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Computational Interpretation of Woven Fabric Deformation

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Abstract : An integrated computer system for fabric design based on textile mechanics has been developed. The system enables the simulation of the mechanical properties of woven fabric at fabric design stage. The behaviors of the tensile, shear and bending of woven fabric have been simulated with the models of previous workers. The responses of the woven fabric with the variation of yarn crimp, fabric density, and yarn size were predicted. The integrated computer system includes a database system containing fabric specification, yarn information, weave, and so forth which are required in woven fabric design. The system always checks the weavability limit of new fabric with jamming conditions before starting simulation. Thus, the system is expected to serve as a useful tool to design new woven fabrics of specified property requirements by supplying the simulated data at the design stage.

1. Introduction

Many attempts to relate the fabric mechanical properties to the fabric performance such as hand, tailorability and suiting appearance have been made [1]. However, the attempts were not very successful because of the structural complexity of fiber assembly. Nevertheless, the desire to systematize the expertise has been increased as the requirements for the development of high value-added fabric increase. Especially, with the remarkable development of technology in apparel industries, the desire has been more increased in recent years. As a result, there have been some achievement [1] in the fabric engineering design whose aim was to meet a specified level of mechanical and physical performance required for specific applications.

The studies on the fabric engineering design could be categorized into two groups. One is the experimental approach. It mainly relates the fabric mechanical properties to the fabric performance with statistical analysis. It enables to check if the fabric meets the requirements of the following processing. This approach has been more activated since the development of the instruments for objective measurement of fabric mechanical properties (e.g., KES-F[2]). However, the study has some difficulty in explaining the principles of fabric response to the external loading as well as the influence of the material properties and the role of structural parameters of the fabric. Thus, the other approach was suggested by Grosberg and Leaf [3] who said, "Theoretical approach can be used to design textile structure although it has been used as a tool to explain what happens". They showed the possibility

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by using an example and proposed a strategy for woven fabric design that could help manufacturer to produce the fabric that would meet the specifications. This approach has the advantage of predicting the mechanical behavior of fabric at the design stage and explaining the role of the structural parameters of the fabric. Thus, it can give an understanding of how to control the structural parameters of the fabric.

However, there are only a few theoretical researches that help to design a fabric based on textile mechanics [3-5]. The main reason is that the characteristic of fiber assembly differs from the classical engineering structures in many ways because of its structural complexities. Thus it has been difficult to formulate and solve the system equation governing the mechanical behavior of fiber assembly. *Table* 1 shows such difficulty. However, with the development of numerical tools, the difficulty has been much removed.

In this study, the integrated computer system based on textile mechanics that helps to design woven fabric has been studied. This system enables the simulation of the mechanical properties of woven fabric such as tensile, shear, and bending behaviors at the fabric design stage. The computer simulation of the fabric mechanical behavior is based on the analytical models developed by other workers [7-11]. We simulated and interpreted the mechanical behaviors of woven fabric with the variations of

Table 1. Classification of mathematical problems and their case of solution by an analytical method [6]

Equations	Linear			Nonlinear		
	One	Several	Many	One	Several	Many
Algebraic	Trivial	Easy	Essentially impossible	Very difficult	Very Difficult	Impossible
Ordinary differential	Easy	Difficult	Essentially impossible	Very difficult	Impossible	Impossible
Partial differential	Difficult	Essentially impossible	Impossible	Impossible	Impossible	Impossible

Textile mechanics problems

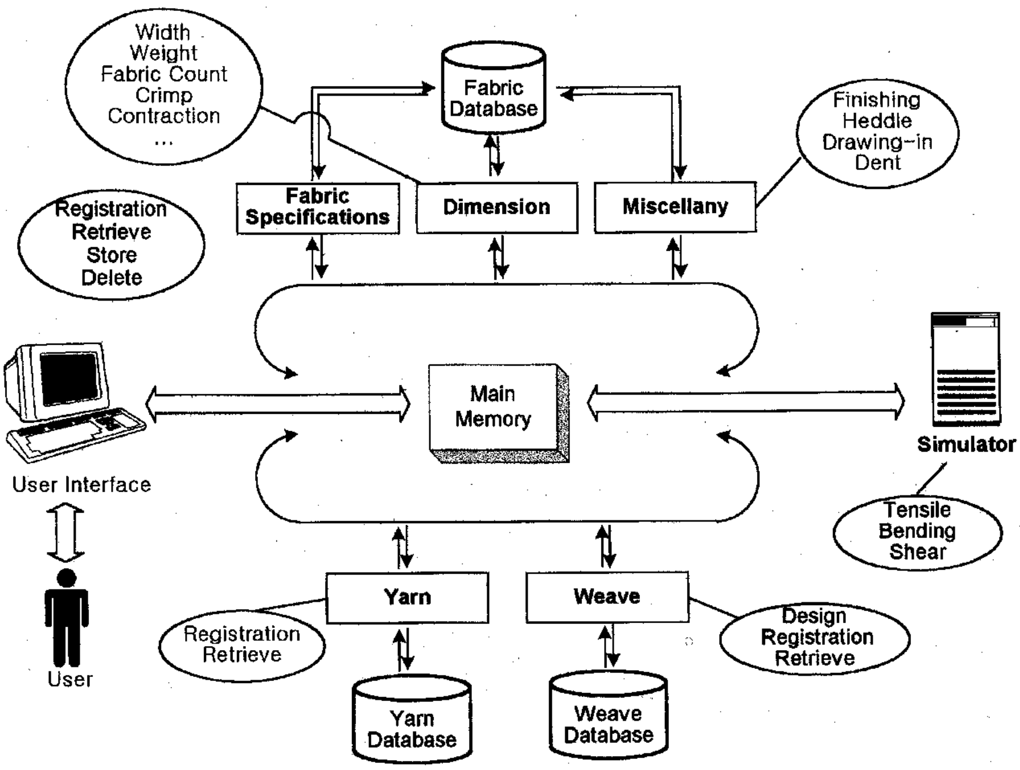

Figure 1. Schematic diagram of the fabric engineering design system.

structural parameters and yarn size using this system. This system always checks the weavability of the fabric using the jamming condition proposed by Peirce [12]. The system also includes a database that contains the fabric specifications, yarn information, weave, etc., which are required in fabric design.

2. Scheme of the Integrated Computer System for Fabric Engineering Design

The integrated computer system for fabric engineering design developed in this study is composed of 6 modules, that is, fabric specification, dimension, yarn, weave, miscellany, and simulator as shown in *Figure* 1. The system starts from the user interface where the user can reach any module. The fabric specification module plays the roles of registering new fabric specification on the fabric database, retrieving and deleting the stored fabric specification from the fabric database. The dimension module interacts with the fabric database. It treats the data related to the fabric dimension such as width, weight, density, and so forth. The miscellany module treats the information on finishing, heddle, drawing-in and dent on the fabric database.

The fabric database contains the information on fabric identity code, designer, dimension, warp and weft yarn code, weave code, and so forth. The yarn and the weave code are connected to the data stored in the yarn and the weave database. If a fabric specification is retrieved from the fabric database, the corresponding information is automatically loaded from the yarn and the weave database into the main memory. Also, the system enables user to store and retrieve independently yarn and weave information for the purpose of designing yarn and weave.

The data retrieved from the databases are transferred into the simulator module. If the transferred data do not violate the jamming condition [12] and are not mismatched with the data required in each analytical model, the simulator module asks which mechanical property is to be simulated. After the selected mechanical property is simulated, the same processing-asking and simulating-is repeated, that is, If the user wants to tune the parameters of the fabric and yarn size to design the fabric which meets some requirements, the processing will be repeated again.

3. Theoretical Model for the Simulator Module

A number of theoretical models for woven fabric have been developed. But, most of them including this study are restricted to the plain weave structure. The computer models used in this system were adopted from the recent analytical models reported by other workers [7-11]. The consistency in assumptions for developing analytical models was considered in selecting the analytical models.

3.1. Tensile Model

The theory used in simulating tensile behavior of woven fabric is based on Kawabatas model [9-10] with Realff's modification [13]. This model makes it possible to describe the entire scope of tensile deformation of woven fabric because it uses the entire deformation behavior of yarn instead of using tensile modulus, which other models generally use. The model assumes that the yarn is circular in cross section and the normal force at the cross over point is determined by the bending resistance of cross yarn. The original geometry is assumed to be known or can be measured. The yarn is assumed to be under no stress before the tensile load is applied. The fabric is assumed to be completely set.

3.2. Shear Model

In developing the computer shear model, Grosberg and Park's result [8] was considered. However, it requires the measurement of the initial shear modulus to obtain the contact length between the warp and weft yarn at the cross over point. Because of the complexity accompanying the estimation of initial shear modulus, Leaf and Sheta [9] made some improvements in predicting the initial shear modulus. This initial modulus is the rigidity due to the rigid intersection between warp and weft yarns. This initial deformation occurs when the shear force is too small to overcome the frictional resistance in the region where the yarns are in contact. The unit cell of this model is determined by fabric density, crimp, and weave angle(θ) which is approximated by the following Peirce's equation [12].

$$\theta = 1.88\sqrt{c} \tag{1}$$

where c is the fractional yarn crimp, given by

$$c_1 = \frac{l_1 - p_2}{p_2},\ c_2 = \frac{l_2 - p_1}{p_1}$$

l_1, l_2 are the warp and weft yarn modular lengths.
p_1, p_2 are the warp and weft yarn spacings.

The above shear model serves as the basic analytical model for computational interpretation.

3.3. Bending Model

There have been a number of studies on the bending behavior of woven fabric [7]. We adopted Ghoshs model [7] which is very sophisticated to describe the role of cross yarn during the bending deformation of fabric. The model also can describe bilinear as well as linear bending behaviors. However, our interest is confined to the linear bending model for consistency with other analytical models used in this study. This model follows Peirce's assumptions [12], that is, the geometry of yarn centerline can be described by elastica, and yarn is assumed to be weightless slender having non-zero bending rigidity. To obtain the geometry of a unit cell, seven coupled differential equations [7] must be solved simultaneously, which are subject to moving boundary conditions.

4. Input and Output of the Simulator Module

Table 2 shows the kinds of input data which are required in the simulator module. The tensile behavior in *Table* 2 means the tensile response of yarn on entire deformation range. The outputs of the models are the force-extension relation for the tensile model, initial shear modulus for the shear model and bending rigidity in the elastic region for the bending model.

Table 2. Input data list required in the simulator module

		Tensile model	Shear model	Bending model
Yarn	Tensile behavior	○	×	×
	Bending modulus	○	○	○
	Diameter	×	○	○
Fabric	Density	○	○	○
	Crimp	○	○	○
	Degree of setting	×	×	○

5. Measurements of Input Data

All samples were conditioned for more than a week at standard laboratory conditions, 20 and 65% RH. Fabric density is measured with the help of standard counting lens. Yarn spacing can be obtained from this density and has a relation with crimp as following equation.

$$Crimp(\%) = 100\frac{(l-p)}{p} \tag{2}$$

where l is the straightened length (or modular length) of yarn and p is the yarn spacing.

The method of measuring the degree of setting (ϕ) is identical to that of Ghosh [7], which was defined as following.

$$\phi = \sqrt{\frac{c_r}{c}} \tag{3}$$

where c is the crimp in the fabric, c_r is the crimp when the yarn is pull out from the fabric and released.

Yarn diameter was measured with photomicroscope and the load-extension graph of yarn was obtained from Instron tensile testing machine (cross head speed: 10 cm/min). Yarn bending modulus was measured with KES-FB2-L pure bending tester [2]. The sample was prepared as shown in *Figure* 2, and then mounted on the tester machine. The sample length between jaws was 2 cm and the number of

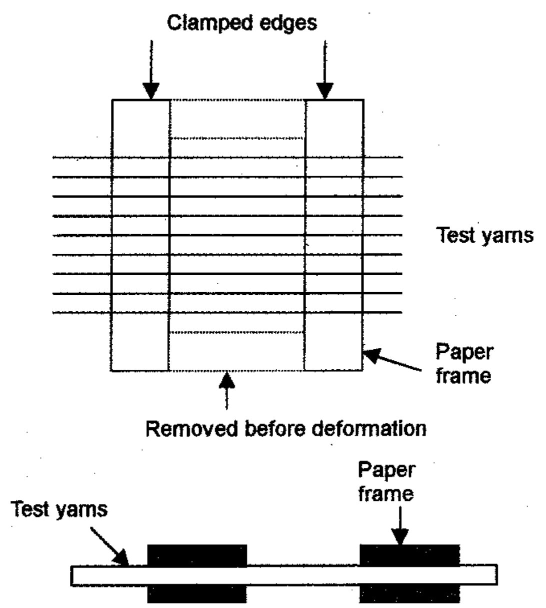

Figure 2. Yarn sample preparation for bending tester with KES-FB2-L[5].

yarns per frame was 9. The bending rigidity per yarn was obtained by dividing the measured rigidity with the number of yarns.

6. Computational Interpretation of Woven Fabric Deformation using the integrated Computer System

Simulations have been performed with the help of the integrated computer system. The responses of woven fabric according to the variations of structural parameters of fabric and yarn size have been discussed. The understanding obtained through the simulation could be utilized in fabric engineering design.

6.1. Tensile Response

The tensile responses of woven fabric with variation of fabric construction have been studied. Fabric constructions are given in *Table* 3. The fabric geometry is determined by measuring the crimp and yarn spacing.

Table 3. Fabric constructions used to simulate the tensile and shear responses of woven fabric

	Fabric density (No./cm)	Crimp (%)	Yarn diameter (cm)	Yarn bending rigidity (gf · cm²)
Warp	44.41	10.2	0.021	7.1210^{-4}
Weft	25.43	7.0	0.021	7.1210^{-4}

To see the effect of crimp on the tensile behavior of the fabric, the tensile responses of fabric with eight different crimp values were simulated. *Figure* 3 shows the trend at different crimp values. The result shows that as warp crimp increases, so does the extensibility of the fabric. It is due to the increased weave angle of the warp yarn at high warp crimp. Therefore, the bending deformation is more important factor than the extension of yarn itself.

Figure 4 shows the effect of pick density on the tensile response of fabric. Unlike the crimp effect, it shows relatively small change with pick density. The *figure* shows that the extensibility increases by small amount as pick density increases. Generally, if the pick density increases, the weft yarn spacing reduces and it causes the distance between the neutral line of fabric and center line of warp yarn to increase, therefore the weave angle of warp yarn increases. This results in the small increase of extensibility.

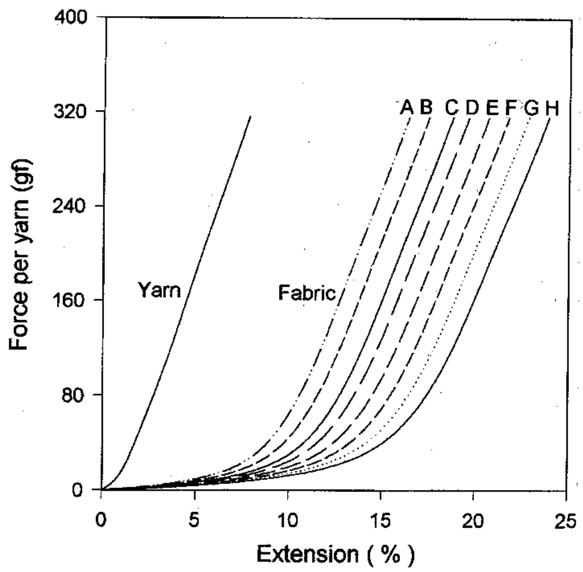

Figure 3. Tensile behavior of yarn and fabric in the warp direction at different warp crimp values (A: 8.0% B: 9.0% C: 10.2% D: 11.0% E: 12.0% F: 13.0% G: 14.0% H: 15.0%.

6.2. Shear Response

The initial shear rigidities [3] were calculated with 5 different crimp values to see the effect of crimp on the shear rigidity of fabric. The used fabric constructions are given in *Table* 3. *Figure* 5 shows that the shear rigidity of the fabric is inversely proportional to the crimp. It is due to the increased yarn modular length with the increased yarn crimp value. This initial shear rigidity is influenced by the bending

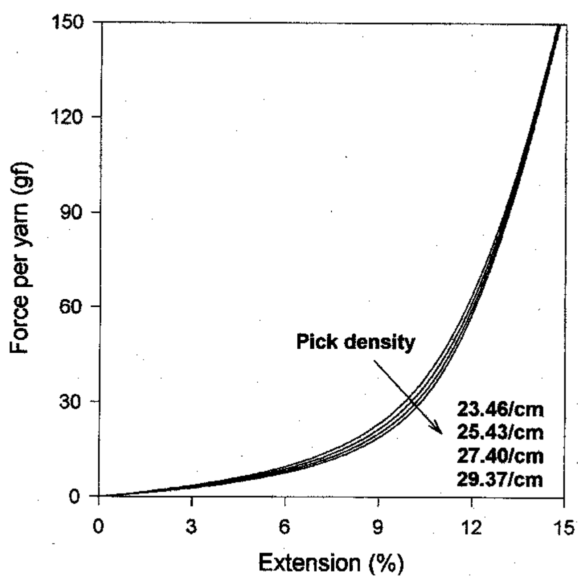

Figure 4. Tensile behavior of fabric in the warp direction at different pick densities.

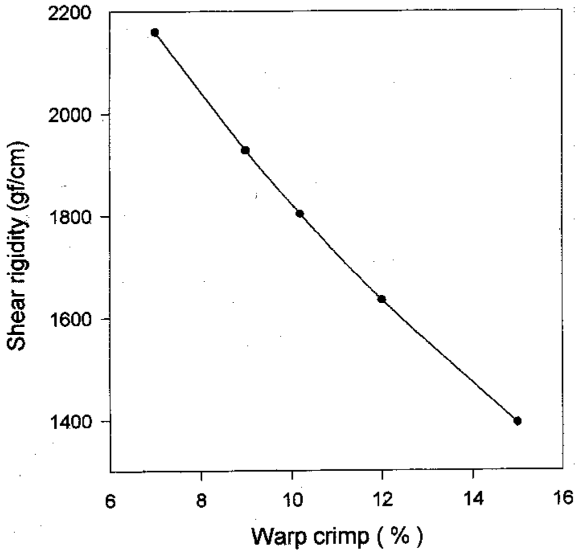

Figure 5. Effect of warp crimp on the shear rigidity of fabric.

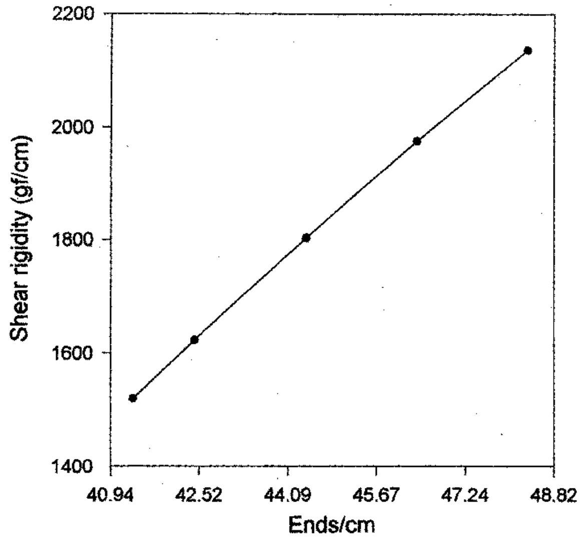

Figure 6. Effect of end density on the shear rigidity of fabric.

resistance of warp and weft yarn in the direction of shear force being applied. In general, if the yarn length increases in a fixed horizontal space, the bending rigidity decreases. Therefore, the shear rigidity decreases with the increase of crimp.

Figure 6 shows the effect of end density on the shear rigidity of fabric. The result shows that the shear rigidity increases with end density. It is due to the shortened yarn modular length which increases the bending resistance of fabric in the direction of shear force being applied.

Figure 7 shows the relationship between yarn diameter and shear rigidity. The result shows that

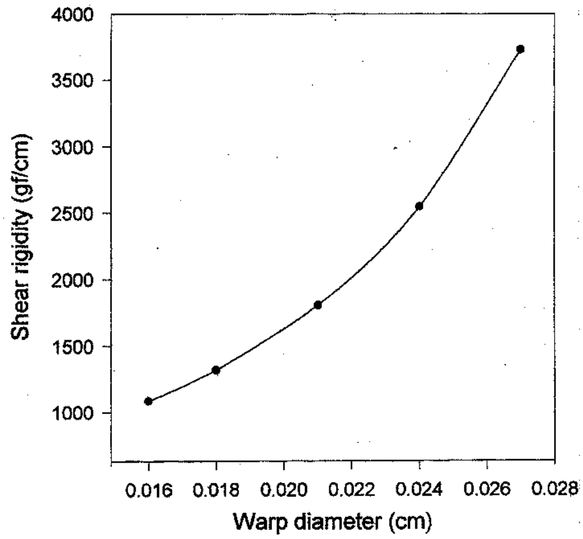

Figure 7. Effect of warp diameter on the shear rigidity of fabric.

Table 4. Fabric constructions used to simulate the bending response of woven fabric

	Fabric density (No./cm)	Crimp (%)	Yarn diameter (cm)	Yarn bending rigidity (gf · cm^2)	Degree of set
Warp	24.41	7.43	0.0145	0.037	0.423
Weft	23.62	6.20	0.0145	0.037	0.382

the shear rigidity increases with yarn diameter. It is due to the increased contact area between warp and weft yarn, which reduces the yarn modular length in unit cell. Generally, the tightness of fabric increases with yarn diameter, which will cause the shear rigidity to increase.

6.3. Bending Response

The fabric bending rigidities were calculated for the fabrics given in *Table* 4. *Figure* 7 shows the effect of the structural parameters on the bending rigidity of the fabrics.

The bending rigidity decreases with crimp value until it reaches the minimum value, and then it starts to increase. According to Abbot [14] and Ghosh [7] there is a critical crimp value to shift the bending rigidity from decrease to increase. The decrease of bending rigidity results from the increased crimp. The effect of crimp can be explained by the following Equation 4 suggested by Abbot [14]. The equation shows that the bending rigidity of fabric decreases as the yarn modular length(l) increases, and the yarn modular length is proportional quantity

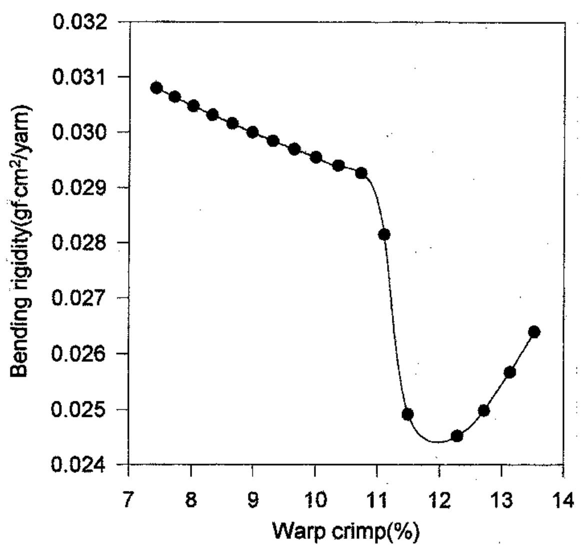

Figure 8. Effect of warp crimp on the bending rigidity of fabric in the warp direction.

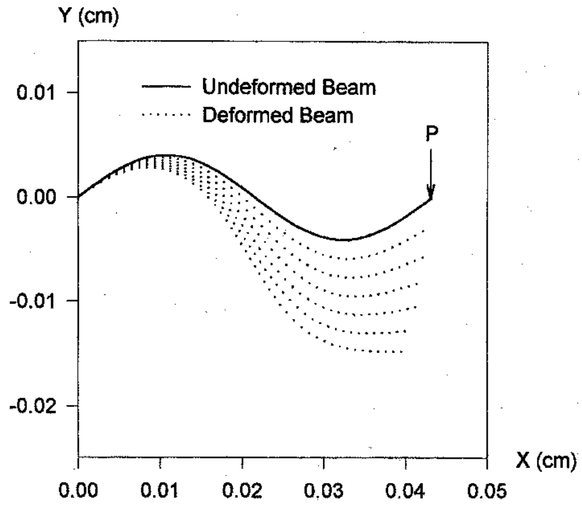

Figure 10. Deformed geometry of a curved beam at different load levels.

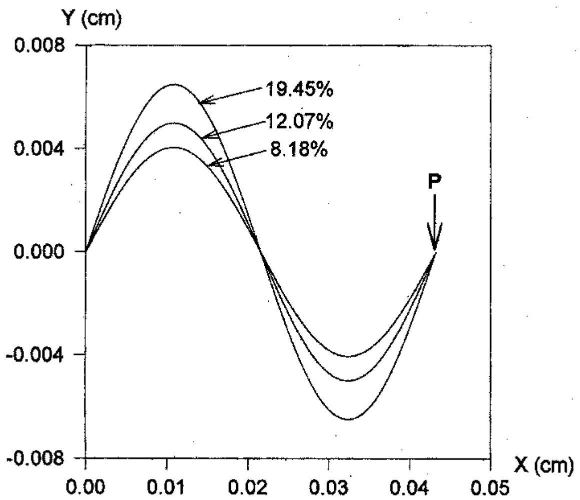

Figure 9. Geometry of curved beams having different crimps but equal horizontal length.

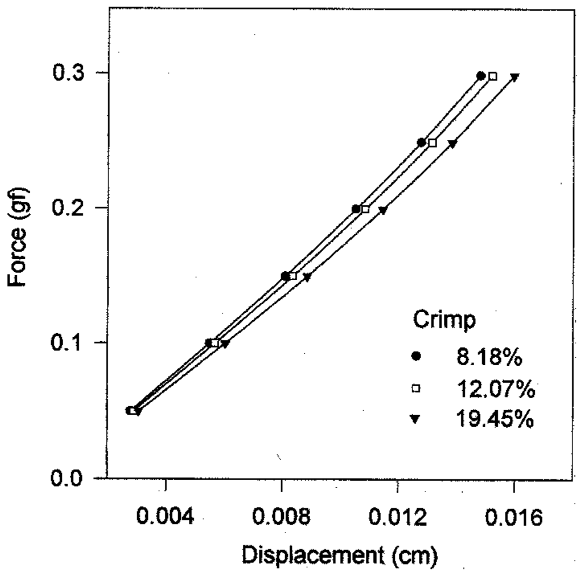

Figure 11. Effect of crimp value on the bending resistance.

to the crimp. Therefore, the bending rigidity decreases as the crimp increases.

$$EI_f = \frac{EI_y p}{lf} \tag{4}$$

where EI_f, EI_y are bending rigidities of fabric and yarn.

l is the yarn modular length.

p is the yarn spacing.

To examine the crimp effect in detail, the bending deformation of curved beams which have different lengths but equal horizontal length was simulated with the help of the commercial software "ABAQUS" [15]. *Figure* 9 shows the beams with the vertical load being applied at their end points. The Finite Element Method was used to obtain the relationship between load and vertical displacement. *Figure* 10 shows the deformed shape of a curved beam at different load levels. We can know that the bending resistance decreases as crimp increases from *Figure* 11, which shows the relationship between load and vertical displacement.

However, *Figure* 8 shows that the bending rigidity starts to increase after passing the minimum position. It is due to the increased contact length between yarns at the cross over point [7]. *Figure* 12 shows that as the crimp value increases, the contact length between the yarns starts to increase when the crimp

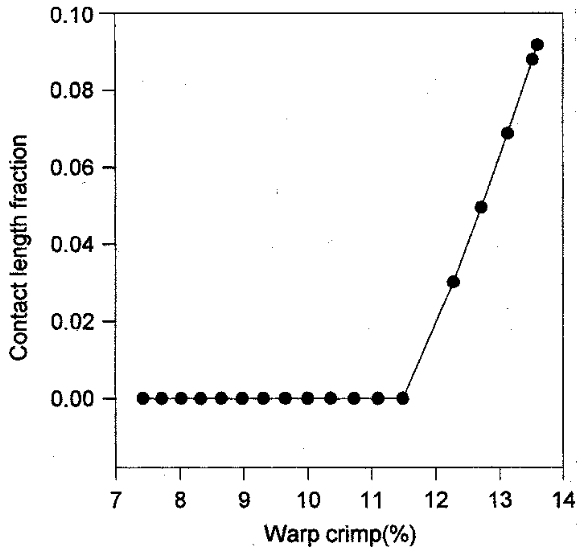

Figure 12. Change of fraction of yarns in contact with cross yarn at different warp crimp values.

reaches a critical value. This result is consistent because the crimp value where the contact length starts to increase accords with the critical crimp value shown in *Figure* 8.

7. Conclusions

The integrated computer system for fabric engineering design based on textile mechanics has been developed. The system enables the simulation of the tensile, shear, bending behavior of woven fabric. The effects of structural parameters such as crimp, fabric density, and yarn size on the mechanical behavior of woven fabric have been simulated based on the computer model and the details of the deformation behavior were examined. From these, it is expected that the system can help the fabric designer to understand explicitly the effects of structural parameters of the fabric.

However, the integrated engineering design system developed in this study using the theoretical models has some limitations in applying the models to the fabric engineering design. For example, these models do not describe hysteresis behavior and energy loss during loading and unloading. And the models can only be applied to the plain weave fabric. Nevertheless the simulated data obtained through theoretical models can be utilized in fabric design because it gives an understanding of the mechanical behavior of the woven fabric. Also, the integrated computer system enables the systematical management of databases containing fabric specifications, yarn data, weave, etc. Thus, the system can be expected to serve as a useful tool in designing new woven fabrics of specified property requirements by supplying the simulated data at the design stage.

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