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Fabric mechanics as a design tool

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A systematic approach to engineer a complex textile structure with the help of modern computational techniques is proposed. It is suggested that textile designers and engineers should start from first principles and then develop powerful new approaches to suit to the special complexities of various textile structure in order to meet the needs of customers and manufacturers. It is also suggested that the textile engineers should accept the cultural change and develop advanced software to create, manipulate and evaluate new fabric structures in order to make the fabric mechanics as a valuable design tool.

Keywords: Biaxial deformation, Computer-aided design, Fabric geometry, Micromechanics, Structural mechanics

1 Introduction

In many branches of engineering, applied mechanics has provided an ability to predict quantitatively the mechanical performance of structures. Despite the fragmented efforts of a few researchers in the first half of this century and the interlocking efforts of a substantial number in the second half, this is rarely achieved for textile materials. This does not mean that the research has been valueless, because the qualitative understanding and the illustrative calculations have stimulated technological advances and helped to solve manufacturing and performance problems.

As we move towards the next millennium, it is worth examining how we can begin to score goals in the engineering design of fabrics. For a variety of technical and cultural reasons, this is likely to happen first in technical textiles, especially when these are used in major engineering projects, but ultimately efforts will be directed to fashion fabrics.

The enormous power of modern inexpensive computer systems provides the hardware to make quantitative design possible. The challenge is to obtain sufficient understanding of textile materials, to generate all the input data on fibre properties, to invent new productive ways of treating the structural mechanics, to write easy-to-use software, and to validate the applicability. For wide-ranging success, it is necessary to start from first principles and develop powerful new approaches, which should be suited to the special complexities of fibre assemblies. Only limited help will come from the traditional methods used by the students of textile mechanics in this century and from the advanced computational techniques used in other parts of engineering.

2 What We Want to Do ?

Fig. 1 shows, in simplified form, two design procedures for textile products. The outer ring of solid black arrows is the path followed, explicitly or implicitly, for thousands of years and still dominant today. On the basis of past experience, a fabric design is proposed, probably using archaic point paper methods. Samples are manufactured, and finishing techniques derived from more sophisticated chemistry are applied. The result is then evaluated by expert or consumer reaction.

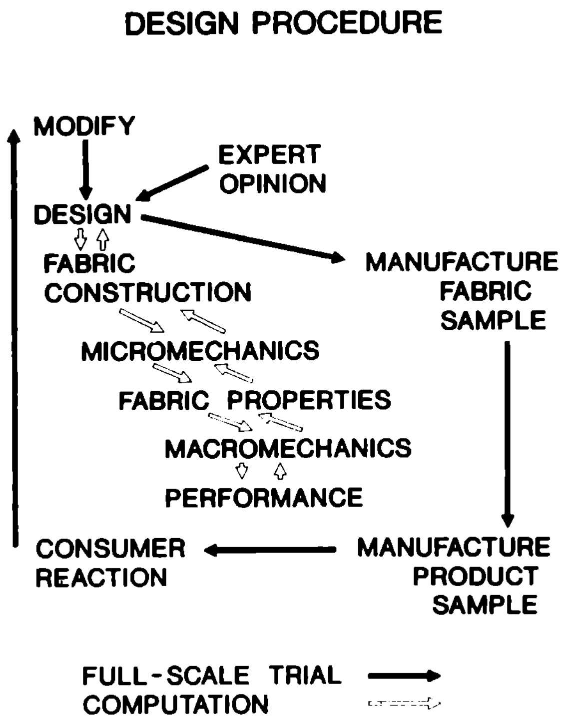

Fig. 1 — Traditional and visionary design procedures

The inner loop of open arrows is what we would like to do. A computer-aided design (CAD) facility would be used to set up the fabric structure and processing procedures. The software would then enable the performance to be predicted and optimised. Micromechanics comprises the computation of basic fabric properties and macromechanics covers the response in complex situations. The operation would be an interactive process, which combines the best use of the skills of the human designer and the computing power of the system. The design process would be one part of a global transfer of information through a textile company, linked to markets and finance on one side and to manufacturing and distribution on the other.

A visionary manifestation, perhaps realised well into the next century, would see designers working at aural/graphical input devices, backed up by databases of fibre and yarn properties and accumulated knowledge of fabrics, and seeing the results of their design choices in the virtual reality of models walking along cat-walks or of ordinary people going about their daily lives. An example of a more immediately attainable objective would be an engineering design office working on the fabric composition and structure for the roof of a large-span textile building.

Fig. 2 shows, in simplified form, the features which must be taken into account in designing fabrics with a quality fit for purpose. All of these depend on two sets of parameters: fibre characteristics and structural geometry. In moving to the limited aims of this paper, colour and pattern diverge first as separate studies, which have so far been the main aim of CAD facilities; and transport through fabrics introduces specialist aspects of mechanics, which will not be followed up. The details of surface contact also bring in special features, but the overall form of fabric laying on a surface depends on "stiffness", which, together with "strength", defines the theme of the paper. These two features are central to fabric mechanics as a design tool.

FABRIC "QUALITY" FEATURES

ITEMS IN ITALICS: *DEPENDENT ON FABRIC MECHANICS*

CONSUMER FABRICS	PHYSICAL ATTRIBUTES	TECHNICAL TEXTILES
DURABILITY breakage & wear change of aesthetics	*FORCES ON FIBRES* fibre fracture fibre fatigue	FAILURE immediate long-term
COMFORT	TRANSPORT heat, moisture, etc	FLOW PROPERTIES
	CONTACT surface & *FORM*	FRICTION etc
AESTHETICS	pattern & colour *HAND & DRAPE*	FIT TO SHAPE
PROCESSABILITY	*MECHANICAL PROPERTIES*	PROCESSABILITY

Fig. 2 — Functional demands for fabrics

In this context, strength and stiffness are terms to be interpreted widely. The simplest criterion of strength is whether the fabric tears under the peak force to be applied. The more general definition encompasses the long-term durability under the conditions of use, which depends on the complexity of fibre fatigue resistance and the forces developed both within the fabric and directly from external action. Although some high-fashion fabrics may be discarded with little sign of wear, minimum levels of strength are always needed; and, in most consumer and technical products, the expected useful life is of practical concern.

Stiffness relates to the diverse modes of deformation by extension, shear, bending and twisting, commonly combined in complex forms of buckling. In consumer products, this determines the important features of drape, handle and contact with the body. In engineering uses, specific levels of deformation may need to be prevented or allowed. The ease of deformation also plays a major role in subsequent processing, whether this is making garments or forming 3-D shapes for composites.

3 What Have We Achieved?

Fig. 3 is an "audit" of the results of half a century of continuous work on textile mechanics. It may be incomplete, but I believe it is a reasonable summary of the situation.

By "solved" I mean that the state of knowledge is such that the mechanical response can be calculated with useful engineering accuracy on the basis of known material properties and definitions of structural geometry. Even so the practical application has been very limited. There may have been some in-house computations, but I know of only one facility that is commercially available for design calculations, and that only recently. This is the computer program developed by TTI Ltd for the US Navy, which is used to calculate the tension/torque/length/twist response of twisted ropes[1].

In fabric micromechanics, the limits for predictions of basic properties at a level of engineering accuracy, as distinct from illustrative guidance, are the biaxial tensile properties of plain weave and plain knit fabrics made from simple yarns. In macromechanics, the use of massive computing power has enabled Breen[2] to make impressive pictorial predictions of the drape of fabrics, using fabric properties measured on KES testers.

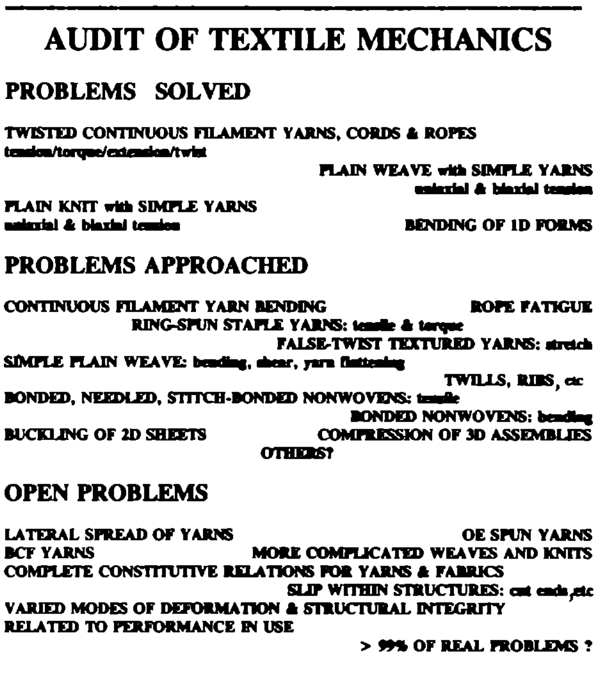

Fig. 3 — The state-of-the-art in textile mechanics

The topics listed as "approached" all have major limitations in the engineering design sense. Many are linear approximations or are based on over-simplified geometries. For some, the necessary input data on fibre properties is not available. Others require measured input data on the materials themselves, such as the lateral contraction of extended nonwoven fabrics, which should be predicted by a proper theory. Nevertheless, they provide a base of understanding for future advances, and, meanwhile, have been useful guides to technology.

Finally, there are a great many problems that have been largely ignored. Some of these are of practical importance in the performance of products. Others are needed in order to determine deformations within fabrics, which are related to practical macroscopic deformations.

3.1 Proven Paths

There are certain approaches that have been shown to be good ways of tackling the problems of fabric mechanics. With possible rare exceptions, the total problem is best approached in the hierarchical way illustrated in Fig. 4. The main division is into micromechanics and macromechanics.

Micromechanics is concerned with predicting the fundamental constitutive relations for any textile structure in terms of the properties of its constituents and their geometrical arrangement. Macromechanics is concerned with predicting the complex deformation of a material subject to the collection of forces imposed in practical situations.

In the established theory of linear elasticity of 3-D anisotropic solids, six components of deformation have to be considered: three extensions and three shear rotations in mutually perpendicular directions. Commonly, the constitutive relation is expressed as a first-order equation, linking six stresses to six strains by a symmetrical matrix, with 21 elastic constants for the most general anisotropy. However, it could alternatively be written as a second-order scalar equation for strain energy with the elastic constants as the coefficients of 21 terms. For isotropic materials, the number of elastic constants reduces to 2, and for other symmetries the number is between 2 and 21. This is the framework to be used for the special class of 3-D textile fabrics, such as multi-layer weaves.

Most textiles are either 1-D fibres and yarns or 2-D fabrics, which for many purposes can be treated as lines or sheets. The transverse deformation may be neglected (in the mathematical sense) or treated separately, though, as mentioned below, this has led to their being undesirably ignored in the practical development of the subject. This simplification reduces the components of deformation for 1-D forms to four (one extension, two

HIERARCHICAL INTERACTION

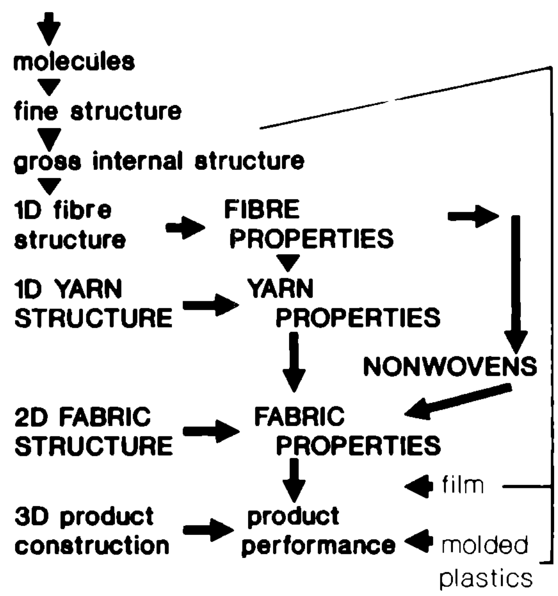

Fig. 4 — Hierarchical method of treating textile mechanics

bending, and one twisting), and for 2-D forms to six (two extensions, one shear, two bending and one twisting).

Linear matrix equations relating stress to strain can be written, but these are of little practical value because most textile materials are subjected to large strain with strong nonlinearity. It is better to develop databases covering the nonlinear relations between strain energy and the components of strain. In addition, hysteresis and time-dependence must be allowed for.

The adoption of energy methods, based on the principles of either conservation or minimisation, has generally been found to be more effective in solving problems than the determination of equilibrium of forces and moments. Apart from the reduction to scalar problems, which are simpler to deal with and suit computation better than vectors and tensors, it is much easier to make useful approximations. Simplification of real geometries can be made in ways that do not cause major errors in estimates of energy, whereas, with forces and moments, there is no alternative to calculate precise shapes along a yarn or across a fabric.

3.2 Limitations of Traditional Methods

Fig. 5 illustrates the method which has been used until now to solve the problems of textile mechanics. It is strongly mathematical with computation brought in at the end in order to solve the equations. Fibre properties are specified by the parameters of linear or nonlinear equations. Geometry is defined by algebraic and trigonometrical equations. Mechanics is analysed by differential and integral calculus.

This approach is believed to be now near its end as a way of making engineering predictions. The rope programs referred to earlier may be its final flowering.

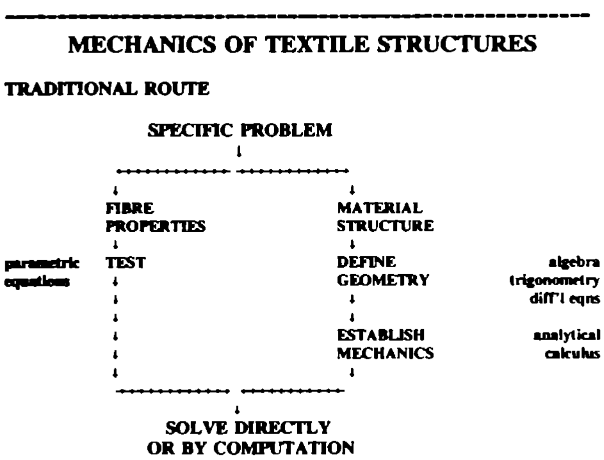

Fig. 5 — Traditional method used in textile mechanics

These solutions derive from the mechanics of continuous filament twisted yarns, which was well worked out and validated by the early 1960's (ref. 3). The geometry is well-defined and easily formulated, and the mechanics depends only on fibre tensile stress-strain curves, which can be nonlinear and have large strain. The assumption of constant-volume deformation for fibres means that the strain energy for the extension of an isolated fibre, subjected only to tension, is the same as that of a fibre subjected to both tensile and transverse forces within a yarn. By a hierarchical approximation, the analysis is easily extended to the more complicated structures, in which multiple levels of twist are superimposed on one another in rope, strand and yarn. The application of the principle of virtual work enables the contact pressures to be calculated, so that the frictional energy losses can be included in the analysis.

The reasonably exact analyses of fabrics are based on the small-strain linear elastic assumption, which predicts that yarns follow elastic paths between crossovers. Yarn cross- sections remain circular. The attempts to introduce other shapes, such as race-course cross-sections, are useful for geometrical calculations, but have severe limitations in mechanics. The predictions are limited to biaxial deformation along the principal axes (warp and weft, wales and courses) of plain weaves and plain knits.

The traditional mathematical methods could certainly be developed further to handle the deformation of fabrics under large forces, when the yarn paths become better defined and strain energies are determinable. However, it is difficult to see how useful sets of equations could be written in order to cover the complexities which occur in the problems that really need to be solved. These include:

- more complex weaves and knits;
- change of yarn volume and shape at crossovers;
- non-linear, time-dependent, inelastic yarn bending properties, which also depend on lateral pressures;
- the association of yarn twisting with bending of yarn into three- dimensional forms; and
- the nature of the deformation at shear of crossovers.

A final limitation of the traditional methods is that they are problem specific. Any appreciable change requires a new analysis and new programs to solve the equations. In addition to the research effort needed, this complicates the use by textile engineers in their busy working lives.

4 The Way Forward

If the traditional methods have reached a dead end, we must look for new ways. The key is to change from a situation in which computation is a hand-maiden to equation-based mathematics to one in which equations are a support to graphical computation. The power of modern computers is such that when we approach a problem, we should first think how the computing will be most effective. Fig. 6 shows a general scheme, which contrasts with the traditional approach in Fig. 5.

Textiles are a technology rooted in geometry, both in the form of fibres and in the ways in which tens or hundreds of millions of fibres can be assembled in particular geometries in textile products. Structural geometry is, therefore, central to all aspects of computer-aided design and prediction. This is illustrated in Fig. 7, which comes from a presentation related to textile composites, but similar links apply everywhere. The geometry is linked to cost, to colour and pattern, to flow through fabrics, to surface contacts, as well as to the mechanics.

A major task is, therefore, to develop comprehensive and user- friendly program packages to input, store and display the geometries of textile structures, including complicated weaves and knits. There are programs, such as SCOTWEAVE, which do this, but they are directed in a rather limited way to conventional textile design needs. The software is at the stage of the first primitive word-processing or spreadsheet programs and needs to acquire the versatility, ease-of-use and power of the modern packages.

As a first stage, the geometries may be expressed in simpler idealised forms, which will be useful for some purposes. However, more realistic forms will be needed

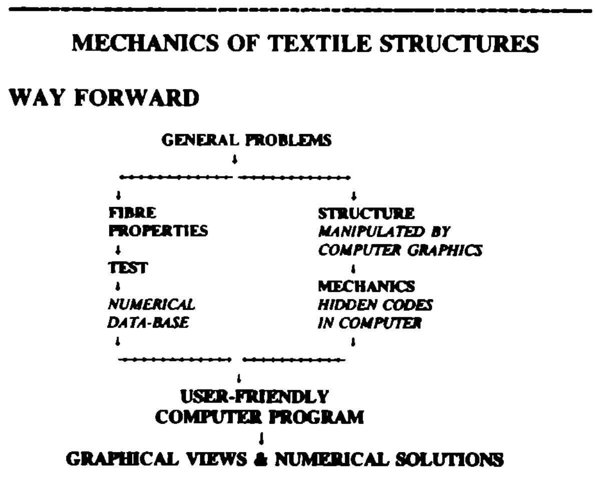

Fig. 6 — The way forward in textile mechanics

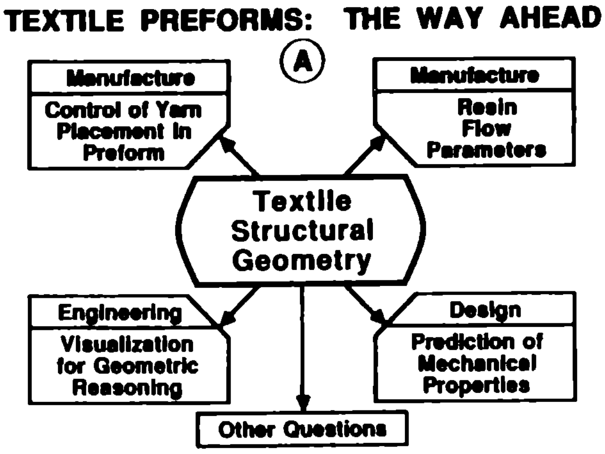

Fig. 7 — The central role of geometry in textile composites

to handle the mechanics. This is especially true for behaviour under low forces, which determines the drape and handle of textiles. Some clever tricks will be needed to realise the fibre rearrangements at cross-overs. Under tensile forces, there is a spreading out, which is caused by a minimisation of path lengths, but this gets complicated by yarn twist and interference from neighbouring yarns. In shear, the details of the geometry are more difficult to visualise correctly, and even idealised forms may aid understanding, though more realistic forms will be needed to predict the mechanics.

The other determining input, namely the fibre properties, is best handled by a numerical database which can be augmented by direct inputs from fibre testing machines. The tensile properties are well defined and available or easily measured. Information on quasi-static properties in other directions and on time-dependence and hysteresis can also be generated. The situation is more difficult with the various fibre fatigue mechanisms, which determine the long-term durability of textile products. The rope programs, already mentioned, have been extended to cover aspects of fatigue[4], but there is a lack of information on the relevant fibre properties. For example, abrasion among fibres within a rope is a cause of failure, particularly in wet nylon ropes under moderate loads. It is clear that the rate of wear on fibres will be a function of the contact forces, geometry and the magnitude and direction of inter-fibre slip, but the data on such rates are neither available nor easy to measure in ways that correctly show dependence on the several determining conditions. These topics provide a challenge to research in fibre science.

Having set up the ways of characterising fabric geometry and fibre properties, the remaining computational task is to solve the mechanics or, in other words, to determine the forces or the strain energy consequent on a given set of deformations. This should be handled by hidden programs, which the user is not aware of, though it is desirable that their principles should be understood. Essentially, this would normally involve energy minimisation.

The result of this part of computational textile mechanics would be that a user could define and explore specifications for fabric constructions, recall fibre properties, and predict the constitutive relations between forces and deformations. The achievement of such a system, which is usable, accurate and versatile, requires a major effort in computer programming and in innovative treatments of the structural mechanics.

The second stage of prediction, when the basic fabric properties are known, is to predict the real world of practical use or manufacturing operations. In order to treat drape, handle and the appearance and feel of garments, much more work is needed on the mechanics of complex buckling, under appropriate combinations of gravitational and localised forces. For durability, the history of applied deformations must be related to what is happening in the material to cause damage to fibres.

4.1 R & D Choices

To be complete and self-standing, the above scheme would require a formidable, perhaps an impossible, amount of work. Fortunately, progress can be made in smaller steps. However, it is helpful to have an outline of the total picture so that the pieces can be filled in effectively. Progress requires clever choices of research topics. It is also necessary to develop what has been lacking so far in the history of the subject, namely a creative interchange between academics making fundamental studies and users in the commercial world.

The following seem to be the priorities for basic research:

- Development of good solid modelling packages, which can give a realistic representation of textile materials. The work of Keefe[5] points the way. Even in the idealised forms, it shows that the geometry is not quite what one expects.
- Creation of general purpose software for mechani s, probably based on the adjustment of structures to minimum energy states, as is done in the powerful molecular modelling packages, which are commercially available.
- Experimental and theoretical research on the deformation of fabrics under small forces which determine drape and handle.

Enhancement of the work on fabric buckling, which is currently limited to an approximate solution of the simplest case of three- fold buckling of a linear elastic sheet[6], to cover the complexities of multiple buckling of real fabrics.

The first potential for useful applications may be among the following:

- Use of structural modelling to give information on simpler problems such as material quantities and costs.
- Computer visualisation of structures to give qualitative help in designing fabrics, and solving problems by providing insights and understanding. For example, flow paths through fabrics could be identified.
- Use of databases of empirical data on fabric properties to indicate performance expectations.
- Graphical indications of drape characteristics based on empirically determined fabric properties.
- Superposition of fabric designs on graphical views of garments.

5 Conclusion

Fig. 8 summarises the system which needs to be built. The computer core will have three main parts: a database of information on fibre and fabric properties; a knowledge-based system which utilises the pool of available expertise and historical data; and a deterministic suite of programs in structural mechanics. These must then be used by fabric designers and engineers to meet the needs of customers and manufacturers.

Forty years ago, we had no choice but to use the traditional mathematical methods. Now, we can use a general purpose commercial program to set up a spreadsheet on a PC. The development of more specialist programs adapted to the special features of textiles and to the industrial needs would make application even easier.

The challenge is there, the tools are available, the potential value is clear: that is the positive side. The negative aspect is that the market is smaller and more diverse than for word-processing, databases, accounting or spreadsheets. The advances are likely to be spread around the world, but, just as with the development of textile testing starting a century ago, computational fabric mechanics will become a standard procedure in the next century.

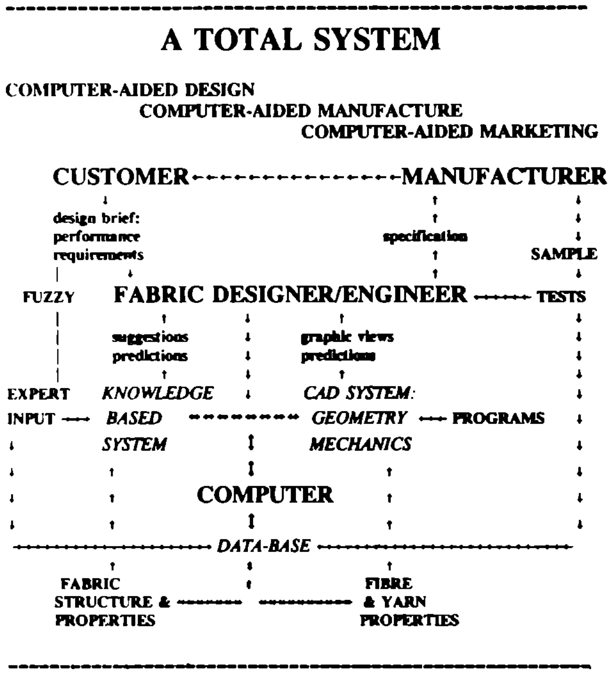

Fig. 8 — The total design system and its interactions

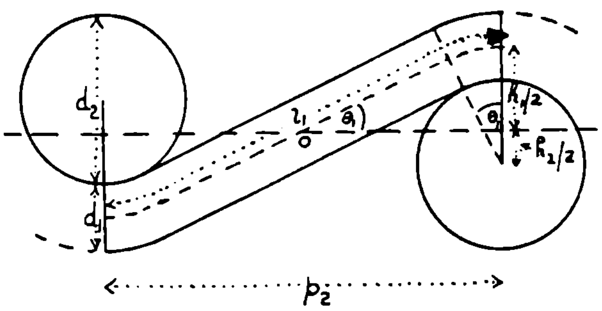

Fig. 9 — Peirce's woven fabric geometry

Peirce's fabric geometry[7], which is a classical base in woven fabric studies, can be used to illustrate the cultural difference. Peirce drew a diagram (Fig. 9) of a plain weave in which circular yarns followed paths alternating between circular wrapped arcs and straight links between crossovers. But this was merely a helpful aid to explanation. In order to solve specific cases, he turned to algebraic geometry and wrote equations defining the structure. Unfortunately, these contained both angles and their trigonometrical functions so that analytical solutions were not possible. Over the years, a variety of means – graphs, nomograms and tables – were used to get numerical values. Finally, computer programs provided flexibility. The analytical approach was followed further in attempts to make the geometry more realistic and to introduce mechanics, sometimes by an uneasy combination of the sophisticated mathematics of elliptic integrals, for yarn axial paths and crude approximations for cross-sectional shapes. Even so, the range of useful engineering prediction was very limited.

The cultural change, which should be made, is to return directly to geometry as a technique. In high school, geometrical problems are solved in two ways: by practical construction using rulers, compasses, set squares and protractors, and by calculation based on geometrical theorems and trigonometry and, for the more advanced, by algebraic geometry. Once the latter techniques were mastered, they were found to be quicker and more accurate. But now, with computer power, we can return with speed, ease and accuracy to graphical constructions. The condition for a line to be tangential to a circle can be determined not by algebraic equations but by letting it move until coincidence is detected. In many more ways, the geometry of textiles structures, the fundamental basis for the advances needed, can be handled graphically. Powerful computational techniques for image creation and manipulation have been developed and are used in fields as diverse as television and crime detection. Textile engineers and designers need similar techniques to create, manipulate and evaluate fabric structures in virtual reality. Fabric mechanics would then be a valuable design tool.

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