The Development and Use of a Robust Modeling Approach for Predicting Structural Performance of Woven Fabrics Using ABAQUS

Ted Diehl[1], Ricky D. Dixon[2], Mark A. Lamontia[3], Jeffrey A. Hanks[4]

E. I. du Pont de Nemours & Company

[1]DuPont Engineering Technology, 101 Beech Street, Wilmington, DE 19880-0840
Ted.Diehl@USA.DuPont.com,

[2]DuPont Engineering Technology, 101 Beech Street, Wilmington, DE 19880-0840
Ricky.D.Dixon@USA.DuPont.com,

[3]DuPont Engineering Technology, 101 Beech Street, Wilmington, DE 19880-0840
Mark.A.Lamontia@USA.DuPont.com

[4]DuPont Advanced Fibers Systems, 5401 Jefferson Davis Highway, Richmond, VA 23261
Jeffrey.A.Hanks@USA.DuPont.com

Abstract: This paper discusses using ABAQUS/Standard and /Explicit to model the structural performance of systems containing woven fabrics. Predicting the mechanical response of structures in which fabrics are a dominant load-carrying component can be extremely difficult, especially for unimpregnated, loosely woven materials. After introducing the structural essence of fabrics, topics include limitations and numerical problems of classical orthotropic lamina models, an improved generalized cargo-net approach, models for membrane-only and general shell behaviors, and experimental measurements utilized to obtain effective modeling constants and other model parameters.

1. Overview of a typical woven fabric

Unimpregnated and slightly-impregnated woven materials are found in many engineering applications covering a broad spectrum of uses. A few examples include military, police, and correctional officer vests, parachutes, airbags, cargo containers, tornado-resistant rooms, and industrial transport belts. Figure 1 pictures typical woven and knitted fabrics. While this paper concentrates on methods to model the mechanical response of orthogonally woven fabrics (Figure 1a and 1b), many of the concepts and approaches discussed here could be applied to the more complicated knitted structures depicted in Figure 1c and 1d.

The left side of Figure 1 shows two types of woven structures, a loose weave (a) and a tight weave (b). Woven fabrics are constructed by interweaving *warp* and *fill* (also called *weft*) yarns in orthogonal directions. Usually a yarn is made from many individual filaments (easily seen in the knit pictured in Figure 1d). A yarn made from a single filament is called a mono-filament (demonstrated in Figure 1a). A balanced fabric has the same construction in both weave directions and thus similar stiffness responses for both weave directions. Unbalanced fabrics have different warp and fill constructions resulting in different orthogonal stiffnesses. Unimpregnated (*dry*) fabrics contain only woven yarns; there is no matrix material (also called resin, filler, or bonding material). Slightly impregnated fabrics contain a small percentage of matrix material.

In a classical "rigid" composite material, the matrix material is a much more significant portion of the entire structure. Unimpregnated and slightly impregnated fabrics exhibit structural behavior that is significantly different from classical composite materials which are typically analyzed by Laminated Plate Theory (LPT).

Figure 2 depicts that woven fabrics behave differently from traditional homogeneous sheet materials such as steel or plastic. To highlight the difference, compare the mechanical response of homogeneous versus woven sheets. For an isotropic, homogeneous material, loading samples cut in various in-plane orientations from a larger sample would produce identical stiffnesses for each direction measured, primary or bias. A woven fabric responds with a relatively high stiffness in its primary warp or fill directions but with an extremely soft stiffness in the bias direction, along an axis rotated 45 degrees from a primary direction. For loosely woven fabrics, bias stiffness can be 1/100 or even 1/1000 of the primary stiffness. This extremely low bias stiffness allows fabrics to endure large in-plane shear strains before buckling/wrinkling occurs. This behavior enables fabrics to assume manifold shapes that have complex multidimensional curvature. This can be simply demonstrated by attempting to conform a homogeneous sheet and a woven sheet to a sphere. The fabric will conform more than the homogeneous sheet before wrinkles develop.

1.1 Approaches for modeling woven fabrics

For any analysis problem two issues that arise immediately are scope and dimension. If the scope is to understand penetration mechanics of an ice-pick stabbing against a correctional officer's vest, then modeling detail must include true-scale representations of yarns and possibly filaments in their actual 3-D woven geometry. Such a model would require solid elements[1] and complex contact interactions. To be computationally feasible, this type of model could only analyze the neighborhood of the penetration area. Such a detailed approach is impractical for analyzing global structural responses of airbags or parachutes loaded by pressure. Here, an equivalent, smeared representation of the fabric's effective material response is employed to enable use of efficient membrane or shell models. This paper concentrates on global-level fabric models.

In an industrial setting, it is important that the modeling approach work well with both ABAQUS solvers, /Standard and /Explicit. Two reasons to utilize ABAQUS/Explicit are (1) that fabrics are often used to mitigate high speed projectiles and blasts loads and (2) that fabric deformations often exhibit large amounts of buckling and wrinkling. A strong negative against the use of ABAQUS/Explicit is solution noise. When analyzing the deformed shapes and strains of a woven belt under quasi-static loading, for example, the results computed from ABAQUS/Explicit can be

---

[1] With some of the new contact logic in /Explicit V6.3, an all beam model for this level of detail may be possible, although this has not yet been attempted by the authors.

very noisy. The structural vibration modes can span a large eigenspectrum of frequency ranging from out-of-plane modes at low frequencies to in-plane modes at much higher frequencies. Because of this, common methods of solution damping in /Explicit do not generally suffice in preventing or removing solution noise without causing significant degradation of solution accuracy. Solutions with large amounts of noise cause problems such as inaccurate interpretation of strain contour plots due to the noise and potential aliasing of data. See (Diehl, 2000) for further details on analyzing noisy data in /Explicit analyses. For quasi-static loading cases, ABAQUS/Standard solutions are preferred because the solutions do not have high frequency solution noise. However, when severe solution discontinuities or instabilities occur, especially in problems involving contact, obtaining converged solutions in /Standard may not always be possible. Thus, the ability to analyze a specific problem using both /Standard and /Explicit is desired; including the ability to restart from one solver to the other.

Since woven fabrics can be engineered from a vast array of filament and yarn materials, the resultant fabrics can have a large range of material responses from linear elastic, to nonlinear hyperelastic, to elastic/plastic, to viscoelastic, and more. Having a "fabric material law" that can represent these various fundamental material responses combined with the effective structural response observed in a fabric due to its woven nature is a significant challenge. By simply looking in the ABAQUS material library, the user finds no specific material law directly designed to model fabrics. So the question becomes what modeling options does one have in ABAQUS? Some possible options are described below.

1.1.1 User material subroutine approach

Coding a user subroutine offers the potential of capturing any available fabric models found in the literature or derived by the person coding the subroutine. This powerful flexibility has significant advantages, but at a costly price. There are at least three negatives to applying this approach with fabrics. First, the theory involved is much more complicated than typical constitutive law development because an effective fabric material law must include the constitutive law of the yarns plus complicated nonlinear coupling terms stemming from the weave undulation and cross-over friction. Second, there are limited published theoretical models of this type, and they almost all assume linear constitutive behavior for the yarns. Third, significant time and energy is required to develop and validate user subroutines. Since it is likely that both /Standard and /Explicit analyses will be used, two subroutines must be coded (one for each solver). It is noted that the additional need in /Standard for the Jacobian of the material law adds significant difficulty to the task. For industrial settings, these negatives outweigh the positives, rendering this approach impractical in most cases.

1.1.2 ABAQUS orthogonal material law approach

A second option is to utilize current ABAQUS capabilities that model orthogonal, linear elastic, plane stress structures using *ELASTIC, Type=LAMINA (or *SHELL GENERAL SECTION). One might initially think that an orthogonal material law approach should be viable, however, this section will highlight problems that occur using this method when modeling fabrics. As a starting point, one can leverage large amounts of experience and information from classical composites theory and similar orthotropic analysis. Also, these orthotropic material laws already exist in ABAQUS, both /Standard and /Explicit.

Figure 3 depicts a simple uniaxial tension analysis of a woven fabric sample (20 x 2) modeled with a *ELASTIC, type=LAMINA material law in ABAQUS/Explicit. The model used S4R shell elements. The material parameters were $E_1 = E_2 = E$, $\nu_{12} = 0$, and $G_{12} = 0.001E$. These values came from experimental measurements of a loosely woven belt material similar to that depicted in Figure 1a. It is important to note that the shear modulus is 1/1000 the value of the primary moduli E_1 and E_2, typical of a loosely woven fabric. The load/displacement plot in Figure 3 shows that the solution produced a linear response until a displacement of about 0.05 (0.25% strain) followed by an artificial instability not present in the physical tests. The associated images of deformed shapes in Figure 3 show a reasonably deformed mesh prior to the numerical instability and a zig-zagging mesh after the instability. At first look, this result looks like hourglassing, but it is not. A similar result occurs when using S4 shells and even lower order triangles S3R. The lower order triangles do not have any hourglass modes. Moreover, solutions in ABAQUS/Standard produced similar results with a valid linear response up to about 0.05 displacement and then a sudden numerical instability causing the solution to halt from non-convergence.

Additional evaluation of the /Explicit model results indicate many of the integration points in the mesh rotated by 45 degrees at instability. This behavior was being caused by the extremely low shear modulus used to represent the fabric. Artificially increasing G_{12} to $0.01E$ generally fixed the numerical instability or delayed it further into the solution. The basic problem with the models is that an orthotropic material law is always orthotropic with principal directions that are orthogonal to each other, regardless of the deformation state. During deformation in the fabric model, the primary stiffnesses defined by E_1 and E_2 are always orthogonal. If in-plane shear deformation occurs, the material points rotate but the material law still enforces that E_1 and E_2 are orthogonal in the rotated state. In a real fabric structure the primary fabric stiffnesses which are governed by the yarn directions do not necessarily remain orthogonal under loading. Figure 4 depicts a single "cell" in a fabric structure after it has been sheared. Yarn directions, which dictate primary stiffness directions, skew into a rhombus upon shearing, meaning their combined stiffness can no longer be represented by an orthogonal material law. For the solutions computed by ABAQUS, the material integration points in the elements experienced nearly instantaneous rotations of 45 degrees when numerical instability occurred. For a regular rectangular mesh, we would expect that the element edges of the mesh deform like the yarn of an actual fabric. By observing the individual element edges from the solution in Figure 3, it is clear that the deformed mesh pattern after instability is not a plausible representation of an actual fabric. If an actual fabric endured such a zig-zag deformation, it would have massive stretching of yarns and unrealistic stretch gradients.

It is noted that classical composites have higher shear moduli than fabrics. Hence, models of classical composites avoid such numerical stability problems. Unfortunately, for unimpregnated and slightly impregnated fabrics, this type of numerical issue renders the simple orthotropic material laws ineffective when used by themselves.

1.1.3 ABAQUS Rebar approach

A woven fabric is highly reinforced with yarns that are oriented in well-defined directions. From this viewpoint, it would seem that ABAQUS' Rebar capability might be useful to model fabrics.

Rebars in ABAQUS are designed to model uniaxial reinforcing members that are embedded inside other materials such as steel rods in cement or cords in tires. Rebar in ABAQUS is implemented as an embedded entity in membrane, shell, or solid elements to produce a *smeared* uniaxial reinforcement effect. Since Rebars are embedded into other elements, their deformation (stretch and rotation) is directly connected to the underlying element's shape function. This kinematic coupling between the Rebar and underlying elements is intended to reinforce the structure much like a given yarn direction reinforces a fabric. Moreover, if two separate Rebar layers are used to model initially orthogonal reinforcement in a membrane, then an in-plane shear load should cause a non-orthogonal reinforcement to develop during deformation just like that of the fabric depicted in Figure 4. Because of these desirable behaviors, it was suspected that a Rebar approach would resolve the numerical issues found using the traditional orthotropic approach of Section 1.1.2.

Unfortunately, test cases run in ABAQUS V6.2 using the Rebar approach also suffered numerical instabilities similar to those of the previous Section 1.1.2. Discussions with ABAQUS, Inc. indicate a bug in the Rebar implementation of V6.2 created the numerical instabilities. The bug has been fixed in ABAQUS V6.3 and now Rebar models of the test case from Figure 3 run successfully in ABAQUS/Standard and in ABAQUS/Explicit when using the option of element-by-element stable time increment estimates. Further evaluation of the Rebar approach on other fabric analyses has not yet been completed by authors. If the Rebar approach demonstrates general applicability, two benefits are that it would allow irregularly shaped meshes necessary for local mesh refinement and that the Rebar reinforcement can work with many of the existing ABAQUS material laws. One significant exception is that it currently cannot utilize the hyperelastic (and hyperfoam) laws. This limitation would prevent modeling highly stretchy fabrics like Spandex™ stretch paints, sport-bras, or bodyshapers with the Rebar approach.

1.1.4 Cargo-net approach

A literal modeling approach of woven fabrics would represent each yarn with beam or truss elements. A smeared or homogenized representation of the fabric would approximate the real weave with fewer, but individually stiffer, yarns such that the global response of the smeared representation was similar to the actual fabric. In many cases, the cross-over points of the undulating and entwined yarns of real fabrics do not move large relative amounts under load (excluding cases like out-of-plane fabric penetration from a projectile). Using a simplifying assumption that the yarns are tied at the cross-overs, the woven fabric becomes similar to a cargo-net (with knotted cross-overs). Models using this construction are sometimes called trellis models. This modeling technique is capable of supporting large, global-scale, fabric models that are computationally efficient. One limitation of a cargo-net model is that localized mesh refinement is very difficult and can only be achieved with complicated constraint equations. The following section describes this modeling approach in greater detail.

2. Cargo-net models

The heart of a cargo-net approach is the use of a net of truss elements. For simplification purposes, the undulating nature of the actual yarns is ignored and the truss structure representing the fabric is made to be initially planar. This assumption ignores an effect called weave coupling that will be addressed in Section 3.[2] A model made strictly of interconnect trusses will have two limitations: it will have zero initial effective shear modulus and limited ability to define surfaces for contact problems. These two problems are overcome by combining trusses with either membranes or shells.

2.1 Truss/membrane approach

For cases where bending effects are negligible, overlaying membrane elements onto a cargo-net of truss elements readily introduces shear stiffness into the model and gives greater flexibility relative to surface definitions for contact and other loadings. Figure 5b depicts the basic cargo-net approach where the membrane (or shell) mesh is aligned and equivalenced directly on top of a cargo-net of truss elements. Utilizing this modeling approach for the problem depicted in Figure 3 eliminated the numerical instability problems in both /Standard and /Explicit. The model was able to run to very large strains without difficulty.

To model a given fabric with this approach, the truss elements in each of the primary yarn directions are sized to represent the equivalent global stiffness that the actual fabric exhibits in that direction. If weave coupling can be ignored, the actual fabric can be simply stretched uniaxially in each of the two primary directions to physically measure the directional fabric moduli E_1 and E_2. This is typically achieved by stretching samples in a tension tester. The directional moduli are then converted directly to effective properties of area and extensional modulus for the truss elements.

The bias direction of the fabric is then measured to obtain the in-plane shear modulus G_{12}. A typical approach to obtain this value from composite materials practice is detailed in Figure 6. The method involves measuring several strains directly on the sample. Since measuring localized strains on fabrics is difficult and prone to large errors, the following equations based on orthotropic material theory and coordinate transformations (Jones, 1999) are recommended:

$$G_{12} = \frac{-\sin^2(\theta)\cos^2(\theta)}{-S_{\text{rot}} + S_{11}\cos^4(\theta) + 2S_{12}\sin^2(\theta)\cos^2(\theta) + S_{22}\sin^4(\theta)} \tag{1}$$

$$S_{\text{rot}} = \frac{1}{E_{\text{rot}}}, \quad S_{11} = \frac{1}{E_1}, \quad S_{22} = \frac{1}{E_2}, \quad S_{12} = \frac{-\nu_{12}}{E_1} = \frac{-\nu_{21}}{E_2} \tag{2}$$

In the equations above, E_{rot} is the apparent modulus that is directly measured on the biased test specimen.

The shear modulus G_{12} is simply assigned to the membrane elements in the model. To avoid pre-processor problems, negligibly small values of principal moduli (1/1000 E_1) are defined for the membrane element. Finally, the membrane element is given a zero Poisson's ratio to be consistent a cargo-net of truss elements with no Poisson effect.

---

[2] If weave coupling is significant in the actual fabric, then the methods described in Section 3 should be utilized to estimate effective values of E_1 and E_2.

Figure 5 shows two separate /Explicit models of fabrics being impacted by moderate-speed projectiles using the cargo-net/membrane approach. The top left image is a 100 mph (160 km/hr) projectile being stopped by a large Kevlar® fabric panel attached to wooden wall studs with discrete nails. The model captures the local pulling of the fabric as well as wrinkle lines. The bottom of Figure 5 shows the robustness of this modeling approach. In this later case, a square section of fabric is nailed on three corners (with the fourth corner free) and a large, fast, projectile is fired into it. The model predicts taught draw lines going from the impact location towards the three nailed corners while the free corner develops a “floppy ear”. The model also demonstrates the ability of the cargo-net model to simulate significant rotation of the yarns in the model.

A negative of this modeling approach is the lack of an in-plane shear-*stiffening* mechanism. In a real fabric, large shear strains as depicted in Figure 5c would not occur because the yarns would bind up against each other. This binding action would cause the shear stiffness to rise significantly as large shear strains developed. The sensitivity to this mechanism depends on weave tightness, yarn-to-yarn friction, yarn stiffness properties, and weave impregnation.

2.2 Truss/shell approach

For some fabric models such as transport belts deforming over manifold shapes that have multidimensional curvature or clothing models that predict wrinkle formation, bending stiffness must also be included. For these models, additional experimental measurements of bending stiffness about the two primary directions of the fabric are required. Because of the weak through-thickness shear stiffness of woven fabrics (similar to inter-laminar shear stiffness in composite theory), the apparent bending moduli from these measurements are almost always less than the in-plane primary modulus.

The fabric model is made by first using the shell element to define the observed primary bending stiffness in both directions and the in-plane shear stiffness. Then the truss elements are used to augment the model to obtain the proper in-plane primary stiffness. The sizing of truss element properties must consider the additive affect of the primary in-plane stiffness already coming from the shell elements.

A limitation of this approach is that the stiffness contributions arising from the shell elements always remain orthogonal at each shell integration point, regardless of the deformation. This applies to both the bending primary stiffnesses and the shell’s contribution to in-plane primary stiffness. An alternative approach to correct for this issue is to use a cargo-net of beam elements instead of shells and trusses. This latter approach appears to be cumbersome and has not been required or attempted by the authors. In the author’s experience, practical problems are such that if large in-plane deformations occur, and yarns are significantly re-aligned, then bending stiffness is usually not dominant and the previous truss/membrane model can be used.

3. Weave coupling in fabrics

Up to this point, the cargo-net approach of modeling woven fabrics has been demonstrated to be viable. It is important to evaluate model accuracy. This issue is problem specific and depends on how well the simplifying assumptions match actual mechanical behavior. A significant area of concern involves capturing the mechanism of *weave coupling*, illustrated in Figure 7. Here, two tests performed on samples taken from the same sheet of fabric are depicted. A uniaxial tension test produces a bilinear fabric response. However, when this same fabric is placed into a rigid square frame, clamped all-around, and loaded in the center with a rounded indenter, the observed effective modulus[3] is linear and approximately equal to an average of the weak and stiff moduli measured in the uniaxial test.

For normal materials, we would expect the apparent modulus from both tests to be similar. This is not the case for many fabrics, however. The cause for this behavior is the weave coupling between the warp and fill yarns. In the uniaxial test, initial stretching of the fabric in one direction tends to straighten-out the undulations of all the yarns in that direction. When this occurs, all the yarns in the cross direction become more undulated. Once the yarn in the testing direction is straight, its stiffness is greater than when it was simply being "unbent". These behaviors cause a bilinear response to be observed.

When the fabric is loaded biaxially (or pseudo-biaxially as in the case of Figure 7b), neither the warp nor fill yarns can fully straighten. Due to this mutual reinforcement, the initial fabric load-deflection response is stiffer than that indicated by a uniaxial test. When highly loaded, the load-deflection response is softer than a highly loaded uniaxial sample because of the remaining undulation in the biaxially loaded specimen.

The weave coupling effect is boundary condition and geometry dependent and cannot be captured generically with the models described in this paper.[4] A practical approach is to tune the stiffness parameters in the FEA model to experiments conducted with boundary conditions similar to the problem at hand.

Weave coupling also controls the effective Poisson's ratio of the woven fabric. The same interaction of unbending and straightening of yarns in each direction results in an apparent cross-direction strain. The nature of the rectangular-meshed, in-plane, cargo-net of truss elements is not able to capture this effect.

Having said that, it is reasonable to wonder how accurate the current cargo-net model will be with some changes in boundary conditions or fabric orientation. Figure 8 represents a cargo-net model and actual experimental data for two sets of boundary conditions and two sets of fabric orientation. The model has the same material constants for all four cases. The model correlates well to the experiments and the results further demonstrate the robustness of the modeling approach. Note that the deformed shapes are plotted in true scale with zero magnification of displacements.

In addition to the cargo-net model, four traditional modeling approaches were evaluated in this series of tests (note that only the cargo-net model results are shown in Figure 8). These other models were shell-only and membrane-only models (no truss overlays); each of which utilized

---

[3] Derived by backing out its value from the raw load displacement data using an FEA model of a fabric.

[4] It may be possible to use the generalized contact capability of ABAQUS/Explicit, V6.3, to simulate weave coupling with a woven (including undulations) mesh of truss or beam elements. This has not been investigated yet.

two material law representations: a simple homogeneous, isotropic material and an orthotropic material. All four traditional models and the cargo-net model produced similar results for the fully-clamped panel test. However, the four traditional models did not reproduce the mechanical behavior with corner-clamping. Only the truss-based cargo-net model was able to represent both the sensitivity to fabric orientation and the resulting load-displacement curvature seen in the data over all the variable ranges. Because the truss elements can rotate about the fabric surface-normal similar to fabric yarns under in-plane shear loading, they are able to best represent the effective stiffening (curvature) seen in the panel test load-displacement data.

It is important to note that all models used for the analysis depicted in Figure 8 utilized only linear constitutive laws. The nonlinearity in the load-displacement curves of Figure 8 arise from kinematic effects of the global structural deformation, not material effects.

4. Conclusions

This paper demonstrates a practical modeling methodology for analyzing the structural performance of fabric-based structures using both ABAQUS/Standard and ABAQUS/Explicit. A computationally efficient cargo-net modeling approach was shown to be robust and reasonably accurate for modeling fabrics at a global level. The model captures the oriented stiffness effects caused by fabric yarns, including the result of non-orthogonal stiffness developed during in-plane shear deformations. Two cargo-net approaches using truss/membrane and truss/shell models were described, and experimental methods were described to obtain model constants. The paper also discussed the added complexity of modeling weave coupling and some practical methods of approximating this mechanism's effect within the current cargo-net approach.

The paper demonstrated severe limitations of using traditional orthotropic lamina theory because of the "always orthogonal" principal directions inherent in the theory. This orthogonality constraint was shown to create numerical instabilities in both /Standard and /Explicit models attempting to simulate woven fabrics.

Reinforcement via Rebar was also investigated to model fabrics. This approach has significant potential, but a bug in V6.2 caused these models, (both /Standard and /Explicit), to produce numerical instabilities similar to the classical orthotropic lamina models. The bug has been fixed in V6.3 of both ABAQUS solvers. Applying Rebar models to fabrics has the significant advantage of allowing local mesh refinement; something that is extremely difficult to achieve with the current cargo-net approach. Finally, a future enhancement to ABAQUS' Rebar capabilities that would enhance fabric modeling is Rebar-to-Rebar coupling relationships. Development of this feature could potentially allow simulating such mechanisms as weave coupling and deformation-induced in-plane shear stiffening.

5. References

1. Bednarcyk, B., "Discussion of "Woven Fabric Composite Material Model with Material Non-Linearity for Non-Linear Finite Element Simulation" by Tabiei and Jaing", International Journal of Solids and Structures, Vol 38, 2001, pp. 8585-8588.

2. Diehl, T., Carroll, D., and Nagaraj, B., "Applications of DSP to Explicit Dynamic FEA Simulations of Elastically-Dominated Impact Simulations," Shock and Vibration, Vol 7, 2000, pp. 167-177.
3. Gasser, A., Boisse, and P., Hanklar, S., "Mechanical Behavior of Dry Fabric Reinforcements, 3D Simulations Versus Biaxial Tests," Computational Materials Science, Vol 17, 2000, pp. 7- 20.
4. Jones, R., M., Mechanics of Composite Materials, Second Edition, Taylor and Francis, 1999.
5. Tabiei, A., and Weitao, Y., "Comparative Study of Predictive Methods for Woven Fabric Composite Elastic Properties," Composite Structures, 2002
6. Tabiei, A., and Ivanov, I., "Computational Micro-Mechanical Model of Flexible Woven Fabric for Finite Element Impact Simulation," International Journal For Numerical Methods in Engineering, Vol 52, 2001.

Acknowledgments

The authors gratefully express their appreciation to colleagues at DuPont active in the effort. Clifford Deakyne was active in the mechanical characterization of the material and structural behavior. Brian Scott consulted in discussions of modeling methods and in performing physical testing of one of the major applications. William Hommes supported the original project activity for one of the key fabric applications. The authors also appreciate the efforts of the ABAQUS development staff, especially Harry Harkness and Bruce Engelmann.

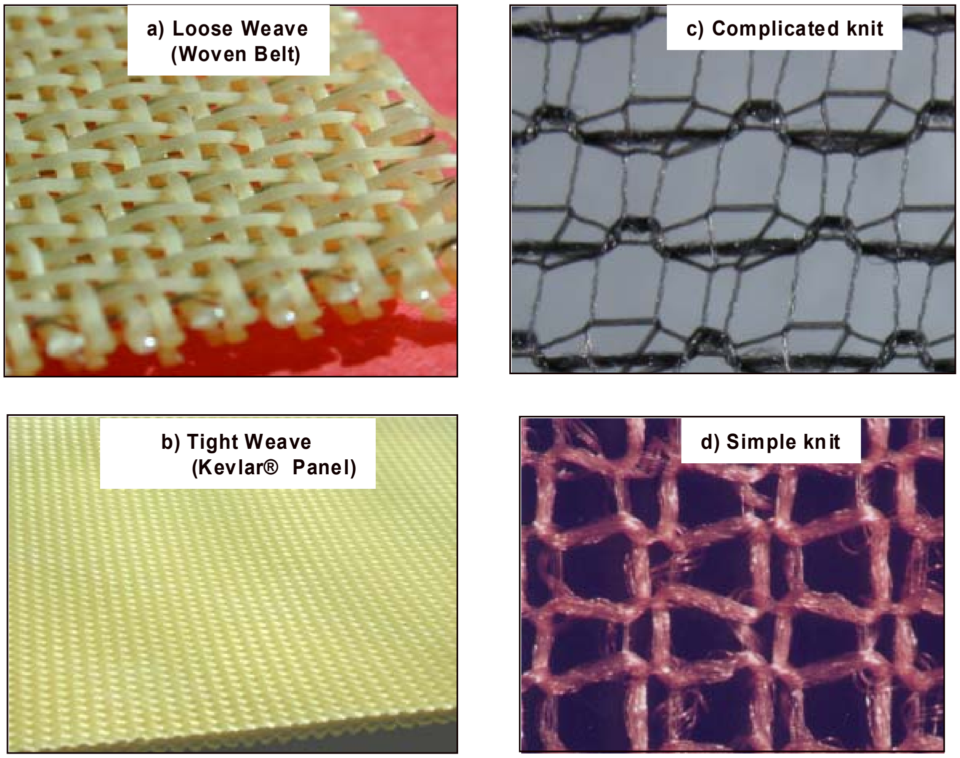

Figure 1. Typical woven and knitted structures.

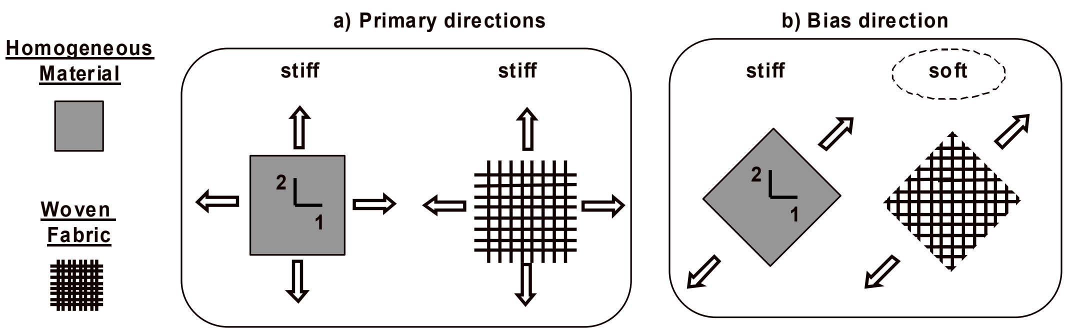

Figure 2. Homogeneous materials exhibit similar stiffnesses when tested in various directions. Woven Fabrics are stiff in fiber directions and very soft in the bias direction.

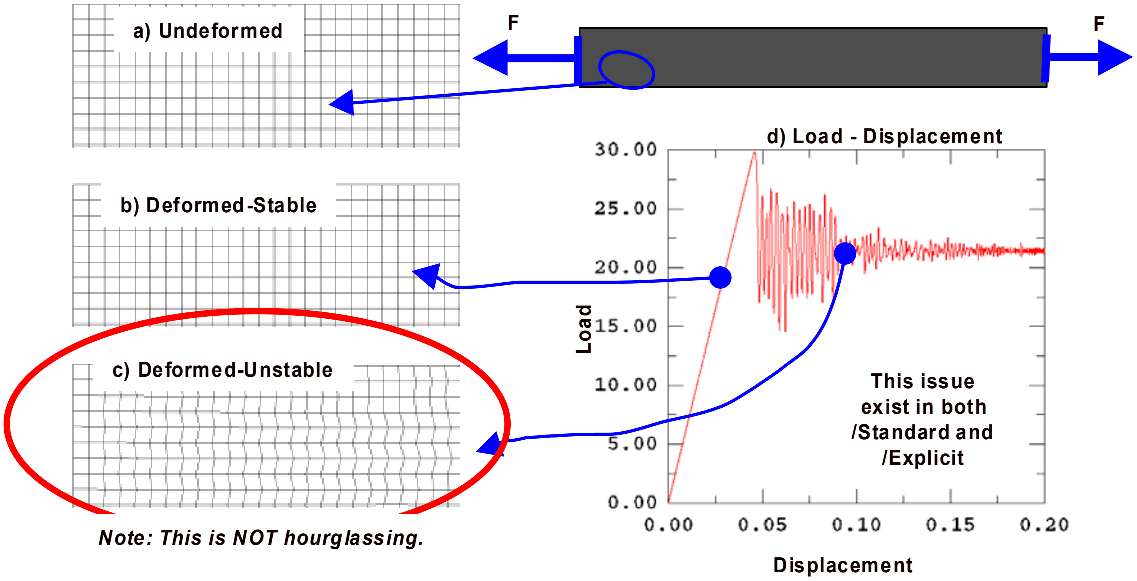

Figure 3. Extremely weak in-plane shear stiffness in woven fabrics often leads to numerical problems.

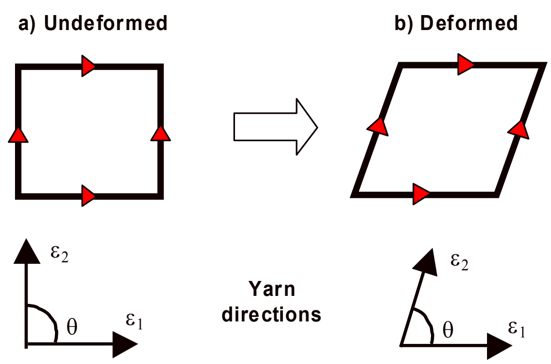

Figure 4. Yarn directions are orthogonal at rest when fabric is undeformed. Under nonuniform loading, yarns of the deformed fabric become non-orthogonal. FEA models that do not include this effect often suffer numerical problems.

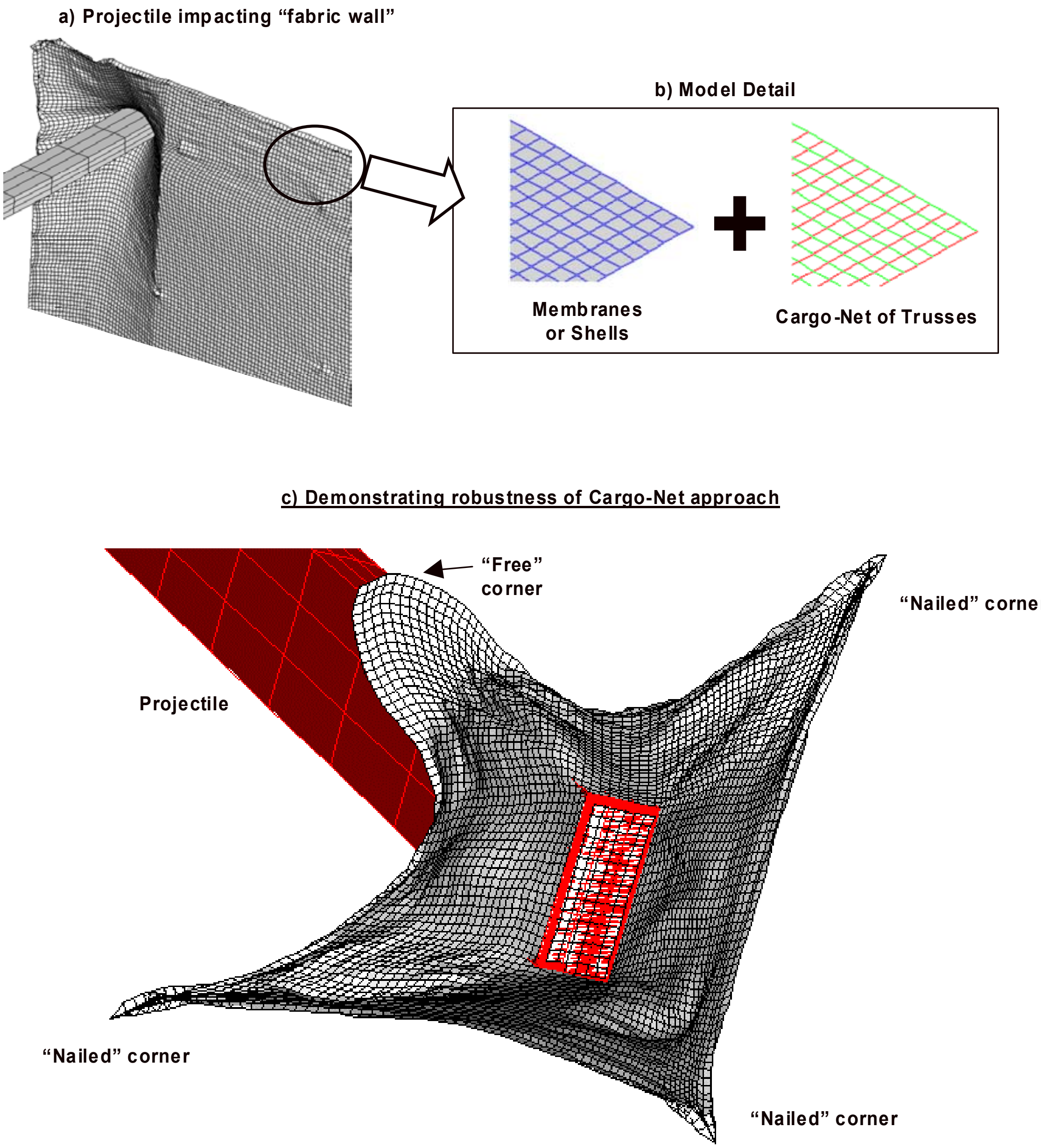

Figure 5. A cargo-net approach to modeling woven fabrics combines a mesh of trusses and membranes/shells to represent the actual fabric.

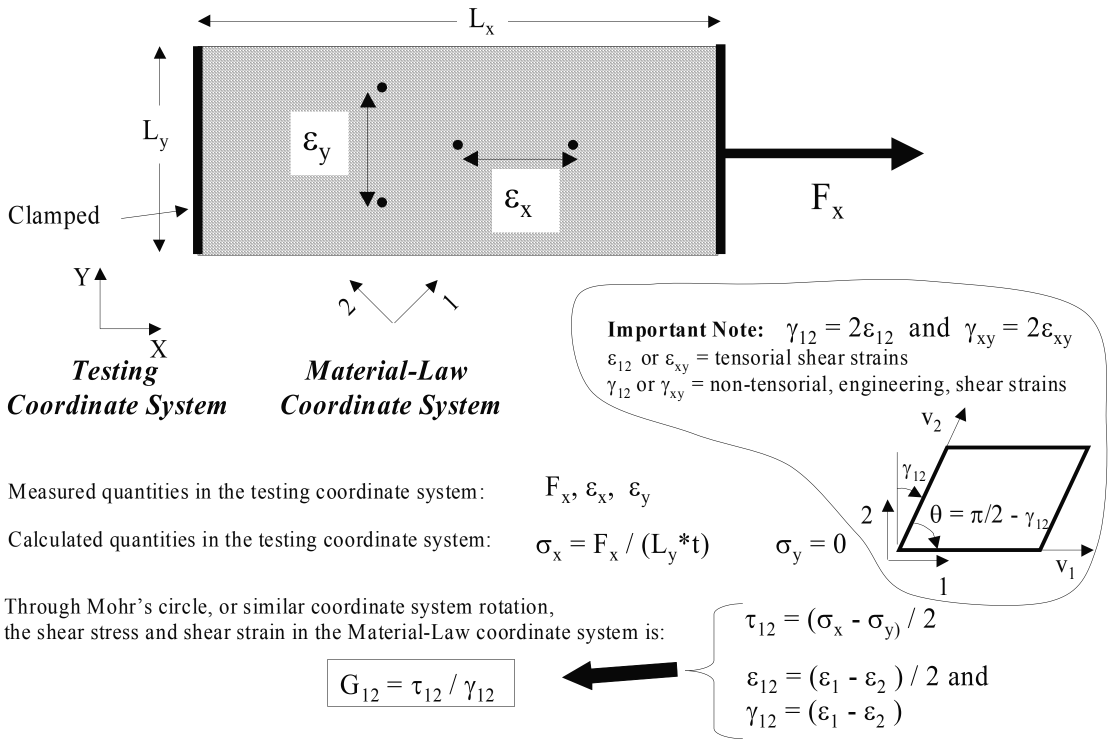

Figure 6. A classical approach to measuring shear modulus G_{12}.

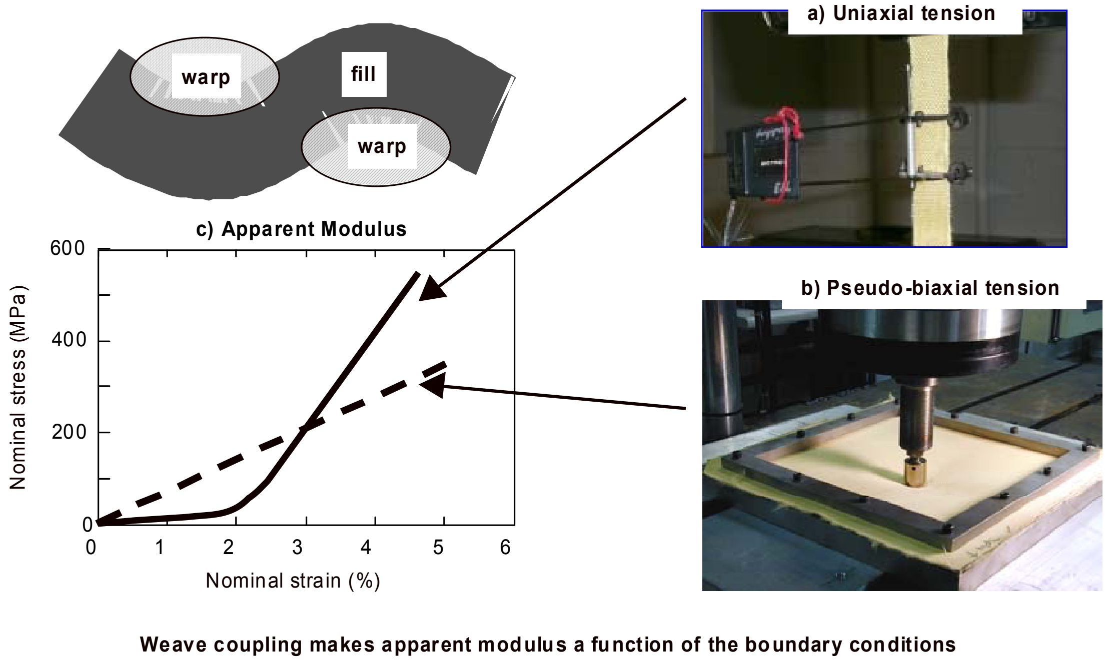

Figure 7. Fabrics can exhibit strong weave coupling. During uniaxial testing, the undulations initially present in the woven fabric are eventually removed at larger deformations, causing the fabric to exhibit a bilinear stiffness response. Biaxial loading of the fabrics preserves some amount of undulation, causing a very different stiffness response.

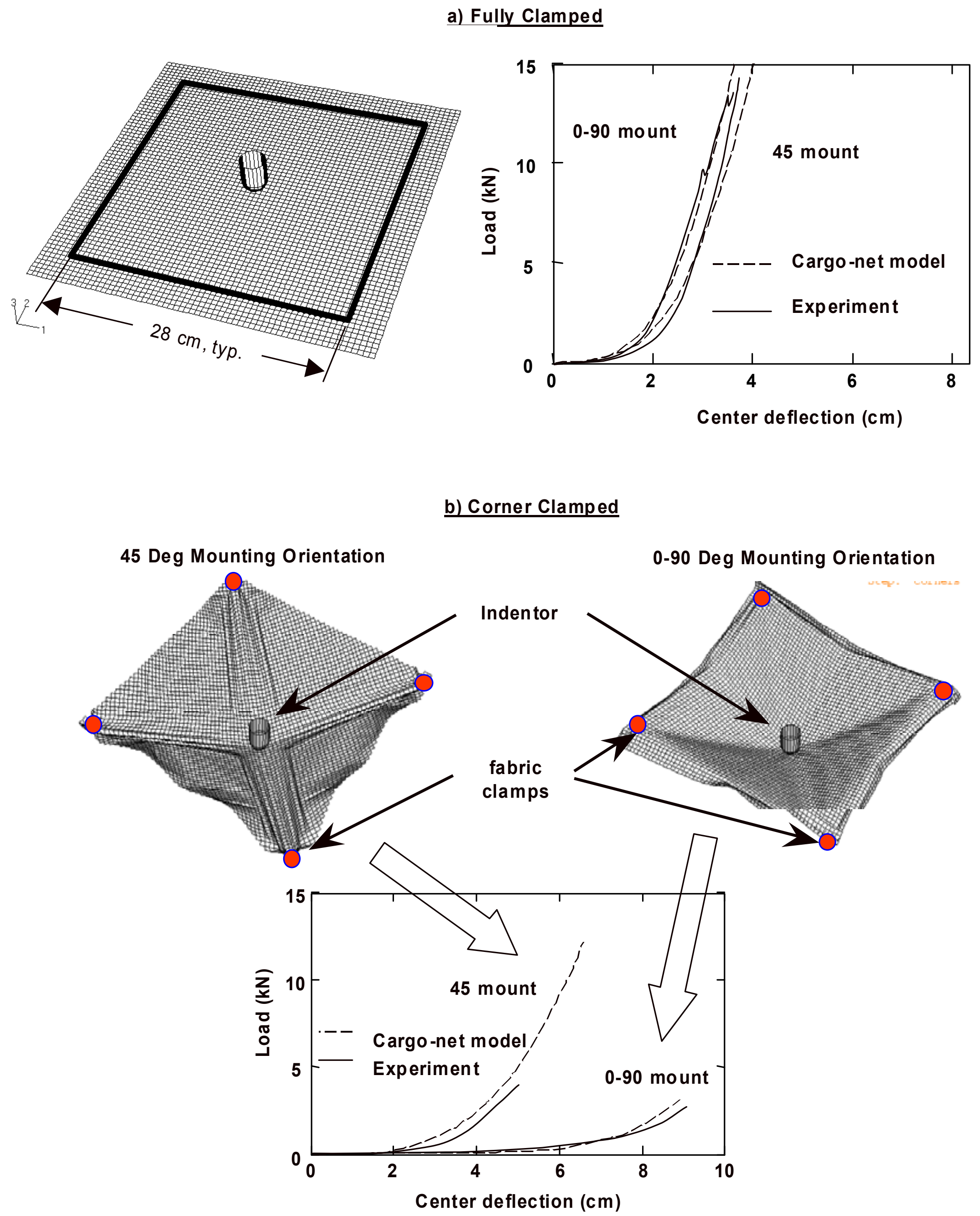

Figure 8. Panel tests used to back-fit cargo-net model parameters.