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Structural Analysis of Wheat Stems

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Abstract

Design and development of improved harvesting, preprocessing, and bulk handling systems for biomass requires knowledge of the biomechanical properties and structural characteristics of crop residue. Structural analysis of wheat stem cross-sections was performed using the theory of composites and finite element analysis techniques. Representative geometries of the stem's structural components including the hypoderm, ground tissue, and vascular bundles were established using microscopy techniques. Material property data for the analysis was obtained from measured results. Results from the isotropic structural analysis model were compared with experimental data. Future work includes structural analysis and comparison with experimental results for additional wheat stem models and loading configurations.

Index Entries: Wheat straw; biomechanics, structural analysis; modulus of elasticity; composite materials.

Introduction

A potential resource for the production of biobased fuels and chemicals is wheat straw. In 1999, American farmers produced greater than 100 million tons of wheat straw *(1).* The effective utilization of crop residues for conversion into fuels and chemicals requires development of improved harvesting, preprocessing, and bulk handling systems for biomass. Design and development of these systems requires knowledge of the biomechanical properties and characteristics of crop residue.

Several design approaches are available to researchers to assist them in the development of biomass systems; examples include analytical, experimental, and numerical techniques. Numerical modeling and simulation in conjunction with experimental analyses is popular among scientists and

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engineers and has been used to simulate a wide variety of structures ranging from automobiles to plants *(2,3)*. The popularity of numerical modeling and simulation is owing in part to advances in computational software, hardware, and mathematical algorithms *(2)*. Modeling is used to improve the understanding of physical phenomena, interpret experimental results, analyze "what if" scenarios, and predict structural response including potential damage. Unfortunately, numerical studies in the field of biomechanics are limited, primarily owing to the complexities of plant physiology, which make it difficult to isolate and measure material properties of biomass constituents *(3,4)*.

The most common numerical solution technique for structural analysis is the finite element method. This technique begins with the development of a geometric model, which is divided into smaller regions called elements that touch without overlapping. For each element the governing differential equations of solid mechanics are approximated using much simpler algebraic equations. A coupled system of equations results, which is readily solved using a computer. Experimentally determined material properties, such as the modulus of elasticity, describing the stiffness of a material, and the Poisson's ratio, characterizing the lateral expansion or contraction of a material in response to an applied load, are required. The results of a numerical simulation are analyzed using graphic software and compared with experimental and analytical results. Several powerful numerical modeling tools for structural analysis are available to researchers including the ABAQUS (www.hks.com) and ANSYS (www.ansys.com) software packages. Models must be used with caution because the underlying assumptions used in their development may not be appropriate for certain materials under specific loads. This is particularly true when modeling plant structures under various loading conditions *(3,5)*.

This article presents preliminary studies using finite element analysis of a wheat stem. The study is motivated by the need to improve existing wheat-harvesting equipment. An isotropic model was used to simulate bending tests of wheat samples, and the results were compared with experimental data.

Approach

A typical wheat stem cross-section is shown in Fig. 1; it consists of several major constituents: epidermis, hypoderm, and inner ground tissue surrounding a hollow core *(6)*. The epidermis is a hard, rigid outer layer rich in cellulose containing tiny pores called stomata, which allow gas exchange between the plant and the atmosphere; the thickness of the epidermis varies between 25 and 30 μ. The hypoderm consists of a cylinder of thick-walled strong tissue (sclerenchyma) about 4 μ thick that encloses small vascular bundles and bands of chlorophyllous tissue. The inner ground tissue (parenchyma) is soft and extends from the hypoderm to the hollow core.

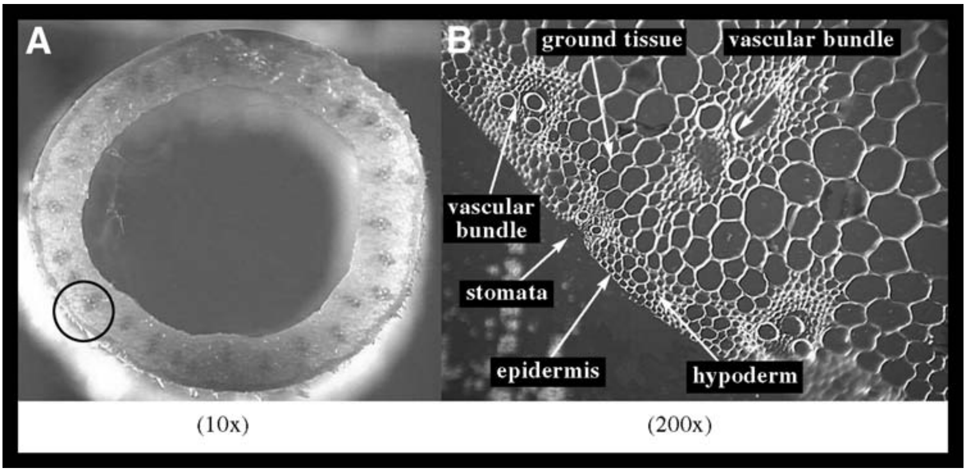

Fig. 1. Cross-sectional images of wheat stem showing major structural constituents. Magnification: **(A)** stem magnified 10 times normal: **(B)** stem magnified 200 times normal.

The inner ground tissue surrounds vascular bundles that are arranged in a ring-type pattern around the hollow core.

Using the theory of engineered composites, several representative models were developed for the wheat stem, ranging from a simple homogeneous three-dimensional (3D) model to a more complex micromechanical model. Each model has its advantages and disadvantages; any attempt to provide the physical details of a plant stem results in a more complex model. With this complexity, comes computational and experimental challenges including determining material properties of individual constituents and providing sufficient detail in the model so that it accurately represents the stem structure.

Strength of materials theory in conjunction with bending tests was used to determine material properties. Bending tests should be conducted for materials whose principal stressing mode is bending such as straw passing through a chopper. The modulus of elasticity of the wheat stem was determined by measuring the maximum displacement of the straw specimen under an applied load. The modulus of rigidity, which characterizes a material's response to an applied torque, was determined by measuring the maximum angular displacement of a straw specimen under an applied torque *(7)*. Shown in Fig. 2 are two types of bending tests, the three-point bend and the four-point bend *(4)*. In each test, a straw sample is placed between two supports, a load is applied to the specimen, and the displacement of the straw sample is measured. Using the displacement, and the sample geometry, the stiffness of the straw sample can be determined. Theoretically, both bending tests should predict the same modulus of elasticity for the wheat stem specimen. A significant difference between

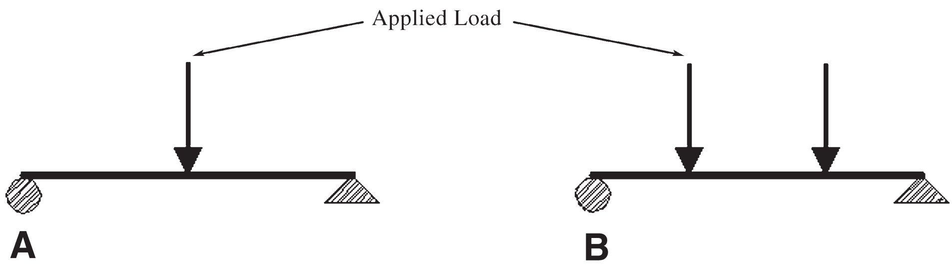

Fig. 2. Schematic representation of **(A)** three-point bending test and **(B)** four-point bending test used for comparison with experimental data.

the two bending tests is that in the four-point bend test the middle section between loading points is subjected to a constant bending moment allowing the stress distribution on the planes normal to the axis of the specimen to be the same. Results from this configuration are based on the desired pure bending stress. By contrast, the three-point bend test applies a single concentrated load at the center of the specimen. This single-point load causes a mixed set of stresses on the planes normal to the axis of the specimen, specifically bending and shear stresses. The mixed-stress state of the three-point bend test vs the single-stress state of the four-point bend test can cause significant differences in the respective measured results.

Several models of wheat stem cross-sections (Fig. 3) were considered for analysis: model A, a homogeneous isotropic model; model B, a transversely isotropic model; model C, a simple micromechanical model; and model D, a complex micromechanical model, in which each constituent is assumed to have unique isotropic properties *(8)*. In model A, the different types of stem tissues are not distinguished from each other, but, instead, the constituents are treated as "bulk tissue," which is a homogeneous mixture with material properties that are the same in all directions. The assumptions for this type of model are understood to be less than accurate, but it provides a simple and straightforward approach for determining trends and testing methods necessary for model refinement and more detailed models. Similarly, model B combines all the tissues into one homogeneous mixture in which the material properties on planes perpendicular to the axial direction differ from those in the axial direction. This model allows a distinction between the general orientation of the cells' structures and mechanical components. It also requires some knowledge of the mechanical behavior of the material in the transverse direction in order to simulate this configuration. Model C distinguishes two types of tissue distributions: a rind, which represents the epidermis and hypoderm tissues, and an inner matrix, which represents the ground tissue and vascular bundles. The material properties of the rind and matrix are assumed isotropic and homogeneous, but they differ from each other. This more detailed model starts to account for each structural component of the stem but, again, does not entirely account for cell orientation. Finally, model D

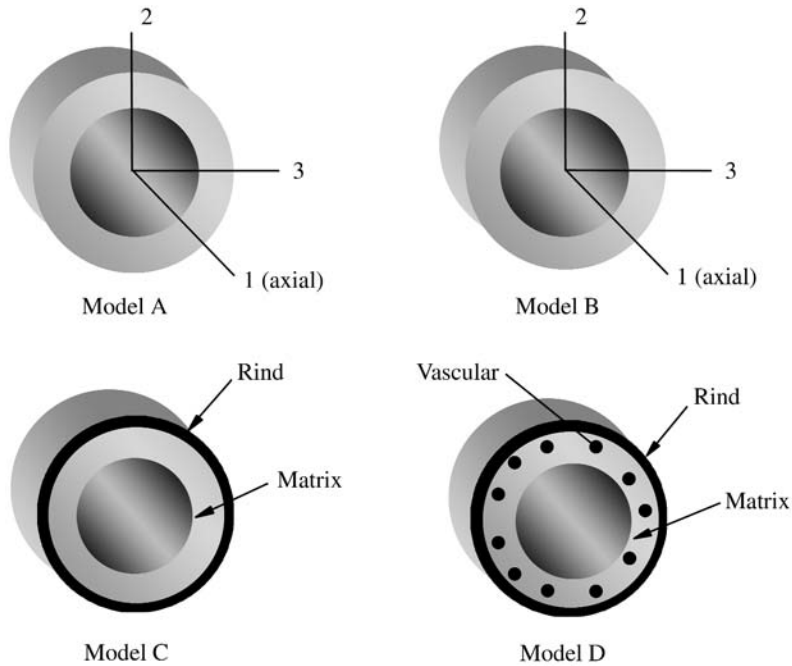

Fig. 3. Schematic representation of four wheat stem computational models. Each model progressively becomes more complex from A to D.

distinguishes three types of tissue distributions: a rind representing the epidermis and hypoderm tissues, an inner matrix representing the ground tissue, and the vascular bundle tissues. The material properties of each tissue are homogeneous and isotropic and differ from each other, making it the most complex of the four models described.

Methods

Ideally, we would have studied model D because it is the most complex and structurally accurate of the four models. However, at this stage of the research, experimental property data are not adequate to support this level of detail. Therefore, based on the experimental data available to verify a modeling method and our desire to gather general information and quantify trends, the most reasonable step forward was to assume that the chemistry of the plant cells provided a homogeneous mixture and use model A. Ultimately, this would provide a fundamental comparison with experimental data from which future work could be based.

Using ABAQUS, a commercially available structural analysis software package, we developed a 3D linear elastic model of a wheat stem using geometric parameters obtained from microscopy techniques. The elliptical, annular-shaped cross-section was approximated as a cylindrically shaped cross-section by averaging the experimentally measured geometric parameters of Westbred 936 samples *(9)*. The area difference between

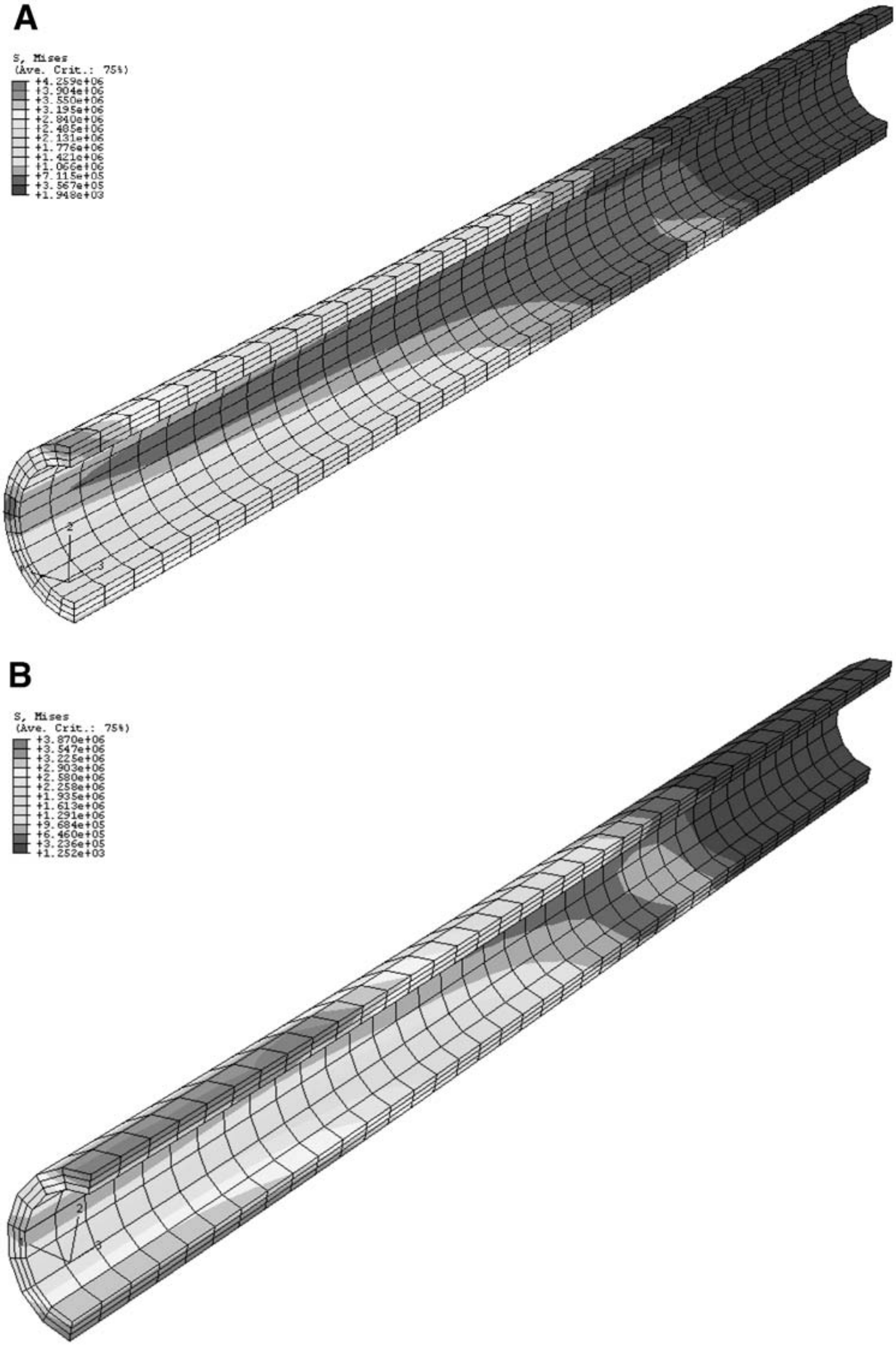

Fig. 4. Contours of Mises Stress distribution for **(A)** three-point bending test and **(B)** four-point bending test.

Table 1
Experimental Material Properties Measured by Wright et al. *(9)*

Bend test	Modulus of elasticity, *E* (GPa)	Modulus of rigidity, *G* (GPa)	Poisson's ratio, ν
Three-point	0.99 ± 0.08	0.53 ± 0.11	–0.07
Four-point	1.3 ± 0.02	0.53 ± 0.11	0.26

Table 2
Published Material Properties

Reference	Modulus of elasticity, *E* (GPa)	Modulus of rigidity, *G* (GPa)	Poisson's ratio, ν
2	4.8–6.6	0.29–0.32	—
10	4.1–5.2	—	—

the actual geometry and the simplified geometry was <0.75%. In an effort to reduce computational time and present graphic results of the wheat stem interior, we modeled only one-fourth of the three-point bend (Fig. 4A) and four-point bend (Fig. 4B) geometry. Taking advantage of the model symmetry, we used approx 1600 computational elements for the three-point bend model and 900 computational elements for the four-point bend model. All computational elements were linear, second order, and hexahedral. The statistical mean of the modulus of elasticity, determined from experimental results, was input into the numerical model *(9)*. Poisson's ratio was extracted from experimental data and input into the numerical model using the following equation:

$$\nu = \frac{E - 2G}{2G} \tag{1}$$

in which, ν is the Poisson's ratio, *E* is the modulus of elasticity, and *G* is the modulus of rigidity.

Table 1 provides the material properties obtained experimentally and utilized in the bend test models. For comparison purposes, Table 2 presents material properties of wheat straw published in the literature *(2,10)*. Load and displacement data were obtained from the simulation results and compared with experimental data. The experimental data used in these comparisons was taken from specific specimens used in the bending tests whose measured material properties were close to the statistical means used in the computational models.

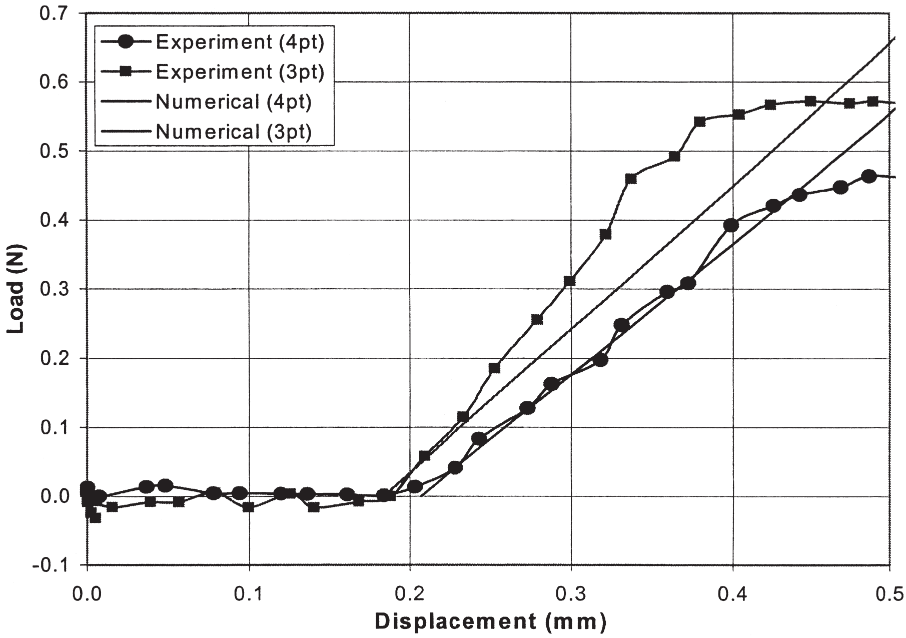

Fig. 5. Comparative graph showing experimental and numerical load displacement curves.

Results and Discussion

The negative value for Poisson's ratio shown in Table 1, which was extracted from experimental data using Eq. 1, is believed to be nonphysical although a significant amount of literature exists discussing the phenomenon *(11)*. The negative Poisson's ratio is postulated to be the result of three factors: applying Eq. 1, which is based on Hooke's law for an isotropic homogeneous material, in a situation in which composite material effects are significant; uncertainty in the experimentally determined values of the modulus of rigidity; and the possibility that the four-point bend test is the better experimental technique for measuring biocomposite material properties such as wheat. Nevertheless, a numerical analysis study of the three-point bend test was conducted.

Figure 5 shows the experimental and numerical results of the three-point and four-point bend tests. These results were obtained by using the statistical means of the experimental modulus of elasticity and modulus of rigidity values as inputs to the numerical models. The comparative graph showing the experimental results, however, is from a single straw specimen whose mechanical property data are close to the statistical means used in the numerics. As Fig. 5 shows, the numerical results from the four-point bend simulation closely approximate the experimental results from the four-point bend test; however, the numerical results from

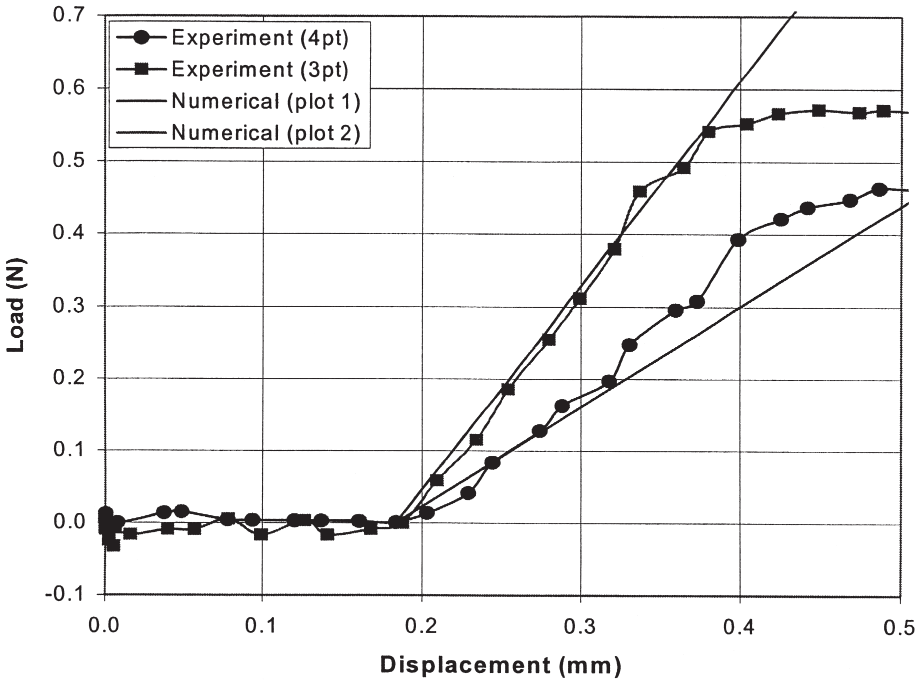

Fig. 6. Comparative graph showing experimental and numerical load displacement curves after reversing modulus of elasticity input to both numerical bending tests.

the three-point bend simulation fall between the experimental three- and four-point bend tests. Based on these results, it can be concluded that the four-point bend experimental procedure would be the technique of choice for determining material properties of wheat under bending-type loading conditions. To confirm this, additional analyses were performed. Utilizing the experimentally determined modulus of elasticity from the three-point bend test as input into the four-point bend model, as well as the experimentally determined modulus of elasticity from the four-point bend test as input into the three-point bend model, two more simulations were performed. Figure 6 shows the numerical results plotted together with the experimental results. "Numerical (plot 1)" is the numerical result obtained by using the experimentally determined modulus of elasticity from the four-point bend test as input into the three-point bend model, and "Numerical (plot 2)" is the numerical result obtained by using the experimentally determined modulus of elasticity from the three-point bend test as input into the four-point bend model. As expected, after analysis of the results in Fig. 5, the three-point bend model utilizing the experimentally determined modulus of elasticity from the four-point bend experiment more closely approximates the experimental results.

Conclusion

Structural analysis models of wheat straw provide insight into experimental results and the mechanical behavior of wheat straw stems. Specifically, the material properties obtained from a four-point bend experiment when used in conjunction with an isotropic and homogeneous structural analysis model more accurately predict the bending characteristics of wheat straw than material properties obtained from a three-point bend experiment.

Acknowledgment

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References

1. Hess, J. R., Thompson, D. N., Hoskinson, R. L., Shaw, P. G., and Grant, D. R. (2003), *Appl. Biochem. Biotechnol*. **105–108,** 43–51.
2. Oran, E. S. (2002), *AIAA J*. **40,** 1481–1494.
3. Niklas, K. J. (1992), *Plant Biomechanics, An Engineering Approach to Plant Form and Function*, 1st ed., University of Chicago Press, Chicago, Chap. 2, pp. 52–75.
4. O'Dogherty, M. J., Huber, J. A., Dyson, J., and Marshall, C. J. (1995), *J. Agric. Eng. Resour.* **62,** 133–142.
5. Niklas, K. J. (1998), *Ann. Botany* **81**, 11–21.
6. Percival, J. (1921), *The Wheat Plant: A Monograph*, 1st ed., Duckworth and Company, London.
7. Parker, H. (1961), *Simplified Mechanics and Strength of Materials*, 5th ed., Parker, H. and Ambrose, J., eds., John Wiley & Sons, New York.
8. Kaw, A. K. (1997), *Mechanics of Composite Materials*, 1st ed., CRC Press, New York, Chap. 35, pp. 159–180.
9. Wright, C. T., Pryfogle, P. A., Stevens, N. A., Steffler, E. E., Hess, J. R., and Ulrich, T. H. (2004), *in proceedings of the 26th Symposium on Biotechnology for Fuels and Chemicals*.
10. Kurzyp, T., Gowin, J., and Koper, R. (1991), Zeszyty Problemowe Posterpw Nauk Rolniczych, **389,** 79–88.
11. Lakes, R. (2001), Negative Poisson's Ratio Materials, silver.neep.wisc.edu/~lakes/Poisson.html (accessed May 4, 2004).