Almost 100 yr ago, Garber and Olson (1919) observed that “lodging in cereals 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.” Lodging has historically been measured by visual counting of lodged stalks at harvest. Unfortunately, this approach is notoriously unreliable because it is confounded by several environmental factors, including disease, pest damage, wind, and rain (Flint-Garcia et al., 2003a).

In regards to maize, three-quarters of a century ago, Hunter and Dalbey (1937) looked forward to a time when laboratory or other controlled methods could provide more reliable data on lodging. Since then, many approaches to stalk lodging have been explored. Some of these have included bending tests, rind penetration, and anatomical measurements (Davis and Crane, 1976; Martin and Russell, 1984; Zuber et al., 1980). However, the genetic relationships for these methods have proven to be weak to moderate (Flint-Garcia et al., 2003a,b,c; Peiffer et al., 2013; Hu et al., 2013). After nearly 100 yr of research on lodging, visual counts of lodging are still the primary method used to quantify lodging resistance (Hu et al., 2013; Lian et al., 2014).

Lodging is clearly a highly complex, elusive problem. Perhaps one reason for the lack of progress has been the fact that this problem has been studied from a purely agronomic perspective. The current study provides a forensic engineering approach to understanding the failure patterns and mechanisms of corn stalk lodging.

ABSTRACT
Stalk lodging is essentially a structural failure. It was therefore hypothesized that application of structural and forensic engineering principles would provide novel insights into the problem of late-season stalk lodging of maize (Zea mays L.). This study presents results from a structural engineering failure analysis of corn stalk lodging, involving detailed inspection and measurements of lodged stalks and a multidimensional imaging study to assess stalk architecture based on structural engineering principles. This work involved infield observation of >20 varieties of lodged corn stalk in eight international locations and detailed geometric analysis of four varieties. Analysis of collected data revealed very strong, yet previously unreported, patterns in corn stalk lodging. Corn stalks predominantly fail (break) by creasing, fall in the direction of the minor diameter of the cross section, and break within 4 cm of a node. These failure patterns, across a broad sampling of varieties and environments, suggest a consistent weakness in maize stalk architecture, indicating that a common solution might be identified to strengthen maize stalks. Structural engineering analysis of stalk architecture and morphology revealed that several geometric stress concentrators (features known from engineering theory to increase local stresses) occur in the predominant failure region of corn stalk. Identified stress concentrators include surface irregularities, sharp changes in diameter, and voids occurring in the stalk pith. Each of these stalk features persist across different international locations, environmental conditions, and hybrid varieties. These findings support the use of new selective breeding approaches that focus on stalk morphology and structural engineering analysis of corn stalk architecture to develop lodging resistant varieties of maize.

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Abbreviations: CT, computed tomography.
The primary purpose of forensic engineering is to determine causes of accidents, device failures, or other unintended events. Forensic engineering principles could therefore potentially identify new patterns or features that are not only correlated with stalk lodging, but that are causally related to stalk strength or weakness. A forensic engineering analysis of lodged corn stalk was therefore conducted, including (i) an observational study of naturally lodged corn stalks in the field, and (ii) a detailed assessment of the corn stalk architecture from a structural engineering perspective. To our knowledge, this is the first time that this approach has been applied to the study of crop lodging.

Several goals and objectives were identified at the onset of this study. First, we wished to assess the value of applying forensic engineering to the problem of stalk lodging. Second, we sought to identify patterns (if any) in lodged corn stalks (e.g., modes of failure, location of failure, etc.). Third, we sought to identify features of the stalk that potentially influence lodging. Identification of these features could prove to be valuable for future breeding studies.

METHoDS
This study consists of two distinct components. The first component was an observational study to obtain new information on the failure patterns of corn stalks in their natural environment. The purpose of this first component was to produce a comprehensive description of corn stalk failure, including types of failure (and rates for each type), locations of failure, and other important information.

The second component of this study involves an assessment and analysis of the corn stalk structure (especially the corn stalk geometry) based on engineering principles and expertise. Several imaging modalities were used to collect relevant information on the corn stalk geometry. Informed by novel failure data and geometric information, engineering theory and expertise were applied to generate new hypotheses of corn stalk failure that are consistent with each of these sources of information.

Observational Study of Naturally Lodged Stalks
Forensic engineering failure analysis begins with detailed examinations of failed specimens. Naturally lodged corn stalks were examined at several locations in Iowa during the fall of 2010 to determine the range of possible failure modes (or types) and to design a methodology for collecting relevant data. This methodology was then used to collect lodging data at four locations in Iowa during the 2012 growing season (fields near Shelby, Ellsworth, Boone, and Williams, IA) and at four locations in South Africa (Rigdar, Migdol, Viljoenskroon, and Rammalutzii, SA) during the 2013–2014 growing season. Environmental conditions from those sites are summarized in Tables 1 and 2. Daily weather data was measured in all four Iowa locations. Weather data for South Africa locations was only available in Migdol and Viljoenskroon. Soil classifications were not taken from South African locations. Drought conditions were prevalent across all four Iowa locations in 2012 with higher temperatures and reduced rainfall being recorded. For example, in 2011 in Boone, IA, average rainfall during the growing season was 109.4 mm mo−1, while in 2012 it was only 55.7 mm. In 2011 there were three large rain events >25 mm of more, while in 2012 there were only two in 2012. In 2011, Williams, IA, had six strong storms but only one in 2012. Even though drought conditions persisted throughout the growing season, timely rains helped produce average yields (13.9–15.7 m3 ha−1).

To reduce the number of potential confounding factors, only stalks with no visible presence of disease or pest damage were included in this study. Additionally, the study focused only on late-season stalk lodging, which occurs between physiological maturity of the grain and the time of harvest. Because the purpose of this research was to identify trends affecting corn in general (not specific varieties), a broad sampling approach was employed that included over 20 commercial and precommercial varieties of dent corn and sweet corn. Data recorded for lodged stalk specimens included distance from the site of tissue failure to the nearest node line, the internode section in which the failure occurred, descriptive photographs of failure patterns, presence of disease or pest damage, a written description of the failure region, etc.
Engineering Analysis of Corn Stalk Architecture

Structural analysis of corn stalk architecture was performed on intact (unbroken) corn stalk specimens. Sampling for this component of the research was distinct from the observational analysis described above. Stalk samples were collected immediately before harvest at Monsanto testing sites near Greenville, IA, in 2011. Stalks were sampled from two replicates of four commercially available DeKalb hybrids seeded at four plant densities (74, 89, 104, and 119 1000-plants ha⁻¹) in a completely randomized design. To prevent spoilage and increase shelf life of the specimens, stalks were placed on a forced-air dryer for 2 d to reduce stalk moisture to a stable level (between 10 and 13%). All specimens were evaluated for disease and insect damage; only fully intact, uncompromised stalk sections were included in this study.

Analysis included laboratory inspection and measurement of stalk tissues using high-resolution X-ray computed tomography (CT) scanning, stereomicroscopy, and scanning electron microscopy. The CT scans were performed on stalks using an X5000 scanner (NorthStar Imaging). Sets of five stalks were scanned together at 7.5 frames per second with each scan consisting of 1200, two-dimensional radiographs. Scan data was calibrated using the density of two known reference objects. Reconstructed three-dimensional scans had a spatial resolution of 90 µm voxel⁻¹ and a 16-bit intensity range. At this resolution, individual vesicles within each stalk are clearly visible.

Geometric analysis of CT scan data was performed using custom computer software developed for this project. This software automatically identifies the location of each node in the digital data set and then uses the nodal locations as reference points for the measurement of numerous geometric and structural engineering attributes including interior and exterior boundaries, rind thickness, maximum and minimum diameter of each cross section, eccentricity of the cross-sectional area, moment of inertia, etc.

Physical examination of corn stalk samples revealed that voids (i.e., holes or cracks) sometimes occur within the pith. Manual inspection of CT data was used to determine the presence and location of voids in scanned stalks. A manual approach was chosen because of the low contrast between the void space and low-density pith tissue, which limits the effectiveness of automatic edge-detection algorithms. This manual analysis produced binary data (presence vs. absence of visible voids) at 10 regularly spaced sample points along each internode section of each stalk. Stalks were inspected using both a stereo microscope and a scanning electron microscope to observe corn stalk cross sections and tissue organization.

Finally, geometric information was combined with failure pattern data to form hypotheses of stalk failure that were consistent with principles of structural failure from the field of engineering.

RESULTS

In-Field Observational Study

Manual inspection of naturally lodged corn stalk specimens revealed that stalks typically broke in one of three ways (i.e., three primary failure modes). These failure modes included snapping, splitting, and creasing. Photographs of each failure mode are shown in Fig. 1.

Overall, 91% of specimens failed as a result of creasing. Stalks that fail in this mode typically display either one or two creases, which are oriented perpendicular to the apical-basal axis of the stalk. Splitting of stalks appears to primarily be a secondary failure mode (i.e., creasing occurs first and, as the crease becomes more pronounced, splitting of the rind occurs). This explanation of failure progression is supported by two observations: (i) manual straightening of failed stalks results in the closure of split tissue, and (ii) laboratory three-point bending experiments (Robertson et al., 2014) also produce splitting as a secondary failure following creasing. Snapping failures were the second most common failure mode, occurring in 7% of examined specimens. Splitting was rarely seen in the absence of creasing (2% of examined specimens). These results are summarized in Fig. 2. Confidence intervals were calculated by applying a standard interval estimation approach (Brown et al., 2001). To calculate confidence intervals proportions were reduced to two: creasing and noncreasing. The resulting 99% confidence intervals are provided in Fig. 2.

Crease failures are closely related to plant physiology. Creases were generally aligned with the major diameter of the stalk cross section and the plants generally fell in the direction of the minor stalk diameter. The direction of primary failure (direction in which the plant fell) was determined using a stalk-based angular coordinate system, with the origin at the center of the stalk cross section and the
zero-degree direction in the direction of the leaf groove. Using the (approximate) symmetry of the stalk about the 0 and 90° directions, only angles between 0 and 90° were recorded (i.e., an angle of 135 and 180° were recorded as 45 and 0° respectively). Failure angles were grouped into bins centered at 0, 45, and 90°, as shown in Fig. 2. The predominant direction of failure was in the 90° direction, which is the direction of the minor diameter of the corn stalk. Overall, 85% of stalks failed in this direction.

Engineering bending analysis of the typical stalk cross section predicts that stalks are stiffer and stronger when bent in the direction of the major cross-sectional dimension, but weaker when bent in the minor diameter direction. While further research is needed on this subject, these differences in stiffness and strength likely explain the propensity of stalk failure in the direction of the minor diameter.

Finally, the primary failure location of lodged stalks is also closely related to stalk physiology. Failure most commonly occurs in close proximity to the node and the meristematic tissue immediately above the node. As shown in Fig. 3, the distribution of failure location is centered about 1 cm above the node, with failure frequency rapidly decreasing with distance from this point. Overall, 89% of specimens failed within 3 cm of the distribution center. Failure was observed less frequently just below the node, where the stalk exhibits dense, tough tissue and a thick rind.

Figure 2. Distributions of failure types and failure directions. Failure direction is defined relative to the leaf groove of each stalk, with the leaf groove as 0°. Due to symmetry of the stalk about the 0 and 90° lines, all angles are presented between 0 and 90°. Failure direction data collected at four South Africa locations only (hence a reduced sample size). Whiskers represent 99% confidence intervals of the reported percentages.

Figure 3. Histogram of failure locations relative to the closest node. The node line is represented by the vertical dashed line. Histogram bins have a width of 0.5 cm.
observed to occur near nodes. Figure 4 consists of images obtained from stereo and scanning electron microscopes that illustrate the differences between internodal and nodal tissue organization. Divots and wrinkling occurring near the node include epidermal wrinkling and divots from undeveloped brace roots can act as engineering stress concentrators thereby lowering the bending strength of corn stalk.

**Engineering Analysis**

Close inspection of stalk morphology from the macro to micro scales reveals several geometric features that may act as stress concentrators. A stress concentrator is a material or geometric feature of a structure that results in increased structural stresses. Because failure always results from stresses that exceed the ultimate strength of the associated material, stress concentrators are often closely related to failure. For example, the small holes in perforated notepad paper act as stress concentrators to ensure that the paper rips along a given line. Several stress concentrators of corn stalk were identified in this study and are described below.

Maximum stresses always occur on the outermost surfaces of structures that are loaded in bending. Gross observations of the exterior surface of corn stalks were therefore performed. These observations revealed that internodal tissues are smoother, more organized, and more regular than tissues near the node. Basal nodes, in particular, often exhibit divots (crater like depressions in the stalk) that are associated with undeveloped brace roots. A significant amount of wrinkling in the epidermal tissues was also observed to occur near nodes. Figure 4 consists of images obtained from stereo and scanning electron microscopes that illustrate the differences between internodal and nodal tissue organization. Divots and wrinkling occurring near the node were found to be nonuniform in terms of shape and size. Surface irregularities such as these typically act as stress concentrators and can substantially increase the propensity of structural buckling (Simitses, 1986).

Sudden changes in any geometric feature can act as a stress concentrator. The CT scan data was therefore analyzed to quantify sudden geometric changes in corn stalk. Analysis of this data revealed that major changes in virtually all geometric features occur in and around the nodal and meristematic tissue (i.e., the predominant failure region of naturally lodged corn stalk). Figure 5 displays graphs of several geometric features of a representative stalk which demonstrate this trend. Such patterns in stalk morphology and geometry were typical of all maize stalks investigated in the study.

Cross-sectional changes in diameter, such as those observed to occur at the node of corn stalk (Fig. 6), are some...
of the most well-known stress concentrators (Shigley et al., 2003). The average reduction (and standard deviation) in major and minor diameters at the node was 13.8% (4.1%) and 10.2% (6.5%), respectively. More gradual changes in diameter were also observed in the intercalary meristem region. As seen in Fig. 5, the diameter typically tapers just after the node line and then becomes relatively constant in the internodal region. While the changes in diameter occurring in the intercalary meristem are less drastic than those at the node, they can still act as stress concentrators.

Finally, we observed drastic changes in rind thickness and tissue density near the node. Rind tissue is thinnest in the internodal region, with thickness increasing rapidly near the nodes. At the node itself, corn stalk is nearly solid. The area moment of inertia—a quantity that is related to structural stiffness under bending as well as stress distribution—was also observed to change rapidly near each node.

The CT scans revealed that virtually all (99%) of the stalks had at least one sizeable void in the pith tissue. Examples of such voids are shown in Fig. 7. Rapid drying during senescence may cause the pith tissue (parenchyma) to crack or split as moisture leaves the stalk too quickly, similar to the splitting that occurs when wood dries rapidly. The presence of sharp corners and uneven pith tissue distribution can act as stress concentrators.

**DISCUSSION**

One goal of the current study was to catalog failure modes and patterns of naturally lodged corn stalk. Consistent failure patterns suggest a consistent structural weakness or a design flaw. Well-designed structures do not have a consistent weakness and therefore they either (i) do not fail at all, or (ii) they fail at a broad distribution of points and in a variety of failure modalities. In the latter case, failure is caused...
by randomly distributed local imperfections in material or geometry, not by a systemic weakness in the design.

The application of forensic engineering techniques revealed strong patterns of corn stalk failure in failure modes, direction, and failure location. Considering the large amount of genetic and environmental diversity inherent in the results (eight international locations, >20 varieties, and multiple years), the consistency of failure patterns was quite surprising. We found that stalk failure almost always occurs within a few centimeters of a node, involves a crease in the direction of the major diameter, and results in the stalk falling predominantly in the direction of the minor diameter. Failures away from the node are very rare in healthy, intact corn stalks, even though rind tissue is thinnest in the internodal regions. Such consistent failure patterns indicate that corn stalk possesses a systemic structural weakness. Furthermore the fact that failures occur in regions of high geometric variation imply a causal relationship between geometric stress concentrators and failure that is strongly supported by engineering theory.

Three predominant stress concentrators (pith voids, surface irregularities, and sharp changes in diameter) are colocated with the predominant failure region of naturally lodged corn stalk. These features appear to be common in many different corn varieties regardless of corn type, growing location, or planting densities. Mechanical three-point bending tests conducted in our lab have revealed that failure frequently initiates at or near one of these stress concentrators.
Concentrators (Robertson et al., 2014). A brief discussion of each stress concentrator, including its potential effects on stalk bending strength, is given below.

It is well accepted in engineering theory and practice that hollow or foam-filled tubes are particularly susceptible to surface imperfections such as the divots seen on the left of Fig. 4 (Simitses, 1986). Geometric imperfections of approximately the same size as undeveloped brace root divots have been reported to decrease the buckling load of anisotropic, hollow tubes by up to 50% (Tennyson, 1968). However, to our knowledge, the scientific literature on plant physiology does not currently contain any mention of how surface irregularities may affect structural strength of plant stems.

While numerous engineering studies have addressed stress concentrations as a result of changes in diameter, a review of the corn and plant literature revealed no mention of this topic. The equations of Shigley et al. (2003) were used to estimate the effect of diameter changes (see Fig. 6) on corn stalk bending strength. These calculations, based on an isotropic rod in pure bending with the average cross-sectional parameters reported in this study, indicate a 300% increase in stress near the node. The anisotropic material properties of corn stalk likely reduce this stress concentration, and further research is required to achieve a more precise prediction. Thus, while nodes are known to increase stalk strength by preventing cross-sectional ovalization (i.e., microbuckling) (Niklas, 1992), the sharp changes in cross-sectional geometry occurring near the node can also act as a stress concentrator. Minimizing or smoothing the sharp changes in geometry that occur near the node might be one avenue for improving stalk strength. Indeed, a recent computational study (Von Forell et al., 2015) has shown that reducing the geometric variation of the surface of corn stalks (i.e., smoothing the surface geometry) causes reductions in stress levels when all other factors are held constant.

The pith of corn stalk is known to act as a mechanical brace thus increasing the bending strength of the stalk (Niklas, 1992; Lu et al., 1987). It prevents the stalk cross section from ovalizing (Niklas, 1998) and resists inward buckling of the rind tissue. Voids in the pith tissue inhibit it from performing these mechanical functions. Surgical destruction of transverse diaphragms of grass stems that serve the same mechanical purpose as the pith tissue (i.e., transverse braces) has been shown to reduce bending strength by up to 20% (Niklas, 1992). Similar results have also been shown in foam-filled, thin-walled tubes constructed from typical engineering materials (Kim et al., 2004; Reid et al., 1986; Chen et al., 2002).

Rather than being a stress concentrator, the increase in rind thickness occurring near the node is likely nature’s approach to handling greater stresses that arise near the node. By increasing rind thickness, more tissue is available on which to distribute bending forces. However, since failures are highly concentrated near the node, the effect of increased rind thickness appears to be insufficient to overcome the stress concentrations imposed by other features. Future studies involving structural finite element modeling of corn stalk may provide more insight on the role of the rind thickness on stress distributions near the node.

**Limitations**

Observational studies such as this one are always limited to observable (and often uncontrollable) events. Stalk lodging is often associated with strong wind and rain storms that strike during the senescence period. Particularly strong storms occasionally flatten entire crop fields. This study relied on natural occurrences of stalk lodging, which could potentially bias the study because the fallen stalks were perhaps unnaturally weak, malformed, or affected by the undetected presence of disease or pests. On the other hand, the patterns revealed in this study persist across many types and varieties of corn, growing locations, growing seasons, and climate, suggesting that plant architecture plays a central role in stalk strength and failure. Since initially reporting these results, several crop scientists have contacted the authors and confirmed the failure patterns reported in this study.

Finally, while the stress concentrators identified in this study are colocated with failure occurrences, and similar geometric features are known in the engineering literature to be stress concentrators, we must always bear in mind that correlation does not imply causality. Engineering theory provides compelling explanations for how geometric features near stalk nodes could affect (and perhaps cause) failure. More focused research will be needed to test and confirm or disprove these hypotheses. If confirmed, these geometric features would enable new approaches for improving stalk strength through selective breeding.

**CONCLUSION**

Corn stalk lodging exhibits strong patterns of failure modes (predominantly creasing), failure orientation (predominantly aligned with the major diameter of the stalk), and failure location (89% of failures originate in a narrow region near the node). These results imply that many varieties of corn suffer from a consistent structural weakness. Several stress concentrators (features known from engineering theory to increase local stresses) are spatially correlated with the predominant failure location of lodged corn stalk. Identified stress concentrators included pith voids, surface irregularities, and changes in cross-sectional geometry. It seems likely that one or more of these factors contribute to the failure patterns observed in this study and may influence maize stalk strength.

Forensic engineering has proven to be a useful approach for investigating lodging of corn and other agricultural crops. In addition, recent engineering analyses of
bending test methodologies (Robertson et al., 2014, 2015) have shown that many prior studies have used inappropriate techniques for assessing bending strength. This may explain the weak to moderate connection between bending strength and lodging in prior studies.

The results of this study suggest that stalk strength is closely related to relatively small and previously unstudied morphological features. It is conceivable that modification of these features (stress concentrators) would require minimal diversion of bioenergy and biomass and, therefore, would not have a detrimental effect on yield. This approach could lead to substantially different results than previous selective breeding studies, which have almost exclusively focused on gross internodal geometries and material properties. In summary, engineering methods and tools appear to hold great promise in addressing the problem of stalk lodging.

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