Preventing lodging in bioenergy crops: a biomechanical analysis of maize stalks suggests a new approach

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Abstract

The hypothetical ideal for maize (Zea mays) bioenergy production would be a no-waste plant: high-yielding, with silage that is easily digestible for conversion to biofuel. However, increased digestibility is typically associated with low structural strength and a propensity for lodging. The solution to this dilemma may lie in our ability to optimize maize morphology using tools from structural engineering. To investigate how material (tissue) and geometric (morphological) factors influence stalk strength, detailed structural models of the maize stalk were created using finite-element software. Model geometry was obtained from high-resolution x-ray computed tomography (CT) scans, and scan intensity information was integrated into the models to infer inhomogeneous material properties. A sensitivity analysis was performed by systematically varying material properties over broad ranges, and by modifying stalk geometry. Computational models exhibited realistic stress and deformation patterns. In agreement with natural failure patterns, maximum stresses were predicted near the node. Maximum stresses were observed to be much more sensitive to changes in dimensions of the stalk cross section than they were to changes in material properties of stalk components. The average sensitivity to geometry was found to be more than 10-fold higher than the average sensitivity to material properties. These results suggest a new strategy for the breeding and development of bioenergy maize varieties in which tissue weaknesses are counterbalanced by relatively small increases (e.g. 5%) in stalk diameter that reduce structural stresses.

Key words: Biomechanics, corn, crop, finite element, lodging, maize (Zea mays), material properties, mechanical stress, sensitivity analysis, stalk.

Introduction

The conversion efficiency of maize stalk forage to viable energy products (second generation biofuel) can be significantly enhanced by selectively breeding for reduced lignin content (Feltus and Vandenbrink, 2012). However, plants with reduced lignin content frequently display unsatisfactory levels of fitness and increased propensity to stalk lodging (Pedersen et al., 2005). This is because lignin is a major structural component of cell walls. For example, reduced-lignin varieties of wood demonstrate a substantially decreased modulus of elasticity (Zhang et al., 2013). A solution to this dilemma may lie in our ability to use engineering tools and techniques to design stalks that can compensate for weaknesses of low-lignin crops.

The multidisciplinary approach implemented in this study is an example of collaboration between engineers and plant scientists. Structural engineers frequently analyse, design, and improve structures composed of materials that demonstrate specific weaknesses. Such expertise could be valuable in our quest to create robust crop varieties from digestible, lignin-deficient cells.
The goal of this research was to use structural engineering tools to analyse lodging in reduced-lignin maize plants and to identify stalk characteristics whose modification could reduce lodging propensity. It is an example of how structural engineering tools can enhance plant research and help address the problem of second generation bioenergy production from maize forage. To accomplish this objective an in silico, structural engineering model of a maize stalk was subjected to a sensitivity analysis. The model provided unique insights into the problem of stalk lodging and was used to identify modifications to the stalk which could compensate for lignin-deficient material weaknesses. A brief explanation of the modelling framework (finite-element modelling) is provided and details of the model creation and simulation process are described.

Materials and methods

Finite-element modelling (Zienkiewicz and Morice, 1971) is one of the most powerful structural engineering tools developed in the last century. This method allows engineers and scientists to obtain detailed information regarding displacements, stresses, forces, and strain responses of complex 3-D structures. The method is founded on the principle of dividing up the structure of interest into small tetrahedral or hexahedral regions called ‘elements’ (similar to approximating a circle with a series of straight lines). The governing equations of mechanics and elasticity are then applied to each element and a computer is used to solve the coupled system of equations that results from the interconnected elements (Cook, 1994). Once solved, graphics software can be used to generate contour plots of stress and strain throughout the entire 3-D structure.

A finite-element model of a maize stalk was developed (Fig. 1A) based on geometric data acquired from quantitative computed tomography (QCT) scans of the fourth above-ground node and adjacent internodes of maize stalks. The QCT data were used to create maize stalk geometry files using Matlab (MathWorks, Natick, MA, USA), and imported for mesh creation (i.e. division of the structure into hexahedral elements) using TrueGrid (XYZ Scientific Applications Inc., Livermore, CA, USA). The major diameter of the model measured at the node line of the stalk was 19.8 mm and the minor diameter was 17.9 mm. The rind thickness in the internode portion of the model varied from 1.5 to 0.84 mm (derived from QCT data). In the immediate vicinity of the node line the stalk was composed entirely of rind tissue (no pith).

![Fig. 1. The nominal finite-element model, including depictions of deformation under bending in each of four directions. The cross-sectional face in the foreground of each model was fixed (zero displacement), and a bending moment was applied to the opposite cross-sectional face (which is not visible from this perspective). Colours represent stress levels, and arrows depict the direction of deformation of the far end of the model. (A) Model geometry demonstrating a bulged node and sharp reduction in diameter occurring at the node line. (B–E) Bending moments applied in each of the four directions with the associated deformation and stress distributions.](https://academic.oup.com/jxb/article-abstract/66/14/4367/2893377)
modulus) had to be varied on an element by element basis. A summary of the variations in material properties inserted into the model are presented in Table 1. Unfortunately, many of the material properties of maize stalks are not well documented (e.g. shear moduli and Poisson’s ratios) and those which have been documented (e.g. Foley and Clark, 1984) have not been quantified in modern maize varieties. To compensate for these uncertainties and to account for biological variation, model behaviour was examined over a broad range of material properties (Cook, 2009; Cook et al., 2014).

The effect of stalk geometry is more difficult to assess because the stalk geometry changes continuously and geometric features are not readily parameterized. Geometric variation was assessed in two ways. First, by creating additional models which were scaled (or stretched) in directions related to stalk physiology. New models were created in which the stalk geometry was increased by 10% in the direction of the major axis of the stalk cross-section, the direction of the minor axis, and simultaneous scaling in both directions. Second, geometric changes along the length of the stalk were ‘smoothed’ by calculating the average cross-sectional area of the stalk. Individual cross-sections were then isometrically scaled (no change in cross-sectional shape) so that each cross-section of the new model matched the average cross-sectional area. This approach reduces geometric change along the exterior of the stalk while preserving the volume (i.e. size) of the model. This was done to assess the influence of shape while holding size constant. Geometric modifications are listed in Table 2.

All models were subjected to the same set of loads and boundary conditions. To compare results, normalized sensitivity values were calculated using the following equation:

\[
S_{ij} = \frac{\Delta \text{output}}{\Delta \text{input}} = \frac{Y_i - Y_0}{X_j - X_0} \frac{Y_0}{X_0}
\]

where \(S_{ij}\) represents the sensitivity of output \(i\) to input \(j\), \(Y_i\) represents model outputs, \(X_j\) represents model inputs, and \(X_0\), \(Y_0\) represent the nominal values of inputs and outputs, respectively. This unit-less formulation is essentially a ratio: percentage change in output divided by percentage change in input. Thus a normalized sensitivity value of 2.0 indicates that a 1% change in input results in a 2% change in model output.

Results

A total of 68 finite-element simulations of the maize stalk were performed (17 variations of material properties, evaluated with 25 Newton metre bending moments applied in each of the four primary anatomical directions). Natural asymmetries in the stalk geometry produced stress distributions which were unique for each loading case. Across the four bending directions, the average maximum stress for the nominal model was 131.6 MPa. Across all simulations, maximum stress varied from a minimum value of 96.5 MPa to a maximum of 167 MPa.

The locations of maximum stresses predicted by the finite-element models correlate well with field observations of naturally lodged stalks. Lodged stalks typically break just apical of a node line (Robertson et al., 2014). In 97% (66/68) of the simulated finite-element models, the highest stresses likewise occurred just apical of the node line (<4 cm). In general, changes to model geometry and material properties had very little effect on the anatomical location of the highest stress.

Analysis of normalized sensitivity values calculated from each model simulation revealed that geometric parameters have a greater influence on stress levels than material properties. Geometric parameters typically exhibited sensitivity values greater than unity (absolute value), while all material parameters exhibited sensitivity values <0.3. Changes in geometry are (on average) 18 times more influential on stalk stresses than are changes in material properties. This finding is corroborated by recent three-point bending experiments in our laboratory in which geometric variables account for the majority of inter-hybrid variation in stalk strength (five commercial hybrids grown at five different planting densities). Fig. 2 depicts the average absolute value of normalized sensitivity values for all material and geometric aspects of the model that were varied in this study. Fig. 3 depicts the reduction in stresses between the nominal and adjusted area models. Notice that the area where maximum stresses develop (red colouration in Fig. 3) is smaller for the adjusted area model even though the total volume of the model is unchanged.

More detailed information on the distribution of sensitivity values is provided in Table 3, which presents mean, median, maximum, and minimum sensitivity values for each model aspect varied in the current study. Notice that all geometric and most material properties have negative sensitivity values. This indicates that increases in these properties will lead to decreased stress. For example, an increase of 10% in the minor axis diameter of the stalk would correspond to a mean decrease in stresses of 13.6%. Interestingly, most material

Table 1. Material properties, symbols, and ranges used to define finite-element models

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E')</td>
<td>Young’s Modulus parallel to fibres</td>
<td>GPa</td>
<td>4.41–9.0</td>
</tr>
<tr>
<td>(E)</td>
<td>Young’s Modulus at 90° to fibres</td>
<td>GPa</td>
<td>0.05–0.50</td>
</tr>
<tr>
<td>(E(\text{pith}))</td>
<td>Young’s Modulus of pith</td>
<td>GPa</td>
<td>0.02</td>
</tr>
<tr>
<td>(G')</td>
<td>Shear Modulus parallel to fibres</td>
<td>GPa</td>
<td>0.01–0.10</td>
</tr>
<tr>
<td>(\nu')</td>
<td>Poisson’s Ratio at 90° to fibres</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>(\nu)</td>
<td>Poisson’s Ratio parallel to fibres</td>
<td>–</td>
<td>0.2</td>
</tr>
</tbody>
</table>

\(^{a}\) Unless otherwise noted, properties refer to the rind.

\(^{b}\) Inhomogeneous material properties were applied to the model based on the spatial distribution of QCT intensity. Modulus values are therefore reported as ranges rather than constants. Within the model, the smaller number indicates the minimum modulus value, while the larger number represents the maximum modulus value.
properties have negative sensitivities, with the exception of \( E' \). This is because \( E' \), (tissue stiffness of the rind parallel to fibres) is the primary load-bearing property. As this property decreases, stresses in the rind also decrease because the pith begins to carry a greater proportion of the bending load.

Results from the adjusted area model suggest that stalks can be significantly strengthened without modifying material properties or the overall size of the stalk. This model removes many stress concentrators (geometric features that increase local stresses). The adjusted area model made the geometric changes that occur at the node more gradual, thus reducing the effect of engineering stress concentrators and lowering stresses. Furthermore, the adjusted area sensitivity values reported in Table 3 represent the most conservative estimates because they are based on the maximum relative change in area applied within the model.

**Discussion**

The sensitivity values reported above suggest that moderate changes in stalk architecture and geometry may be used to compensate for weakness inherent in easily digestible bioenergy crops. For example, results indicate that the stress increases due to a 50% reduction of \( E \) or \( G' \) would be offset by an increase in overall stalk size of ~5%. While more research in this area will certainly be required, these results provide encouraging evidence for this new strategy for producing crops that are digestible yet durable.

The sensitivity results presented above are also a valuable resource for prioritizing the next steps in future investigations. We note that stresses are much more sensitive to geometric factors than to material properties. The measurement and determination of the most influential geometric features is therefore of great interest. Also, because the measurement of tissue properties is typically very time consuming, the sensitivity of material properties should be used to prioritize tissue property measurement experiments, and in particular to investigate how lignin reduction affects the most influential material properties.

Naturally, this kind of modelling is not without limitations. Models are always based on a number of simplifications and assumptions. As an example, rather than attempting to model failure (which is notoriously difficult and unreliable), this study focused on modelling stresses. The sensitivity of these stresses was examined over a wide range of material properties to account for uncertainties associated with material property measurements and estimates (e.g. tissue properties of nodal and intermodal regions have not been fully quantified experimentally). We do not believe that the addition of more complex material properties will significantly affect the outcomes of this study as the model was generally less sensitive to material property modification in general. Structural models of maize stalk do not currently account for biological processes. However, we interpret this limitation as one of undeveloped potential rather than as an inherent limitation. Other fields of research have demonstrated that structural models can be developed that are coupled with biological processes (Weinans et al., 1992).

**Table 2. Geometric modifications with abbreviations used in other figures and tables**

<table>
<thead>
<tr>
<th>Modification</th>
<th>Abbreviation</th>
</tr>
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<tbody>
<tr>
<td>Stalk cross-section increased by 10% in the direction of the major axis</td>
<td>Major</td>
</tr>
<tr>
<td>Stalk cross-section increased by 10% in the direction of the minor axis</td>
<td>Minor</td>
</tr>
<tr>
<td>Stalk cross-section increased by 10% in both major and minor axis directions</td>
<td>Maj. &amp; Min.</td>
</tr>
<tr>
<td>Geometry adjusted by scaling each cross-sectional area to the same value as the average cross-sectional area of the model (no change in volume)</td>
<td>Adj. Area</td>
</tr>
</tbody>
</table>

**Fig. 2.** The average magnitude of normalized sensitivity values for each type of variation, illustrating the general difference in sensitivity between geometric and material parameters. See Table 2 for abbreviations.

**Fig. 3.** Comparison of stresses between (A) the nominal model and (B) the adjusted area model. Colours represent stress levels.
In addition, a smoothing of rapid geometric changes occurring near the node could potentially be used to develop more robust plant morphologies.

The advantages of structural modelling in bioenergy studies were also discussed briefly. These advantages include the ability to exercise independent control over all model parameters, the removal of confounding factors, and (in comparison to multi-year breeding studies) a shortened time to results. Collaborations between plant scientists and biomechanical engineers promise to provide many new insights into plant form and function. In particular, we see many opportunities for plant scientists and engineers to work together to develop optimally efficient crops that are simultaneously strong and digestible.

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References


Conclusion

This study demonstrates the utility of engineering tools in addressing the problem of stalk lodging in second generation bioenergy crops. The goal of the study was to determine how maize stalks might be modified to compensate for material weaknesses associated with forage digestibility (reduced lignin). Results suggest that relatively small changes in plant morphology can compensate for decreases in material strength and stiffness associated with increased digestibility. In particular, results from the above analysis suggest that a 5% increase in diameter and rind thickness could potentially compensate for a 50% reduction in tissue stiffness (modulus).