Development of a Parameterized Model of Transverse Maize (Zea mays L.) Stalk Morphology

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Development of a Parameterized Model of Transverse Maize (*Zea mays* L.) Stalk Morphology

Ryan A. Larson

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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Stalk lodging, or failure of the stalk structure, presents a serious problem in the production of maize (*Zea mays* L.). Lodged stalks negatively impact crop yields by inhibiting further grain growth and often prevent the harvest of the grain. Addressing this problem requires the development of new maize hybrids that exhibit enhanced lodging resistance, which in turn requires an understanding of the parameters that influence lodging resistance. Current methods make use of specimen-specific geometry and material properties, but these methods have limited ability to examine geometric effects and can require excessive time. A parameterized model of the maize stalk has the potential to overcome these limitations.

The purpose of this study was to develop a model of the maize stalk cross-section that could accurately predict transverse stiffness. Principal component analysis was utilized to discover underlying geometric patterns that could be used as parameters in a cross-sectional model. Using the resulting principal components, a series of approximated cross-sections was created that represented various levels of fidelity to real cross-section geometry. The real and approximated cross-sections were modeled in transverse compression with a prescribed deformation load, and the predictive accuracy of each approximated model was calculated. A sensitivity study was also performed to quantify the strength of individual parameter effects. The simplest model, an elliptical cross-section, accurately predicted transverse stiffness while minimizing the number of model parameters. This model may later be used as a basis for a three-dimensional parameterized model of the maize stem.

Keywords: biomechanics, finite-element modeling, maize, parameterized models, plants
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Ryan A. Larson
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CHAPTER 1. INTRODUCTION

1.1 Background

Human history cannot be separated from agriculture. For millennia, domestication and development of plants have provided humans with food, and where a surplus existed, the means to develop economically [1]. The development of improved grain cultivars has direct impacts on human prosperity. As world populations continue to grow, grain yields become more and more critically important, and selective breeding must rise to the ever-changing challenge.

The problem of stalk lodging acts as a large barrier to improved grain yields (Figure 1.1). Permanent displacement by part of the above-ground portion of the stalk characterizes the phenomenon of lodging. In engineering parlance, this is defined as failure. Stalk lodging is a common problem among agriculturally-important monocot crops, such as bamboo (*Phyllostachys aurea* Carrière ex A. Rivière & C. Rivière), corn (*Zea mays* L.), rice (*Oryza sativa* L.), and wheat (*Triticum sphaerococcum* Percival). Lodged stalks present challenges that render grain difficult to harvest at best and unusable at worst. For U.S. corn, these losses amount to an average of 5% per year, or about $3 billion [2]. Discovering and addressing the issues underlying stalk lodging are critical to limiting these losses and improving annual grain yields.

1.1.1 Physiology

Maize stalks can be thought of in engineering terms as vertically oriented, foam-filled cantilever beams. The dense outer tissue, referred to as rind in this thesis, consists of many tightly packed vascular bundles. The inner, foam-like tissue, referred to as pith, contains relatively few vascular bundles (see Figure 1.2) [3]. The general shape of the maize stalk cross-section is elliptical, with a notch on one side where the ear grows [4]. In addition, tightly-bound leaf sheaths surround the maize stalk.
The structure of the maize stalk consists of nodes, where leaves originate from, and internodes, which are sections of stem between nodes, and give the stalk a similar appearance to bamboo when the leaves are removed [5]. At nodes, the tissue is dense and thicker than found in internodes, which make up most of the length of the stalk. The notch seen in the stalk cross-section alternates sides with each internode.

Maize and other grasses grow in length from multiple intercalary meristems, which are located just above the nodes, as well as apical meristems at the tip of shoots [6]. Meristems can be thought of as “growth plates” of the plant. Multiple internodes grow and lengthen simultaneously in a sigmoid pattern [6]. As a maize plant matures, it goes through reproductive stages of tasselling and ear formation, and then the plant dries [6]. Stalk lodging that occurs during this dry stage is referred to as late-season stalk lodging [5].

1.2 Literature Review

This thesis will put forth new techniques for examining late-season stalk lodging in maize, but the work developing lodging-resistant varieties of grain stalks goes back nearly 100 years. Borlaug is noted for having developed wheat varieties that were resistant to stem rust fungus, but especially for developing dwarf varieties of wheat that were high-yielding and experienced
reduced lodging rates compared to their predecessors [7]. In a conference presentation, he noted that lodging was recognized as a limiting factor in wheat as early as 1948, but selection for lodging resistance required considerable breeding efforts [7]. The dwarf varieties of wheat, which were eventually developed, resulted in yield breakthroughs in Pakistan, India, Turkey, Afghanistan, and Tunisia. However, lodging again became the limiting factor as a new yield ceiling was reached. Borlaug proposed the development of triple dwarf varieties to combat the new limit [7]. His work established that changing the morphology of grain stalks can have impressive effects on yield and lodging resistance [7].

Zuber and Grogan produced one of the first studies to examine stalk morphology and lodging resistance correlations [8]. In addition to measuring stalk lodging rates (via field counts of lodged stalks) and plant height, they also quantified properties of the second and third internodes above the ground. For the second internode, length, diameter, and breaking strength were measured, and for the third internode, diameter, rind thickness, and crushing strength were measured. Strong correlations were reported between rind thickness and crushing strength for the third internode, indicating potential connections between rind thickness and lodging resistance.

Thompson used the methods proposed by Zuber and Grogan to address the problem of confounding environmental factors [9]. The typical procedure for characterizing lodging consisted of field counts of lodged plants, which gave population-level effects, but no information about

Figure 1.2: Visualization of stalk morphology at the cross-section level.
the parameters that influence lodging in individual plants. Applying Zuber and Grogan’s crush test measurement technique to two inbred hybrids of corn, Thompson was one of the first to conclude that these measurement methods might be successfully applied to selective breeding for stalk lodging resistance.

Cloninger further examined stalk morphological characteristics and their relation to stalk lodging resistance [10]. He also used the crushing test method proposed by Zuber and Grogan as a measure of stalk lodging resistance. His study found that rind and pith geometry and density both have effects on lodging resistance in maize. Using a constant rind thickness assumption, he examined the contribution of the rind to crushing strength by taking crushing strength measurements with intact specimens and specimens with the pith excised. The contribution of the rind was expressed as a percentage of the intact sample’s crushing strength. Cloninger’s study was one of the first papers that attributed stalk strength partially to what we refer to as pith in this thesis [10]. However, this study didn’t examine why the rind and pith effects were different. Cloninger also found that crosses involving lodging-resistant varieties resulted in thicker rinds than those crossed with lodging-susceptible varieties, and rind thickness was found to be highly correlated with crushing strength for multiple treatments. Despite these results, crushing strength was acknowledged as a limited method for evaluating stalk lodging resistance, as some hybrids were more susceptible to stalk rot while maintaining good crushing strength [10]. Cloninger also acknowledged the need for other non-destructive testing methods that would be more effective in selective breeding programs.

Speck et al. established that the loads experienced by plant stems in the field are dominated by aerodynamic forces [11]. Deriving analytical expressions of plant stem cross-sectional area and axial moment of inertia, they estimated what they termed “mechanical effectivity” of stem structures by comparing the relative section modulus of stems of different hybrids. They did not provide conclusions about specific plant species, but articulated tools that could be used to describe the structural adequacy of vascular plants.

Schulgasser and Witztum were the first to note the gap in the research with regard to examining plant stems as structural members [12]. Common engineering assumptions (isotropic materials, linear effects) had been made for plant stems for decades, despite the fact that ovalization had been recognized in plant stems as early as 1942 [13]. Continuing to use the common
engineering assumptions and formulae for bending appears to have led the effects of ovalization on plant stem failure to be overlooked.

Schulgasser and Witztum acknowledged that plants are essentially biological composite structures and have materials that are far from isotropic; in particular, longitudinal stiffnesses dominate circumferential stiffnesses. They found that for diameter-to-thickness ratios present in real plant structures, ovalization can and does have an important influence on failure [12]. Their study established the dominant influence of anisotropy in the failure behavior of plants. They also acknowledged the experimental difficulties of acquiring Young’s moduli to describe this anisotropy, particularly in the circumferential direction. At that time, there were no data in the literature describing anisotropic plant stem properties. Consequently, they made some inferences on the ratio of longitudinal-to-circumferential elastic properties in plant stems by comparing data for lumber, which was well-established at the time. Their study resulted in some surprising but important findings, especially that the degree of ovalization at which buckling occurs is independent of all physical parameters [12]. This was true even for geometry and relative stiffnesses. However, geometry factors were found to influence the requisite loads. They concluded that given the various priorities plants seek to balance, many plant structures might already be optimized so multiple failure modes occur simultaneously.

Niklas built upon the work of Schulgasser and Witztum by analyzing failure modes due to axial compression in hollow stem segments of *Arundinaria tecta* (Poaceae) [14]. He discovered three primary failure modes: (1) tissue failure in the nodal transverse diaphragm; (2) Brazier buckling (buckling due to ovalization of the stem cross-section) [15]; and (3) longitudinal cracking of internodal walls. These failure modes were supported by later studies [16].

Ma et al. conducted a study of maize cultivars, which were released from the 1950s to the 2000s, and sought to find correlations between stalk morphological traits, yield, and lodging rates [17]. Their two-year study found that stalk-lodging rates decreased with the maize cultivar-release year, but they held that these effects could be attributed to breeders selecting primarily for improved yield rather than resistance to stalk lodging. No significant relationship to stalk lodging had been found in the cultivars for plant height; ear height; ear ratio (ear height to plant height); mean rind puncture strength of lower internodes; and mean breaking strength of internodes measured at the tasselling stage of growth [17]. Rind puncture strength, breaking strength, and
crushing strength were not significantly correlated with stalk lodging in this study, which suggests a gap in the ability of these methods to measure stalk strength and resistance to lodging. Importantly, this study claimed that improving lodging resistance of maize cultivars could not be achieved by intentionally selecting for stalk mechanical traits [17]. This claim went against numerous other studies, but might be explained by their use of field counts of lodging, which have been shown to be heavily confounded by environmental variables. Indeed, in the second year of the study their experimental crops endured a typhoon, which introduced a number of confounding variables. Still, this study had value in highlighting some of the weaknesses of the measurement tools, which had been used for decades.

Leblicq et al. set out to develop better crop processing techniques through characterization of crop deformation behavior [18]. Their study built upon the work of Schulgasser by adapting mechanical models of ovalization and buckling to plant stems. They performed three-point bending tests on short stalk samples of wheat and barley, using support spans of 50 mm. Assessing the ovalization and buckling models’ ability to explain the force-deformation curves of actual samples, they found their models were able to fit the real behavior with high correlation coefficients ($R^2 = 0.98$ and $R^2 = 0.97$, respectively). In addition, they were able to compare measured and estimated stem diameters and wall thicknesses, with stem diameters having $R^2 = 0.84$ and wall thicknesses having $R^2 = 0.69$. Some of the limitations in accuracy on this point were determined to come from adapting a circular cross-section model to non-circular plant stems (the species involved had cross-sections that were roughly elliptical). They found that parameters that interacted with stalk bending included crop species, growing conditions, stem diameter, and wall (rind) thickness. Their results led them to affirm that the rind-pith structure increases bending resistance of plant stems.

Beginning in 2014, Robertson led a series of papers that made great gains in characterizing the causes of maize stalk lodging and studying the material properties and geometric parameters that correlate to lodging resistance. Robertson, Smith, Gardunia, and Cook first examined the assumptions that had been made in three-point bending tests of plant stems [19]. They held that despite three-point bending tests being used on plant stems as far back as 1906, the testing methodologies that had been used were inducing artificially low results. Robertson et al. hypothesized that lower maximum loads would be found when the loading anvil in a three-point-bending test was placed at an internode versus when the anvil was placed at a node in three-point bending. They also
hypothesized that node-loading would produce failure patterns that matched in-field observations, which had not been the case in the literature to that point.

To test this hypothesis, four commercial hybrids of dent corn were sampled at four planting densities. Each sampled stalk was tested in both internode-loaded and node-loaded configurations to reduce experimental variation, with node-loaded tests performed first. Loads were applied at a constant rate of displacement until failure of the stalk was detected. Afterward, the adjacent internode that had not been subjected to failure was used for the corresponding internode-loaded test. Internode tests used a span of 100 mm, consistent with existing literature. It was found that node-loaded tests consistently resulted in failure near the loaded node, but not propagating through the node. This was more consistent with failure patterns observed in the field, as opposed to the consistent failure of internode-loaded samples directly at the anvil with a single straight crease. A quantitative comparison was performed between the induced moments at the center of the internode for each testing regime; this was done to compensate for differences in geometry at the anvil, which would result in different moments. It was found that internodes from node-loaded tests experienced much higher bending moments than was required to cause failure in the same sections for the internode-loaded tests. These induced moments differed by 54%, which the authors recommended to treat as a minimum estimate of the difference between internode- and node-loaded testing methods.

These results showed that previous literature involving three-point bending tests of plant stems were consistently underestimating the material stiffness values. They also showed the importance of span length in limiting the required transverse compression force to achieve a desired moment.

In 2015, Robertson, Smith, and Cook expanded on these ideas and performed a comparative study of testing methodologies on bamboo (Phyllostachys aurea), giant reed (Arundo donax), and maize [20]. Building on their previous hypothesis, they applied the node-loading method to three-point bending, four-point bending, and transverse compression. Following the comparison methods set out in the 2014 paper [19], they found that in all testing regimes and for all plant stem species examined, node loading resulted in higher measured stiffness values than internode loading. They were able to confirm again that internode loading induces premature local buckling [20]. An important finding from this study was that results from internode-loaded tests were
not a strong predictor of results from node-loaded tests. This finding indicates that previous studies that implemented three-point bending tests on internodes might not be as accurate as originally thought [20].

Another 2015 paper by Robertson et al. expanded on the ideas of Niklas [14] by applying forensic engineering techniques to the problem of maize stalk lodging [16]. They performed detailed geometric analysis of four maize varieties, with field observations covering over twenty varieties. This was seminal work, which has influenced much of what has come since in terms of research developments. In their study, Robertson et al. were able to establish that natural lodging events in corn occur in multiple failure modes and locations, as Niklas had [14,16]. However, with a wide sampling regime they were able to discover a widespread weakness in corn-stalk structure, which was not peculiar to specific varieties. The weakness being, namely, that the primary and overwhelming failure mode is Brazier buckling [16]. They also established that stalks fall in the direction of the minor diameter of the cross-section and break within 4 cm of a node. This established a failure region, which could be further examined in detail with additional research. The results of the study heavily supported a research focus on stalk morphology factors for development of lodging-resistant maize varieties, since it had already been established that geometric factors heavily influence critical loads for Brazier buckling [12,15].

In 2016, Robertson, Lee, Julias, and Cook proposed the development of non-confounded selective breeding tools to address the issue of environmentally confounded measurements previously mentioned by Thompson [9,21]. Stiffness and strength do not necessarily correlate [22], but they hypothesized that stalk flexural stiffness would be a stronger predictor of stalk strength than other measurements. They designed a study to correlate stalk strength with stalk flexural stiffness, rind penetration resistance, and stalk bending strength. They found drastically different results between the predictors, with stalk flexural stiffness predicting 81% of variation in stalk strength and no confounding influences, and rind penetration resistance predicting 18% of variation in stalk strength, but with confounding environmental variables such as hybrid, planting density, and planting location [21]. Robertson et al. concluded that stalk flexural stiffness is a good predictor of stalk strength and could be a useful selective breeding tool for stalk lodging resistance.

With more reliable measurement tools established, Robertson, Julias, Lee, and Cook set out in 2017 to examine morphological traits and their relation to stalk bending strength [4]. This study
implemented methods taken from the bone literature to perform a detailed geometric analysis of maize stalks using x-ray computed tomography (CT) scans. Examination of the maize stalk section modulus indicated that it was highly predictive of stalk strength. Because section modulus is derived directly from geometry, it was largely independent of confounding environmental factors. To make collection of geometric data easier, stalk cross-sections were assumed to be elliptical [4]. This assumption was supported by strong correlations of the elliptical section modulus with stalk strength. Indeed, the elliptical section modulus predicted stalk strength with four times the accuracy of rind penetration resistance [4]. Robertson et al. projected that the elliptical cross-section could be a good starting place for a parameterization of the maize stalk.

Al-Zube, Robertson, Edwards, Sun, and Cook then developed a method for measuring the compressive modulus of elasticity for pith-filled plant stems (where the term pith is defined the same way as in this thesis) [23]. This effort was complicated by the fact that plant stems are highly sensitive to buckling, but using established methods as a starting place, Al-Zube et al. produced two methods for measurement of the compressive modulus of elasticity of pith-filled node-node specimens, with average repeatability of ±4%. This paved the way for future studies to take more confidence in these measurements, which are critical to understanding buckling in plant stems.

Al-Zube, Sun, Robertson, and Cook then undertook a study that sought to determine what testing methods would yield the most accurate and reliable results for measuring the modulus of elasticity in plant stems. They performed testing in three modes (bending, compression, and tensile) and found that they resulted in similar stiffness values, with good repeatability considering they were measuring biological samples. However, bending tests were considered advantageous because of their higher repeatability and their ease of use as compared to the other testing methods. Al-Zube et al. also established the spatial variation of the modulus of elasticity throughout the stalk.

Using the previously described literature, Cook et al. published in 2019 a description of a new field measurement apparatus (DARLING) that could reliably measure stalk flexural stiffness and stalk bending strength of in vivo maize stalks [24]. This was the first field-use device designed to induce natural Brazier buckling failure observed in typical lodged stalks. Testing of the device again affirmed that flexural stiffness values are strongly correlated with bending strength of
maize stalks [24]. Field results with the device validated against lab test results of the same stalk specimens.

Very recent work indicates current developments in the field. Sekhon et al. produced a study that was more comprehensive than previous works in relating stalk lodging and stalk bending strength [25]. Using the DARLING apparatus as well as traditional stalk lodging counts, their study examined stalk bending strength as well as other traits historically assumed to be related to stalk lodging resistance, such as rind-puncture resistance, cellulose content, hemicellulose content, and lignin content. They were able to demonstrate that field measurements of stalk bending strength can be used to provide accurate estimates of stalk-lodging incidence.

The doctoral dissertation by Stubbs pushed the examination of morphological traits in a more computational direction [26]. Stubbs related data from in vivo, in vitro, and in silico studies to examine the underlying failure mechanisms and assumptions in plant stem models. He developed a method for determining the transverse material properties of maize stems by performing lab compression tests on stalk specimens with and without the pith; using CT scan data to construct specimen-specific finite element models, he then back-solved for the necessary material properties to achieve the actually-observed deformations [26]. This work was also set out in a paper by Stubbs, Sun, and Cook [3] These methods relied on assumptions of homogeneity in rind and pith tissues, but Stubbs also contributed heavily to groundwork that aimed to guide multi-scale finite element modeling techniques for plant stems that would take into account the inherent heterogeneity of the system [3,26].

Most recently, Stubbs, this author, and Cook investigated the hypothesis that geometric factors are more influential in determining structural strength than tissue properties [27]. A suite of physical and virtual experiments was run to examine the hypothesis. Specimen-specific finite element models were created from CT scan data, and the models were validated against physical tests of their corresponding physical samples. Once validated, the virtual models were used to perform sensitivity studies on material properties, as well as to determine the influence of geometry via statistical analysis (being limited in direct control over geometric factors) [27]. It is this point in the research that this thesis aims to fill.
1.3 Problem Statement

Current research is limited to specimen-specific models that are insufficient to fully examine and predict the factors that affect stalk strength [27]. The inability of specimen-specific methods to directly interrogate geometric parameters of individual stalk samples is a serious obstacle to determining the relative effects of these parameters on stalk strength, and consequently lodging resistance. In addition, specimen-specific methods inherently require more time to produce data, and therefore sample sizes are accordingly restricted (see Figure 1.3).

![Flow chart of the specimen-specific modeling process](image)

Figure 1.3: Flow chart of the specimen-specific modeling process. This process can take anywhere from 4 to 12 hours to complete.

A parameterized model of the maize stalk has the potential to solve these issues. Parameterization turns complicated systems with unclear relationships into simpler systems and independent variables. Such systems are much easier to analyze and interpret. And with fully-parameterized geometry, researchers could easily create large sets of synthetic data that represent realistic populations of corn stalks.

The primary goal of this thesis was to develop a parameterized cross-sectional model of the maize stalk cross-section. The ideal model would be parsimonious, demonstrating an appropriate balance between model fidelity and the total number of model parameters. In this paper we place an emphasis on reducing the total number of cross-sectional parameters since we recognize that the
next step in this research will be to extend each of these parameters into the longitudinal dimension. The secondary purpose of this study was to assess the influence of each geometric and material parameter on transverse deformation. By necessity, this study does not account for all aspects of the complex three-dimensional loading experienced by a maize stalk, but it establishes a solid foundation for efficiently considering these additional factors in future studies.
CHAPTER 2. METHODS

2.1 Approach

In the field, maize stalks experience complex dynamic loading. The primary component of this loading is a bending mode imposed by wind loading. Maize stalks predominantly fail in bending due to localized Brazier buckling (Figure 2.1) [16]. This type of failure is entirely determined by the degree of cross-sectional ovalization [12].

![Figure 2.1: An example of a maize stalk that failed in Brazier buckling [16].](image)

Transverse compression of the maize cross-section was used in this study as an approximation of the ovalization that occurs during full three-dimensional bending. This was accomplished by creating two-dimensional plane strain computational models that represent the maize specimens shown in Figure 2.2. We frankly acknowledge that transverse compression is not the same stress state as three-dimensional bending. However, transverse compression shares many similarities to ovalization that the stalk experiences just before buckling, and this approach leverages validated modeling procedures [3]. Two-dimensional models also provide an appropriate balance between computational cost and model complexity: these models accurately capture many important features of the maize stalk, but are far simpler than full three-dimensional models. By thoroughly
analyzing these simpler models before moving onto the more complex models, we avoid the pitfalls that are associated with the use of “over-developed models” [28].

In the following paragraphs, we describe the method whereby the cross-sectional shapes of maize cross-sections were extracted from CT scans and analyzed via principal component analysis to extract geometric patterns. These patterns were then used to create specimen-specific finite-element models. A set of secondary models were then created for each specimen-specific model. These secondary models each constituted a different level of approximation. Comparisons between the structural response of specimen-specific and approximate models was used to assess the relationship between geometric complexity and accuracy of each model.

Figure 2.2: A typical transverse compression test specimen [3].

2.2 Cross-sectional Data

In a previous study, we described a process whereby intact corn stalks were imaged using x-ray computed tomography [4]. The database of CT scans created in that study was the basis for the cross-sectional data and models used in this study. The scan region centered on a node while also capturing the two adjacent internodal regions. The CT cross-sections used in this study were drawn from thirteen sample points ranging from 40 mm above the node to 40 mm below the node. The spacing of sample points decreased around the node in order to provide higher
fidelity where the maize stalk is known to fail most frequently [16]. Cross-sections were taken from all thirteen sample points for each of the 980 stalks in the data set, totaling 12740 unique samples (hereafter referred to as Group I). Figure 2.3 provides an illustration of the scan region, the associated sampling points, and representative cross-sectional images.

Figure 2.3: Illustration of the CT scan region and the sampling scheme used in principal component analysis and finite-element models. Group I data was used for principal component analysis and produced various approximations of the Group II data. The vast majority of buckling failure occurs in the region covered by Group II [16]. Representative cross-section scans are shown on the right for reference.
2.3 Geometric Analysis and Principal Component Decomposition

The goal of geometric analysis was to decompose the shape of the maize cross-section into components of varying influence. Edge-detection techniques were used to identify the interior and exterior boundaries of the rind region for each cross-sectional CT image. This process allows a short disc-shaped specimen to be effectively modeled using a two-dimensional plane strain finite-element model, as shown in Figure 2.4. This modeling approach has been empirically validated in previous studies [3].

Principal component analysis (PCA) was used to decompose the cross-sectional geometry of the maize stalk. There are two powerful advantages of PCA. First, it is often the case that the first few principal components can be used to create highly accurate approximations. By definition, if all principal components are used then an exact reconstruction of the original data is obtained. Second, the patterns produced by this method are mutually independent of one another. Each principal component captures a separate feature, as defined by the distribution of variance in the original data.

Principal component decomposition was based on a polar coordinate system located at the geometric center of each cross-section. A total of 360 circumferential sample points were extracted for each cross-section (one per degree). Since circumferential values were identical for all cross-sections, principal component analysis was performed on the corresponding radial data only.

An initial attempt to decompose geometry using only principal component analysis had unfavorable results, which will be discussed in the Results section below. A hybrid method was therefore used which combined least-squares regression with principal component analysis. In our prior research, we observed that a simple ellipse with a constant rind thickness provides an excellent approximation of maize stalk cross-sections [4]. Using this knowledge, an ellipse was fitted to each cross-section using a least-squares approach. The ellipse captured the gross shape of the cross-section, but did not account for finer morphological features (see Figure 3.2). The remaining features of the maize stalk were decomposed by subtracting the elliptical approximation of each cross-section from the original cross-sectional data. The resulting data described all non-elliptical features of each cross-section and were analyzed using PCA to obtain a useful decomposition scheme. Figure 3.2 in the Results section illustrates the manner in which the ellipse
and non-elliptical principal components were used to approximate a representative maize cross-section.

Based on prior research in which we found excellent agreement between models and experimental test specimens [26], we further reduced the number of possible parameters by assuming a constant rind thickness. The rind thickness of each cross-section was obtained by computing the average distance between the exterior and interior boundaries. In turn, the interior boundary of the approximate model was determined by offsetting the approximated exterior boundary by the corresponding rind thickness. As will be shown, this approach provided an accurate approximation of the maize cross-section with a minimum number of morphological parameters, since principal component analysis only needed to be performed on the exterior boundary of the cross-section.

This geometric decomposition provided a very detailed approximation of the cross-sectional morphology of the maize stalk when using just five principal components. Thus, the morphology of each cross-section was described by eight parameters: major and minor diameters of the ellipse, rind thickness, and five principal components. Static depictions of this decomposition are provided in Figure 3.2. However, animated plots are much more effective for visualizing the principal components.

2.4 Finite-element Models

With the morphology of the maize cross-section fully parameterized, we were able to create two-dimensional finite-element models in which different parameters were varied and/or omitted. This allowed a full exploration of the connections between morphological features and structural response.

Finite-element models were created in ABAQUS/CAE 2017 by specifying the internal and external boundaries of the rind and pith regions, and run in ABAQUS/Standard. Each region was then assigned a material stiffness. Because maize tissue is well-approximated as transversely isotropic [3], and because these models were based upon the plane stress assumption, both the rind and pith regions were modeled as isotropic materials.

Finite-element meshes were generated using the Medial Axis Algorithm [29]. Adequate element sizes were determined from a mesh convergence study.
As shown in Figure 2.4, the major axis of each cross-section was oriented in the horizontal direction and loading was applied in the vertical direction, along the minor axis. A fixed boundary condition was applied at the bottom of each cross-section. A displacement of 0.005 mm was applied directly opposite to the fixed boundary condition. The primary outcome of each simulation was the transverse stiffness (i.e. force/deformation slope) of the entire model to transverse compression. An example deformation plot is shown in Figure 2.5.

![Figure 2.4: Illustration of a representative model and its loading in finite element analysis.](image)

2.5 Experimental Design

The experiments in this study had three purposes: (1) to assess the geometric fidelity of the decomposition method described above, (2) to assess how the inclusion of each geometric parameter influenced the predictive accuracy of the resulting finite-element models, and (3) to assess the sensitivity of each structural parameter on transverse compression. The following sections describe the experimental designs that were used to investigate these purposes.
2.5.1 Assessing the fidelity of the geometric decomposition

An assessment of geometric discrepancy was performed by comparing the original cross-sectional geometry of a particular cross-section (from the CT scan) to various geometric approximations. For each unique cross-section, a series of approximate geometries was created: these started with an ellipse to which principal components were successively added until all 360 principal components were included (at which point an exact recreation of the original geometry was obtained). Because all models were specified using the same set of 360 circumferential points, the error between each approximation and the corresponding original geometry was easily quantified by the radial difference between the two shapes at each circumferential point. To allow comparisons of errors from differing cross-sections, these error values were normalized by dividing each individual error value by the associated minor diameter of each cross-section. The population of all error values for each level of geometric approximation was used to assess geometric fidelity of the various approximations.

2.5.2 Assessing parameter influence on structural response

A subset of the cross-sectional data used for PCA was chosen for structural analysis, referred to as Group II in Figure 2.3. First, 5 of the original 13 slice locations were chosen (-10, -5, 0, 5, and 10 mm from the node). These slice locations were chosen because they resided in
the known failure region of the stalk [16]. A set of 70 stalks were randomly chosen for analysis, and cross-sectional data was taken at each of the 5 slice locations for each stalk. This resulted in a subset of 350 unique cross-sections. These cross-sections were the basis for the subsequent finite-element models.

For each of the Group II cross-sections, a reference finite-element model was created from the original interior and exterior boundaries. A corresponding elliptical approximation model was then created. Next, a series of more refined models was created. Two schemes were used: (1) a cumulative approximation scheme in which principal components were added to the ellipse in sequence (exactly as described previously), and (2) an approach in which each approximation consisted of the ellipse plus a single principal component. Comparisons between the transverse stiffness of the reference model and each of these approximate models were used to assess the significance of the first five principal components. With a total of seven different models in each scheme, this resulted in 2450 different models for each scheme. Altogether, 3850 unique models were run. This experimental design is outlined in Table 2.1.

Table 2.1: Experimental design used to create finite-element models of varying geometric complexity, which were then used to assess the influence of each geometric parameter on structural response.

<table>
<thead>
<tr>
<th>Cumulative</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference Model</td>
</tr>
<tr>
<td>2</td>
<td>Ellipse</td>
</tr>
<tr>
<td>3</td>
<td>Ellipse + PC 1</td>
</tr>
<tr>
<td>4</td>
<td>Ellipse + PCs 1-2</td>
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<tr>
<td>5</td>
<td>Ellipse + PCs 1-3</td>
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<tr>
<td>6</td>
<td>Ellipse + PCs 1-4</td>
</tr>
<tr>
<td>7</td>
<td>Ellipse + PCs 1-5</td>
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<table>
<thead>
<tr>
<th>Individual</th>
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<tbody>
<tr>
<td>1 Reference Model</td>
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<tr>
<td>2 Ellipse</td>
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<tr>
<td>3 Ellipse + PC 1</td>
</tr>
<tr>
<td>4 Ellipse + PC 2</td>
</tr>
<tr>
<td>5 Ellipse + PC 3</td>
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<tr>
<td>6 Ellipse + PC 4</td>
</tr>
<tr>
<td>7 Ellipse + PC 5</td>
</tr>
</tbody>
</table>

2.5.3 Confirming material/geometry interactions

Because the primary purpose of this study was to investigate the cross-sectional morphology, the material properties were not of primary concern. Nevertheless, in keeping with the impor-
tance of including biological variation when creating such models [28], we desired to incorporate
the type of material property variation that is representative of such specimens. We sought to
quantify the extent to which material properties affected (i.e., interacted with) results of the mor-
phological analyses. This was accomplished by running a subset of the previously-mentioned
analysis four times using different combinations of low and high rind and pith properties. The low
and high values were defined as the 5th and 95th percentile values from a normal distribution of
stalk material properties determined in prior research [3]. These analysis sets were identical in
every way except for the material properties used. A paired t-test was then performed for each
combination of material sampling schemes (for a total of six combinations) to assess whether an
increase in material stiffness would result in a different sensitivity for the same geometry. Be-
because no practically significant material-geometry interaction was discovered, material properties
were subsequently selected for each model based on random sampling from the ranges reported
in prior research [3]. For the rind, values were sampled from a normal distribution with a mean
of 807.5 MPa and a standard deviation of 335.2 MPa. For the pith, values were sampled from a
normal distribution with a mean of 25.98 MPa and a standard deviation of 10.30 MPa.

2.5.4 Assessing structural sensitivity to model parameters

The cases shown in Table 2.1 provide insight on the inclusion/exclusion of various mor-
phological features captured by the principal components. However, this approach has limitations
because the ellipse cannot be excluded. To quantify the influence of each morphological parameter,
a series of local sensitivity analyses were performed. In order to allow comparison between sensi-
tivity values, a normalized sensitivity approach was used. This involved changing one parameter
at a time by 10% and then computing the normalized sensitivity as the percent change in output
divided by the percent change in input, as shown here:

\[
S = \frac{(y_{\text{new}} - y_{\text{ref}})}{y_{\text{ref}}} \frac{y_{\text{ref}}}{(x_{\text{new}} - x_{\text{ref}})} \frac{x_{\text{ref}}}{x_{\text{new}}} 
\]

(2.1)

In this equation, \(x_{\text{ref}}\) and \(y_{\text{ref}}\) represent the input and response in the reference case while
\(x_{\text{new}}\) and \(y_{\text{new}}\) represents the input and response values from the modified case.
Reference models consisted of an ellipse plus the first five corresponding principal components (i.e., the last row in the cumulative column of Table 2.1). The two parameters describing the model’s material properties were also included in the sensitivity analysis. As such, each model consisted of ten parameters: three describing the ellipse (major diameter, minor diameter, and rind thickness); five coefficients describing the scaling of the five principal components; and two material properties. Thus, the sensitivity analysis for each reference model consisted of a reference case and ten additional cases corresponding to variation of each of the ten model parameters. With 350 reference models, the full sensitivity analysis required the creation of 3,850 finite-element models.
CHAPTER 3. RESULTS

3.1 Assessment of the morphological decomposition

Initial results of principal component analysis were not favorable toward distinct features. As shown in Figure 3.1, the notch was not successfully separated from the rest of the cross-sectional features, but was present in multiple principal components. It had previously been assumed that principal component analysis would deem pure ellipse components as the most influential, and all other minor features would be separately composed. This was not the case, but the highly elliptical nature of the first principal component was still evident. Since the conflation of apparent parameters was undesirable for model simplicity, a hybrid ellipse and principal components approach was used.

Figure 3.1: Qualitative results of performing principal component analysis directly on exterior boundary data. The first principal component contains both ellipse and notch data.

The use of a hybrid ellipse and principal components approach allowed the original geometry of each cross-section to be decomposed and reconstructed. Various levels of geometric approx-
imation were obtained by using a varying number of principal components. Figure 3.2 shows the process of re-composing the geometry of a single cross-section by including an increasing number of principal components.

![Example progression of cumulative geometric models](image)

Figure 3.2: Example progression of cumulative geometric models. The gray outline represents the original cross-sectional geometry while the black lines depict geometric approximations.

An analysis of total geometric error supports what the eye perceives in Figure 3.2. A convergence plot was created to depict the manner in which the distribution of error values approaches zero as all 360 principal components are included. This convergence plot is provided in Figure 3.3. As seen in the table, the width of the error distribution reduces drastically between the ellipse alone and the inclusion of the first principal component, with mild improvements as more principal components are included. By the inclusion of five principal components, 95% of the error distribution has a magnitude less than 1.5%.
Figure 3.3: The distribution of radial error values as a function of the number of geometric parameters included in the model. Since the ellipse alone was the zeroth case, it is represented on the log scale by the label “Ellipse” on the horizontal axis. Percent geometric error is reported relative to the corresponding minor radius. For clarity, the horizontal axis is presented using a base 5 log scale.

3.2 Influence of principal components on structural response

The structural response of interest was the transverse stiffness of each model (i.e., the slope of the force/deformation slope resulting from each finite element simulation), since the applied deformations were designed to stay within the linear region of material behavior. The most striking result in both the cumulative and individual model creation schemes was the close similarity between the structural stiffness of the original cross-section and a simple ellipse. The average percent difference between ellipse and reference model was approximately 1% (median value of -0.77%, standard deviation of 1.06%, n = 350).

The results of comparisons for the cumulative model scheme were very promising. The previously mentioned mesh convergence study indicated a mesh noise level of ±2%, meaning the same geometry could be run multiple times and produce responses with ±2% error. For models consisting of an ellipse plus five principal components, virtually all cases exhibited a percent dif-
ference of less than 1% error (median value of -0.08%, standard deviation of 0.30%, n = 350). The pattern of error reduction as successive principal components were added to the model is depicted in Figure 3.4. As shown in Figure 3.4, both the width of the distribution and the mean error tended to decrease in magnitude as successive principal components were added to the geometric approximation.

Figure 3.4: Distributions of reaction force error for cumulative principal component model creation (i.e., ellipse + increasing numbers of principal components).

An alternative scheme is to add individual principal components to the ellipse (rather than adding them cumulatively, as above). This approach would be expected to be less accurate than the successive approach, and this was found to be the case. The error distributions associated with the ellipse and ellipse plus individual principal components is shown in Figure 3.5.
3.3 Influence of tissue properties

The primary results of interest in this study were relative differences between the reference model and other cases. Because all models were linear in nature, material properties were expected to have a linear influence on the associated response. This was confirmed by statistical comparisons between the analyses performed with high material properties vs. low material properties. Results of this comparison were statistically insignificant, with the difference distribution having a mean and and standard deviation of -0.0014 and 0.0039, respectively (paired t-test, n = 20, p-value = 0.1336).

Figure 3.5: Distributions of reaction force error for non-cumulative geometric model creation (i.e., ellipse + a single principal component).
3.4 Sensitivity results

The influence of each model parameter on transverse stiffness was quantified by computing normalized sensitivities. These results indicated that the most influential parameters were related to the morphology of the ellipse and tissue properties (see Figure 3.6). The rind thickness was found to have the highest influence on transverse stiffness, with a mean sensitivity of 0.97. This indicates that a 1% change in rind thickness would (on average) increase the transverse stiffness by 0.97%, which is essentially a 1:1 influence. The three most influential parameters were rind thickness, major diameter, and the Young’s Modulus of the pith tissue. The Young’s Modulus of the rind and the minor diameter had relatively low sensitivity values (0.3 and -0.08, respectively). Of greatest interest is the fact that all principal components had sensitivity values of less than 0.01, indicating that all principal components exerted a negligible influence on structural response.

3.5 Validation

This work used previously-validated methods as a basis for the finite-element models [3]. To further strengthen the case that the parameterized model provides a good estimate of the true stalk cross-section behavior, a small validation study was run using the transverse compression models from Stubbs, 2019 [3]. The parameterized ellipse model was fit to the cross-sections from the aforementioned study and loaded with the same displacement. Identical values for mesh seed size, rind stiffness, and pith stiffness were used between the original models and the ellipse approximation models. The transverse stiffness responses were tabulated for both model sets and a linear regression analysis was performed. The ellipse models were able to fit the real behavior with reasonably high correlation coefficients ($R^2 = 0.925$). This gives additional confidence in the ellipse model’s ability to predict behavior of real stalks outside the data set used to develop the model.
Figure 3.6: Distributions of reaction force error for non-cumulative geometric model creation (i.e., ellipse + a single principal component). Sensitivities are ordered by magnitude.
CHAPTER 4. DISCUSSION & CONCLUSIONS

4.1 Effectiveness of the ellipse

The purpose of this study was to develop a parameterized two-dimensional morphological model of the maize cross-section as a first step towards the development of a parameterized three-dimensional model. The results shown in Figures 3.4 and 3.5 indicate that the use of an ellipse introduces only a relatively small amount of error as compared to the original geometry of the stalk cross-section. This conclusion is reinforced by the results of Figure 3.6, which show that the parameters of the ellipse exert far more influence on the structural response than any of the principal components.

Since the ellipse is fully defined by just three parameters: major diameter, minor diameter, and rind thickness, the entire cross-sectional model can be described by five parameters: three for the ellipse, and two for the tissue (see Figure 4.1). This compact representation provides a very convenient way to parameterize the cross-section. Furthermore, the small number of cross-sectional parameters is expected to greatly simplify the future research required to obtain a three-dimensional parameterization of the maize stalk geometry.

4.2 Limitations

This study has certain limitations, which are discussed in this section in order of their respective influence on the results. These limitations should be evaluated in the context and purpose of this study, which was to develop a parsimonious cross-sectional model of maize stalk geometry.

The most significant limitation in this study is the assumption of constant rind thickness. An alternative (and more accurate) approach would have been to also decompose the interior boundary of the maize stalk using a separate ellipse and additional principal components. This approach was not used because it would have significantly increased the number of model parameters. The results
shown in Figure 3.4 indicate that a single ellipse with a constant rind thickness is within $\pm 2\%$ of the response of a corresponding model that is based directly on CT scan data geometry.

The second important limitation of this study is that it relied upon loading conditions that necessarily differ from those experienced by an actual stalk in bending. As stated previously, Brazier buckling is determined by the amount of transverse ovalization that occurs when a stalk is subjected to a bending load [12, 18]. In a true Brazier buckling case, ovalization is achieved by the longitudinal forces of tension and compression induced by bending loads. Transverse ovalization was achieved in this study by applying a transverse compression load to two-dimensional models of the maize cross-section (Figures 2.2 & 2.4). This approach was chosen because (a) it builds upon previously validated cross-sectional models of the maize cross-section [27], (b) it allows a means of quantifying resistance to transverse deformation using a two-dimensional model. However, it must be acknowledged that this approach does not take into account effects of the three-dimensional stress state, nor the effects of anisotropy that become clear in a full three-dimensional model. The stress states of bending and transverse compression are very different, but the stiffness of the system in transverse compression and bending-induced ovalization have similar sensitivities [12]. Since this thesis only examines the stiffness responses, this analogy is reasonable even if the stress behavior is different.

Additional and relatively minor limitations include the use of several simplifying assumptions. Tissues were modeled as transversely isotropic and linear elastic. The plane-stress assump-
tion was invoked to further simplify our analysis. All simulations were static in nature and did not include any dynamic effects. However, since the primary goal was to develop a useful and accurate geometric model, not to investigate the actual mechanics of transverse ovalization, we believe that each of these assumptions are justified and appropriate.

4.3 Conclusions

This study represents the first attempt to create a parameterized model of the maize stalk cross-section. The maize stalk geometry was approximated as an ellipse with additional features captured using principal component analysis. Cross-sectional models were compared to the actual maize stalk morphology using both relative geometric error and structural response to transverse deformation.

The results of this study indicate that a simple ellipse consisting of just three parameters: major diameter, minor diameter, and rind thickness is capable of providing an excellent approximation of the actual maize stalk geometry. In comparing the ellipse to actual maize cross-sections, the ellipse approach exhibited less than ±8% error in 80% of all cases. And because most geometric errors had a weak influence on structural response, the discrepancy between transverse stiffness of the ellipse and actual cross-sections was less than ±2% for 75.17% of all models examined in this study. Of course, the approach outlined in this study can also be used to create more refined models of maize stalk geometry by including additional principal components.

These findings are significant because they efficiently support the long-term research need for three-dimensional parameterized models. Such models are computationally expensive, which makes a simultaneous study of longitudinal and cross-sectional features impractical. The cross-sectional models developed in this study will allow future studies to focus purely on the longitudinal patterns inherent in maize stalk morphology. Once fully parameterized models are developed, advanced analyses will be possible, such as optimization of the maize stalk morphology.

4.4 Future Work

Work is already under way to apply the methodologies that resulted in the elliptical cross-section model toward the longitudinal features of the maize stalk and produce the first three-
dimensional parameterized model of the maize stalk. Measurements of the ellipse parameters along the entire stalk exist for the same CT data used in this study, and preliminary principal component analysis has already been performed on this data. It appears as of this writing that a relatively small number of principal-component-based parameters will be required to describe the geometry of the full maize stalk.

The next step in this process will be to perform a study similar to that outlined in Table 2.1, where a series of successive geometric approximations of randomly sampled corn stalks are tested in bending, torsion, and axial compression to determine the required number of parameters to accurately produce the behavior of real corn stalks. This process will likely require additional steps that weren’t required for the transverse model, namely that the principal components will have to be fit with known functions that can be described in few variables. This fitting process may induce other effects in the ability of the parameterization to successfully approximate real stalks, and that will need to be accounted for.

The potential of parameterized models of stalk structure to influence future research and development of more lodging-resistant hybrids of corn is massive. For example, entire studies could be conducted using the synthetic model to generate artificial populations with sample sizes too large to feasibly obtain from the field. The turnaround times would be drastically shortened, and the barrier to entry for research in this field would be reduced, as the necessary equipment and resources to conduct this research would be diminished. Additionally, because of parameterization, studies could be performed where stalk structure is optimized against a cost function such as plant biomass. In this way, it would be possible to examine the claims of Schulgasser and Witztum that plant structures are already optimized against failure so that multiple failure modes are reached simultaneously [12]. These optimization studies could also inform selective breeding studies that could result in new hybrids with improved stalk lodging resistance.

This study set out with the specific goal to determine a parameterized model for transverse compression in maize, but the methodologies used have wider-reaching applications beyond this particular crop. As has been noted in several places in this thesis, many other important agricultural crops share a similar stalk structure to maize, such as oats, barley, wheat, sugar cane, and rice. Even plants with a hollow stalk, such as bamboo, might successfully be modeled using these principles.
In the long-term, the work contained in this thesis will provide the basis for a new tool that could be used in maize phenotyping and breeding trials. Eventually, plant breeders will be able to use such a tool to predict the stalk-lodging resistance of individual maize stalks with a relatively small number of physical measurements. More importantly, plant biomechanics researchers and plant breeders will be able to determine which stalk parameters should be altered to develop improved stalk-lodging resistant hybrids of maize.
REFERENCES


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