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Optimization of Fabric Manipulation during Pick/Place Operations

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A textile fabric is a very complex non-linear mechanical system. For many reasons, it is necessary to be able to predict the drape and deformation of fabric parts over complex objects while they are being manipulated during certain manufacturing operations. It is nearly impossible to obtain "closed form" mathematical solutions for such problems, and thus numerical methods are sought. The physical model used to make such predictions is of the utmost importance. Many researchers have modelled fabrics as an assemblage of their constitutent fibres or yarns. Such models have little practical value for general fabric structures due to the prohibitive number of such fibres and yarns. A very tempting modelling theme is to consider the fabric structure as a flexible continuum that undergoes arbitrarily large displacements and rotations. The effect of the interacting fibres (or yarns) is accounted for through the overall material response. In this research, certain fabric drape and manipulation problems are investigated where the fabric part is modelled as a very flexible beam (or strip). Thus, motion is restricted to bending in a single plane. To produce simulations, the analyst must provide data regarding: initial configuration of the fabric part, material properties, and external loads.

The loading can consist of self-weight, prescribed forces at arbitrary points on the part, or prescribed displacements at arbitrary points on the part. The formulation includes the ability to ascertain the effects of the fabric coming into contact with a rigid object of arbitrary shape. To follow is a brief review of the literature that has influenced our work, particularly in the area of fabric material response and fabric drape.

The earlier work on fabric mechanics was mainly concerned with measurement of flexural rigidity. Peirce[1] initiated research in the area of fabric bending behaviour and material properties measurement. He measured flexural rigidity and bending modulus of fabrics using the cantilever test, and also modelled a typical woven fabric. This model was widely used in later works. Abbott[2] reported on measurement of flexural rigidity of fabrics using five different experimental methods, especially the Peirce cantilever test. In 1960[3], he presented factors (clustering and rigidity factors) on the flexural rigidity of the fabric. Cooper[4] measured flexural rigidity of fibres, yarns and woven fabrics using the cantilever test. Research concerning fabric buckling behaviour followed. Dahlberg[5] conducted research on plate and shell buckling of fabrics and obtained load-deflection curves through experimentation. Fabric parts were modelled as thin plates, and analysed using Euler's column buckling formula. Lindberg *et al.*[6], using various commercial fabrics, analysed and discussed load-deformation curves obtained for shearing, plate buckling, and shell buckling. Lindberg[7] also discussed the phenomena of buckling for two fabrics

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attached to each other. Grosberg and Swani[8] presented papers about bending and buckling of fabrics, and explained that bending behaviour is governed by a bending rigidity factor and an internal frictional couple. In research on the fabric bending curve, Chicurel and Suppinger[9] studied deformed configurations of a coplanar crimped fibre with bending and stretching deformations included. The minimum potential energy principle was used. In 1963, they presented a theory for three-dimensional crimped fibres with twisting deformation also included. Konopasek and Hearle[10] formulated a model for three-dimensional fabric bending capable of treating large deformations. Moment-curvature equations, moment and force equilibrium equations, curvature-orientation equations, and orientation-co-ordinate equations were used to describe the fabric bending curve. The fourth order Runge-Kutta method was used for numerical integration of a large set of non-linear differential equations. Lloyd *et al.*[11] studied folding of heavy fabric sheets.

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THE MODEL WAS AS EFFICIENT AS THAT OF THE FRICTION COUPLE THEORY

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Brown *et al.*[12] presented a paper about large deflection bending of woven fabrics in automated material handling, especially for layout of a fabric on a flat work surface. A computer program was developed based on Konopasek's theoretical formulation. Clapp and Peng[13] published a paper concerning buckling of woven fabrics. Their method was equivalent to the simplified version of Konopasek's technique, and used the Timoshenko beam theory. The claim was made that the model was as efficient as that of the friction couple theory. In their next paper[14], the effect of fabric weight was incorporated into a theoretical model based on Grosberg's[15] frictional couple theory. Clapp *et al.*[16] proposed a very simple experimental scheme to establish the complete moment-curvature response for a fabric from a single test. Clapp and Peng[17] presented a comparison of linear and non-linear bending models for predicting fabric deformation in automated handling. A third order moment-curvature relationship was used for non-linear material behaviour. Simulations were performed for the laying of fabrics. The results were compared with experimental data.

For problems involving three-dimensional fabric drape, the reader is referred to [18-37].

Our research can be viewed as an extension and generalization of past work. Many of the papers reviewed above deal with a specific geometry and set of loading/boundary conditions. This article describes the results of a formulation that yields a general approach for solving problems where a wide range of geometries and boundary/loading conditions are anticipated. This feature will be illustrated through a set of numerical examples below.

FORMULATION

Simo, *et al.*[38,39] have recently presented a comprehensive finite element-based treatment of geometrically exact beam theory. We have adapted this theory for fabric drape and manipulation studies by including the effect of fabric contact with an arbitrary surface. The mechanical properties of the fabric including axial stiffness *(EA)* and bending stiffness *(EI* or *"B")* are required as input data. Currently, our implementation can handle a non-linear moment curvature response. A full description of the computational details of this formulation

Fabric 1	40% polyester/60% cotton twill weave, orchid colour. Bleached, dyed, finished, and preshrunk in a pure finish
Fabric 2	65% polyester/35% cotton plain weave, blue colour. Bleached, dyed, finished and preshrunk in a resin finish
Fabric 3	100% cotton twill weave, yellow colour. Bleached, dyed, finished and preshrunk in a pure finish
Fabric 4	65% polyester/35% cotton twill weave, cream colour. Bleached, dyed, finished and preshrunk in a resin finish

TABLE I.
Test Fabric Descriptions

will be presented during the AARC conference and documented in future journal publications.

FABRIC MATERIAL PROPERTIES

We have performed simulations and experiments on a group of four test fabrics supplied by the Galey and Lord Company. A description of these fabrics is shown in Table I.

The physical properties of these fabrics is shown in Table II. The thickness t was measured directly, while the cross sectional area A and the second moment of area I were calculated according to $A = t$ and $I = t^3/12$, respectively. Thus, A and I are based on a 1 cm wide strip fabric. The weight per unit area is indicated by ω.

Figure 1 shows the Kawabata bending test for the four fabrics. From this test, a value for bending rigidity is produced ("*B*" value). This is effectively a bending rigidity *(EI)* per unit width of fabric. Recall that this value represents the average slope of the moment-curvature response at curvatures of 0.5 and 1.5 cm, for positive and negative curvatures.

	Fabric 1	Fabric 2	Fabric 3	Fabric 4
t (cm)	0.0292	0.0267	0.0483	0.0406
A (cm^2)	0.0292	0.067	0.0483	0.0406
I (cm^4)	2.075×10^{-6}	1.586×10^{-6}	9.37×10^{-6}	5.58×10^{-6}
ω (gmf/cm^2)	0.0165	0.0149	0.0283	0.0255

TABLE II.
Physical Properties for Test Fabrics

	Fabric 1	Fabric 2	Fabric 3	Fabric 4
$(EA)_{eff}$ (gmf/cm)	1,126	1,515	1,418	2,809
$(EI)_{eff}$ (gmf-cm^2/cm)	0.080	0.090	0.275	0.386
$(GA)_{eff}$ (gmf/cm)	1,126	1,515	1,418	2,809

TABLE III.
Effective Linear Elastic Properties of Four Test Fabrics (Per Unit Width, Warp Direction)

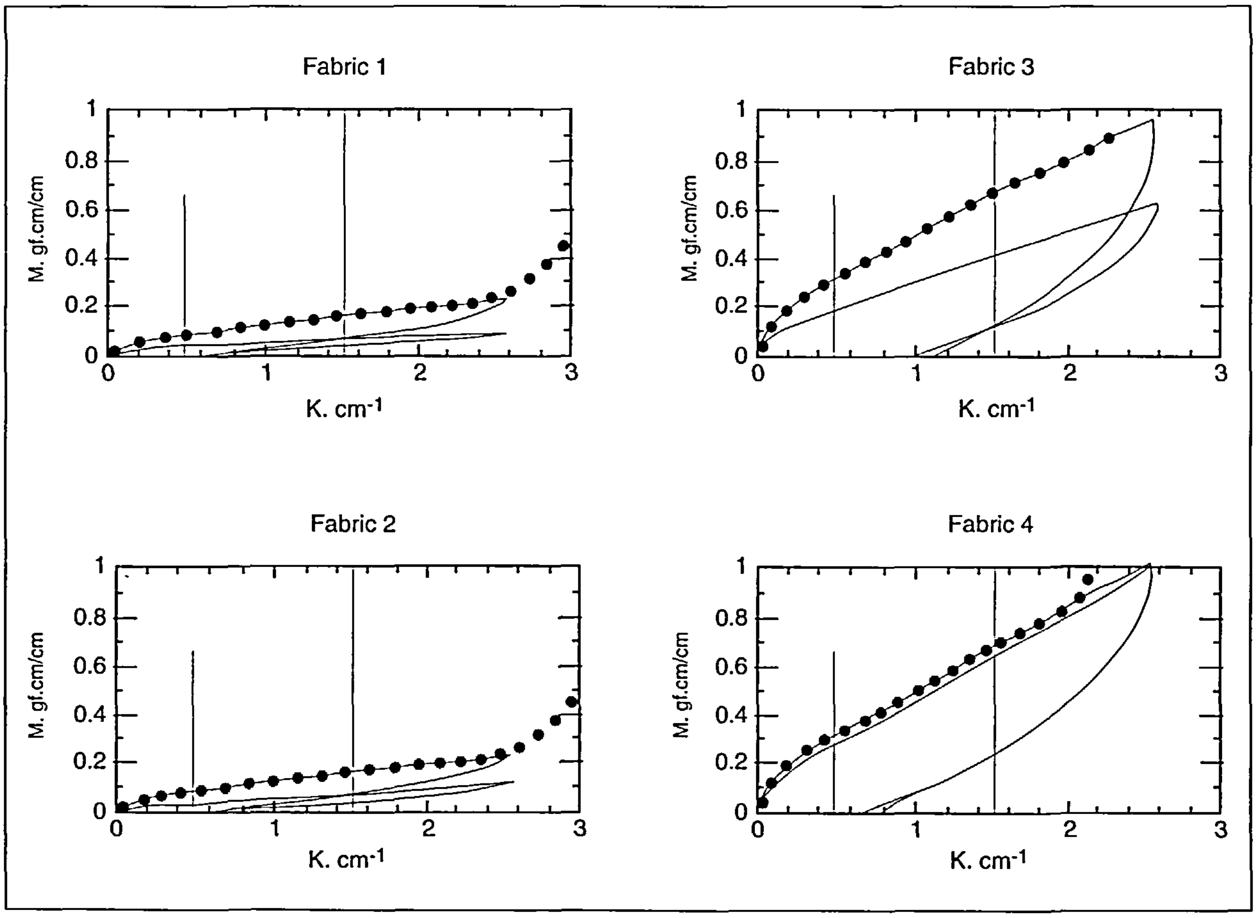

FIGURE 1.
Kawabata Moment-curvature *(M – x)* Data for Test Fabrics

These values are reported in Table III as $(EI)_{eff}$, for the warp direction. We term these *effective* properties because neither E nor I is measured directly. Since a fabric is not a homogeneous material, the A and I values calculated above are imprecise. However, by viewing A and I as true physical properties and E as an effective property, we can calculate an effective EA (axial rigidity). These values are reported in the table also. The transverse shear rigidity, GA (G = shear modulus) of the fabric has been estimated to be equal to the axial rigidity. Numerical experiments have shown relative insensitivity to the values of $(EA)_{eff}$ and $(GA)_{eff}$ for fabrics loaded primarily by their own self weight.

Table IV shows polynomial curve fits to the actual moment curvature ($M - x$ or $M - K$) Kawabata data. These non-linear equations are used in the simulations to compare with results using the simple linear relationship $M = (EI)_{eff}\kappa$.

RESULTS

Numerical simulations for a group of representative problems related to fabric manipulation and drape are presented next. These examples exhibit the capability of the formulation to cope with large displacements/rotations and contact. Applications specific to textile mechanics are presented: folding, placement on a work surface, pick-up from a work surface. Optimization of fabric manipulator paths is also discussed for the pick/place operations. All simulations use material properties measured directly from actual fabrics, whose properties are listed above. Simulation results are compared with experiment in all cases.

Fabric-folding Operation

Figure 2 shows a simulation and experimental results for a fabric folding operation. In this case, a 10 cm-long sample of fabric 1 is folded over on to itself. The right end of the

Fabric	Polynomial curve fit of actual $M - x$ data (warp)
Fabric 1	$M = 0.34722x - 0.57762x^2 + 0.54667x^3 - 0.23081x^4 + 0.03544x^5$
Fabric 2	$M = 0.39253x - 0.63481x^2 + 0.58009x^3 - 0.23870x^4 + 0.03599x^5$
Fabric 3	$M = 1.53573x - 2.82874x^2 + 2.84729x^3 - 1.27439x^4 + 0.20789x^5$
Fabric 4	$M = 1.34842x - 2.59202x^2 + 2.87504x^3 - 1.41688x^4 + 0.25567x^5$

TABLE IV.
Polynomial Curve Fit of Actual $M - x$ Data

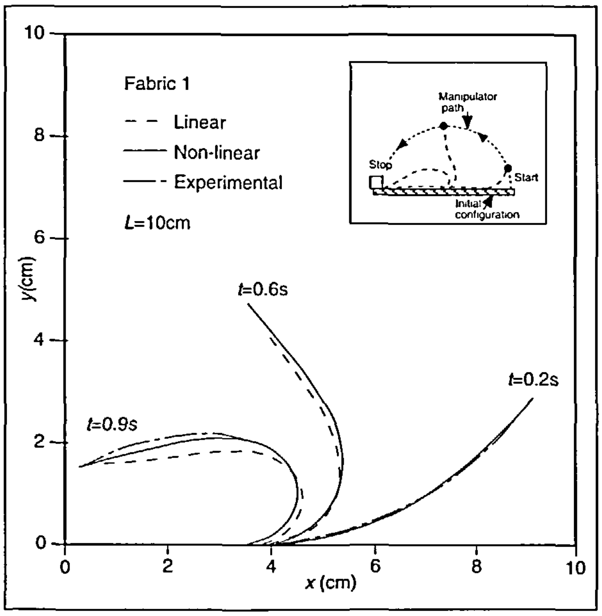

FIGURE 2.
Fabric-folding Problem, Comparison Linear versus Non-linear Bending Response (Fabric 1)

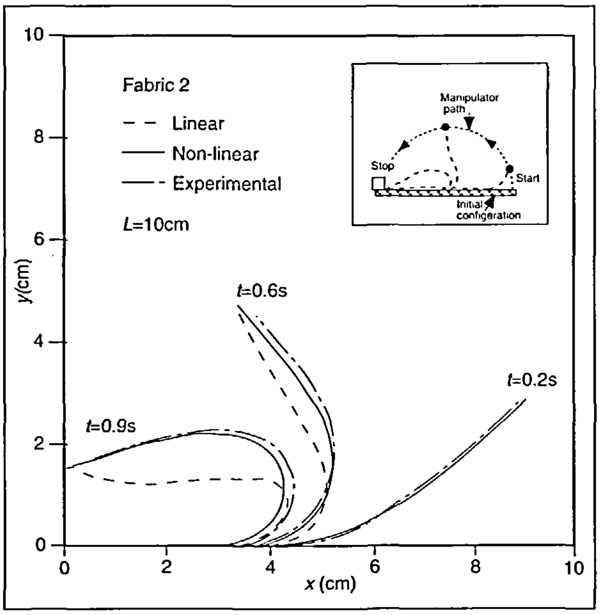

FIGURE 3.
Fabric-folding Problem Comparison Linear versus Non-linear Bending Response (Fabric 2)

fabric is manipulated along a semi-circular path, while the left end is assumed fixed. Simulations were done using both a linear response for the bending rigidity and the full non-linear moment-curvature response. Linear elastic behaviour was assumed for the axial and transverse shear response. On comparing with the experimentally measured intermediate drape shapes, it is seen that incorporation of the non-linear bending response yields superior results. Figure 3 shows results for fabric 2. Here the difference between the linear and non-linear results is even more striking.

Fabric Place Operation

Figure 4 shows a simulation and experimental results for a fabric placing operation. Here a piece of fabric is initially suspended vertically with the bottom end just contacting the work surface. The top end of the fabric is then manipulated along a straight-line path. Figure 4 shows the results for a 10 cm-long strip of fabric 3. Figure 5 shows similar results for

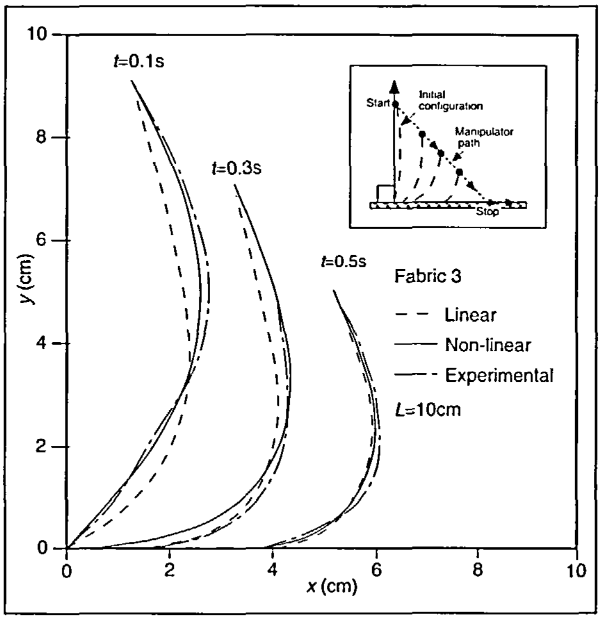

FIGURE 4.
Fabric Lay-down Problem, Comparison Linear versus Non-linear Bending Response (Fabric 3)

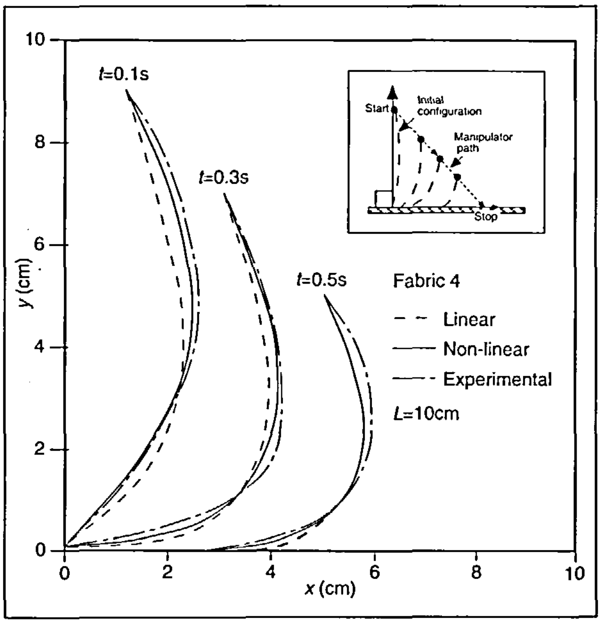

FIGURE 5.
Fabric Lay-down Problem, Comparison Linear versus Non-linear Bending Response (Fabric 4)

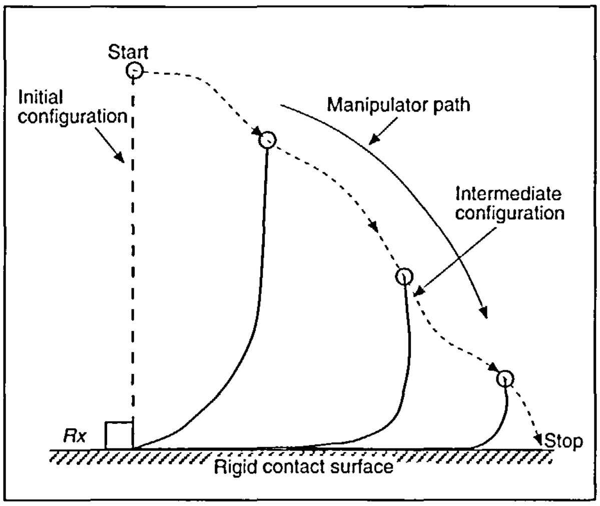

FIGURE 6.
Fabric Lay-down Problem, Optimized Manipulator Path to Minimize Reaction Force

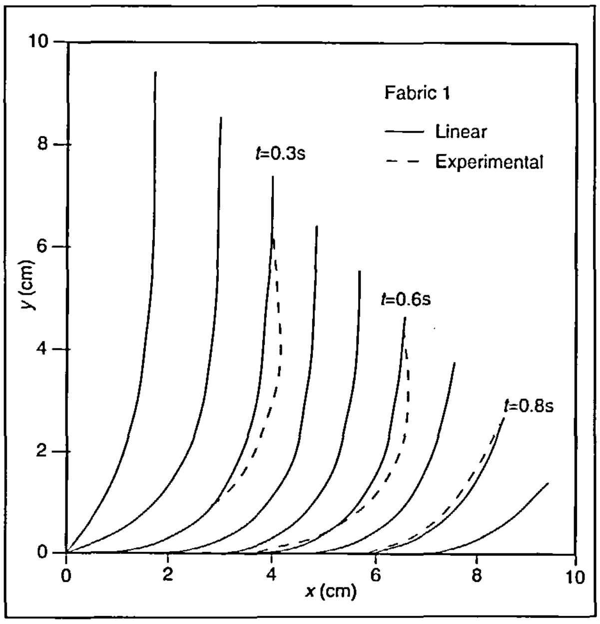

FIGURE 7.
Fabric Lay-down Problem, Fabric Drape Shapes for Optimum Manipulator Path (Linear Material)

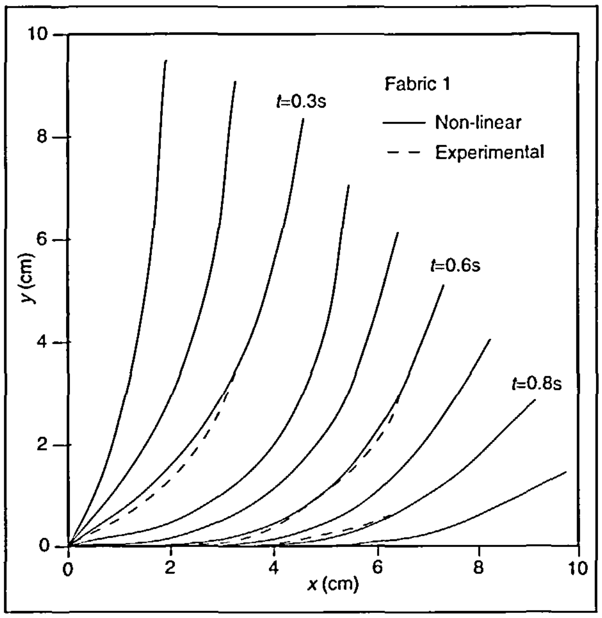

FIGURE 8.
Fabric Lay-down Problem, Fabric Drape Shapes for Optimum Manipulator Path (Non-linear Material)

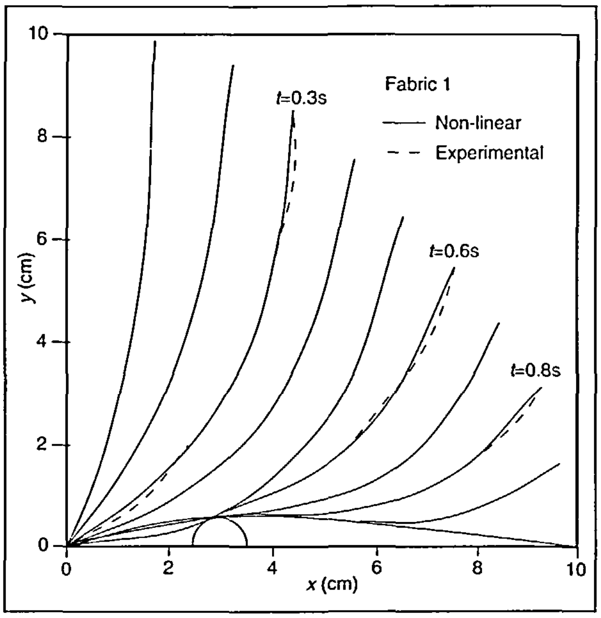

FIGURE 10.
Fabric Lay-down Problem (with Bump), Fabric Drape Shapes (Non-linear Material)

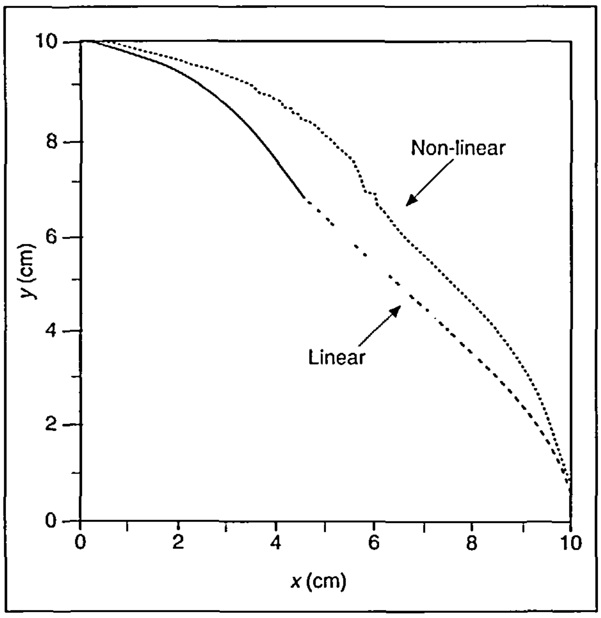

FIGURE 9.
Fabric Lay-down Problem, Optimized Manipulator Path to Minimize Reaction Force

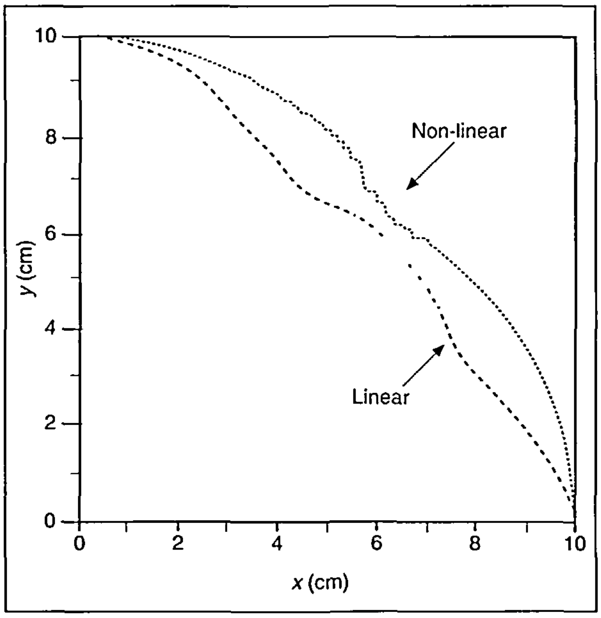

FIGURE 11.
Fabric Lay-down Problem (with Bump), Optimized Manipulator Path (Linear versus Non-linear Material)

fabric 4. Again, the simulated response using the non-linear moment curvature response agrees very closely with experiment.

Fabric Place Operation — Optimization

Figure 6 shows a schematic of what we term an "optimum" place operation. The goal of the place operation is to lay a piece of fabric out on a work surface while minimizing the constraint reaction force. The idea is to decrease the possibility of the fabric wrinkling near the fixed end. The objective is to determine the path of the manipulator (not necessarily semi-circular) to accomplish this. Figures 7 and 8 show intermediate drape shapes for the linear and non-linear moment-curvature response for fabric 1. Figure 9 shows the required path for the manipulator in each case.

To illustrate the robustness of our approach, we show similar results including the effect of a rigid semi-circular

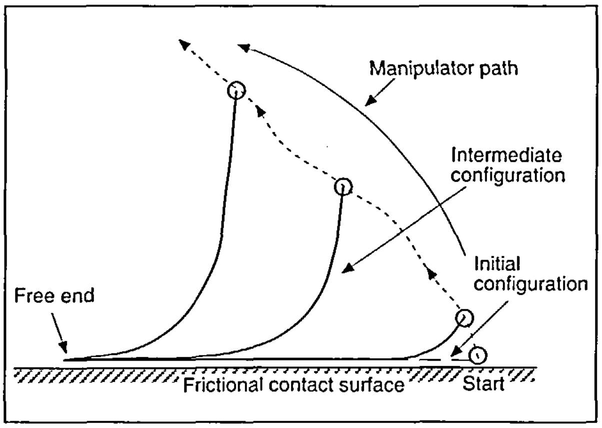

FIGURE 12.
Fabric Pick-up Problem, Optimized Manipulator Path to Minimize Free End Displacement

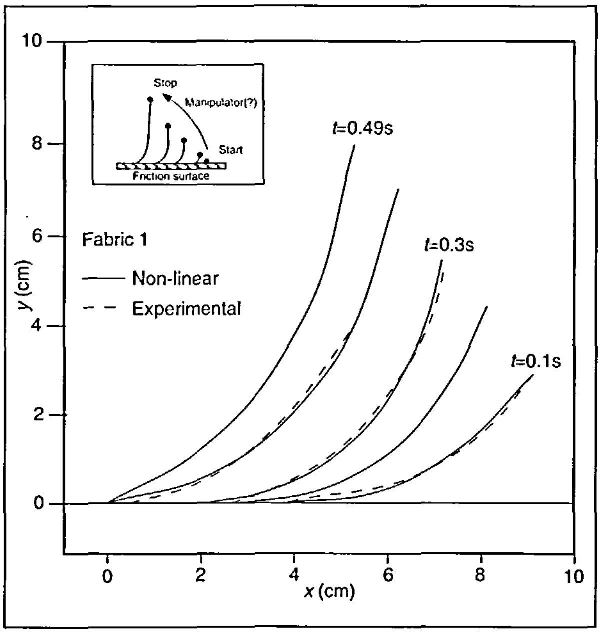

FIGURE 13.
Fabric Pick-up Problem, Fabric Drape Shapes (Non-linear Material)

bump on the work surface. Figure 10 shows the intermediate drape shapes for the non-linear response, and Figure 11 shows the required manipulator paths.

Fabric Pick Operation — Optimization

Figure 12 shows a schematic of what we term an "optimum" pick-up operation. The goal of this operation is to pick up a piece of fabric from a work surface while minimizing the sliding motion of the free end. The idea is to decrease the possibility of sliding during manipulation. The objective is again to determine the path of the manipulator to accomplish this. Figure 13 shows intermediate drape shapes for the non-linear moment-curvature response for fabric 1. Figure 14 shows the required path of the manipulator for each case.

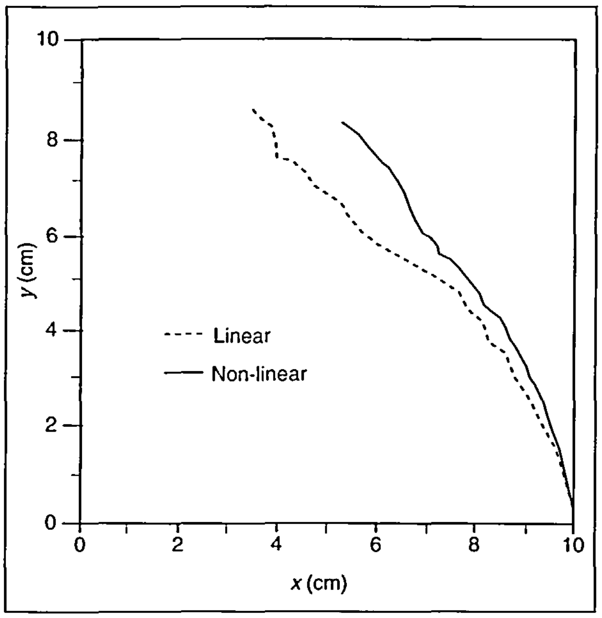

FIGURE 14.
Fabric Pick-up Problem, Optimized Manipulator Path (Linear versus Non-linear Material)

CONCLUSIONS

A general large displacement beam theory has been used to formulate a finite element-based numerical method for simulating fabric drape, manipulation and contact. A broad class of fabric mechanics problems including these effects can be solved effectively. Numerical results have been presented corresponding to real fabric materials.

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