An Up-Close Model Characterizing a Highly Nonlinear, Fluffy-Cored, Skinned, Composite Material Used in a Local Buckling Analysis

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Abstract: Analyzing highly flexible, layered, composite sheets bent around tight radii can be very challenging. A particularly difficult case to analyze is a sandwich structure consisting of two monolithic skins and a fluffy "cotton-like" core. As the sheet is bent into a tight radius, the structure's deformation becomes highly nonlinear with localized layer buckling of the skin relative to its fluffy core. During this buckling the core experiences large strains, often causing material damage or failures in the core. This paper describes how a mixture of elastic and plastic material laws, contact approaches, and element formulations are used in conjunction with numerous experimental data sets to produce a viable model for highly flexible, fluffy-cored composite sheets enduring tight bends.

Keywords: composite, sheet, buckling, sandwich structure, core, fluffy-cored, laminate.

1. Introduction

A classical skin-core-skin composite structure is an aircraft honeycomb sandwich where the stiff honeycomb core separates stiff skins and manages shear flow in the composite. This paper considers a dramatically different skin-core-skin composite structure, namely a highly flexible, "paper-sheet-like" composite structure. The composite materials that are addressed in this paper are relatively thin sheets. They have bending and in-plane properties that are much closer to that of a sheet of paper or thin plastic sheet than those of a relatively rigid laminate composite.

Many modern, highly flexible, sheet materials utilize a composite structure for a variety of reasons. The material developer is often trying to strike a balance between cost, structural performance, weight, and other requirements such as porosity. To satisfy this myriad of constraints, some sheet structures utilize a skin-core-skin structure. One class of such sheet structures contains a “fluffy” core material that has a consistency similar to a cotton ball. This fluffy core might be built as a single layer or may be derived using several fluffy layers. Skin materials for these composite sheets have properties that range from a slightly more consolidated version of the fluffy core to a completely homogeneous material with properties that are several orders of magnitude stiffer and stronger than the core. The various layers of the sheet are then held all together by mechanical entanglement and/or adhesion (wax, glue, thermal bonding, etc.).

Figure 1 contains several images showing the fluffy-cored composite sheet structure response to being bent into a tight radius – the skin on the compressive side of the sheet buckles. Buckling often causes severe damage to the core material and other undesirable effects such as failure of the core and possibly the skin. The goal of analysis in this type of problem is to develop a model that is capable of representing the different constituents and the deformation mechanisms that occur so that one might determine an improved composite design that will limit such buckling and damage.

2. Modeling approach

To develop the model, we first consider the structural response of a simple layered structure. Consider a soft-cover book as an approximate analogy to a many-layered skin-core-skin structure.[1] Figure 2 depicts the bending of the soft-covered book under three different boundary conditions. When the book is bent in a manner that allows the individual pages to freely slide relative to each other (Figure 2a), no buckling occurs. Neglecting frictional effects, the global bending stiffness observed in this case is simply the sum of the individual bending stiffnesses of each page. There is no additional stiffness caused by the "parallel axis theorem effect" (the ad^2 term) because the ability to carry the in-plane shear stress required for this effect is absent. As constraints are added to minimize the global sliding of the pages (Figure 2b and 2c), the global bending stiffness increases and localized page buckling develops on the bottom side of the structure. This behavior is similar to the behavior observed in the skin-core-skin structures of Figure 1.

This soft-cover book analogy can be the starting point of models for skin-core-skin structures once one additional improvement in the analogy is implemented. The discrete end conditions utilized in Figure 2b and 2c must be replaced with continuous page-to-page shear constraints such as a compliant adhesive smeared between all the pages. With this addition, the analogy describes the primary buckling behavior that is depicted in Figure 1. It includes representations of the core and skin, nonlinear material response of the individual material layers, and large deformation post-buckling kinematics. It is noted that models that rely solely on a classical composite shell approach will not have sufficient local detail to properly represent the buckling behaviors observed. Instead we shall use a modeling approach that combines solids, beams (shells in 3D cases), and softened contact.

Figure 3 depicts a 2D ABAQUS model of a skin-core-skin sheet. The model as shown represents a case where the core is 50% of the sheet's thickness, and the top and bottom skins are each 25% of the sheet's thickness. The sheet is similar in thickness to a typical sheet of copier paper. The model utilized a layered approach, idealizing the skin-core-skin sheet structure as numerous reinforcing layers embedded in matrix materials. The matrix materials are represented with solid elements and the reinforcing layers are modeled with beams (shells in 3D analyses). The model

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[1] The soft-cover represents the skin and the book's pages represent the core.

utilizes softened contact between the reinforcing layers to account for through-thickness densification that occurs during tight radii bending. The model as shown was a 2D /Standard model. The authors also evaluated 3D /Standard and 3D /Explicit models, explained later.

Further clarification is helpful to fully understand how the core's through-thickness tension, compression, and shear behavior are modeled. Both Figures 1 and 2 demonstrate that fact that as the composite sheet buckles, the system resistance to the layers spreading apart is much softer than the resistance to the layers coming closer together (compressing). This type of complex behavior is usually difficult to model with a single constitutive law. It is easier to utilize two mechanisms in the FEA model that, in actuality, mimic the real physical mechanisms. First, a tabular version of softened contact between each of the reinforcing layers simulates a densification behavior whenever any portion of the reinforcing layers (beams in 2D or shells in 3D) is placed into through-thickness compression. The compressive load that acts to decrease the spacing between reinforcing layers is increasingly resisted by the softened contact constraint — simulating densification. The softened contact exhibits no resistance to the reinforcing layers spreading apart or sliding relative to one another (contact friction is not included in the model). The solid elements representing the core-matrix model both the normal tensile stiffness and the layer-to-layer shear stiffness (reinforcing layers sliding relative to each other). Since the core-matrix solid elements will also act in compression, the values used on the softened contact representation are compensated accordingly to obtain the proper combined nonlinear densification resistance.

In the ideal world, we would know the individual properties of each layer making up the core and the skins as well as the adhesion properties that bond them all together. Unfortunately, this data is rarely available; the analyst is only given the complete sheet structure to obtain property data. To help de-convolve the measured global sheet properties and assign localized component properties (skin properties, matrix properties, etc), the analyst often relies on casual observations from the product and its manufacturing process to develop initial model parameters.

For the type of sheets depicted in Figure 1, it was known that the skins were much stiffer and stronger than the core. Thus the *matrix core* was assumed to govern through-thickness (y-direction) adhesive behavior; normal and shear, between the reinforcing layers. Properties of the matrix skin (the outer layers of solid elements that exist in the region designated as skin) are assigned so that it contributes to global membrane and bending behavior of the sheet. The reinforcement beams participate in membrane, bending, and through-thickness densification resistance (via softened contact). Since the core material was much softer than the skins, the beam properties in the core are assumed to be some small fraction of the beam properties in the skin.

3. Material measurements and model calibration

Figure 4 depicts deformation modes that were applied to the composite sheet to calibrate the individual model components described in Section 2. If all the model input parameters (number of layers, material constants for each model component, etc.) are totaled up, it quickly becomes apparent that the five test modes shown will not uniquely define all the model parameters. Moreover, several of the material responses that are measured from the tests depicted in Figure 4 are nonlinear and include plasticity. Other information about the sheet's manufacturing process is required to make additional assumptions so that model calibration is tractable. As a result, the model calibration ultimately results in an iterative optimization problem. The analyst initially assigns model input parameters and then compares model responses to the test modes. Adjustments in model parameters are then made until acceptable agreement across all test modes is found.

To give some perspective to this, a few sample representations of physical measurements for three of the global deformation modes depicted in Figure 4 are presented in Figures 5 and 6. These modes are membrane tension, through-thickness tension, and through-thickness shear. The data is representative of the materials depicted in Figure 1. Figure 5 demonstrates that the membrane tension behavior of the entire sheet exhibits elastic/plastic behavior. The test data also shows that the response variability across a number of samples is modestly large. Note that at a value of 15% nominal strain, some samples produced almost twice as much stress as others. In addition, some samples had failed at a strain of around 12% while others lasted up to 17%.

Figure 6, showing through-thickness tensile and shear behavior, demonstrates that the observed variability in these two modes is dramatic, even though the tests were carefully done on specially designed fixtures that were highly instrumented by experience test engineers. The large variability observed in the tests has two main contributors: the random and variable nature of the cotton-like core material itself and the inherent difficulties in testing structural properties of very thin sheet-like structures in their through-thickness direction. In the through-thickness test, it was assumed that all the deformation was attributed to the core response since the skin response was much stiffer. Plotted along with the raw data of Figure 6a is the average measured membrane tensile modulus of the sheet. This modulus is nearly vertical relative to the though-thickness data, further confirming the assumption that the skins were much stiffer than the core. Given this fact, the model required only a reasonable estimate of the core's tensile behavior. A linear modulus of 0.017 times the membrane modulus was chosen as an estimate of the average core tensile behavior exhibited among the various samples tested.

Figure 6b shows the actual through-thickness shear data. The near vertical line on the shear graph is the membrane shear modulus of the sheet derived from the tensile membrane sheet modulus in Figure 6a (via Hooke's law, using an assumed Poisson's ratio of 0.2).[2] Similarly, the core shear modulus was derived from the core tensile modulus of Figure 6a (via Hooke's law, using an assumed Poisson's ratio of 0.2). Figure 6 demonstrates that for a first order estimate, it was possible to model the core material tensile and shear behavior using isotropic Hooke's law. An enhancement to this approach would be the use of an elastic/plastic representation, possibly with failure. The authors have successfully utilized both approaches for this class of problem.

4. Results

Figure 7 depicts the response of an ABAQUS/Standard version of the model to a tight bend. The model evaluated a 1.0 inch (25.4 mm) long strip that was rigidly glued on one side for half of its

[2] It is noted that since most of the materials are fibrous in nature, their effective Poisson's ratio will be small and not anywhere near incompressible. Considering this fact and the large variability in the material behavior itself, the sensitivity to the assumption of the Poisson's ratio utilize here is negligibly small.

length and then pulled into a tight bend as shown in Figure 7d. Compared to the experimental result shown in the photograph (and those from Figure 1), the model depicted the basic mechanisms both in locations on the sheet and in relative deformation magnitude. The model showed bulging (skin buckling), densification, and core shearing.

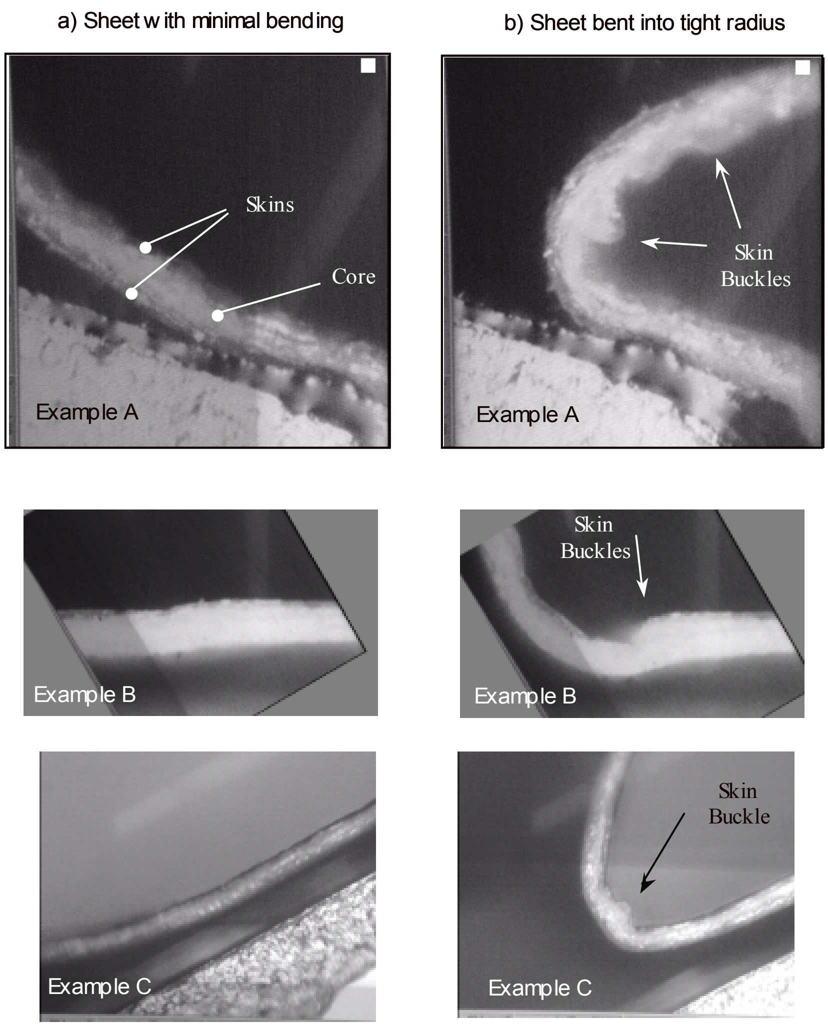
Figure 8 compares a /Standard model to a /Explicit model. The models both simulate bending the sheet into a tight radius. However there are two important differences between the models: sheet length and far-field boundary conditions. The /Explicit model was made much shorter to decrease solution time and minimize problems with low frequency dynamics of a long tail. Because the /Explicit model was made so short in length, the boundary conditions applied to the free end (tail) to induce a tight bending radius were slightly different from that used in the /Standard model. Despite these differences, the example demonstrates that the approach also worked well in /Explicit. In fact, /Explicit was more robust relative to modeling increasingly severe buckling and core failure (not shown here). When the /Standard model was pushed to solve a very tight bending radius (Figure 8b), the analysis frequently failed to complete because of convergence problems. Use of *STABALIZE might have been able to make the /Standard models run farther, but such tight radii were ultimately not required and thus this approach was not investigated further.

5. Conclusions

This paper has demonstrated an ABAQUS modeling approach to analyze thin sheet structures constructed from a fluffy core encased by skins that are bent into a tight radius. The models have utilized a layered approach, idealizing the skin-core-skin sheet structure as reinforcing layers embedded in matrix materials. The technique also used softened contact algorithms in a novel way to model through-thickness densification. The paper presented both ABAQUS/Standard and ABAQUS/Explicit implementations that were able to produce the same general structural behaviors and mechanisms seen in actual sheet materials of this type, namely localized skin buckling, through-thickness densification, and core shearing.

6. Acknowledgment

The authors gratefully express their appreciation to colleagues at DuPont active in the effort. John Bletsos and James Addison supported original development of these models. Delisia Dickerson helped provide much of the experimental data. We also appreciate the efforts of the ABAQUS technical support staff and development staff. Their suggestions for modeling approaches were both useful and timely.



Examples A through C are different samples taken from the same sheet. The various responses shown are caused by modest property variations over the sheet.

Figure 1. Examples of a fluffy-cored composite sheet exhibiting localized skin buckling when the sheet is bent into a tight radius.

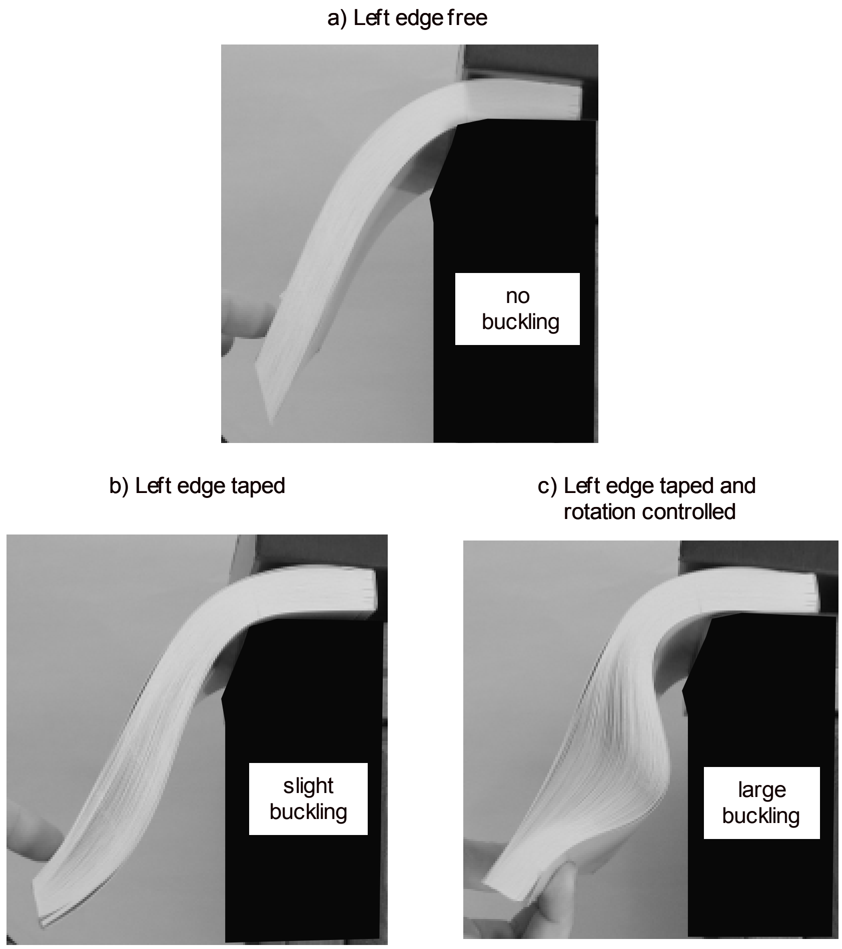
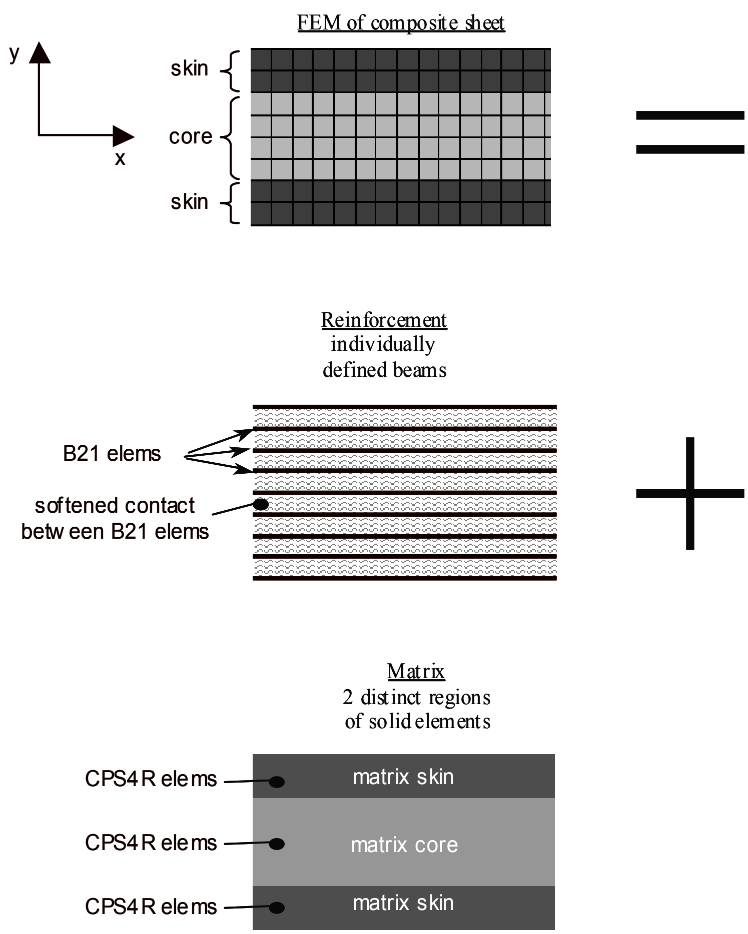


Figure 2. Deformation characteristics of a soft-cover book.



Notes:
1.) Example show n w as a /Standard 2D model.
2.) The mesh w as defined so that the beam elements and solid elements had aligned and overlapping meshes that shared one common set of nodes.

Figure 3. ABAQUS model representing fluffy-cored, skinned, composite sheet.

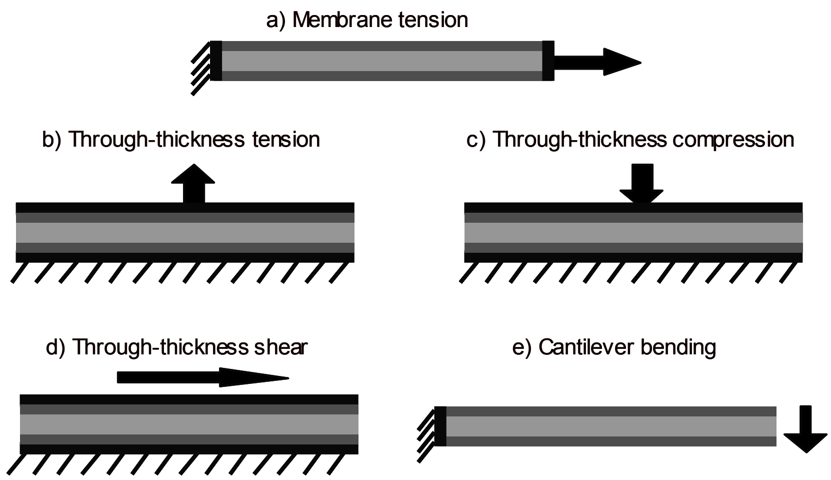


Figure 4. Global deformation modes utilized to calibrate model.

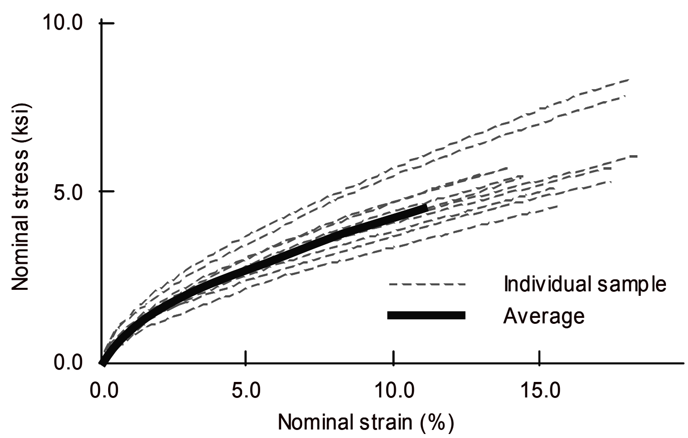


Figure 5. Typical global membrane tension response for an actual skin-core-skin sheet material.

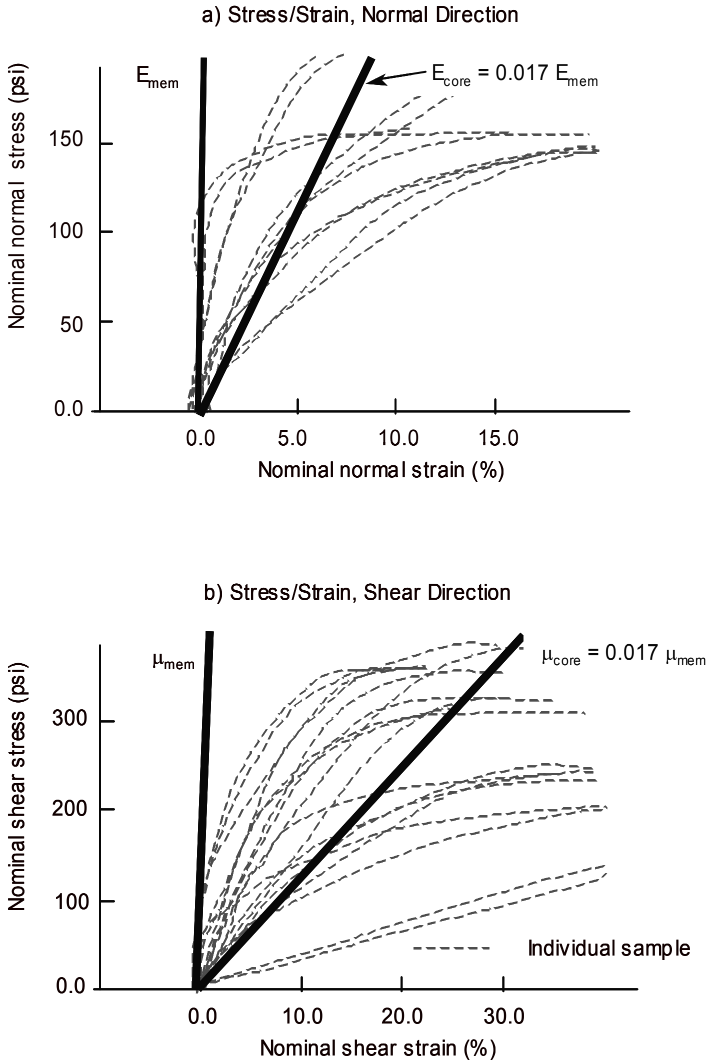


Figure 6. Typical through-thickness material response for an actual skin-core-skin sheet material.

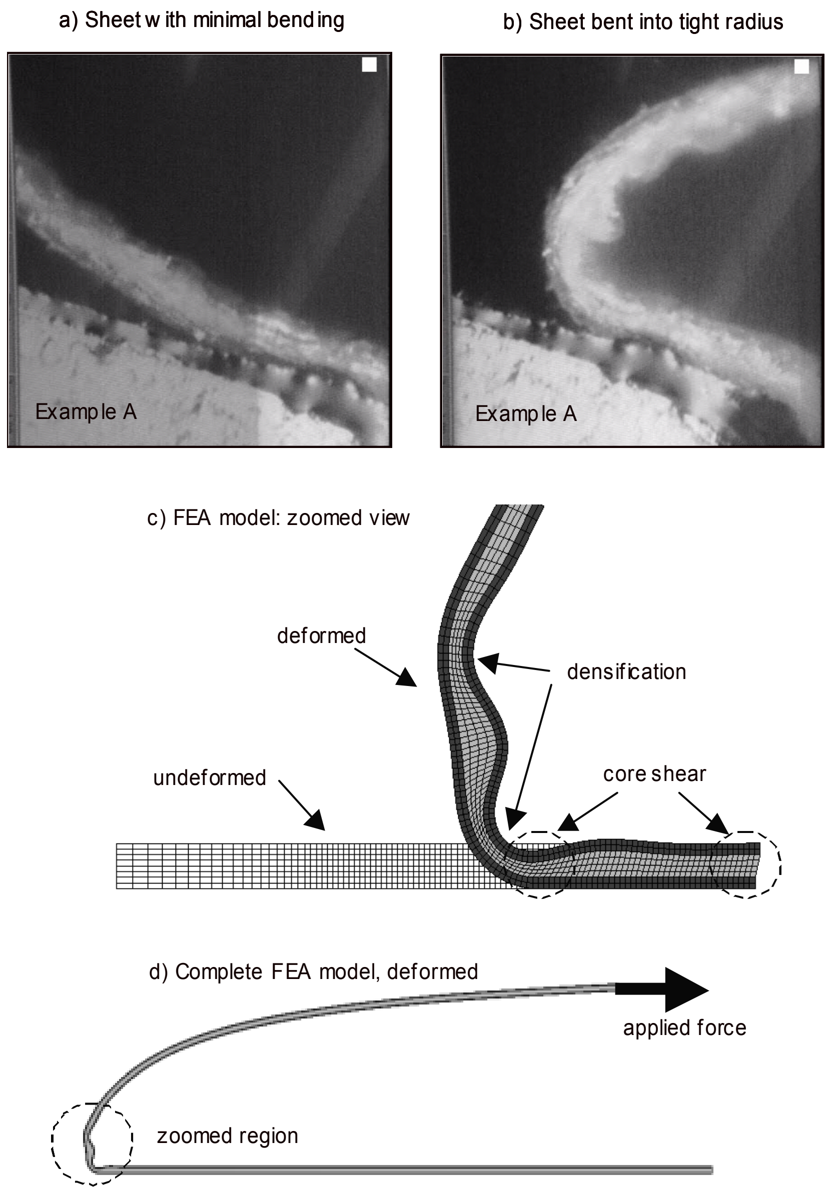
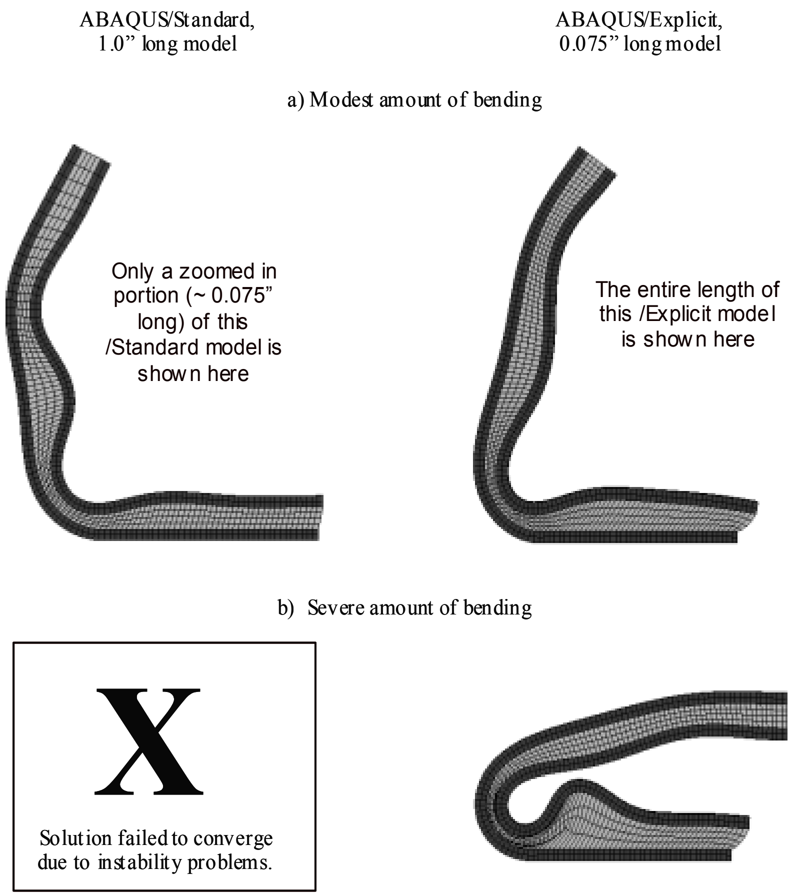


Figure 7. ABAQUS/Standard model's response to a tight bend.



Note: The fact that the /Standard model was much longer than the /Explicit model caused the far-field boundary conditions to influence the two models slightly differently.

Figure 8. Comparison of /Explicit and /Standard models.