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THE CHALLENGE OF CHANGING FROM EMPIRICAL CRAFT TO ENGINEERING DESIGN

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Abstract

Textiles have developed as high-quality materials on the basis of highly developed but empirical craft skills. The second half of the 20th century resulted in many academic papers on the analysis of the applied mechanics of fibre assemblies. However, although these researches led to useful qualitative insights, there was almost no quantitative application by industry. Several factors cause the time to be now ripe for a change to an engineering design culture. There are major challenges in dealing with assemblies of millions of fibres, with nonlinear, visco-elastic-plastic mechanical properties, in anisotropic structures subject to large deformations and strains. The paper describes two approaches to accessible modeling, fibre rope modeling and TechText CAD. The most useful methodology for modeling yarns, woven fabrics and fabric buckling is discussed. The priority is to develop software that industry uses, thus setting up a creative interchange, which will lead to advances.

1. Introduction

Over ten thousand years ago, early men and women found ways to collect natural fibres, align and twist them into yarns, and interlace them into fabrics, which found uses as clothing, shelter and an increasing range of other purposes. The geometrical and mechanical operations of the design engineer, which are now the place of computer-aided design (CAD), were subjectively hidden in the links between the mind and the fingers. By the time of the ancient civilizations, simple hand-operated tools had been invented for spinning and weaving. Varied yarns and fabric constructions were being made. But apart perhaps from some simple sketches, there was nothing that could be called engineering design in the modern sense.

The Industrial Revolution starting in the late 18th Century brought new power-driven machines to simulate the old processes and modern engineering began. Academic research in mechanics, following Galileo and Newton, led in a wide range of manufacturing and construction industries to the growth in the 19th and 20th centuries of an engineering design culture, at first with slide rules, draughtsmen and Roark and Young's *Formulas for Stress and Strain*, and now with CAD. Engineering design came to the textile industry through the development of the academic subject of the mechanics of machines. The wave of machine and process inventions in the second half of the 20th Century brought in control engineering design. But, at the heart of the textile industry in the interaction of fibres and yarns with machines and the construction of the products, the old intuitive, qualitative practice remained as the industrial practice. Apart from some relatively trivial mathematics concerned with pattern, dimensions, weight and cost, design was an empirical process, based on experience, trial and error.

In a remarkable change of culture, the aesthetic side of textile design in pattern and colour has gone in the last 25 or so years from a suspicion of CAD to its common acceptance. Why has the technical side of the industry not had a similar change of culture? Partly it is due to the strength of the craft-based experience and the fact that trial-and-error is acceptable for most textile uses. It is also due to the difficulties of the subject. As is recognized by applied mathematicians, who have looked at textile problems, there are major challenges in dealing with assemblies of millions of fibres, with nonlinear, visco-elastic-plastic mechanical properties, in anisotropic structures subject to large deformations and

strains. Extensive textile research, with numbers running into hundreds of people, began in the 1920s. Peirce laid the foundations with characterisation of properties and geometry of structures, but there was little applied mechanics analysis until the formation of Fabric Research Laboratories in the 1940s, which led on to a proliferation of research. However, there has been little effort on the part of academic researchers, concerned with their PhDs and publications, to make the advances accessible to industry. Consequently, there was no creative interchange between academic innovators and industrial users. The major challenge now is to bring this about. Even in companies with large research departments, applied mechanics has been a poor relation of chemistry and conventional engineering.

2. The state of the art

Nine years ago, I gave the audit of textile mechanics shown as Figure 1. The situation has changed little since then and the use of "solved" is somewhat optimistic. One of the problems has been that, while the early work treated the basics of the problems in a simplified way, much of the later work has concentrated on elaborating the mathematics but leaving this based on unrealistic physical assumptions. A typical example is the work on fibre migration of yarns. A model of complete migration runs into the difficulty of multiple occupation of space at the core of the yarn, just as the spokes of a wheel cannot go to a point at the centre. I followed Treloar in avoiding the problem by postulating a limiting central radius. The published attempts to treat the mathematics more rigorously are not useful, because the fibres follow paths of partial migration and that is the real problem to be studied – but it is poorly defined and so unattractive to mathematical purists.

PROBLEMS "SOLVED"	
TWISTED CONTINUOUS FILAMENT YARNS, CORDS & ROPES tension/torque/extension/twist	PLAIN WEAVE with SIMPLE YARNS uniaxial & biaxial tension
PLAIN KNIT with SIMPLE YARNS uniaxial & biaxial tension	BENDING OF 1D FORMS
PROBLEMS APPROACHED	
CONTINUOUS FILAMENT YARN BENDING RING-SPUN STAPLE YARNS: tensile & torque	ROPE FATIGUE FALSE-TWIST TEXTURED YARNS: stretch
SIMPLE PLAIN WEAVE: bending, shear, yarn flattening	TWILLS, RIBS ETC
BONDED, NEEDED, STITCH-BONDED NONWOVENS: tensile	BONDED NONWOVENS: bending
BUCKLING OF 2D SHEETS	COMPRESSION OF 3D ASSEMBLIES
	OTHERS?
OPEN PROBLEMS	
LATERAL SPREAD OF YARNS BCF YARNS	OE SPUN YARNS MORE COMPLICATED WEAVES AND KNITS
COMPLETE CONSTITUTIVE RELATIONS FOR YARNS & FABRICS	SLIP WITHIN STRUCTURES: cut ends etc
VARIED MODES OF DEFORMATION & STRUCTURAL INTEGRITY RELATED TO PERFORMANCE IN USE	
	> 99% OF REAL PROBLEMS ?

Figure 1: Audit of textile mechanics, Hearle (1994).

3. Accessible modelling

3.1 Interaction with industry

If the textile industry is to move from empirical craft to engineering design, the priority is to develop software that is taken up by industry and easily used. This is most likely to be successful if it first addresses simple operations, which technologists in the industry have to deal with. This will lead to a culture in which solutions of more difficult design needs are called for. In the last few years, I have

been associated with two projects which aim to give practical utility to the mechanics of textile structures.

3.2 Fibre rope modeller

The first example relates to a demanding engineering application of a textile structure: high-performance ropes to moor oil-rigs in a depth of 1000 to 3000 meters. A typical installation might involve 16 lines with a total length of 30 kilometers, made of a polyester rope with a 1500-tonne break load and a linear density of about 35 kg/m (35 Mtex). The lines are expected to withstand cyclic loading from wind, wave and current action for 20 years – and the consequences of failure would be severe. Interaction with marine engineers, who have programs to model rig responses, has forced rope manufacturers and textile consultants into an engineering design culture. In connection with US Navy plans, not yet put into practice, to moor large floating bases off-shore, Tension Technology International (TTI) was contracted to develop software to model rope performance. With later support from DTI, Fibre Rope Modeller (FRM) is now being used by a major ropemaker in rope design – perhaps the first example of a numerically predictive mechanical design of a textile product.

FRM followed the modelling of twisted continuous filament yarns, which had given good predictions for large-strain, nonlinear, load-extension properties, but was extended in several ways. Firstly, it was necessary to take account of the multiple twist levels in rope structures. Secondly, the modelling covered the tension-torque-length-twist relations. Thirdly, because of a need to model fatigue behaviour, internal contact pressures, slip and friction forces were included. This work is described by Leech et al (1993) and Hearle et al (1993).

3.2 TechText CAD

The second example, also supported by DTI and carried out by UMIST and TTI, was the development of more general software, TechText CAD, for use by the technical textiles industry, though it is also applicable to consumer textiles. The DTI grants are aimed at technology transfer, not new research, so that our aim was to convert some of the academic work on the structural mechanics of textiles into a CAD package that was easy to use and directed at industrial needs. The programs were planned to cover woven, knit and braid structures, but initial progress concentrated on single-layer woven fabrics with a limited amount of work on weft knit structures. The development has been in three parts. At UMIST, X Chen and X Ai covered structural geometry and P Potluri and V S Thammandra covered uniaxial and biaxial deformation. M Overington of TTI was responsible for the overall program integration.

As indicated in Figure 2, the program is in a standard WINDOWS format. To open a new weave structure, there are three options. A weave formula is preferred by numerically inclined users. Point paper is the traditional method, which was developed for hand mark-up. With a computer it is just as easy and more realistic to use a mesh, clicking on a crossover to switch between warp and weft on top. These forms are illustrated in figure 2 for a plain weave. Manipulations, such as invert, rotate, enlarge, swap or create herringbone and other patterns, are available.

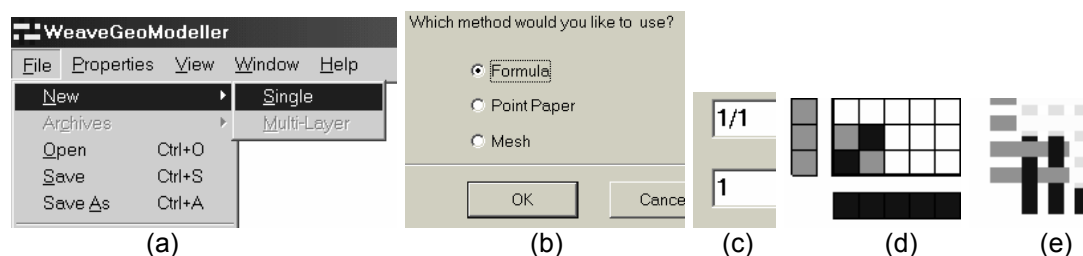


Figure 2: (a) Entry of a weave. (b) Choice of method.
(c) Plain weave formula. (d) Point paper. (e) Mesh.

The fabric is then defined by yarn dimensions, warp and weft spacing, and one crimp value. A 3D picture is obtained, as shown in Figure 3. This model can be zoomed in or out, translated, rotated by angle or mouse, and sliced to show section views, as indicated by the different views of the fabric in Figure 3. Currently, the program allows for circular, lenticular or racetrack yarn cross-sections, as shown in Figure 4. This weave structure and geometry facility, in itself, is a relatively simple application of computing, though the development of the programs was not a trivial exercise. There

are many similar examples in the literature. The important point is that it puts the operation into a familiar operating system that takes users out of the tedium of making point-paper diagrams, which is still a common practice, into a fast, easy-to-use IT procedure appropriate to the 21st Century. Another facility enables existing point-paper diagrams to be scanned into the system.

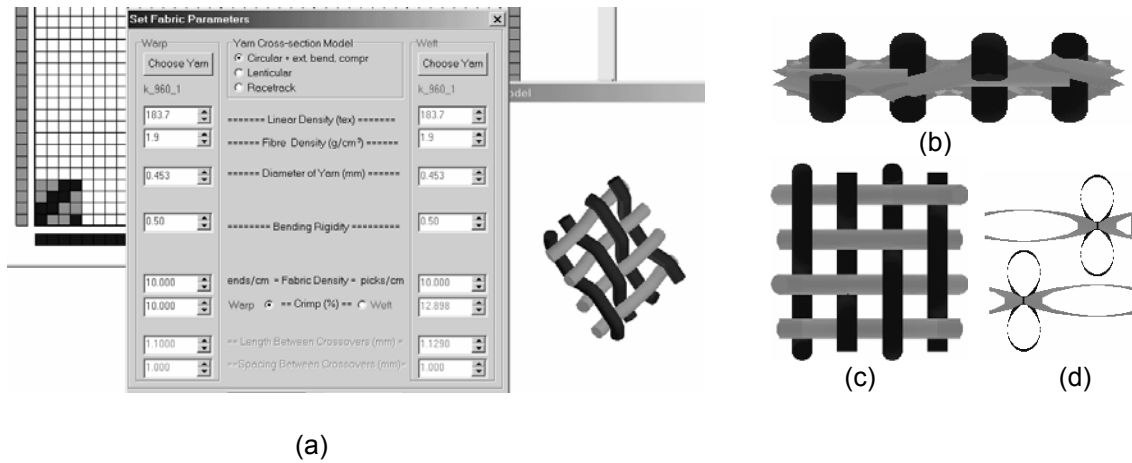


Figure 3: (a) Montage showing insertion of twill weave in point paper, insertion of yarn and fabric parameters, and 3D view of fabric. (b,c) Other views of fabric. (d) Slice through fabric.

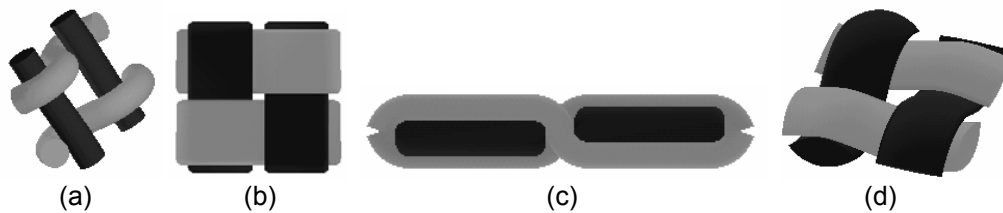
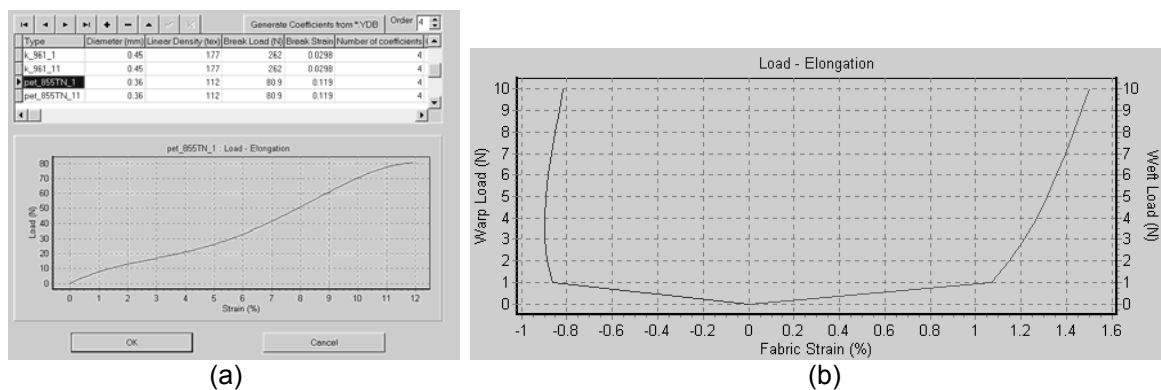


Figure 4: Yarn cross-sections. (a) Circular. (b,c) Race track. (d) Lenticular.

Mechanical modelling is based on the energy method proposed by Hearle and Shanahan (1978). The methodology and current limitations are discussed further below. The program allows for yarn extension, yarn bending and the flattening of yarn cross-sections. Using a procedure successfully used for FRM, large-strain yarn extension is specified by the coefficients of a polynomial, which matches the measured stress-strain curve. Bending stiffness comes from measured or estimated values. Flattening, which as discussed below, needs more research is introduced by an empirical parameter. As this is a technology transfer exercise, the modelling is limited to plain weaves, since there has been little if any analytical studies of the mechanics of more complex weaves. The race-track cross-section, which is a useful model for geometrical predictions, is unsuitable for mechanical modelling because of the high bending energy at the sharp corners, which exceeds the reduction in bending energy in the straight sections. Circular, for which a Poisson's ratio can be used to allow for reduction in diameter, or lenticular, which allows for change of shape as well as volume, are used.



(a)

(b)

Figure 5: (a) Input of a yarn extension. (b) Computed biaxial deformation.

Figure 5 shows the input of yarn stress-strain and a computed biaxial deformation. The jump from zero strain reflects the fact that the fabric as specified is not in the stress-free state. In this plot, obtained at an early stage of the work, the adjustment from zero strain does not occur in the computation until the first loading point to be calculated. This was changed in later plots. The example in Figure 5 is more easily extensible weftwise than warpwise, so that warp contraction continues due to the high weft extension, even though warp load is increasing. Eventually, some warp extension occurs, probably because yarn extension has become easier.

Figure 6 shows a typical uniaxial yarn extension plot, in which warp extends and weft contracts, and the deformation of a 3D model. In this example, the fabric adjusts to zero load by contracting warpwise and extending weftwise. An alternative facility enables the strains to be shown based on the stress-free dimensions.

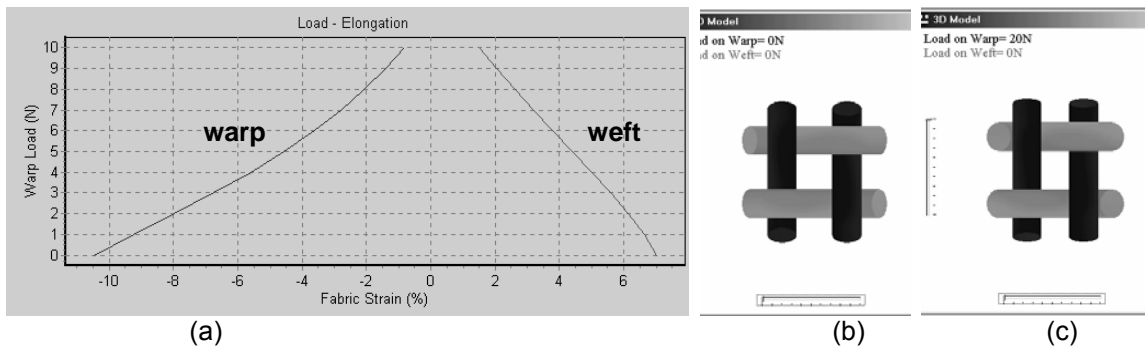


Figure 6: (a) Uniaxial loading with warp extension and weft contraction. (b,c) 3D model under zero load and uniaxially loaded.

Good agreement between TechText CAD predictions in uniaxial loading and experimental data are reported by Hearle et al (in press) for plain-weave fabrics in nylon-monofil by Dastoor et al (1994) and in cotton by Kawabata et al (1973).

Characterisation of fabrics can be expressed in a great variety of ways. Any selected set of independent variables is associated with many dependent variables – and the choice changes. Konopasek, in what led to the commercial program TK Solver, recognized this in modelling Peirce's woven fabric geometry and developed a network algorithm, which allowed any set of variables to be used as input in order to calculate the total set. TK Solver models are incorporated in TechTextCAD in order to make it easier to use.

In its current state of development, TechText CAD offers a useful facility for practical use. Many of the limitations are due to lack of knowledge. Current research at UMIST under the TechniTex core research project is addressing these problems, some of which are discussed below.

4. Methodology of mechanical modelling

4.1 Problems and procedures

The above account describes a way of tackling the most urgent problem in meeting the challenge of changing from empirical craft to engineering design: providing software that industry can use and thus opening the way to a creative interchange between users and developers. Figure 1 shows that there are a formidable number of problems that require research. I favour two guiding principles. (1) We should not be seduced by mathematical analysis, which gives equations to be solved by computing at the end of the process. At the start, we should look at problems in terms of how they can best be treated computationally, using graphical and numerical methods to the best advantage. (2) We should adopt a sceptical attitude to the use of software packages that have been designed for other purposes, e.g. finite element programs optimized for modelling rigid solids. We should look for clever ways that are suited to the behaviour of fibres and fibre assemblies.

The general approach should be hierarchical. The properties at a given level are computed from the geometry at that level and the mechanical properties at the next lower level, through the sequence fibre→yarn→fabric→macroscopic response. There is an inherent assumption that strains are effectively uniform over the elements involved in the computation. Fibres, yarns and other 1D forms are characterized by the relations between stress and strain in extension, twist and two directions of bending, and planar fabrics by two extension directions, shear, two bending directions and twist. As illustrative examples, I will comment on three topics, covering the three levels of interaction, but also choosing one that is so well defined that it has been solved and used, one in which I believe that mathematics has been too dominant and one in which the use of general engineering programs has been too dominant.

4.2 Yarns and ropes

The simplest analysis of the load-extension properties of twisted continuous filament yarns was first derived by Gegauff in 1907 and rediscovered by Platt 40 years later. It takes account of four factors of $\cos\theta$ for a fibre at a helix angle θ : reduced elongation and increased length; reduced component of tension and increased area of action. Averaging $\cos^4\theta$ from $\theta = 0$ at the centre of the yarn to $\theta = \alpha$ at the surface gives $\cos^2\alpha$ as the conversion factor from fibre to yarn for the stress-strain curve. This analysis neglects a number of factors, notably the effect of transverse forces between fibres within the yarn. In the 1950s, I and my students developed force-equilibrium models, which took account of these factors. The mathematics was not difficult, but was complicated. One predictive equation ran to five lines. However, the major limitation was that the analysis was limited to small-strain, linear or bi-linear conditions. Then in 1963 Treloar and Riding presented an energy method that included the effects of transverse forces, lateral contraction, large strains, and nonlinear fibre stress-strain relations. Subsequently, I reformulated the analysis to give five equations that were easily solved numerically on a computer. Agreement between experiment and theory was excellent, except for a slight difference at low stress due to filaments at the core being slightly buckled in real yarns instead of straight as in the ideal geometry. In later analyses, torque and twist were introduced. This is the basis for the statement in Figure 1 that the mechanics of twisted continuous filament yarns has been “solved”. The crucial step was the change from force-equilibrium to energy methods.

Solutions by energy methods can be obtained in three ways. The direct methods depend on conservation of energy, which was the basis of the above treatment, or on the condition that equilibrium is a minimum energy state. In order to determine internal forces in ropes, as described in 3.2, Leech et al (1993) introduced the Principle of Virtual Work;

4.3 Woven fabrics

The majority of papers on woven fabric mechanics have been based on force-and-moment equilibrium, with Kawabata’s saw-tooth approximation being widely used, The mathematical derivations are extensive. Both Leaf and his colleagues, as described in his paper at this conference, and De Jong and Postle have used energy methods but in a strongly mathematical form. There are severe limitations to these methods, both in terms of restrictive assumptions in the structural mechanics and in the range of fabrics, mostly restricted to plain weave.

In my view, a more direct approach to modelling by an energy method is preferable. The aim at this hierarchical level is to determine constitutive relations, probably stored as a numerical data-base, for a fabric subject to uniform strain.

$$\begin{aligned}
 &\text{total energy of a fabric subject to a given set of forces} \\
 &= \text{potential energies of applied forces} \\
 &\quad + \text{yarn tensile strain energy} \\
 &\quad\quad + \text{yarn bending and twisting energy} \\
 &\quad\quad\quad + \text{yarn flattening energy}
 \end{aligned}$$

The other inputs needed are the geometry of the structure and a suitable numerical minimisation routine. For elastic systems, energy minima are clearly defined. For inelastic or frictional systems, there will be stable states when both positive and negative deformations lead to an increase in energy. A particular advantage of this approach is the separation of terms, which means that they

can be considered individually, thus avoiding most of the complications of interactions, which are unavoidable with force methods.

The potential energy terms are products of power or moment and displacement, $F \cdot x$ or $M \cdot \theta$. Tensile strain energy is known from experiment or yarn modelling. Yarn bending has been extensively considered in the published work, sometimes involving the use of elliptic integrals to determine elastica paths. In principle, it is well understood and bending energy is given by the integral of the product of bending moment and curvature. Twisting would need to be taken into account when yarns follow 3D paths. A practical problem is that for a yarn of N filaments, the bending stiffness can vary over an N^2 range, depending on where the yarn lies between a solid rod and a set of independent filaments. In contact zones, the curvature is partly determined by the yarn bending stiffness, which will be affected by the contact forces, and partly by the resistance to flattening of the crossing yarn.

This leads to an aspect of the problem that I believe has been unduly neglected in the past: the effect of yarn flattening on woven (and knit) fabric mechanics. Some clever research is needed both to develop qualitative understanding of the effects and to find the best way of treating it. For monofilaments and perhaps for hard-twisted yarns, it may be adequate just to assume a reduction in diameter at constant volume. For less cohesive yarns, where fibres can move laterally, the problems are more difficult. One approach is to assume a particular yarn shape and then relate flattening energy to the ratio of major and minor axes. As mentioned above, racetrack geometry is unsuitable, but lenticular can be used. One problem is how to obtain values of the flattening coefficient. The other is that, even for plain weave fabrics where flattening is orthogonal, the assumed geometry may be insufficiently realistic. For non-plain weave fabrics, the "flattening" (really change of area and shape) is multiaxial.

I incline to the view that mechanical modelling may be more successful if it is less prescriptive. The state of a fabric can be defined by positions of yarn centres at a limited number of positions. For a simple plain weave in planar deformation, three positions, one of which is an origin, are sufficient; for out-of-plane deformation, two more are needed. In more complicated weaves, some positions within a repeat unit must be included. Yarn extension, bending, twisting, and flattening could be related to changes in position of the defining points. This provides a framework for an approach to energy minimization. In the simplest application of such a model, a set of linear coefficients could be used to give each energy term. A more complete model could define each term by a set of polynomial coefficients. This has been done successfully for yarn extension. In regard to bending and twisting, where there is a knowledge base, and more importantly in the neglected area of yarn flattening, the research challenge is to find the best way to determine the necessary relations *either* experimentally or by theoretical yarn modelling.

Such an approach divorces the mechanics from any explicit geometry. The role of research in the geometry of fabric structure, which may be needed for purposes such as determination of flow paths, is then to find a suitable geometric model that adequately fits the state of the fabric as given by the specified positions, even if it is not exactly correct in mechanical terms. Some more innovative research may find ways of linking yarn shape to the mechanics. For example, the use of a soft rubber rod or a flexible tube with a soft filling might be effective analogues of a soft yarn; this is a place where a finite-element package might be useful as a sub-program.

4.4 *Fabrics in double curvature*

A great advantage of textile fabrics compared with paper and most other sheet materials is that, because of their low resistance to shear and area change, they can deform smoothly in double curvature. This is important in drape and handle of consumer textiles and in conformability of textile preforms for composites. The closest approach to this problem in conventional applied mechanics is plate and shell theory, but this is inadequate to treat the subtleties of textile fabrics.

A solution to this problem is needed to achieve a goal of the IT Age, the virtual catwalk. The aim is to enable someone buying an article of clothing on-line to view on a screen how they would really look when moving around in the garment. It is worth noting that there are three levels of reality in such simulations. In cartoons, unrealistic distortion is preferred. For realistic animation, in which film-makers have achieved great success, it is only necessary that the image should look right to the viewer. The third level, which is our concern, is to relate the fabric forms to the actual fabric

properties and applied forces. This is much more difficult and some IT specialists who came optimistically to the problem have retreated. Leaving on one side the dynamic problem, the first step is to model the quasi-static buckling of textile fabrics in complex situations.

Most researchers have attempted to solve the total complex problem by the use of finite-element or similar methods. However, such programs are not designed to tackle the full anisotropy and nonlinearity of textile fabrics. The models are thus restricted in their validity, as well as being horrendously expensive in computer power and time. They have not provided practically applicable ways of meeting the commercial needs.

In my view, a more fundamental approach is needed. The problems should be tackled from the bottom up not the top down. Research should elucidate the basics of how fabrics buckle in three dimensions, and find clever ways, which are right for textile fabrics, to build up to the more difficult problems. The simplest case, which was addressed by Amirbayat and Hearle (1986), is buckling of a circular specimen pushed in equally from three equilateral directions. This can be modelled, in a reasonable approximation to reality, by a central dome of double curvature and an outer zone of alternating folds of single curvature. Distorted versions of such a form make up the complex patterns of buckling of fabrics on the sleeves of jackets and in many other situations. The problem has to be solved by minimising the sum of the fabric strain energies of the double-curvature zone (in-plane and out-of plane) and the single-curvature zones plus gravitational potential energy. The treatment by Amirbayat and Hearle is limited by mathematical approximations, geometry, symmetry and linear elasticity, though accepting the independence of tensile and bending properties, which means that EI does not define bending stiffness. I have little doubt that better ways of treating the problem could be found, but the approach leads the way to deal progressively with more realistic input of fabric properties and more complicated modes of deformation – and then, hopefully, to practical CAD software.

5. Conclusion

I should perhaps apologise for any arrogance in dismissing the last 60 years' research on structural mechanics of textiles, to which I contributed in ways that I would not now want to follow. However, I wanted to present a clear message on how I think that we can meet the challenge of changing from empirical craft to engineering design.

- The priority is for academia and IT groups to develop software that industry would use – and for industry to take it up – thus providing for a productive creative interchange.
- Some knowledge is ready for technology transfer, but many problems require more research.
- Researchers should concentrate on direct computational procedures that are appropriate to the complex behaviour of fibre assemblies and based on simple relationships - and beware of the temptations of complicated mathematics and of software optimized for other materials.
- Approach the total problem hierarchically, with energy methods usually being best.
- A similar approach is needed to model the interaction of fibres with machines in processing.

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