Stems of Steel: Combating Lodging with Forensic Engineering

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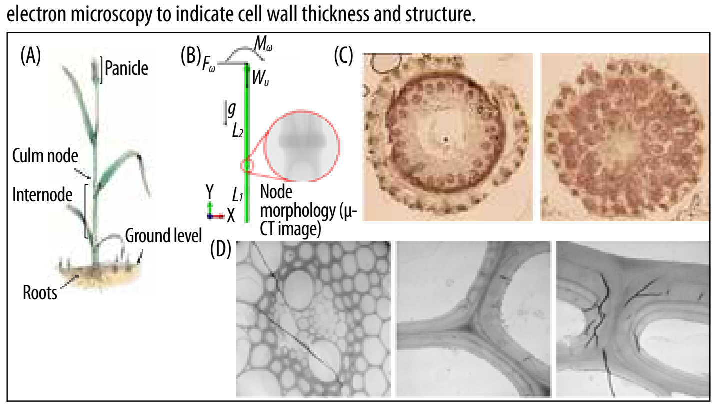
Skyscrapers do not fall over during a storm; neither should your crop. Lodging, the act of a plant falling over, can occur during high winds and/or hard rainfalls. If lodging is severe, there is either yield reduction (biomass or grain) or complete crop loss. To mitigate losses, lodging-resistant small grains and forages need to be developed. Garber and Olson in 1919 stated, "lodging is dependent on so many factors of unequal value in the different sorts that no one factor seems to be correlated closely enough with lodging to be of much value as a selection index." These sentiments have not changed 100 years later. Therefore, an innovative partnership between ARS, University of Minnesota (UMN) ag researchers, ag engineers, and civil engineers tackled lodging by utilizing structural forensic engineering.

Structural engineers rely on computer modeling to optimize design of wide-span bridges, high-rise buildings, and lightweight aircraft structures. Modeling techniques in structural engineering have reached a level of sophistication enabling reliable prediction of extremely complex structural behavior. Basic mathematical modeling components address the key physical principles of static and dynamic equilibrium and material behavior, then these equations are solved on a computer. Numerical values can then be used to create a visual image of the most likely place for material failure. The team used these techniques from structural engineering to analyze and understand the failure methods of small grain stalks with the goal of understanding underlying structural reasons leading to lodging.

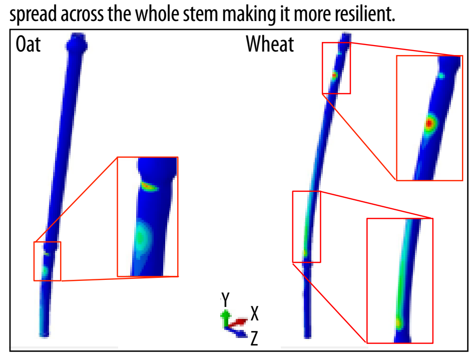
To build the plant-based model, engineers first needed detailed plant information at various scales (Figure 1). Plant biologists from the UMN oat breeding program measured large-scale oat, barley, and wheat traits such as inflorescence size, weight, stem length, and diameter of known lodging-resistant and lodging-susceptible varieties. Since weather plays a large part of whether lodging will occur, these traits were measured during three growing seasons. Biologists identified species-specific traits correlated with lodging resistance. Stems that were wider or had solid stems at the second internode appeared to be more lodging resistant.

Figure 1. The types of biological traits needed to build an engineering model. (A) Macro plant measurements such as diameter and length, (B) Micro-CT images of internal structures, (C) Light microscopy of internode and node cross-sections to indicate location of tissue types, (D) Trans-electron microscopy to indicate cell wall thickness and structure.



Stems were imaged using micro-CT, light microscopy, and trans-electron microscopy for more detailed information on cell arrangement and cell wall construction (Figure 1). The 3-D micro-CT images showed internal structural changes in tissue density where node and internode meet depending on crop and lodging susceptibility. Light microscopy determined differences in vascular and ground tissue location and concentration, while trans-electron microscopy images visualize variation in cell wall thickness. All these micro traits were included in the engineering model. Researchers even determined cell wall chemical makeup, such as lignin and cellulose concentrations. All this information was used to calculate strength and material properties of plant stems for the engineering plant model.

Figure 2. Finite Element Model of likely stem failure points. Blue indicates no wind strain; red areas are regions likely to break during a specific wind speed or load. For wheat, wind stress is spread across the whole stem making it more resilient.



Engineers then built a virtual model of a stem (Figure 2) using calculated material properties from various plant measurements. The model's estimated strength and elasticity were compared to those of field-grown plants. The model indicated where the weakest part of the stem was for each species (Figure 2). Minor differences in stem structure and composition resulted in oats failing directly below second node, while wheat allowed for stress to be spread across second internode with failure occurring below third node. Field observations found oat lodging before wheat, and stems buckling at second node in oat and third node in wheat.

To further determine if plant models were accurate, simulations were run to estimate how the computer-generated stem would move in various wind conditions. Once again, real plants placed into a wind tunnel at the UMN St. Anthony Falls Laboratory were compared under the same wind conditions to which the computer plant was exposed. Very small differences found in the internal structure of oat and wheat stems again were enough to cause visual movement differences between the two simulations. Models accurately simulated real stem movement and where stems broke if exposed to a heavy wind load.

Throughout this project, minor differences in plant structure, cellular arrangement, and composition were found between lodging-resistant and lodging-susceptible varieties of oats, wheat, and barley. However, Garber and Olson's "no factor seems to be correlated strongly enough with lodging to be much value" is still valid; none of the differences identified were strong enough to be used as breeding targets to prevent lodging. However, with the addition of the computer engineering model, researchers can now simulate how changing a group of traits together impacts lodging resistance. Once those suites of traits are identified, breeders use those traits as breeding targets that can have an impact on lodging resistance. For example, a low lignin oat stem can be lodging-resistant if the second internode and node are wider by 20%. These types of engineering models can be used to address other complex issues with negatively associated traits, such as digestibility and yield.