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ENGINEERING DESIGN OF TEXTILES

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ABSTRACT

The engineering design of textiles continues to follow the traditional empirical methods, and, for technical as distinct from aesthetic design, has not adopted CAD as used in other industries. The reasons for this and the need for change are discussed. The paper reviews the state of the art in the structural mechanics of yarns and fabrics. The major challenge is to develop programs that industry will use and so open up a creative interchange between academic researchers and industrial users. A description of key features of TexEng, which an easy-to-use program aimed at meeting this challenge, is given.

OLD AND NEW DESIGN CULTURES

What is engineering design? And to what extent is it practised in the textile industry? Until about 100 years ago, engineering was an empirical skill. Bridges, buildings, machines, vehicles and all the other constructs needed by mankind were designed on the basis of experience and practical trials – with disastrous errors often leading to advances. Geometry linked to drawing was backed up by empirical rules of thumb on what loads could be carried and what might be needed to meet other performance requirements.

The wealth of practical knowledge and skills developed over thousands of years enabled the production of textile materials to be an outstanding example of this form of engineering design. Experience and trial-and-error formed the design protocol; intuition led to advances. Point paper and weaving plans were the design tools. The flowering of textile research in research institutes and universities after the First World War led to an exploration of the academic science of fibres and textiles. In a commercial and industrial context, this led to advances through a growth of qualitative understanding, but the empirical design tradition remained as it was. Even the exploitation of the new manufactured fibres followed an empirical path of development. The possible quantitative performance predictions of the academic work were not taken up by industry.

The combination of strength and flexibility in unbonded fibre assemblies held together by frictional forces makes wonderful products. From ancient times, the needs for clothing of the proletariat and fashion for the aristocrats were provided by woven and knitted fabrics. A range of technical uses from sails and tents to conveyor belts and tyre fabrics was also met by textiles. The current *Extreme Textiles* exhibition at the Cooper-Hewitt National Design Museum in New York shows how this tradition has been exploited in new materials for space, medicine, sport, buildings, and transportation, as well as advances in more traditional applications such as ropes and nets (McQuaid, 2005). However a conversation with a manufacturer of materials for medical implants confirmed the preference for working through traditional practical trials – and eschewing mechanical modelling.

In most other branches of engineering, design procedures changed. The growth of the science of applied mechanics, starting with Galileo and Newton and augmented by giants like Euler and Hamilton as well as others who worked on the details, made quantitative predictions possible. In the education of mechanical and civil engineers, the design tools were provided in the first half of the 20th century by such classic works as Love's *Treatise on the Mathematical Theory of Elasticity*, Timoshenko's several books and, as a simpler text-book, Den Hartog's *Strength of Materials*, with Roark and Young's *Formulas for Stress and Strain* being a *vade mecum* of the equations that design engineers evaluated on their slide rules. Other scientific advances led to quantitative design in aerodynamic, electrical and chemical engineering. In the second half of the 20th century, computers replaced slide rules and computer-aided design (CAD) made more elaborate calculations and modelling possible. The application of this new form of quantitative engineering design, which replaced empiricism and augmented the qualitative insights, led to enhanced performance in traditional uses, such as bridges, and made possible the technological transformation of the 20th century.

In most respects the changing design culture passed by the textile industry. There are some exceptions. The machinery spawned the academic subject of *mechanics of machines*, covering gears. levers and drives. The textile machinery industry has embraced CAD – but this is almost entirely in the machine actions independently of the fibres and yarns passing through the machines. For example, a conversation with company engineers indicated that there was no attempt to model the movement of fibres in air-streams in the outstanding development of air-jet spinning by *Murata*; intuition and practical trials led to the commercial success. Modern engineering design is used for fibre-reinforced composites, which notably are included as *Extreme Textiles* in the exhibition, but these were developed in the mechanical engineering sector and have an affinity with rigid materials, subject only to small strains. Rope engineering is a particular example discussed below.

In the application of science, there is a major difference between the two halves of the textile processing industry. The chemical part, wet processing, has embraced science. The manager of a dyehouse or a finishing plant would regard himself as a chemist. Not so in the mechanical part. The manager of a spinning plant or a weaving shed would not regard himself as a member of the applied mechanics community, even though his work is overseeing mechanical actions and the mechanical performance of the textile products.

CONDITIONS FOR A CULTURAL CHANGE

Why has the textile industry not adopted a modern engineering design culture? There are several reasons. One is conservatism. Another is that it is not absolutely necessary. Bridges must be built so that they do not fall down; aircraft must fly. The structures are large; the costs are high; performance continually needs to be increased;

the design process for new models is long. Quantitative engineering design is needed for safety and to optimise cost-benefit. In contrast to this, most textile products are small-scale; individual costs are low; failure in a trial is a nuisance but not a disaster; design times are short.

There is a more fundamental reason. The science of flexible fibre assemblies is an extremely challenging subject and is little related to the mainstream 20th century development of applied mechanics. As I wrote in 1979: *Textiles are solid materials, but little of direct relevance to textile behaviour will be found in any textbook on the mechanics of materials. Table 1 lists some features which distinguish textile materials from those usually studied in engineering materials. In ordinary engineering, the development of discontinuities, of porosity, of buckling, of long-range displacement, of surface roughness, or of a soft elastic yielding under transverse pressure are often taken as signs of failure of the materials, and the need for mechanical analysis ceases with the onset of these phenomena: but in textiles their manifestation signals the value of these materials, and the beginning of the region where the mechanical analysis is of most interest* (Hearle, 1980). The convenient assumptions of small strains in an isotropic continuum are not applicable to flexible fibre assemblies, and fibre materials are not elastically governed by Hooke's Law with two elastic constants or ideal elastic-plastic, but are anisotropic and visco-elastic.

Table 1: IMPORTANT DISTINCTIONS

common engineering materials	*intermediate categories*	*textile materials*
RIGID	flexible solid sheets	FLEXIBLE
HOMOGENEOUS		DISCONTIUOUS
HARD		SOFT
IMPERVIOUS	soft loose fillings of no strength	POROUS
SMOOTH		TEXTURES
STRONG		STRONG

The above causes lead to another. There has been no creative interchange between those doing the basic research and engineers using it. The best academic work has opened up the fundamentals of the subject; the worst has concentrated on mathematical sophistication, which is of little practical value. Textile engineers have not found methodology that they could apply.

There are several reasons why this is bound to change in the 21st century. The general development of IT culture means that young people entering industry expect to use computers to help solve their problems. The wealth of practical experience, which was available when a textile technologist worked in the same area throughout a career, is dissipating with changing employee patterns. The diversity of fibres and textile manufacturing methods is increasing greatly, opening up more choices and more problems. Textiles are finding uses in more demanding applications where the project engineers expect engineering data on the performance of the material. If the techniques are available, modelling predictions are cheaper than time-consuming pilot studies, and are welcomed by the engineering community.

The fundamental reason is in Moore's Law. The huge increase in computer power and reduction in cost means that the difficult problems can be tackled. The history of computing is that advances are first used by specialists and then taken up by the majority. Once started the changes occur rapidly. In the aesthetic aspects of the industry, designing for pattern and colour, CAD went from almost nowhere in 1975 to common practice by 2000.

Although research has elucidated only a few of the problems in textile mechanics to a level for industrial performance prediction, the more urgent priority is to introduce programs that are easy to use and truly help the engineer in industry.

CURRENT STATE OF THE ART

Yarns and ropes

The mechanics of twisted continuous filament yarns had been effectively worked out by the 1960s. An energy method led to one integral and four algebraic nonlinear equations, which are easily solved numerically (Hearle, 1969). The inputs are the fibre stress-strain curve and yarn linear density and twist. Although there are some approximations in the model, the predictions are good, except that the stresses at low strain are slightly less than expected because of some buckling of filaments at the centre of yarns. The reason for success is that twisted continuous filament yarns can be modelled by a well-defined geometry, which consists of superimposed layers of helices with constant twist period, and consequently there is a direct relation between yarn extension and the extension of the filaments. In real yarns, the filaments migrate in radial position, but, over short lengths, the idealised model is a good approximation.

The same methodology has been applied to the multiple twist levels of ropes (Leech 1993). A hierarchical procedure is followed. Typically the sequence of twist levels is [yarn as produced] → [rope yarn] → [strand] → [rope]. The inputs to the computer program, *Fibre Rope Modeller* (FRM), are the dimensions and tensile properties of the component yarns and the twist inserted at each manufacturing stage. The predictions agree well with measured rope load-elongation properties, except that typically break loads of well-made ropes are about 10% less than computed due to lack of optimum load-sharing. The geometric modelling enabled relative fibre motions in various slip modes to be computed and, applying the principle of virtual work, the internal transverse pressures between rope components to be determined. FRM is now being used by the leading UK rope manufacturer to design high-strength ropes, such as the 2000 tonne break-load polyester rope used to moor an oil-rig in 1400 meters of water in the Gulf of Mexico. This is one of the first examples of a textile design calculation being used in a modern engineering design sense.

FRM was extended to compute responses under cyclic loading conditions (Hearle et al, 1993). The modelling takes account of fibre creep and hysteresis heating. Slip and pressure are determinants of inter-fibre abrasion. Buckling of some components at low rope tensions leads to axial compression fatigue; modelling was adapted from previous studies of buckling of heated pipelines (Hobbs et al, 2000). This part of FRM gives useful guidance but is limited in predictive power by lack of experimental values for rates of fibre abrasion and axial compression fatigue.

Collaboration between marine engineering consultants, *Noble Denton*, and fibre rope consultants, *Tension Technology International* (TTI), supported by a consortium of rope makers, rope users and certifying authorities, led to the production of *Deepwater Fibre Moorings; an engineers' design guide* (TTI and Noble Denton, 1999). The main criteria to be met in use are peak loads safely below rope break load, rig offsets less than an acceptable distance, and long enough life. Mooring analysis programs existed to predict the response of steel wire and cable moorings. However, these moorings are controlled by the weight of the rope and changes in the catenary, whereas as fibre rope moorings are controlled by the tension due to the extension of a taut rope. In principle, tension is given by (modulus x extension). The problem is that viscoelasticity means that fibre modulus is not a well-defined property. It depends on the nature of the loading and the previous loading history. There is the further complication that rope constructions tighten up under cyclic loading. The collaboration made it possible to specify test procedures to give a minimum value of *post-installation stiffness*, which related to offsets, and a maximum value for *storm stiffness*, which related to peak load. Limits were given for the number of cycles at low tension to avoid axial compression fatigue (e.g. <100,000 cycles at <10% of break load for polyester; <2,000 cycles at <5% of break load for aramids). A number of Joint Industry Projects, carried out by TTI and the National Engineering Laboratory, of cyclic loading on large test-rigs have provided data on moduli and effects of long-term testing (with the right products, no failure after millions of cycles). Polyester ropes have the best combination of properties for deepwater moorings and their long-term life is better than for steel ropes under similar conditions.

The combination of modelling and testing has given oil companies the confidence to moor oil-rigs in deep water. A typical installation would consist of 20 km of 50 Mtex polyester rope with break load of 2000 tonne and, in total, weighing 1000 tonnes. Collaboration between textile experts and applications engineers is the way forward for engineering design of textiles for demanding uses. Combinations of theoretical modelling and practical testing are needed to meet performance and safety requirements and to optimise cost-benefits. Experience in use must also be taken into account. Unexpected problems cannot be avoided. For example, in an early deep water mooring off the coast of Brazil, a rope section removed for testing showed a reduced break load due to minute crustaceans penetrating the rope and abrading the fibres. Once recognised, this problem could be eliminated by protecting the rope or substituting a steel section at the relevant depth, but it had not been anticipated despite extensive design studies.

Other yarns

The treatment of continuous filament yarns can be modified to take account of slip at fibre ends in compact ring-twisted staple fibre yarns. An elaborate theoretical analysis, which took account of fibre migration but was limited to small strains, was reduced to a semi-empirical equation (Hearle, 1965):

yarn strength or modulus / fibre strength or modulus

$$= \cos^2\alpha \, [\, 1 - (2 \operatorname{cosec}\alpha / 3L) \, (a\,Q / 2\,\mu)^{1/2} \,] = \cos^2\alpha \, (1 - K \operatorname{cosec}\alpha)$$

where α = surface twist angle, L = fibre length, a = fibre radius, Q = migration period and μ = coefficient of friction.

Now it would be possible to apply the same principles to an individual-fibre computational model to give improved predictions. The major limitation would be to define the migration paths of the fibres. A full theoretical computation would require treatment of the more difficult problem of modelling the process of yarn formation. An alternative design methodology would be to be to create a data-base of values of the empirical factor K and use a neural network or other soft procedure to give values for particular cases.

The several forms of open-end spun yarns require modelling in terms of their structures. Bulky wool yarns have proved more difficult to model, because the structure changes as the fibres move closer together. Modelling of false-twist textured yarns, with alternating fibre helices and pig-tails, and air-jet textured yarns. with projecting loops, needs to be advanced to take account of modern computer power (Hearle et al, 2001).

Woven fabrics

The mechanics of woven fabrics raises more difficulties. One problem is that the zero-stress state is not well defined. Agreement is needed on the definition of a reference state under low biaxial loading. Another difficulty is that there is no direct geometrical relation between the fabric deformation and the component yarn deformations, since the latter depend on a balance between yarn extension, yarn bending and yarn flattening. One consequence of this is that fabric geometry as specified will not in general be in equilibrium. The first stage of a mechanical analysis is to determine the zero-stress state. In practice this is complicated by the ways in which fabrics can become set in different states as a result of relaxation. Furthermore, the yarns go through different states as they go from contact regions at crossovers to free regions between crossovers, with more complicated forms in non-plain weaves.

The majority of the many papers on woven fabric mechanics have been based on equilibrium of forces and moments. Most have been limited to plain weaves and simplifying assumptions, such as Kawabata's saw-tooth model, have been necessary. In my opinion, this approach will not lead to engineering design methods.

The alternative is the energy-based approach of Hearle and Shanahan (1978). This is now being more strongly developed in a graphical computing mode in a research project at the University of Manchester. The fabric geometry is flexibly formulated by defining yarn paths by spline-fitting through specified points and by defining yarn cross-section by the lengths of a set of radial vectors. The mechanics is treated by minimisation of [yarn extension energy + yarn bending energy + yarn flattening energy] through adjustments of the geometry when the fabric is held to given dimensions. Determination of strain energy at small increments of deformation means that tensile forces can be found from conservation of energy. Yarn extension energy is well defined. Yarn bending energy is fairly well understood. The neglected feature of yarn flattening energy, which depends on change of volume and shape, needs more research.

Progress can be helped in other ways. One is to concentrate on control points. Three primary control points, given by the fabric repeat, are needed to specify the fabric's biaxial deformation. Additional primary control points are needed for fabric shearing and bending. For a plain weave, the primary control points also define the internal displacements, but additional secondary control points are needed for non-plain weaves. Another is to identify special cases. For monofilament and highly twisted yarns, yarn flattening can be ignored, except for a Poisson's ratio effect usually at constant volume. For very soft yarns, the free zone between crossovers disappears. Simplifications of this sort, although lacking in academic rigour and generality, offer better prospects of developing useful engineering design software.

Other fabrics

In mechanical terms, braided fabrics are simply a variant of woven fabrics. Simple plain knits have been modelled by equilibrium of forces and moments with limitations similar to those for woven fabrics. The energy method should be developed for the various knit fabric structures.

Modelling of bonded, needled and stitch-bonded nonwovens has followed the familiar pattern of aiding qualitative understanding but not quantitative engineering design predictions. Random networks could be modelled by individual fibre computations, but the problem, as with staple yarns, is to define yarn paths. In the absence of detailed process modelling, semi-empirical procedures are needed for engineering design.

Other mechanical properties

The above discussion has been primarily concerned with tensile properties, but there are others that are important for textile performance. The transverse compressibility of yarns has been mentioned in connection with flattening energy in fabrics. For fabrics, there are six fundamental directions to be modelled: in-plane, two tensile and one shear; out-of-plane, two bending and one twisting, the latter, which is related to bending on the bias, being frequently ignored. Solution of these problems covers fabric micromechanics and gives the constitutive relations for yarns and fabrics. The hierarchy is:

fibre properties + yarn structure
↓
yarn properties + fabric structure
↓
fabric properties

Macromechanics covers more complex deformations and modes of behaviour, which are relevant to a totality of engineering design. These include features such as pilling and bagging of fabrics, where modelling has been limited, and heat and moisture transmission, where modelling is advanced. Two examples illustrate ways to approach the problems.

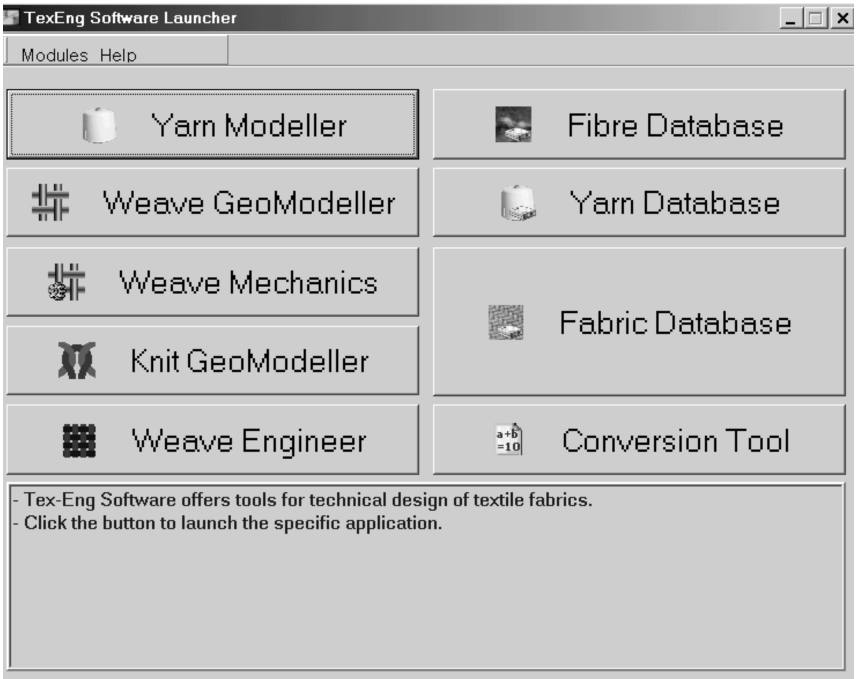
Many attempts at modelling of drape by finite-element programs have been reported in the literature. However, these include unjustified simplifications and demand excessive computer time. In my view, it is not a useful approach to apply software developed for other systems. Programs adapted to the particular features of textiles are needed. Drape is just one manifestation of complex buckling of fabrics. I believe that progress will come from a fundamental study of the mechanics of buckling, elaborating the study of symmetrical threefold buckling of a linear elastic sheet (Amirbayat and Hearle, 1986) to cover more realistic and complicated forms.

Bulk and compressibility of fibre assemblies is another important problem. Here the pioneering individual-fibre computational modelling of Beil and Roberts (2002) shows the way forward. Again this is based on energy minimisation of the forms of fibre segments between contact points.

USEFUL SOFTWARE

How can we make the increasing knowledge of the structural mechanics of textiles into engineering design procedures that will be used in industry? This is necessary, not only for its inherent value, but as a means of developing a creative interchange between academic research and practical utility. The critical need is for programs that are easy to use and answer the questions that engineers and managers want answered.

In TexEng Ltd, we offer programs developed in the Textiles and Paper Group, School of Materials, University of Manchester in association with TTI Ltd in forms which run in a familiar WINDOWS mode on a PC. The entry screen is shown in Fig. 1.

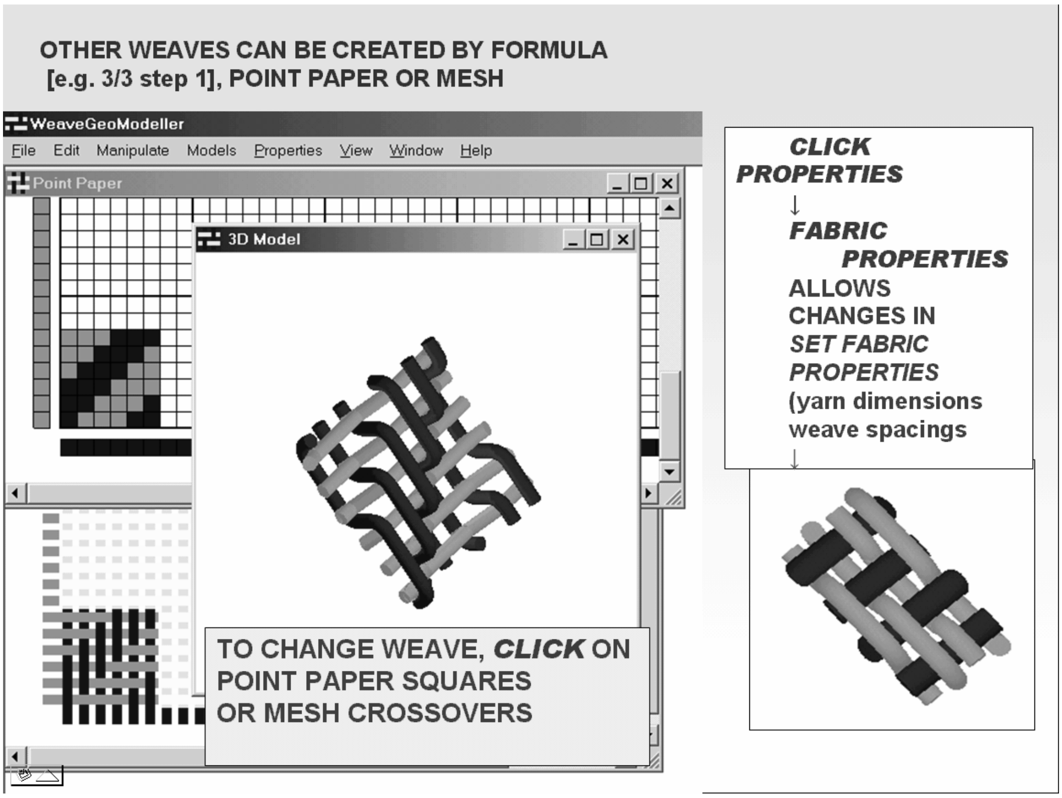


- Tex-Eng Software offers tools for technical design of textile fabrics.
- Click the button to launch the specific application.

Fig. 1. Entry screen for TexEng programs.

Yarn Modeller covers the established model for twisted continuous filament yarns and will include empirical rules for other yarns.

Weave GeoModeller covers the structure of single-layer woven fabrics. Fig. 2 shows montages from several windows. A file is created in three stages. (1) Weave can be input by traditional point paper, mesh, which is easy for computer usage and more illustrative, or, for the mathematically inclined, by formula. (2) Yarn dimensions are input; circular, lenticular and racetrack cross-sections are current options. (3) Warp and weft spacings and one crimp value complete the fabric specification. If needed, conversion tool transforms input values for other parameters to those required for the program. Three-dimensional views of the fabric can be manipulated in various ways. For example, slice allows the viewer to see how pore sizes change through the thickness of the material, which is relevant to transmission properties. Weave GeoModeller is the basic program that allows particular applications to be developed. For example, in one project in the University of Manchester, a filtration module is being developed. Knit GeoModeller is similar to Weave GeoModeller but is currently limited to plain, rib and purl single-layer and interlock rib double–layer weft knits.

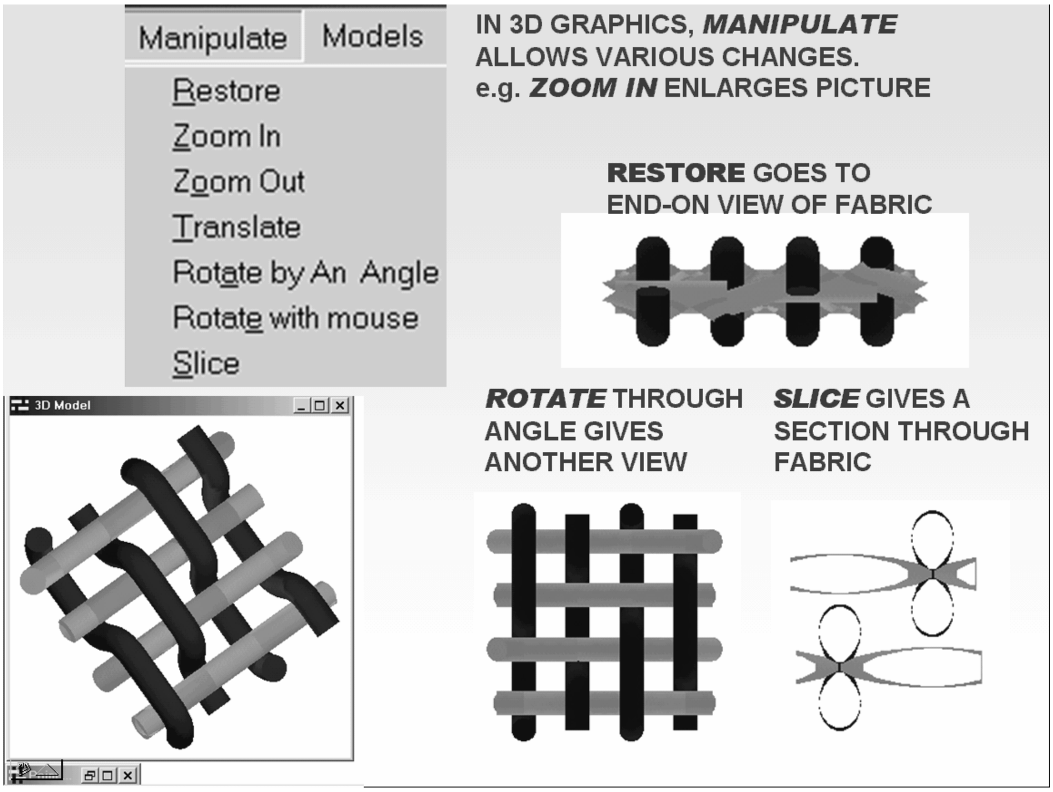


OTHER WEAVES CAN BE CREATED BY FORMULA
[e.g. 3/3 step 1], POINT PAPER OR MESH

CLICK
PROPERTIES
↓
FABRIC
PROPERTIES
ALLOWS
CHANGES IN
SET FABRIC
PROPERTIES
(yarn dimensions
weave spacings
↓

TO CHANGE WEAVE, *CLICK* ON
POINT PAPER SQUARES
OR MESH CROSSOVERS

(a)



IN 3D GRAPHICS, ***MANIPULATE*** ALLOWS VARIOUS CHANGES. e.g. ***ZOOM IN*** ENLARGES PICTURE

RESTORE GOES TO END-ON VIEW OF FABRIC

ROTATE THROUGH ANGLE GIVES ANOTHER VIEW

SLICE GIVES A SECTION THROUGH FABRIC

(b)

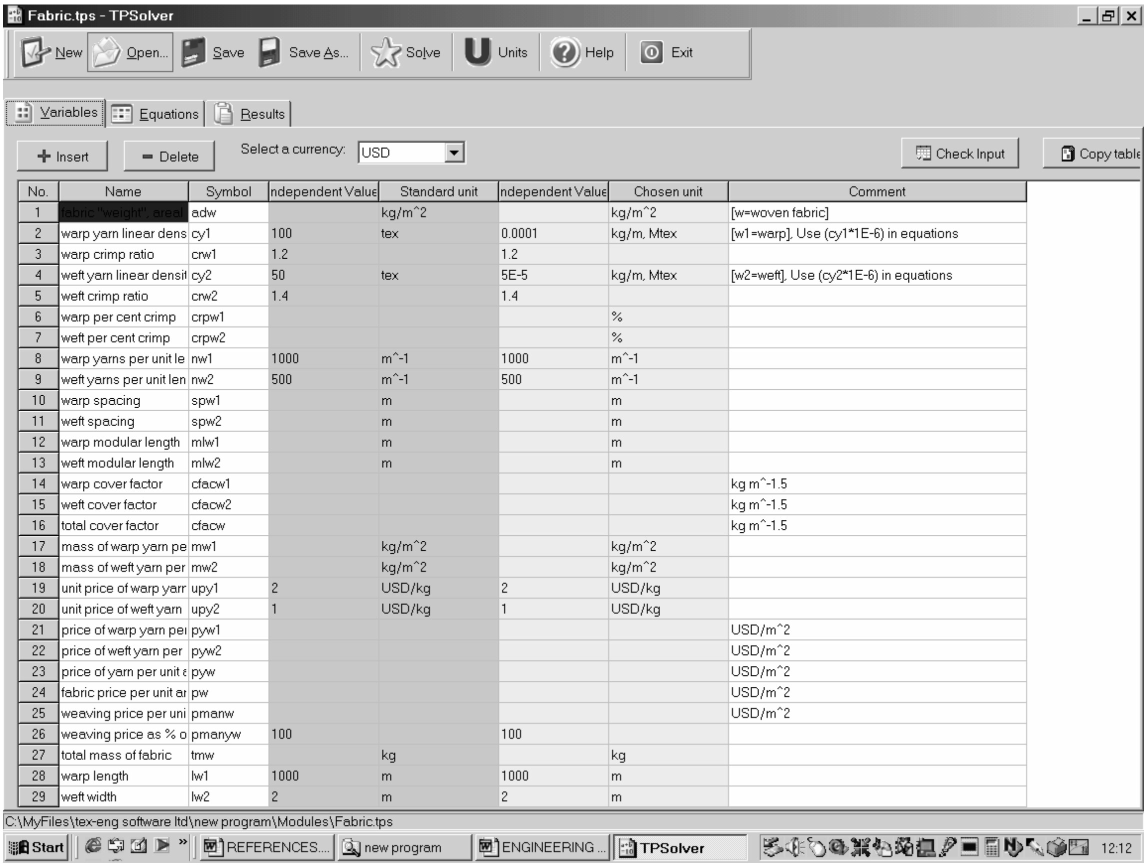
Fig. 2. Montages from Weave GeoModeller.

The currently available application in TexEng is Weave Mechanics, which is based on an energy method described by Sagar et al (2002). The additional inputs are yarn tensile properties, specified by break load, break extension and shape of stress-strain curve through polynomial coefficients, bending stiffness and flattening stiffness. The predictions agree well with experimental data on plain-weave cotton fabrics from Kawabata et al (1973) and monofilament nylon fabrics from Dastoor et al (1994). However, as indicated above, more theoretical research and validation is needed for more complicated woven fabric problems.

Fibre Data-Base and Yarn Data-Base, which can also store results from Yarn Modeller, are sources of inputs to the modelling programs. Fabric Data-Base stores the files of models that have been run. It can also be used to store experimental data on fabrics; ways of using this data to give empirical predictions will be developed.

Conversion Tool derives from a pioneering development of a question-answer program by Konopasek (Hearle et al, 1972). Formulation of a great many textile problems involves a multiplicity of relevant variables, a few of which are independent and more are dependent. However the choice of independent variables depends on circumstances. Fibre dimensions are a trivial example. Three alternatives are: given fibre diameter (μm) and density (g/cm^3), find linear density (tex); or, given linear density and density, find diameter; or, improbably, given linear density and diameter, find density. With woven fabrics, as illustrated in Fig. 3, the number of useful quantities is much larger: thread spacings or the reciprocals, ends per unit length, modular lengths, crimp values in various forms, weave angles, cover factors, fabric weight, etc for both warp and weft. The program has a facility for switching between the variety of units that may be used. Other features, such as costings, are included. The program can also cover empirical relations, such as:

fabric break load = conversion factor x number of ends x yarn break load



No.	Name	Symbol	ndependent Value	Standard unit	ndependent Value	Chosen unit	Comment
1	fabric "weight", areal	adw		kg/m^2		kg/m^2	[w=woven fabric]
2	warp yarn linear dens	cy1	100	tex	0.0001	kg/m, Mtex	[w1=warp], Use (cy1*1E-6) in equations
3	warp crimp ratio	crw1	1.2		1.2		
4	weft yarn linear densit	cy2	50	tex	5E-5	kg/m, Mtex	[w2=weft], Use (cy2*1E-6) in equations
5	weft crimp ratio	crw2	1.4		1.4		
6	warp per cent crimp	crpw1				%	
7	weft per cent crimp	crpw2				%	
8	warp yarns per unit le	nw1	1000	m^-1	1000	m^-1	
9	weft yarns per unit len	nw2	500	m^-1	500	m^-1	
10	warp spacing	spw1		m		m	
11	weft spacing	spw2		m		m	
12	warp modular length	mlw1		m		m	
13	weft modular length	mlw2		m		m	
14	warp cover factor	cfacw1					kg m^-1.5
15	weft cover factor	cfacw2					kg m^-1.5
16	total cover factor	cfacw					kg m^-1.5
17	mass of warp yarn pe	mw1		kg/m^2		kg/m^2	
18	mass of weft yarn per	mw2		kg/m^2		kg/m^2	
19	unit price of warp yarr	upy1	2	USD/kg	2	USD/kg	
20	unit price of weft yarn	upy2	1	USD/kg	1	USD/kg	
21	price of warp yarn pei	pyw1					USD/m^2
22	price of weft yarn per	pyw2					USD/m^2
23	price of yarn per unit ε	pyw					USD/m^2
24	fabric price per unit ar	pw					USD/m^2
25	weaving price per uni	pmanw					USD/m^2
26	weaving price as % o	pmanyw	100		100		
27	total mass of fabric	tmw		kg		kg	
28	warp length	lw1	1000	m	1000	m	
29	weft width	lw2	2	m	2	m	

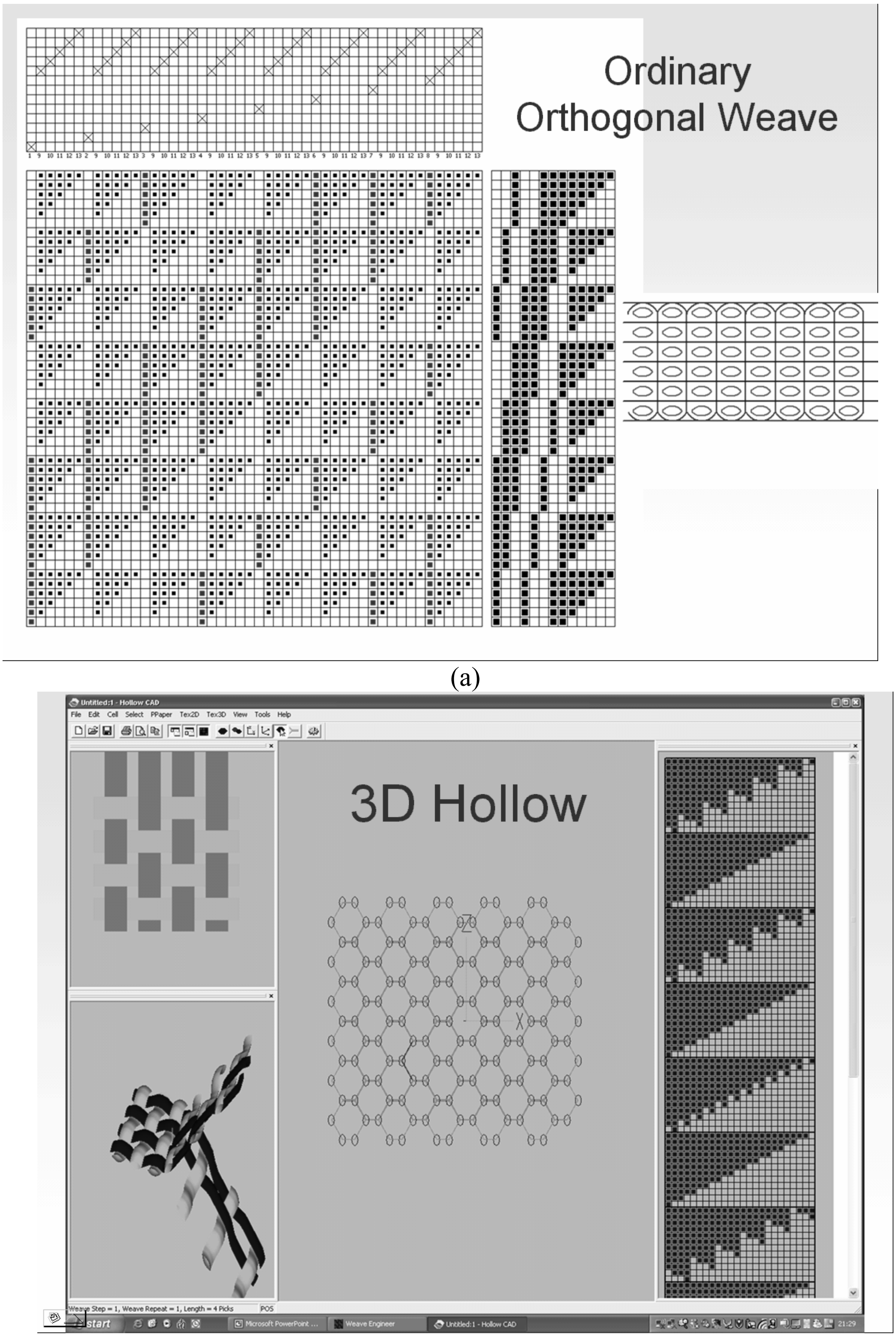
C:\MyFiles\tex-eng software ltd\new program\Modules\Fabric.tps

Fig. 3. Conversion tool screen.

Weave Engineer is a program developed by Xiaogang Chen and Isaac Porat for 3D fabrics, which are important for composite preforms. It covers the weave specification and a view of the topology of the fabric, as illustrated in Fig. 4. The information can be transmitted to the electronic Jacquards or other control means of weaving machines; this part of the program can also be used with Weave GeoModeller for single-layer fabrics.

CONCLUSION

The last three-quarters of the 20th century showed a great flowering of fibre and textile research, including the structural mechanics of fabrics. This increased understanding and stimulated invention, but it was not adapted to quantitative engineering design in the way that happened in other industries. Partly, this was due to the difficulty of the problems. Great simplifications were needed in models to be treated by hand calculations and even by early computing facilities. Most research gave generic results, or just a few examples, and did not give ways of taking account of the options in the choice of design parameters. The challenge for the 21st century is for the technical aspects of textiles. A creative interchange between academic



(a)

(b)

Fig. 4. Weave Engineer screens.

researchers and industrial user will transform how the industry operates in the design of textiles to optimise performance and cost benefit and will open up new markets for fibre assemblies in common and extreme applications.

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