journal of Operational Research*, Vol. 179, No. 3, 847-868

Ogulata, S.N. ; Sahin, C. ; Ogulata, T.O.& Balci, O. (2006), The prediction of elongation and recovery of woven bi-stretch fabric using artificial neural network and linear regression models, *Fibres & Textiles in Eastern Europe*, Vol. 14, No. 2(56), 46-9

Park, S.W.; Hwang, Y.G.; Kang, B.C. & Yeo S.W. (2000). Applying Fuzzy Logic and Neural Networks to Total Hand Evaluation of Knitted Fabrics. *Textile Research Journal,* Vol. 70, No. 8, 675-681

Purwanto, D. ; Agustiawan, H. & Romlie, M.F.; (2008). The Taguchi-neural networks approach to forecast electricity consumption. *In: IEEE Canadian Conference on Electrical and Computer Engineering*, pp.1941-1944, 4-7 May 200, Niagara Falls

Saemi, M.; Ahmadi, M. & Varjani, A.Y. (2007). Design of neural networks using genetic algorithm for the permeability estimation of the reservoir. *Journal of Petroleum Science and Engineering,* Vol. 59, 97– 105

Sanjari, M. & Taheri, A. K. & Movahedi, M. R. (2009). An optimization method for radial forging process using ANN and Taguchi method. *The International Journal of Advanced Manufacturing Technology,* Vol.40, No. 7-8, 776–784

She, F.H.; Kong, L.X.; Nahavandi, S. & Kouzani, A.Z.(2002). Intelligent Animal Fiber Classification with Artificial Neural Networks. *Textile Research Journal*, Vol. 72, No. 7, 594-600

Shopova, E.G.& Vaklieva-Bancheva, N.G.(2006). A genetic algorithm for engineering problems solution, Comput. *Chem. Eng. Vol*. 30, No.8, 1293–1309

Taheri, M. & Mohebbi, A. (2008). Design of artificial neural networks using a genetic algorithm to predict collection efficiency in venturi scrubbers, *Journal of Hazardous Materials*, Vol. 157, 122–129

Tilocca, A.; Borzone, P.; Carosio, S. & Durante, A. (2002). Detecting Fabric Defects with a Neural Network Using Two Kinds of Optical Patterns. *Textile Research Journal,* Vol. 72, No.6, 545–551.

Torres, M.; Hervás, C. & Amador, F. (2005). Approximating the sheep milk production curve through the use of artificial neural networks and genetic algorithms, *Computers & Operations Research*, Vol. 32, 2653–2670

Tu, J.V. (1996). Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes. *Journal of Clinical Epidemiology*, Vol. 49, No. 11, 1225–1231

Valverde Ramirez, M.C. & De Campos Velho, H.F. ; Ferreira, N.J. (2005). Artificial neural network technique for rainfall forecasting applied to the São Paulo region, *Journal of Hydrology*, Vol. 301 (1-4), 146-162

Versace, M.; Bhat, R.; Hinds, O. & Shiffer M. (2010). Predicting the exchange traded fund DIA with a combination of genetic algorithms and neural networks. *Expert Systems with Applications* (article in press)

Whitley, D.(1995); Genetic algorithms and neural networks, In: J. Perioux, G. Winter, M. Galan and P. Cuesta (eds), *Genetic Algorithms in Engineering and Computer Science*, John Wiley & Sons Ltd.

Wu, S.J.; Shiah, S.W. & Yu W.L. (2009). Parametric analysis of proton exchange membrane fuel cell performance by using the Taguchi method and a neural network. *Renewable Energy*, Vol. 34, 135–144

Xu, S. & Chen, L.(2008) A Novel Approach for Determining the Optimal Number of Hidden Layer Neurons for FNN's and Its Application in Data Mining. *Proceedings of 5th International Conference on Information Technology and Applications (ICITA 2008)*, Pp. 683-686, ISBN 978-0-9803267-2-, Cairns, Queensland, 23-26 June 2008, AUSTRALIA

Zeydan, M. (2008), Modelling the woven fabric strength using artificial neural network and Taguchi methodologies, *International Journal of Clothing, Science and Technology*, Vol. 20, No. 2, 104-118

9

Data Base System on the Fabric Structural Design and Mechanical Property of Woven Fabric

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1. Introduction

The structure of fabrics is very important, because fabric geometry gives considerable effects on their physical properties. Therefore, the studies for fabric structure have been carried out with following areas:

1. prediction of fabric physical and mechanical properties
2. education and understanding related to the fabric structural design
3. the area related to the fabric and garment CAD systems

Among them, the researches for the prediction of fabric physical and mechanical properties with fabric structure have been performed by many textile scientists. But the education and understanding related to the fabric structural design have been emphasized on the theoretical aspects. But the optimum fabric design plan is recently needed with the relevant fabric shrinkage in dyeing and finishing processes for making the various emotional fabrics for garment. For responding this need, the difference of fabric design plan such as fabric density, yarn count and finishing shrinkage has to be surveyed with weaving looms such as water jet, air-jet and rapier looms, and also has to be analyzed with weave patterns such as plain, twill and satin. On the other hand, recently, there are many commercial CAD systems such as fabric design CAD for fabric designers and pattern design CAD including visual wearing system for garment designers. But there is no fabric structural design system for weaving factories, so the data base system related to the fabric structural design for weaving factories is needed. Many fabric weaving manufacturers have some issue points about fabric structural design. The 1st issue point is that there is no tool about how to make fabric design according to various textile materials such as new synthetic fibers, composite yarns, and crossed woven fabrics made by these new fibres and yarns. As the 2nd issue point, they also don’t have the data about what is the difference of fabric structural design such as fabric densities on warp and weft directions according to the weaving looms such as WJL, RPL and AJL. And 3rd issue point is that there is no data about how the difference of fabric structural design is among weaving factories even though they have same looms and they use same materials. Therefore, in this topic, a data base system which can easily decide warp and weft fabric densities according to the various yarn counts, weave construction and materials is surveyed by the analysis of design plan for synthetic fabrics such as nylon and PET and worsted and cotton fabrics. Furthermore, the analyses for easy deciding of fabric design from new materials and for making data base related to this fabric structural design are carried out as the objectives of this topic.

2. Background of fabric structural design

The first study for the fabric structural design was started in 1937 by Peirce paper(Peirce, 1937), which is the Peirce's model of plain-weave fabrics with circular yarn cross section. And he also proposed fabric model with an elliptic yarn cross section. In 1958, Kemp proposed a racetrack model(Kemp, 1958). Hearle and Shanahan proposed lenticular geometry (Hearle & Shanahan, 1978) for calculation in fabric mechanics by energy method in 1978. And many researches related to the fabric mechanical properties under the base of fabric structural model were carried out by Grosberg (Grosberg & Kedia, 1966), Backer (Backer, 1952) Postle(Postle et al., 1988). Lindberg(Lindberg et at., 1961) extensively studied fabric mechanical behavior related to the tailorability. Then the sophisticated measurement system of fabric mechanical properties was developed by Kawabata and Niwa(Kawabata et al., 1982) which is called KES-FB system. Another fabric mechanical measurement system called the FAST was developed by CSIRO in Australia(Ly et al., 1991). Recently new objective measurement systems(Hu, 2004) such as Virtual Image Display System(VIDS) and Fabric Surface Analysis System(FabricEye®) have been developed for the analysis of fabric geometrical properties. On the other hand, nowadays there are many CAD systems(i-Designer, Texpro) related to the fabrics design such as weave construction, color and pattern. And also there is pattern design CAD(Texpro, Harada & Saito, 1986) including visual wearing system(VWS) for garment designer. But there is no fabric structural design system related to the decision of the fabric density according to the fibre materials, yarn linear density, and weave pattern. Therefore, a data base system which can easily decide warp and weft densities according to the various yarn counts, weave constructions and materials is required through the analysis of design plan for worsted, cotton, nylon and polyester fabrics as shown in Figure 1(Kim, 2002).

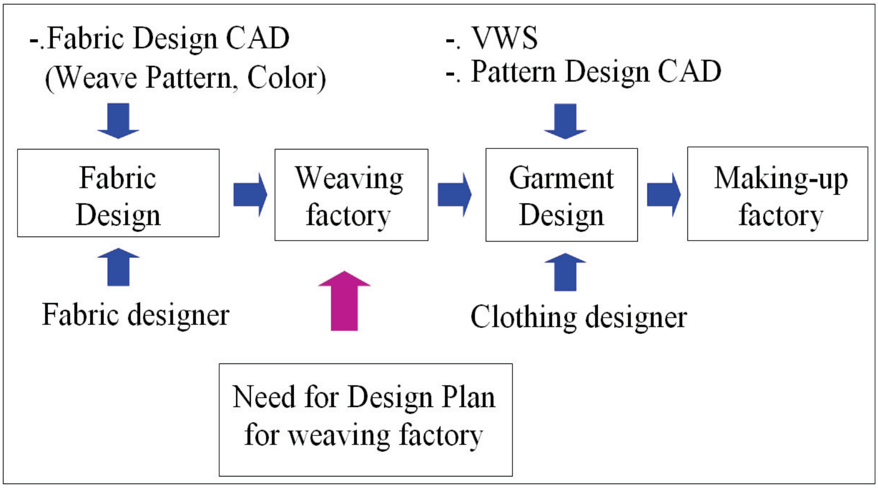


Fig. 1. Diagram for need of fabric structural design system for weaving factory

Figure 2 shows milestone of detail analysis steps related to the data-base system of the fabric structural design in relation with existing fabric design and wearing systems of garment(Kim, 2005). The final goal of this analysis is aiming to link with virtual wearing system, pattern design CAD and drape analyzer. As shown in Figure 2, in the 1st step, the data base of weave pattern and fabric factors has to be made using yarn count, fabric density and weave pattern from which weave density coefficient (WC) and warp and weft density distributions are calculated. And weave density coefficient can be analyzed according to weaving factories and loom types. Furthermore, weave density coefficient and yarn density coefficient (K) can be analyzed with cover factor of fabrics. In the 2nd step, the data base of various physical properties of fabrics is made with dyeing and finishing process factors, which affects fabric hand and garment properties measured by KES-FB and FAST systems. In the 3rd step, these data bases have to be linked with visual wearing system (VWS), pattern design CAD and drape analyzer. In this topic, the case study of data-base system of the fabric structural design in the 1st step shown in Figure 2 is introduced and analyzed with various kinds of fabric materials and structural factors.

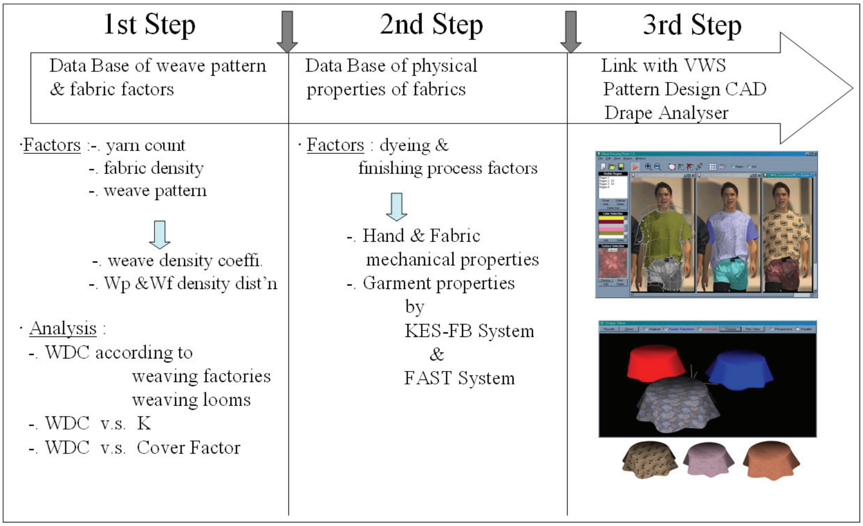


Fig. 2. Detail milestone of analysis steps in relation with existing fabric design and wearing systems of garment

3. Major issues of the mechanical property of the woven fabric related to the fabric structural design

Many researches about mechanical property of the woven fabric according to the yarn and fabric parameters were carried out using KE-FB and FAST systems (Oh & Kim,1993, 1994). Among them, the PET synthetic fabric mechanical properties according to weft filament yarn twists, yarn denier and fabric density were analysed and discussed with these yarn and fabric structural parameters. On the other hand, the worsted fabric mechanical properties according to the looms such as rapier and air jet were also analysed and discussed with weaving machine characteristics (Kim & Kang, 2004, Kim & Jung, 2005). Similar studies were also performed using the PET and PET/Tencel woven fabrics (Kim et al., 2004). The researches related to the fabric mechanical property according to the dyeing and finishing processes were also carried out (Kim et al., 1995, Oh et al., 1993). These are the discrete research results such as 1st and 2nd step shown in Figure 2. There are no informations about how these mechanical properties affect to the garment properties shown on step 3 in Figure 2. This is major issue point of the mechanical property of the woven fabric related to the fabric structural design. Fortunately, in i-designer CAD system, visual weaving performance is available by input the fabric mechanical properties measured by KES-FB system. So, the data base in 1st and 2nd step shown in Figure 2 is needed and these data bases have to be linked with existing visual wearing system, pattern design CAD and drape analyzer shown on 3rd step in Figure 2.

4. Current trends of the data base system of the fabric structural design

4.1 Procedure of data base system of the fabric structural design

Figure 3 shows the procedure of data base system of the fabric structural design. In Figure 3, yarn diameter is calculated using yarn count and weave factor is also calculated by weave structure using number of interlacing point and number of yarn in one repeat weave pattern. Then the weave density coefficient is decided using yarn diameter, weave factor and warp and weft densities. And conversely the warp and weft density distribution is made by yarn diameter, weave factor and weave density coefficient. Peirce(Peirce, 1937) proposed equation 1 as a fabric cover factor which is recommended to weaving factories by Picanol weaving machinery company(Picanol, 2005). In equation 1, yarn and fabric correction factors are shown in Table 1 and 2, respectively.

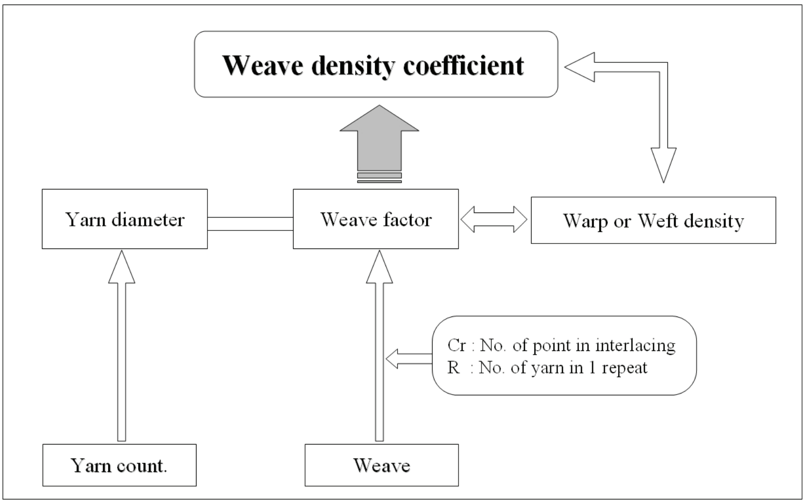


Fig. 3. Procedure diagram of data base system of the fabric structural design

$$\left(\frac{\text{ends/in}}{\sqrt{\text{Ne}}}+\frac{\text{picks/in}}{\sqrt{\text{Ne}}}\right)\times \text{yarn correction factor}\times \text{fabric correction factor} \qquad (1)$$

Type of yarn	Correction factor
metallic	0.3
glass	0.6
carbon	0.9
cotton, flax, jute, viscose, polyester	1.0
acetate, wool	1.1
polyamide	1.2
polypropylene	1.4

Table 1. Yarn correction factor

Drill/twill weave		Satin weave	
Pattern	Peirce	Pattern	Peirce
2/1	0.819	1/4	0.709
3/1	0.769	1/5	0.662
2/2	0.746	1/6	0.629
4/1	0.763	1/7	0.599
5/1	0.714	1/8	0.578
6/1	0.694		
7/1	0.689		
4/4	0.671		

Table 2. Fabric correction factor

On the other hand, Prof. M. Walz(Park et al., 2000) proposed equation 2 as a little different equation form, but which is applicable to the various fabrics made by all kinds of textile materials. In equation 2, yarn and fabric correction factors are also shown in Table 3 and 4, respectively.

$$C(\%) = (dw + df)^2 \times Dw \times Df \times b \tag{2}$$

$$where, \quad d_{w,f} = \frac{a}{\sqrt{Nm}} = \frac{a\sqrt{dtex}}{100}\text{: yarn diameter(warp, weft)}$$

where

C(%): cover factor
Dw: warp density (ends/inch)
Df: weft density (picks/inch)
a: yarn correction factor (Table 3)
b: fabric correction factor (Table 4)

Basilio Bona (Park et al., 2000) in Italy proposed empirical equation 3 for deciding fabric density on the worsted fabrics.

$$D = K \times \sqrt{Nm} \times C_f \tag{3}$$

where, D: fabric density (ends/m)
K: density coefficient
Nm: metric yarn count
C_f: weave coefficient

Type of yarn	Correction factor
metallic	0.39
glass	0.71
carbon	0.86
cotton, flax, jute, viscose	0.95
polyester	0.92
acetate, wool	0.98
polyamide	1.05
polypropylene	1.17

Table 3. Yarn correction factor

Drill/twill weave		Satin weave	
Pattern	Walz	Pattern	Walz
2/1	0.69	1/4	0.50
3/1	0.58	1/5	0.45
2/2	0.56	1/6	0.42
4/1	0.49	1/7	0.39
5/1	0.43	1/8	0.38
6/1	0.41		
7/1	0.40		
4/4	0.39		

Table 4. Fabric correction factor

$$\left(C_f = \frac{R}{R + C_r} \times f_c \times f_f \times f_j \right)$$

f_c: cover factor
f_f: floating factor
f_j: jumping factor

Equation 3 is modified as equation 4 for the cotton fabrics.

$$D = K_c \times 0.0254 \times \sqrt{Ne \times 1.694} \times C_f \tag{4}$$

where, Ne: English cotton count
Kc: Yarn density coefficient (cotton)
where:
- Comber yarns : 425~350 (12 ~17 MICRONAIRE)
- Sea & Island cotton : 425, American cotton : 375
- Card yarns : 350~290 (14 ~22 MICRONAIRE)

But, in synthetic filament yarn fabrics such as nylon and polyester, more effective parameter is needed. So, weave density coefficient, WC is made by equation 5.

$$WC = \left[\frac{d_w + d_f}{25.4} \right]^2 \times D_w \times D_f \times WF \tag{5}$$

where, $d_{w,f}$: yarn diameter (warp, weft)

WF : weave factor

$D_{w,f}$: warp, weft density

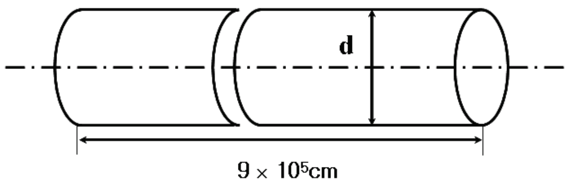
In equation 5, assuming that $D_w \times D_f$ is constant, it becomes as equation 6.

$$D_w \times D_f = \frac{WC}{WF} \times \left[\frac{25.4}{d_w \times d_f} \right]^2 = const. \tag{6}$$

WC in equation 5 can be converted to K and Kc in equation 3 and 4, conversely K is converted to WC and also WC in equation 5 can be compared with cover factor, C given in equation 1 and 2, which is shown in next case study.

4.2 Calculation of fabric structural parameters

In equation 6, d_w and d_f are calculated by yarn linear density, equation 7 as shown in Figure 4. WF is calculated by equation 8 as shown in Figure 5. In Figure 4, calculated yarn diameter by equation 7 is shown in polyester, nylon and rayon yarns, respectively. As shown in Figure 5, calculated weave factors by equation 8 are shown according to the various weave patterns. For plain weave, weave factor (WF) is calculated as 1 using R=2 and Cr = 2. In a little complicated weave pattern as a derivative weave, weave factor (WF) is calculated as 0.76 using R=4 and Cr=3 as an average value by two types of repeat pattern in the weft direction. And in a very complicated weave pattern, Moss crepe, weave factor is calculated as 0.538 using R=120 and Cr=56.06.



Yarn	Density	Yarn diameter (mm)
PET	1.38	$0.01246\sqrt{Den.}$
Nylon	1.14	$0.01371\sqrt{Den.}$
Rayon	1.52	$0.01189\sqrt{Den.}$

$$Den.(g) = \rho_f (g/cm^3) \times V(cm^3) = \rho_f \times \frac{\pi d^2}{4} \times 9 \times 10^5 \tag{7}$$

where, d: yarn diameter

ρ_f: fibre density

Den: denier

V: volume

Fig. 4. Diagram between yarn count and diameter

$$WF = \left[\frac{R + C_r}{2R} \right]^2 \tag{8}$$

where, WF: weave factor

R: No. of yarn in 1 repeat

Cr: No. of point in interlacing

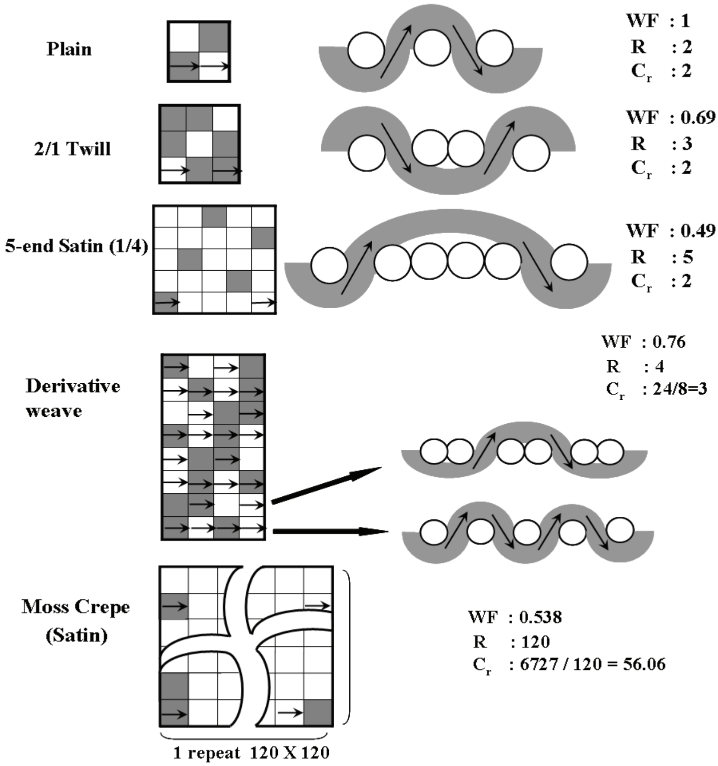


Fig. 5. Diagram of various weave constructions.

4.3 Case study of synthetic fabrics

Design plan sheets of polyester and nylon fabrics woven by various looms were selected as a specimens from various weaving manufacturers such as A, B, C, D, E and F as shown in Table 5, respectively, Table 5 shows the distribution of these specimens.

	PET fabrics						Nylon fabrics
	A company	B company	C company	D company	E company	Sub -total	F company
Loom	WJL	RPL	AJL+RPL	WJL+RPL	WJL+RPL		
Plain	26	4	14	46	5	95	516
Satin	10	41	20	4	8	83	24
Twill	60	28	33	4	9	134	113
Other	-	25	51	-	32	108	185
Sub-total	96	98	118	54	54	420	838

Table 5. Distribution of specimens

For calculation weave density coefficient as shown in equation 5, yarn diameter is first calculated using equation 7.

$$Den = \rho_f \times \frac{\pi d^2}{4} \times 9 \times 10^5 \tag{9}$$

where, ρ_f: fibre density (g/cm^3)
d: yarn diameter (mm)
Den: yarn count (denier)

For polyester filament, yarn diameter, d is $0.01246\sqrt{Den}$ and for nylon filament, that is $0.01371\sqrt{Den}$. On the other hand, weave factor, WF is also calculated using equation 8 and R, Cr in the one repeat weave pattern of fabrics. Through this procedure, yarn diameter, d and weave factor, WF are calculated for all the specimens of nylon and polyester fabrics. Finally weave density coefficient, WC is calculated using d, WF and warp and weft fabric densities, Dw and Df of the all the nylon and polyester fabrics. And WC is plotted against various yarn counts using equation 5 and conversely warp and weft density distribution is presented with various weave density coefficients and weave patterns using equation 6.

1. The distribution of weave density coefficient according to the looms

For four hundreds twenty polyester fabrics, the diameters of warp and weft yarns were calculated using deniers by equation 7, and weave factor was calculated by one repeat weave construction. The weave density coefficient was calculated using equation 5. Figure 6 shows the diagram between weave density coefficient and yarn count for the polyester fabrics woven by water jet loom. And Figure 7 shows that for rapier loom. As shown in Figure 6, the weave density coefficients of PET fabrics woven by WJL were widely ranged from 0.2 to 1.8, on the other hand, for rapier loom, was ranged from 0.4 to 1.4 as shown in Figure 7. And in Figure 6, the values for satin fabrics were ranged from 0.6 to 1.0, which were lower than those of the plain and twill fabrics. Around the yarn count 150d, 300d and

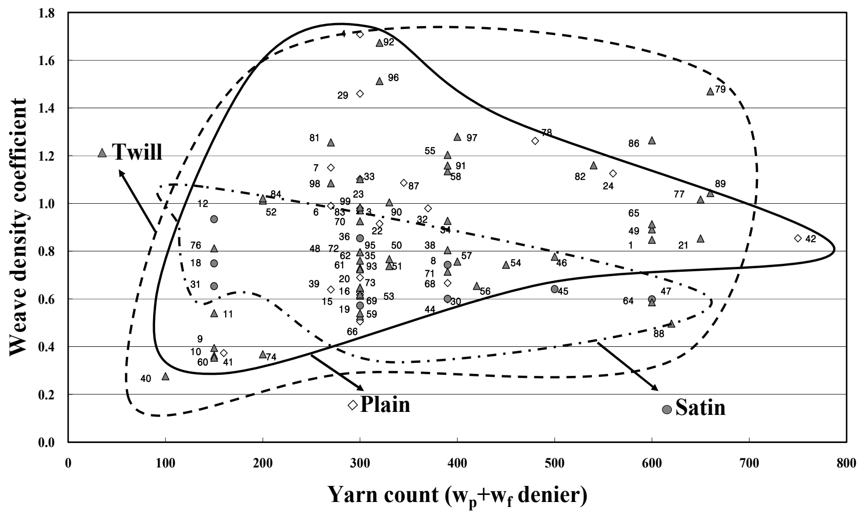


Fig. 6. The diagram between weave density coefficient and yarn count for PET fabrics (WJL).
(▬▬▬ : Plain, ... : Twill, ▬ · ▬ · : Satin)

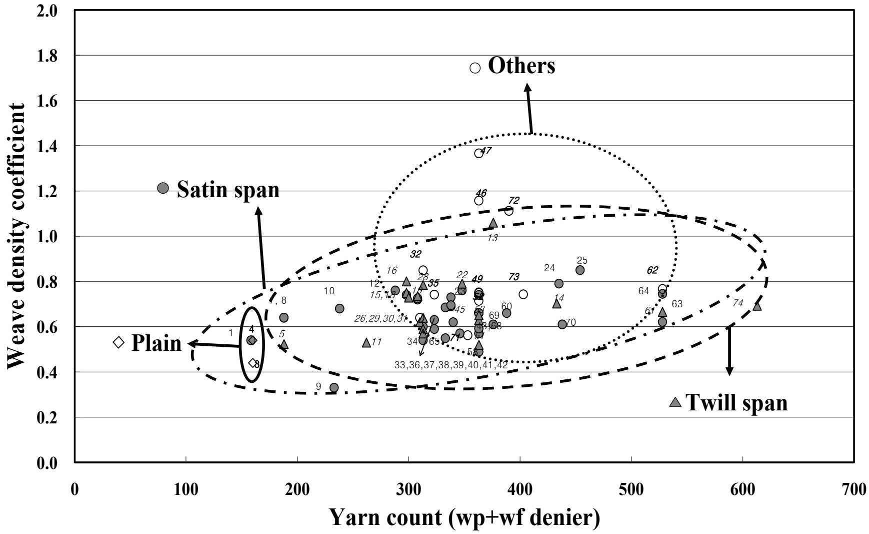


Fig. 7. The diagram between weave density coefficient and yarn count for PET fabrics (RPL). (———— : Plain, ... : Twill, ▬ · ▬ · : Satin, ... : Others)

400d for the twill fabrics, it is shown that the weave density coefficients are ranged from 0.4 to 1.0 for 150d, ranged from 0.5 to 1.7 for 300d and also from 0.6 to 1.3 for 400d. This demonstrates that the weave density coefficients of fabrics woven by water jet loom were widely distributed according to the end use of fabrics for garment.

2. The comparison of the weave density coefficient between polyester and nylon fabrics

Figure 8 shows the diagram between weave density coefficient and yarn count for polyester and nylon fabrics woven by water jet loom for the specimens of higher weft yarn count than warp. As shown in Figure 8, the weave density coefficient of nylon fabrics are widely ranged from 0.5 to 3.0, and comparing to polyester fabrics, the weave density coefficients of nylon fabrics are higher than those of PET fabrics. Especially, in polyester fabrics, plain, twill and satin weave patterns were widely divided to each other on weave density coefficient and yarn count, on the other hand, in nylon fabrics, it was shown that plain was most popular and many specimens were concentrated around yarn count 200d region. Figure 9 shows the weave density coefficients of polyester and nylon fabrics according to the weaving looms. As shown in Figure 9 (a), (b) and (c), the weave density coefficients of polyester fabrics woven by water jet loom were ranged from 0.4 to 1.5, those woven by air jet loom are ranged from 0.7 to 2.0 and woven by rapier loom was ranged from 0.5 to 2.8. And yarn count also showed wide distribution in water jet and rapier looms, but air jet loom showed a little narrow distribution. This phenomena demonstrate that the versatility of rapier loom was the highest comparing to the other weaving looms. On the other hand, comparing Figure 9 (a) with Figure 9 (d), the weave density coefficients of nylon fabrics were ranged from 0.5 to 3.0, while in polyester fabrics they were ranged from 0.4 to 1.5. Nylon fabric showed much wider distribution and much larger values of the weave density coefficient.

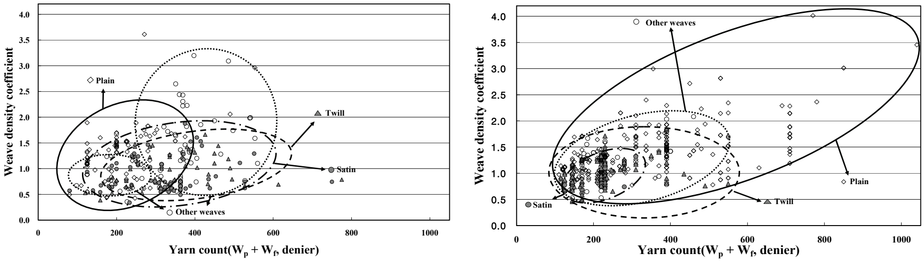
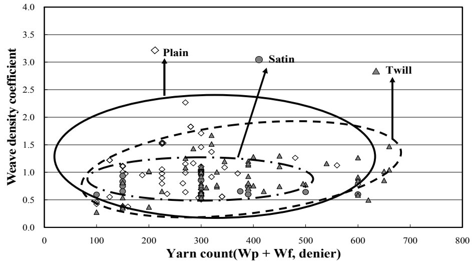
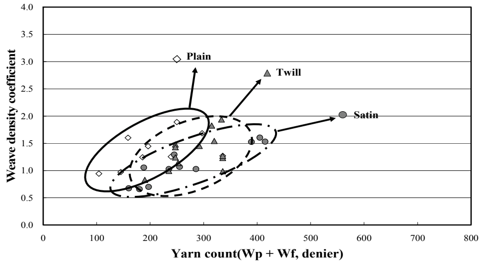


Fig. 8. Comparison of weave density coefficient between PET and Nylon fabrics (Wp<Wf). (▬▬▬ : Plain, ... : Twill, ▬ . ▬ . : Satin, ... : Others)

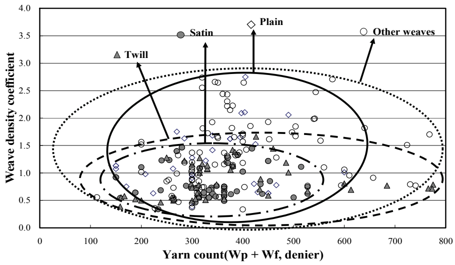
PET



(a) WJL

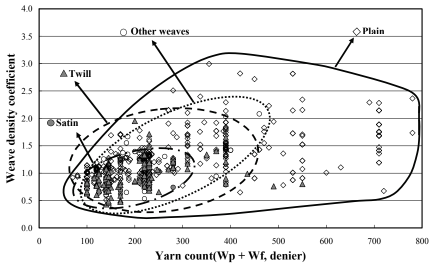


(b) AJL



(c) RPL

Nylon

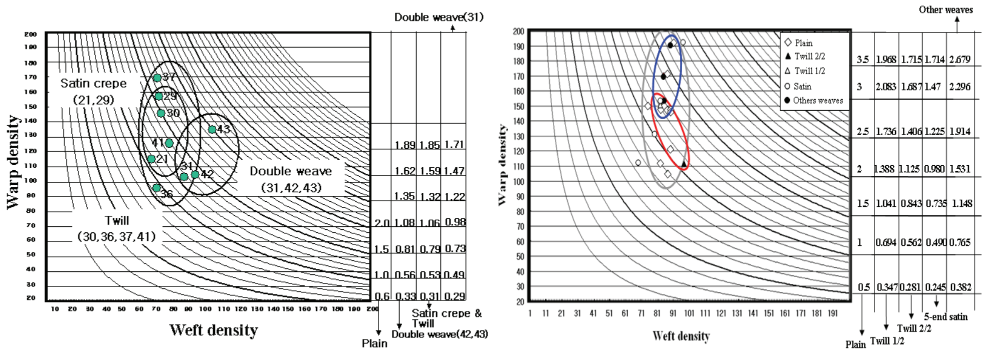


(d) WJL

Fig. 9. The weave density coefficients of polyester and nylon fabrics according to the weaving looms. (▬▬▬ : Plain, ... : Twill, ▬ . ▬ . : Satin, ... : Others)

3. The density distribution

Figure 10 shows fabric density distribution calculated and simulated by equation 6 for polyester and nylon fabrics with 2 kinds of yarn counts. Figure 10 (a) shows warp and weft density distributions of polyester fabrics with various weave density coefficients and various weave patterns with warp and weft yarn counts 150 deniers. As shown in this Figure 10 (a), specimen no. 21 and 29, satin crepe fabrics, have almost same weft density of fabrics, but warp density of fabrics were different according to the end use of fabric for garment. And as shown in Figure 10 (b), many specimens of plain fabrics have same weave density coefficient, but it was shown that warp and weft densities were different one another according to the end use of fabric for garment. Then it was shown that it was very convenient to decide warp and weft fabric densities for good hand of fabrics.



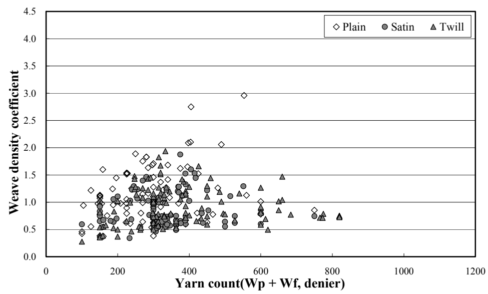
(a) PET (b) Nylon

Fig. 10. The diagram between fabric density of PET and Nylon fabrics

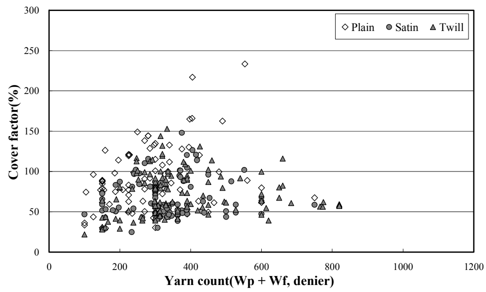
4. Comparison between weave density coefficient and cover factor

Figure 11 shows the diagram of weave density coefficient (WC), cover factors by Picanol and Prof. Walz which are calculated by equation 5, equation 1 and equation 2 using the specimens shown in Table 5, respectively. As shown in Figure 11(a), weave density coefficients of PET plain fabrics are widely ranged from 0.5 to 3.0. On the other hand, stain fabrics are distributed from 0.5 to 1.5, and for twill fabrics, ranged from 0.3 to 2.0. This phenomena demonstrate that plain fabrics show broad and wide distribution of weave pattern, and satin shows narrow distribution, which means the versatility of plain weave pattern. And also it is shown that 90% of all specimens' weave density coefficient is ranged from 0.5 to 1.5, which shows similar distribution to cover factor shown in Figure 11(b), proposed by Prof. Walz as equation 2. On the other hand, cover factors proposed by Picanol, which are calculated by equation 1, are distributed from 25% to 90% as shown in Figure 11(c). It is shown that Picanol's cover factor is much lower than those of WC and Prof. Walz equations, And comparing between WC and Prof. Walz equation, WC is about 30% higher than that of Prof. Walz equation. The reason seems to be due to the yarn correction factor 'a' and fabric weave correction factor 'b' in equation 2.

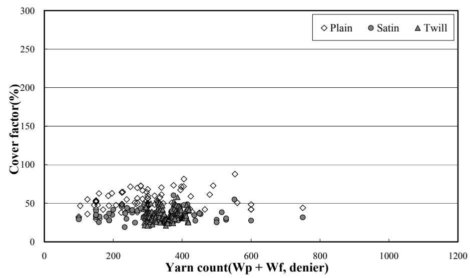
Figure 12 shows the same diagram for nylon fabrics. As shown in Figure 12(a), the weave density coefficients of all Nylon fabric specimens are distributed from 0.5 to 4.0 which are much wider than those of PET fabrics comparing with Figure 11(a). It is shown that weave



(a) Weave density coefficient



(b) Cover factor by Prof. Walz

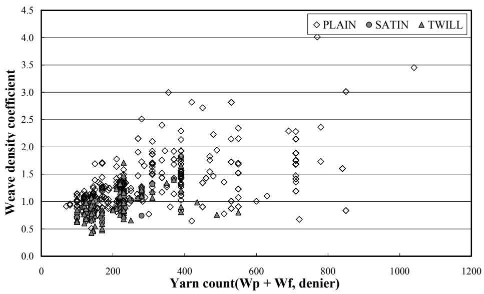


(c) Cover factor by Picanol

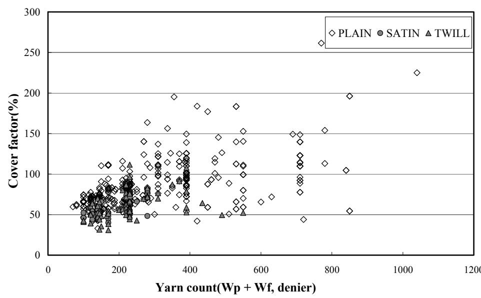
Fig. 11. Comparison among WC, cover factors of Picanol and Prof. Walz for PET fabrics

density coefficients of plain fabrics are widely distributed from 0.5 to 4.0. On the other hand, the weave density coefficients of twill and satin fabrics are ranged from 0.5 to 1.5, which is much lower and narrower than that of plain. As shown in Figure 12(b), cover factors by Prof. Walz are distributed from 50% to 200% which shows lower distribution than that of weave density coefficient as shown in Figure 12(a). It is shown that cover factor values by Picanol equation shown in equation 1 are distributed from 30% to 100% which is much lower than those of WC and Prof. Walz equations. And comparing between PET and nylon fabrics as shown in Figure 11(b) and Figure 12(b), in nylon fabrics, cover factors of satin and twill are distributed from 50% to 100%, but plain is widely distributed from 30% to 200% as shown in Figure 12(b). In PET fabrics shown in Figure 11(b), cover factors of all weave patterns such as plain, twill and satin are widely distributed from 30% to 150%. This phenomena demonstrate that plain weave patterns of nylon have higher density than those of satin and twill weave patterns, in one hand, the density of all weave patterns such as plain, twill and satin in the PET fabrics has almost same level. The cover factors of the nylon fabrics proposed by Picanol which are shown in Figure 12(c) ranged from 30% to 100% are much higher than those of PET fabrics which are shown in Figure 11(c).

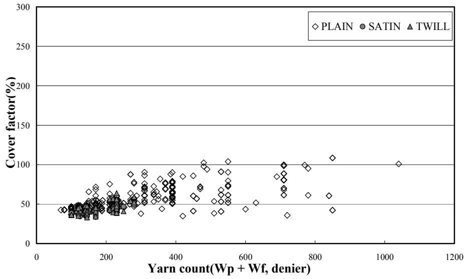
Figure 13 shows density coefficient, K of the polyester and nylon fabrics calculated by equation 3. As shown in Figure 13, the density coefficient, K is distributed between 400 and 1600 both polyester and nylon fabrics. Mario Bona (Park et al., 2000) in Italy is recommending this value as 800 for synthetic fabrics. Comparing to this recommended value, both polyester and nylon fabrics show much higher values than recommended value,



(a) Weave density coefficient



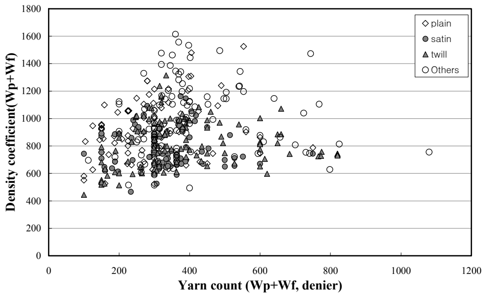
(b) Cover factor by Prof. Walz



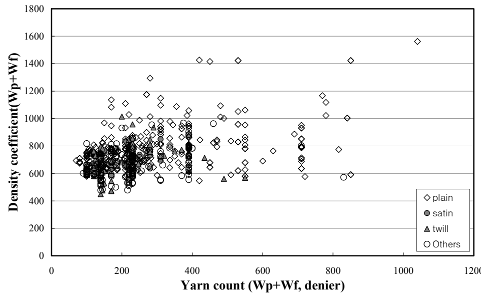
(c) Cover factor by Picanol

Fig. 12. Comparison among WC, cover factors of Picanol and Prof. Walz for nylon fabrics

800. As well known to us, the equation 3 proposed By M. Bona is based on density calculation of the worsted fabrics. Applying to synthetic fabrics as shown in Figure 13, the density coefficient distribution of the PET fabrics is mainly ranged between 600 and 1000 and for nylon fabrics, which is much more concentrated at this region. This results demonstrate the validity of the recommended value, 800 by M. Bona.



(a) PET



(b) Nylon

Fig. 13. Diagram of K against yarn count of polyester and nylon fabrics

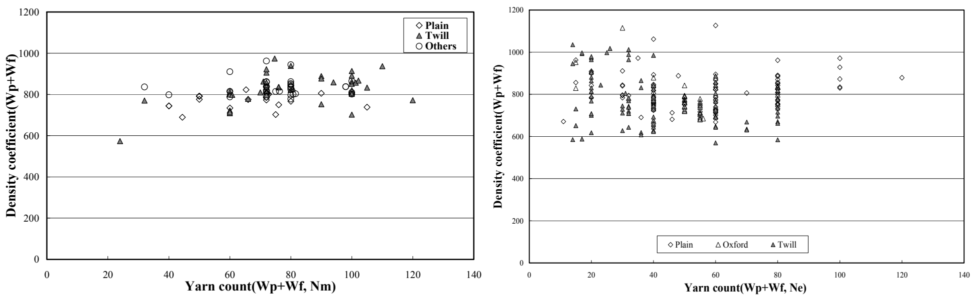
4.4 Case study of worsted and cotton fabrics

Various fabrics woven by worsted and cotton staple yarns were selected as specimens, respectively. Table 6 shows these specimens. For the worsted fabrics of one hundred thirteen, density coefficient, K was calculated using equation 3. For the cotton fabrics of four hundreds seventy nine, density coefficient Kc was calculated using equation 4.

Weave pattern \ Materials & Loom	Worsted fabrics	Cotton fabric
	Sulzer	Air-jet
Plain	35	243
Twill	48	156
Others	30	80
Total	113	479

Table 6. Specimens of worsted and cotton fabrics

Figure 14 shows the diagram between density coefficient and yarn count for worsted and cotton fabrics. It is shown that the density coefficient, K of worsted fabrics is ranged from 600 to 1000, for cotton fabrics, almost same distribution is shown. Comparing to synthetic fabrics such as polyester and nylon in which were ranged from 400 to 1600, as shown in Figure 14, natural fabrics such as worsted and cotton show lower values. Figure 15 shows weave density coefficients, WC calculated by equation 5, of worsted and cotton fabrics. As shown in Figure 15(a), the weave density coefficients of worsted fabrics are ranged from 0.4 to 0.8, for cotton fabrics, they are ranged from 0.2 to 1.0. Comparing to synthetic fabrics, which were shown in Figure 11(a) and 12(a) and ranged from 0.5 to 3.0, WC of the worsted and cotton fabrics show much lower values as below 1.0. Figure 16 shows weave density coefficient WC calculated by equation 5 and cover factors, calculated by equation 1 and 2 for worsted fabrics. As shown in Figure 16(a), weave density coefficients of worsted fabrics show the values below 1.0, and cover factors also show below 100%, especially the cover factor by Picanol shows lower values than Prof. Walz as below 50%. These values are much lower than those of synthetic fabrics shown in Figure 11(a) and 12(a). Figure 17 shows the diagram for cotton fabrics. The same phenomena are shown as worsted fabrics.

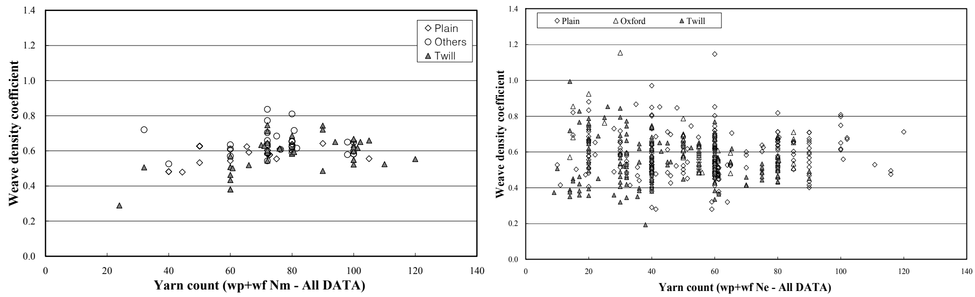


(a) Worsted (b) Cotton

Fig. 14. Diagram between density coefficients and yarn counts for worsted and cotton fabrics

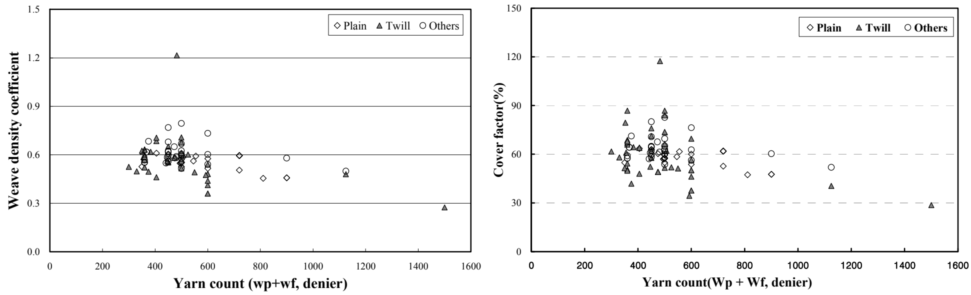
4.5 Relationship between weave density coefficient and shrinkage of dyeing and finishing processes

Figure 18 shows relationship between weave density coefficient and finishing shrinkage in dyeing and finishing processes of PET fabrics woven in the weaving company as shown in Table 5. The finishing shrinkages are distributed from 2% to 40% as shown in Figure 18. It is

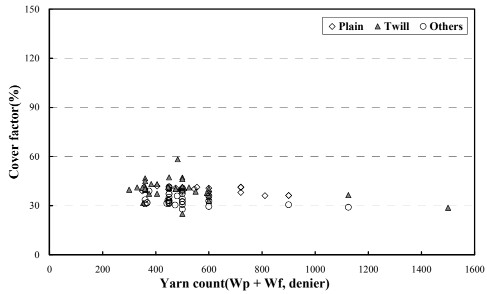


(a) Worsted (b) Cotton

Fig. 15. Diagram of weave density coefficients of worsted and cotton fabrics



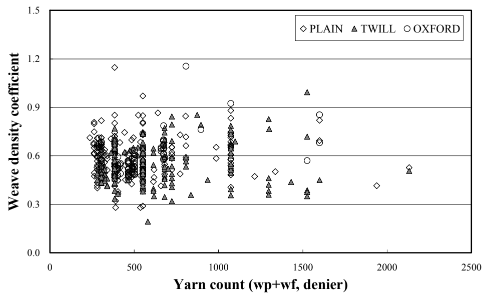
(a) Weave density coefficient (b) Cover factor by Prof. Walz



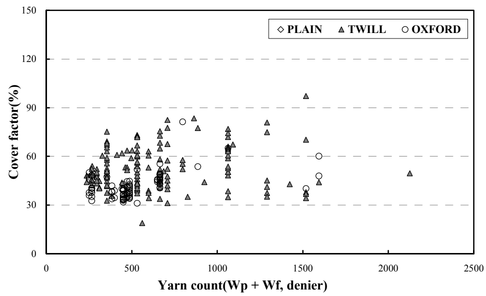
(c) Cover factor by Picanol

Fig. 16. Diagram of weave density coefficients and cover factors for the worsted fabrics.

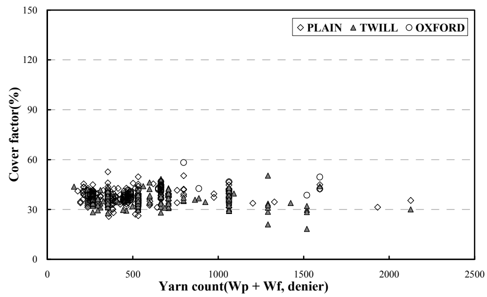
shown that finishing shrinkage varies according to the weave pattern such as plain, twill and satin. The shrinkages of plain fabric are ranged from 5% to 20%, for twill fabrics, three types of shrinkages levels are divided, one group is below 8%, 2nd group is ranged from 12% to 20%, 3rd group is ranged from 25% to 40%. The finishing shrinkages of the satin weaves are ranged from 12% to 23%(Kim et al., 2005). Figure 19 shows finishing shrinkages distributions from data-base of polyester plain fabrics manufactured by each company fabrics manufactured in A company is ranged from 5% to 20% and for C company, it is shown in the Table 5. As shown in Figure 19, the distribution of finishing shrinkage of PET



(a) Weave density coefficient



(b) Cover factor by Prof. Walz



(c) Cover factor by Picanol

Fig. 17. Comparison among WC cover factors by Picanol and Prof. Walz for cotton fabrics

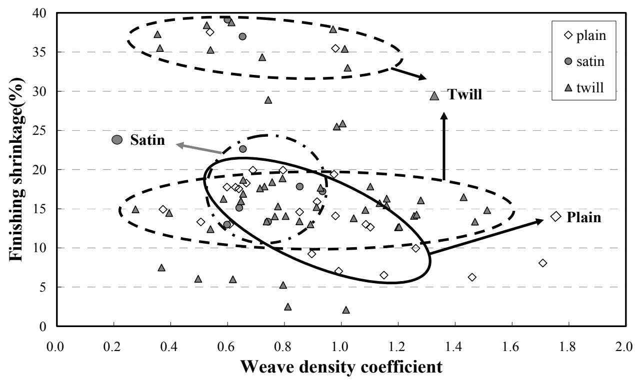


Fig. 18. Diagram between weave density coefficient and fabric shrinkage of PET fabrics woven in A company

ranged from 10% to 25%. This result gives us important information for fabric quality by getting finishing shrinkage according to the fabric manufacturers and weave density coefficients. Figure 20 shows weave shrinkages distributions of nylon fabrics manufactured by F company shown in Table 5. As shown in Figure 20, the weave shrinkages of nylon fabrics vary with weave patterns such as plain, satin and twill, which weave shrinkage values are shown as 7%, 8% and 10%. Figure 21 shows weave and finishing shrinkages of worsted fabrics shown in Table 6. As shown in Figure 21, the weave and finishing shrinkages of worsted fabrics are also distributed with weave patterns such as plain and twill, which are ranged from 2% to 10%.

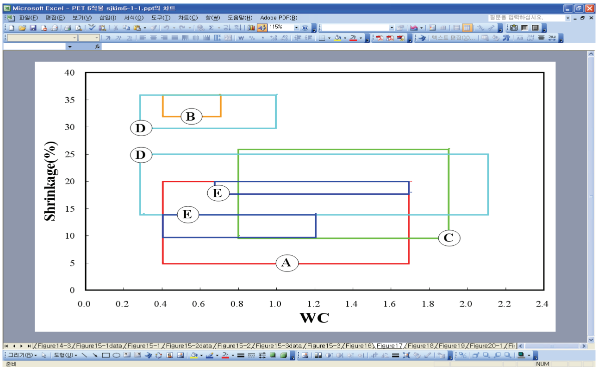


Fig. 19. Diagram between weave density coefficient and finishing shrinkage of PET fabrics woven by each company.

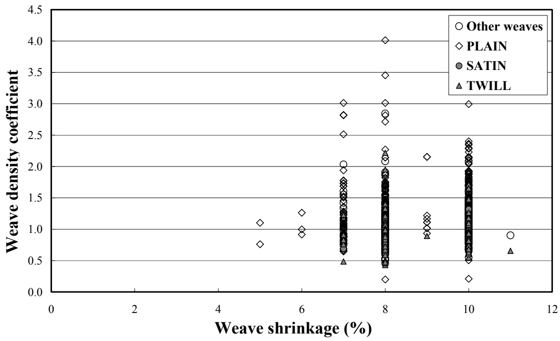


Fig. 20. Relationship between weave shrinkage and WC.

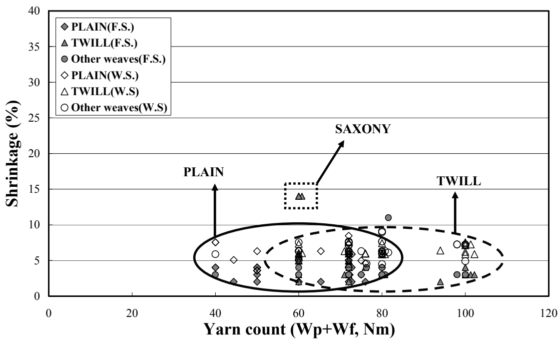
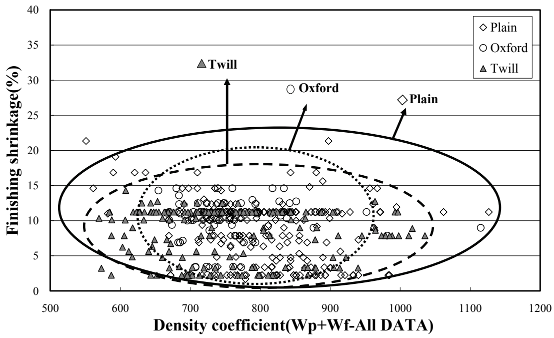
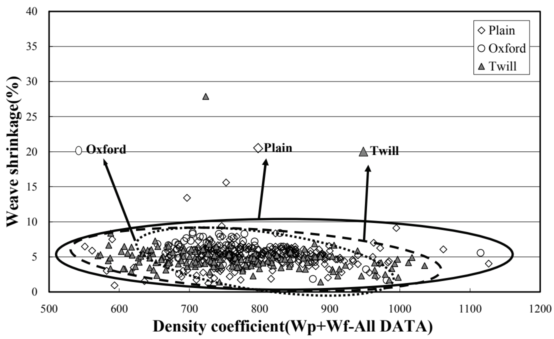


Fig. 21. Weave and finishing shrinkages according to the yarn count (F.S. : finishing shrinkage, W.S. : weave shrinkage)

Figure 22 shows finishing and weave shrinkages of cotton fabrics shown in Table 6. As shown in Figure 22, finishing shrinkages of cotton fabrics are distributed from 2% to 20%, on the one hand, weave shrinkages are ranged from 1% to 10%. It is shown that these shrinkages vary with weave patterns.



(a) Finishing shrinkage



(b) Weave shrinkage

Fig. 22. Diagram between density coefficient and shrinkage of cotton fabrics

5. Future challenges of the data base system for the fabric structural design

Even though a lot of commercial CAD systems(i-Designer, Texpro) for both fabric and pattern have been introduced, any system for weaving factories has not been developed. Therefore, a data base system related to the fabric structural design for weaving factory is needed to be explored. The yarn count, weave pattern and fabric density of 420 polyester fabrics and 838 nylon fabrics shown in Table 1 were used for making data base system, which were divided by weave patterns, weaving looms and weaving manufacturers. The reason why makes data base system according to the weaving manufacturers is explained as for examining the difference of fabric design according to each weaving factory. Figure 23 shows the diagram from data base between weave density coefficient and yarn count according to the weaving manufacturers. As shown in Figure 23, weave density coefficient is easily found according to the weaving manufacturers. It is shown that the distribution of weave density coefficients of PET fabrics manufactured in A company by water jet loom (WJL) is ranged from 0.2 to 1.8 according to the yarn linear density distributed between 100 and 800 denier. For the PET fabrics manufactured in C company by air-jet loom (AJL) and rapier loom (RPL), it is distributed between 0.6 and 2.4 according to the yarn linear density distributed between 100 and 850 denier. On the other hand, the weave density coefficients for the B, D and E fabric manufacturers are differently distributed with narrow distribution of the yarn linear density. This result from data base related to the fabric structural design gives us important information for the weave density coefficients according to the yarn denier and fabric manufacturers. Figure 24 shows the diagram from data base between weave density coefficient and yarn count according to the looms. It is shown that the distribution of weave density coefficients and yarn denier of PET fabrics woven by rapier

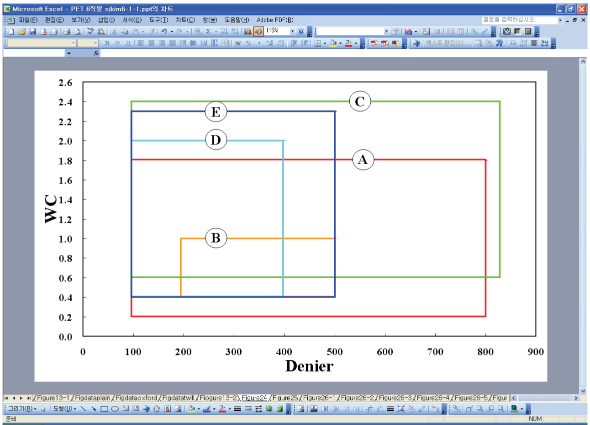


Fig. 23. Data base diagram between weave density coefficient and yarn count according to the weaving company. (PET)

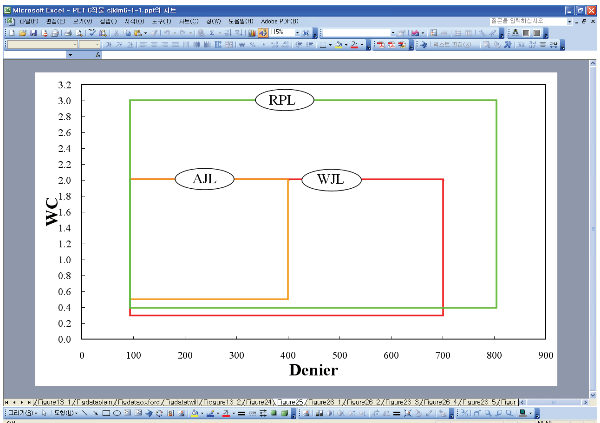
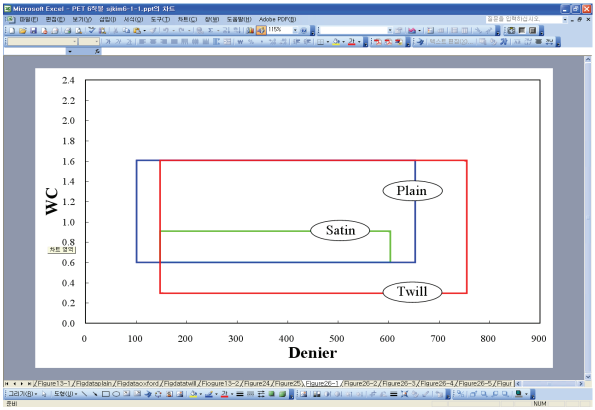
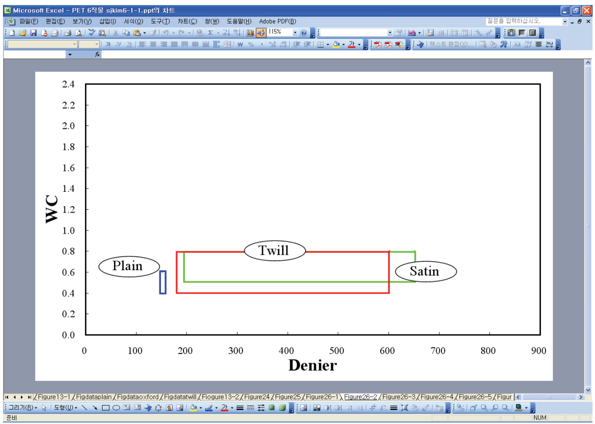


Fig. 24. Data base diagram between weave density coefficient and yarn count according to the looms. (PET)

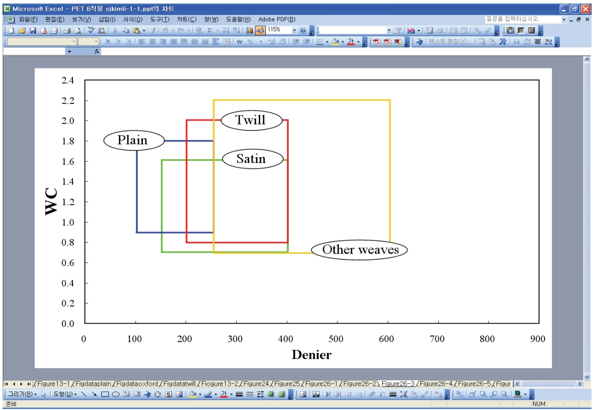
loom is the widest and air-jet loom is the narrowest. Figure 25 shows the diagram from data base between weave density coefficient and yarn count according to the weave pattern of each weaving manufacturers. It is shown that the distribution of weave density coefficient of twill fabrics of the A company is ranged from 0.3 to 1.6, and for plain weave pattern, it is ranged from 0.6 to 1.6, and the distribution of the satin is very narrow. These phenomena as shown in B, C, D and E company are differently distributed according to the weave pattern. Figure 26 shows the diagram of shrinkage of polyester fabrics according to the weaving companies (A, B, C, D and E) and weave patterns (plain, twill and satin) from data base. This result from data base related to the weave density coefficient gives us important information for the finishing shrinkage according to the fabric manufacturers and weave pattern.



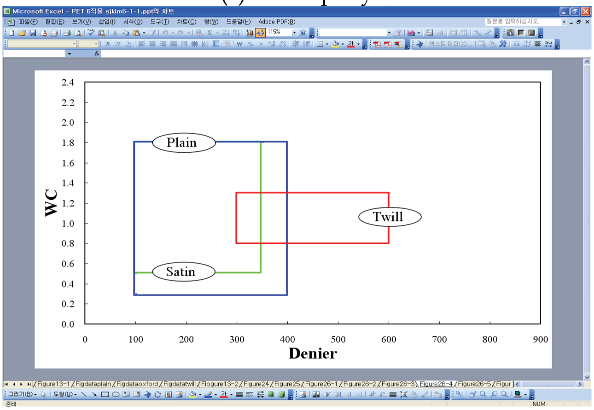
(a) A company



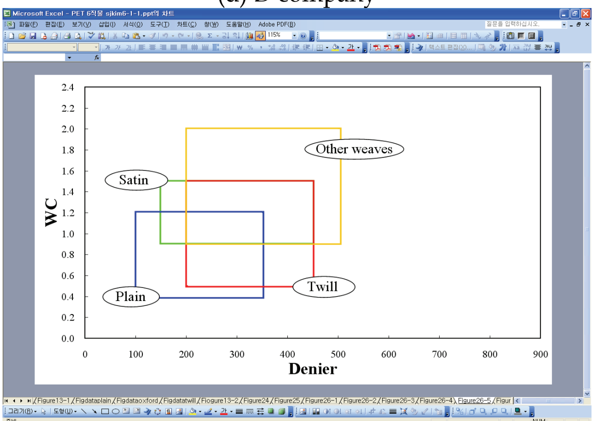
(b) B company



(c) C company



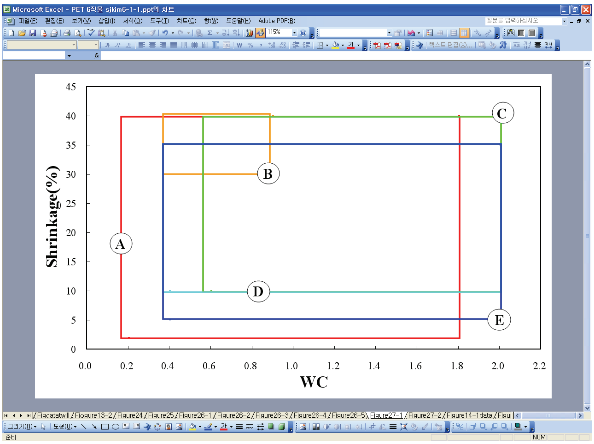
(d) D company



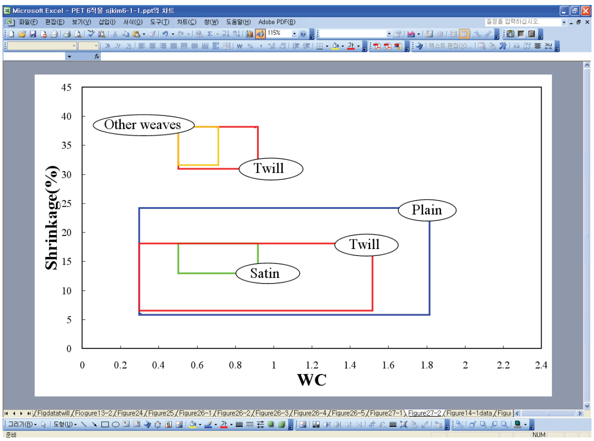
(e) E company

Fig. 25. Data base diagram between weave density coefficient and yarn count according to the weave patterns of each weaving manufacturers. (PET)

Figure 27 shows the application fields of fabric structural design data base system. As shown in Figure 27, final objectives of this topic is aiming to make a data base system with connection of the existing systems such as virtual wearing, pattern design CAD and drape analyzer, i.e. for getting some virtual wearing effect and some drape properties, this data base system is to give the answer about what is the best decision for woven fabric structural design component such as weave density coefficient, weave factor and yarn count. This topic is the first step for wide spreading this application fields to the existing woven fabric and clothing CAD systems.



(a) according to company



(b) according to weave pattern

Fig. 26. Data base diagram of shrinkage of polyester fabrics.

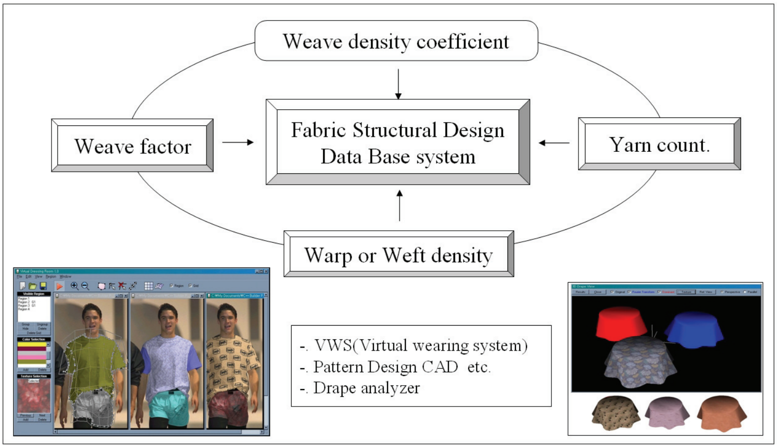


Fig. 27. The application fields of fabric structural design data base system

6. Summary

There were many tries for linking with visual wearing system of garment using fabric mechanical properties, and also there are many CAD systems such as fabric design CAD and pattern design CAD using many data bases on the computer. But there is no fabric structural design data base system linked with fabric physical properties and process conditions. The reason is due to too many factors considered for making such kind of data base system. As a 1st step for making data base system related to the fabric structural design, the data base between fabric structural parameters such as yarn count, fabric density, weave pattern and cover factor and process parameters such as weave and finishing shrinkages has to be constructed and analyzed using various kinds of fabric materials such as worsted, cotton, nylon and polyester fabrics. Through this procedure the estimation of the fabric density with given warp and weft yarn counts and weave construction seems to be possible. It makes easy application for new fabric design and also makes it possible to estimate the weavable fabric density according to the various types of looms for loom machinery maker. For getting the final goal of this topic, further study as follows is needed. 1st is to make data accumulation such as fabric structural design parameters and dyeing and finishing process parameters according to the various weaving companies and looms they are using. 2nd is to make data base for measurement of the physical properties of fabrics such as drape coefficient and mechanical properties. Finally, these have to be applied to the existing virtual wearing system and pattern design CAD.

7. References

Peirce, F. T. (1937). *The geometry of cloth structure*, J. Text. Inst., 28, pp. 45-96

Kemp, A. (1958). *An extension of Peirce's cloth geometry to the treatment of nonlinear threads*, J. Text. Inst., 49, pp. 44-48

Hearle, J. W. S. & Shanahan, J. W. (1978). *An energy method for calculations in fabric mechanics, part* I: *principles of the method*, J. Text. Inst., 69, pp. 81-89

Grosberg, P. & Kedia, S. (1966). *The mechanical properties of woven fabrics, part I: the initial load-extension modulus of woven fabrics*, Text. Res. J., 36, pp. 71-79

Backer, S. (1952). *The mechanics of bent yarns*, Text. Res. J., 22, pp. 668-681

Postle, R.; Carnady, G. A. & Jong, De. S. (1988*). The Mechanics of Wool Structures(eds),* Chichester Ellis Horwood, U.K

Lindberg, J.; Behre, B. & Dahiberg, B. (1961). *The Mechanical properties of textile fabrics part III: shearing and buckling of various commercial fabrics*, Text. Res. J., 31(2), pp. 99-122

Kawabata, S.; Postle, R. & Niwa, M. (1982). *Objective Specification of Fabric Quality,* Textile Machinery Society of Japan

Ly, N. G.; Tester, D. H. Buckenhan, P. Roczniok, A. F. Adriaansen, A. L. Scazsbrook, F. & De, J. (1991). *Simple instruments for quality control by finishers and tailors*, Text. Res. J., 61(7), pp. 402-406

Hu, J. (2004). *Structure and Mechanics of Fabrics*, The Textile. Institute., CRC press http://www.i-designer.co.kr, i-Designer. http://www.texclub.com, Texpro.

Harada T, Saito M. (1986). *Japanese Journal of Textile System, 45, pp. 305*

Kim, S. J. (2002). Data Base System and Its Application of PET Woven Fabric, *Proceedings of 2nd International Fibre Symposium*, pp. 10-17, Fukui University, September and 2002, Fukui University, Fukui

Kim, S. J. (2005). The Preliminary Study for Data-Base System of The Various Fabrics, *Proceedings of 3nd International Conference on advanced Fiber/Textile Materials 2005 in Ueda*, pp. 225-226, Shinshu University, August and 2005, Research Center for Advanced Science and Technology Faculty of Textile, Ueda

Oh, A. G. & Kim, S. J. (1993). Study on the Mechanical Properties of Polyester Woven Fabric (1) – Tensile Behavior under Low Sterss. *Journal of The Korean Fiber Society, 30.*, 9., 641-651, 1225-1089

Oh, A. G. & Kim, S. J. (1993). Study on the Mechanical Properties of Polyester Woven Fabric (2) – Nonlinearity of Shear Properties. *Journal of The Korean Fiber Society, 30.*, 10., 719-730, 1225-1089

Oh, A. G. & Kim, S. J. (1993). Study on the Mechanical Properties of Polyester Woven Fabric (3) – Nonlinearity of Bending Properties. *Journal of The Korean Fiber Society, 30.*, 12., 919-927, 1225-1089

Oh, A. G. & Kim, S. J. (1994). Study on the Mechanical Properties of Polyester Woven Fabric (4) – Compressional Properties. *Journal of The Korean Fiber Society, 31.*, 5., 361-368, 1225-1089

Oh, A. G. & Kim, S. J. (1994). Study on the Mechanical Properties of Polyester Woven Fabric (5) – Surface Properties. *Journal of The Korean Fiber Society, 31.*, 6., 425-433, 1225-1089

Kim, S. J. & Kang, J. M. (2004). Effects of Rapier Weaving Machine Characteristics on the Physical Properties of Worsted Fabrics for Garment (1). *Journal of The Korean Society for Clothing Industry, 6.*, 6., 765-771

Kim, S. J. & Kang, J. M. (2004). Effects of Rapier Weaving Machine Characteristics on the Physical Properties of Worsted Fabrics for Garment (2). *Journal of The Korean Society for Clothing Industry, 6.*, 6., 772-777

Kim, S. J. & Tung, K. J. (2005). Effects of the Projectile and the Air-jet Weaving Machine Characteristics on the Physical Properties of Worsted Fabrics for Garment (1). *Journal of The Korean Society for Clothing Industry, 7.*, 1., 101-105

Kim, S. J. & Tung, K. J. (2005). Effects of the Projectile and the Air-jet Weaving Machine Characteristics on the Physical Properties of Worsted Fabrics for Garment (2). *Journal of The Korean Society for Clothing Industry, 7.*, 1., 106-110

Kim, S. J.; Sohn, J. H. Kang, J. M. & Park, M. H. (2004). Effects of Weaving Machine Characteristics on the Physical Properties of PET Fabrics (I). *Journal of The Korean Society of Dyers and Finishers, 16*., 4., 206-215

Kim, S. J.; Sohn, J. H. Kang, J. M. & Park, M. H. (2004). Effects of Weaving Machine Characteristics on the Physical Properties of PET Fabrics (II). *Journal of The Korean Society of Dyers and Finishers, 16*., 4., 216-224

Kim, S. J.; Sohn, J. H. Kang, J. M. & Park, M. H. (2004). Effects of Weaving Machine Characteristics on the Physical Properties of PET Fabrics (III). *Journal of The Korean Society of Dyers and Finishers, 16*., 5., 278-283

Kim, S. J.; Sohn, J. H. Kang, J. M. & Park, M. H. (2004). Effects of Weaving Machine Characteristics on the Physical Properties of PET Fabrics (IV). *Journal of The Korean Society of Dyers and Finishers, 16*., 5., 284-291

Kim, S. J. & Kang, J. M. (2004). Effects of Weaving Tension Characteristics on the Surface Properties of PET Fabrics for the Sensitive Garment (I). *Journal of The Korean Society for Emotion & Sensibility, 7*., 4., 25-33

Kim, S. J. & Park, K. S. (2005). Effects of the Rapier Weaving Tension Characteristics on the Surface Properties of PET Fabrics. *Journal of The Korean Society for Clothing Industry, 7*., 6., 673-679

Kim, S. J. (2008). Effects of the Air-Jet Loom Characteristics on the Hand Properties of the Sensitive Mixture Fabrics. *Journal of The Korean Society of Dyers and Finishers, 20*., 6., 63-68

Kim, S. J.; Oh, A. G. Cho, D. H. Chang, D. H. & Song, J. S. (1995). Study on Correlation between Fabric Structural Parameter and Processing Shrinkage of Polyester Woven Fabric. *Journal of The Korean Fiber Society, 32*., 5., 480-487, 1225-1089

Kim, S. J.; Oh, A. G. Cho, D. H. Chang, D. H. & Song, J. S. (1995). Study on Correlation between Mechanical Properties and Warp Density of Polyester Woven Fabric. *Journal of The Korean Fiber Society, 32*., 5., 488-493, 1225-1089

Oh, A. G.; Kim, S. J. Cho, D. H. Chang, D. H. Kim, S. K. Kim, T. H. & Seo, M. H. (1993). Study on Correlation between Mechanical Properties and Processing Shrinkage of Polyester Woven Fabric. *Journal of The Korean Fiber Society, 30*., 11., 803-816, 1225-1089

Instruction of Manual (1937). Picanol

Park, S. H.; Kim, S. J. Shin, B. J. & Lee, M. H. (2000). Theory and Application of Woven Fabric Design for Garment, *ic Associates Co. LTD*., Seoul

Kim, S. J. & Hong, S. G. (2005). The Comparison Between Nylon and PET Fabrics, *Proceedings of the 34th Textile Research Symposium*, pp. 33-34, Fuji Institute of Education and Training, August and 2005, Textile Science Research Group in the Textile Machinery Society of Japan, Fuji

Kim, S. J. & Park, K. S. (2005). The Fabric Hand Analysis between Domestic and Foreign Worsted Fabrics, *Proceedings of the 34th Textile Research Symposium*, pp. 85-86, Fuji Institute of Education and Training, August and 2005, Textile Science Research Group in the Textile Machinery Society of Japan, Fuji

Kim, S. J.; Park, K. S. & Hong, S. K. (2005). A Study on the Relationship Between Fabric Design Condition for Garment and Shrinkage on the Dyeing and Finishing Process. *Journal of The Korean Society of Dyers and Finishers, 17*., 5., 267-274

Kim, S. J. (2006). A Study on the Synthetic Fabric Design System. *Journal of The Korean Society for Emotion & Sensibility, 9*., 3., 243-249

Hong, S. G. & Kim, S. J. (2004). A Study on the Data-Base of Fabric Design System on the Nylon Woven Fabrics, *Proceedings of The Korean Society for Clothing Industry Conference*, pp. 253-256, EXCO, October and 2004, The Korean Society for Clothing Industry, Daegu