The Effect of Plant Weight on Estimations of Stalk Flexural Stiffness and Stalk Lodging Resistance

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Abstract

Background: Stalk lodging (breaking of agricultural plant stalks prior to harvest) is a multi-billion dollar a year problem. Stalk lodging occurs when bending moments induced by a combination of external loading (e.g. wind) and self-loading (e.g. the plant's own weight) exceed the bending strength of plant stems. Previous studies have investigated external loading and self-loading of plants as separate and independent phenomena. However, these two types of loading are highly interconnected and mutually dependent. The purpose of this paper is twofold: (1) to investigate the combined effect of external loads and plant weight on the flexural response of plant stems, and (2) to provide a generalized framework for accounting for self-weight during mechanical phenotyping experiments used to predict stalk lodging resistance.

Results: A method of properly accounting for the interconnected relationship between self-loading and external loading of plants stems is presented. The interconnected set of equations are used to produce user-friendly applications by presenting (1) simplified self-loading correction factors for a number of common external loading configurations of plants, and (2) a generalized Microsoft Excel framework that calculates the influence of self-loading on crop stems. The effect of self-loading on the bending strength measurements of wheat is examined in detail. A survey of several other plants is conducted and the influence of self-loading on their structural response is also presented.

Conclusions: The self-loading of plants plays a potentially critical role in determining the structural response of plant stems. Equations and tools provided herein enable researchers to account for the plant's weight during mechanical phenotyping experiments used to determine the flexural rigidity and bending strength of plant stems. Results demonstrated that ignoring the self-loading of some plants can result in errors of 25% for flexural stiffness and 20% for bending strength.

Keywords: bending, biomechanics, computational, flexural, plant, lodging, stalk, stem, stiffness, strength, weight

Background

Yield losses due to stalk lodging (breakage of crop stems or stalks prior to harvest) are estimated to range from 5-20% annually [1,2]. Despite a growing body of literature surrounding the topic of stalk lodging in wheat, barley, oats, and maize [3–7], a detailed study on the interconnected relationship between external loading (e.g. wind) and self-loading (e.g. plant weight) on stalk bending strength and stalk flexural stiffness has not been reported. In particular, previous biomechanical models of stalk lodging have examined the influence of morphology, material, and weight on stem failure, while others have separately analyzed the effects of externally induced bending forces (e.g., wind) on stem failure [3,4,8–15]. However, the effects of self-weight and external loads on stem failure are inextricably connected. The bending moment induced from self-weight is a function of the distance between the plant's base and its center of gravity. As external loads displace the center of gravity away from the base of the stem, the bending moment induced from self-weight increases. Although previous studies have independently looked at external loads [4,5,16] and self-weight loading [3], the authors are not aware of previous investigations into the interplay between these factors. A more complete understanding of the interconnected relationship between self-loading and external loading is necessary to improve the accuracy of mechanical phenotyping experiments used to determine stalk flexural stiffness and stalk bending strength (i.e., measurements of stalk lodging resistance).

Several phenotyping devices have been developed to assess the stalk lodging resistance of grain crops [24]. In general, these devices apply an external load to either a single plant or to a group of plants and measure the accompanying deflection of the plant stem(s). A biomechanical model is then used to determine the flexural stiffness or bending strength of the plant sample(s). Measurements of flexural stiffness and bending strength are highly correlated with natural occurring stalk lodging and are therefore often used as surrogate measurements of stalk lodging resistance. Although biomechanical models of plants can vary widely, a typical biomechanical model of a grain plant undergoing stalk lodging will consider the stem as a cantilever beam in bending, as shown in Figure 1. The loads applied to this beam can vary from a single point load at the top of the stem, to a distributed load applied along the entire length of the stem as shown in [22]. Standard engineering beam equations are then used to calculate the mechanical properties of the stem (e.g., flexural stiffness and bending strength). For example, the device developed by Cook *et al*. [6,41] laterally pushes a maize stalk, measuring the force applied to the stem and its deflected angle. Then, leveraging the cantilever beam model equations, the flexural stiffness and the bending strength of the stem is calculated. However, these calculations ignore the effect of self-weight and thus underpredict the actual strength / stiffness of the plant.

To more accurately calculate stem bending strength and flexural stiffness from mechanical phenotyping data it is necessary to calculate the total applied bending moment (M_{TOTAL}) to the plant. The total applied bending moment is equal to the summation of externally applied bending loads (M_{ext}) and bending loads induced from self-weight (M_{int}) It should be noted that externally applied bending loads can arise from any externally applied force (e.g., the wind, mechanical testing equipment, an adjacent plant pushing on the plant of interest or loads applied from a phenotyping device). However, bending loads induced from self-weight can only arise from the weight of the plant itself. The equations developed in this study can be used to account for any of the external loads mentioned above. Let us first consider the case of a mechanical phenotyping device used to assess stalk lodging resistance. As mentioned previously a typical phenotyping device for assessing stalk lodging resistance of grain crops applies an external bending load (M_{ext}) to a plant stem and measures its deflection (δ) [24,42,43]. The externally applied moment (M_{ext}) and plant displacement (δ) data are then analyzed to determine the flexural stiffness (EI) of the stem or the bending strength of the stem using Castigliano's energy method, where the displacement of the beam is equal to the partial derivative of the internal potential energy of the system with respect to the applied load. For example see [17]:

$$EI = \frac{\int M_{ext} \frac{dM_{ext}}{dQ} dx}{2\delta} \quad \textbf{(1)}$$

where Q is the dummy load used for the load-moment derivative [17]. The effect of self-weight on plant deflection is ignored or assumed to be negligible in these analyses. In other words this type of analysis assumes bending strength = M_{TOTAL} = M_{ext}, whereas in reality bending strength = M_{TOTAL} = M_{ext} + M_{int}. In some instances researchers have removed leaf blades, grain heads, and all plant biomass above the grain prior to mechanical testing to limit the effect of self-weighting (i.e. to minimize M_{int}). However, it is unclear if such measures are adequate. To more accurately characterize flexural stiffness and stalk bending strength the contribution of self-weight to plant deflection and to the induced bending moment M_{TOTAL} needs to be calculated.

The purpose of this paper is therefore twofold: (1) to investigate the combined effect of external loads and plant weight on the bending strength and flexural stiffness of plant stems, and (2) to provide a generalized framework for accounting for self-weight during mechanical phenotyping experiments used to predict stalk lodging resistance.

Methods

Box 1: *Glossary of Terms*

Term	Definition
δ	Horizontal deflection (mm)
EI	Flexural stiffness (mm^2)
F	Externally applied force (N)
f_M	Geometric coefficient for applied moments
f_F	Geometric coefficient for applied forces
h	Height (mm)
L	Location where loading is applied (mm)
M	Externally applied moment (Nmm)
M_{ext}	Total induced moment from externally applied forces and moments (Nmm)
M_{int}	Total induced moment from self-loading (Nmm)
M_{TOTAL}	Total applied moment (sum of M_{ext} and M_{int}) (Nmm)
Q	The Castigliano's Method dummy load (N)
S	Section modulus (mm^3)
w	Weight (N)
W	Weight-induced moment (Nmm)
$\sigma_{bending}$	Bending stress (N/mm^2)
Z	Vertical position where deflection is being calculated (mm)

Derivation of Closed Form Solution

To determine the contribution of self-weight to the bending strength and flexural stiffness of plant stems, we must first derive a closed form solution for the internal bending moment of the stem (M_{TOTAL}). Figure 1 depicts the free body diagram of a plant stem with an arbitrary loading applied at two locations. This stem depicts two weights (w) (e.g. stem weight, grain weight), as well as two externally applied loads (F) and two externally applied moments (M). Note that as mentioned before the externally applied loads and moments can be arise from any externally applied force. Commons sources of externally applied forces include phenotyping devices, wind, adjacent plants and mechanical testing equipment.

As the stem deflects, the moments induced from self-weights will increase as a function of the deflection of the stem. For the weight (w) at each location, we can calculate the induced moment from self-weight (W) as the product of the weight and the weight's offset (i.e., the deflection of the stem at the location of the weight (δ)). Thus for the two locations shown in Figure 1, we have:

$$W_1 = \delta_1 w_1 \quad \textbf{(2)}$$

$$W_2 = \delta_2 w_2 \quad \textbf{(3)}$$

It should be noted that Equations 2 and 3 assume that the maximum moment induced by self-loading is applied to the entire length of the stem. For more detail, see the Limitations section.

However, the offsets (δ_1 and δ_2) in equations 2 and 3 are not known and are a function of the externally applied moments and forces. Using engineering theory for beam deflection and the theory of superposition of loading [17], we can calculate the deflection of the stem at height h_1 (i.e., location 1) as a function of the applied forces, applied moments, and weight-induced moments. Equation 4 shows this calculation, where the first row of equation 4 concerns loads, moments and weights at location 1 (i.e., at height h_1) and the second row of equation 4 concerns forces, moments and weights at location 2 (i.e., at height h_2).

Applied Forces | Applied Moments | Weight-Induced Moments

$$\delta_1 = \boldsymbol{F_1} \cdot \frac{{h_1}^3}{3EI} + \boldsymbol{M_1} \cdot \frac{{h_1}^2}{2EI} + \boldsymbol{W_1} \cdot \frac{{h_1}^2}{2EI} \quad \text{Loc. \#1}$$

$$\boldsymbol{F_2} \frac{3h_1 h_2 - {h_2}^2}{EI} + \boldsymbol{M_2} \frac{2h_1 h_2 - {h_2}^2}{2EI} + \boldsymbol{W_2} \frac{2h_1 h_2 - {h_2}^2}{2EI} \quad \text{Loc. \#2} \qquad \textbf{(4)}$$

Similarly, we can write the deflection of the stem at h_2 as:

Applied Forces | Applied Moments | Weight-Induced Moments

$$\delta_2 = \boldsymbol{F_1} \cdot \frac{{h_1}^2(3h_1 - h_2)}{6EI} + \boldsymbol{M_1} \cdot \frac{{h_2}^2}{2EI} + \boldsymbol{W_1} \cdot \frac{{h_1}^2}{2EI} \quad \text{Loc. \#1}$$

$$+ \boldsymbol{F_2} \cdot \frac{{h_2}^3}{3EI} + \boldsymbol{M_2} \cdot \frac{{h_2}^2}{2EI} + \boldsymbol{W_2} \cdot \frac{{h_2}^2}{2EI} \quad \text{Loc. \#2} \qquad \textbf{(5)}$$

Thus we have four linearly independent equations (Equations 2 through 5) allowing us to solve for four unknown values (W_1, W_2, δ_1, δ_2). It should be emphasized that for all equations in this manuscript (including equations 4 and 5) locations are numbered from the top of plant down (i.e., location 1 is above location 2 which is above location 3…)

Equations 2 through 5 can be generalized to account for any number of locations (n) along the length of the stalk. First, for any loading location L, at a height h_L along the stalk, deflected by δ_L, Equations 2 and 3 can be generalized as:

$$W_L = \delta_L w_L \qquad \textbf{(6)}$$

Next, Equations 4 and 5 can be generalized by noting that each force, moment or weight (F, M, or W, shown in bold in Equations 4 and 5) is multiplied by a geometric coefficient. The geometric coefficient for each term is a function of the height where the deflection is measured and the height at which the loading is applied. This geometric coefficient can be denoted as either f_F (for forces) or f_M (for applied moments or weight-induced moments). As such, for any vertical location Z at a height of h_P, the deflection δ_P is calculated by summing the product of each load, moment or weight (F, M, or W) and its corresponding geometric coefficient (f_F or f_M) at every loading location (from L=1 to L=n). Note that this geometric coefficient assumes a constant flexural stiffness (EI), as discussed in the Limitations section. Thus the generalized form of Equations 4 and 5 can be written as:

$$\begin{array}{lclclclc}
 & & \text{Applied Forces} & & \text{Applied Moments} & & \text{Weight-Induced Moments} & \\
\delta_P = & & \boldsymbol{F_1}\cdot f_F(Z,1) & + & \boldsymbol{M_1}\cdot f_M(Z,1) & + & \boldsymbol{W_1}\cdot f_M(Z,1) & \text{Loc. \#1} \\
 & + & \boldsymbol{F_2}\cdot f_F(Z,2) & + & \boldsymbol{M_2}\cdot f_M(Z,2) & + & \boldsymbol{W_2}\cdot f_M(Z,2) & \text{Loc. \#2} \\
 & & \vdots & & \vdots & & \vdots & \\
 & + & \boldsymbol{F_L}\cdot f_F(Z,n) & + & \boldsymbol{M_L}\cdot f_M(Z,n) & + & \boldsymbol{W_L}\cdot f_M(Z,n) & \text{Loc. \#L}
\end{array} \qquad \textbf{(7)}$$

Where “location 1” is the most apical location of interest and “location L” is the most basal location of interest. Equation 7 can now be consolidated into a fully generalized form of:

$$\delta_P = \overset{\text{Applied Forces}}{\sum_{L=1}^{n} F_L \mathfrak{f}_F\,(Z,L)} \quad + \quad \overset{\text{Applied Moments}}{\sum_{L=1}^{n} M_L \mathfrak{f}_M\,(Z,L)} \quad + \quad \overset{\text{Weight-Induced Moments}}{\sum_{L=1}^{n} W_L \mathfrak{f}_M(Z,L)} \tag{8}$$

Where the geometric coefficients for the forces and moments are defined as [18]:

$$\mathfrak{f}_F(P,L) = \begin{cases} 3h_L {h_P}^2 - \dfrac{(h_L - h_P)^3}{6EI}, h_P \geq h_L \\ \dfrac{{h_L}^2(3h_L - h_P)}{6EI}, \ \ h_P < h_L \end{cases} \tag{9}$$

$$\mathfrak{f}_M(P,L) = \begin{cases} \dfrac{h_L(2h_P - h_L)}{2EI}, h_P \geq h_L \\ \dfrac{{h_P}^2}{2EI}, \ \ h_P < h_L \end{cases} \tag{10}$$

Equations 6 through 9 can also be put into a generalized matrix form. From Equations 6 and 8 we see that for any number of weights at any number of locations (n), we will have *2n* unknown values (δ_1, δ_2, … δ_n, W_1, W_2, .. W_n), and *2n* linearly independent equations. By rearranging these equations and converting them to matrix notation we can write:

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & -f_M(1,1) & -f_M(1,2) & \cdots & -f_M(1,n) \\ 0 & 1 & \cdots & 0 & -f_M(2,1) & -f_M(2,2) & \cdots & -f_M(2,n) \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & -f_M(n,1) & -f_M(n,2) & \cdots & -f_M(n,n) \\ -w_1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & -w_2 & \cdots & 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & -w_n & 0 & 0 & \cdots & 1 \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \\ W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} = \begin{bmatrix} \sum_{L=1}^{n} F_L f_F(1,L) + \sum_{L=1}^{n} M_L f_M(1,L) \\ \sum_{L=1}^{n} F_L f_F(2,L) + \sum_{L=1}^{n} M_L f_M(2,L) \\ \vdots \\ \sum_{L=1}^{n} F_L f_F(n,L) + \sum_{L=1}^{n} M_L f_M(n,L) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{11}$$

Where the first matrix in the equation is a square matrix of size *2n* x *2n*, and the second and third matrices in the equation are column matrices of size *2n* x *1*. Within the square matrix, the top left and bottom right *n* x *n* submatrices (shown in green text) are identity matrices, the bottom left *n* x *n* submatrix (shown in blue text) is a diagonal matrix of the negative weights (-w), and the top right *n* x *n* submatrix (shown in orange text) is the negative geometric coefficients of the weight-induced moments, as calculated by Equation 10. We can then solve this matrix equation by taking the inverse of the multi-colored matrix and multiplying by the right-most vector to calculate the deflections and weight-induced moments:

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \\ W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 & -f_M(1,1) & -f_M(1,2) & \cdots & -f_M(1,n) \\ 0 & 1 & \cdots & 0 & -f_M(2,1) & -f_M(2,2) & \cdots & -f_M(2,n) \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & -f_M(n,1) & -f_M(n,2) & \cdots & -f_M(n,n) \\ -w_1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & -w_2 & \cdots & 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & -w_n & 0 & 0 & \cdots & 1 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{L=1}^{n} F_L f_F(1,L) + \sum_{L=1}^{n} M_L f_M(1,L) \\ \sum_{L=1}^{n} F_L f_F(2,L) + \sum_{L=1}^{n} M_L f_M(2,L) \\ \vdots \\ \sum_{L=1}^{n} F_L f_F(n,L) + \sum_{L=1}^{n} M_L f_M(n,L) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{12}$$

We can now look at the total moment (M_{TOTAL}) of any cross-section along the length of the stem. In particular, M_{TOTAL} can be written as a function of h_P and h_L, by considering all of the loads that are applied to the stem above the cross-section of interest (i.e, for $h_L \geq h_P$),

$$M_{TOTAL}(h_P) = \sum_{L=1}^{n\,[h_L \geq h_P]} F_L(h_L - h_P) + \sum_{L=1}^{n\,[h_L \geq h_P]} M_L + \sum_{L=1}^{n\,[h_L \geq h_P]} W_L \quad \textbf{(13)}$$

Finally, we can write the bending stress of the stem in terms of the internal moment and the section modulus of the cross-section ($S(h_z)$):

$$\sigma_{bending}(h_P) = \frac{M_{TOTAL}(h_P)}{S(h_P)} \quad \textbf{(14)}$$

Note that "section modulus" is an engineering term used to quantify the cross-sectional distribution of mass about its centroid and is used in making flexural stiffness and bending strength calculations [17].

Finite Element Modeling and Data Triangulation

As a form of data triangulation [18] to confirm no mistakes were made in the derivation of the closed form solution presented above, a series of 768 non-linear finite element models of plant stems were developed. Finite element models are a numerical technique used by engineers to quantify the detailed mechanical response of complex structures and materials [44]. It should be noted that nonlinear finite element models (i.e. "large displacement" simulations) are valid for both small and large displacements. In this simulations the stems were modeled as 2-noded linear beam elements in a 2-dimensional analysis [19,20]. The bottom node of the stem model was fixed in all degrees of freedom (U1 = U2 = UR3 =0). A mesh convergence study was performed to ensure adequate mesh density. Analyses were run non-linearly, recalculating the system stiffness matrix at each solution increment. In other words, the models were fully capable of accounting for nonlinear effects due to large deformations. The models were developed in Abaqus/CAE 2019 [19,20] and analyzed in Abaqus/Standard 2019 using a direct, full Newton solver [19,20]. Model development and post-processing were automated through a series of custom Python scripts. Python scripts can be obtained upon reasonable request to the authors. Stems were modeled with a weight at height h_1, applied force at height h_2, and applied moment at height h_3. It should be noted that because 2-noded beam elements were used, the model was partitioned at h_3 so that moments could be directly applied to nodes. The beam was modeled with the radius values such that that the resulting moment of inertia were as presented in Table 1 using the equation $I = \frac{\pi}{4}r^4$ [17]. A full parametric sweep of all relevant input parameters (i.e. factors) to the model was conducted. In particular, a factorial design of experiments was utilized with 8 factors. The factors were the elastic moduli of the beam (E), the moment of inertia (I) of the beam, the heights of the applied moments, forces and weights (h_1, h_2 and h_3), the magnitude of the applied moment (M), the magnitude of self-weight (W), and the magnitude of the applied force (F). The moduli, moment of inertia, heights, weights, and moments were evaluated at two different levels. The force was evaluated at 6 levels. Thus a total of 768 unique models were constructed covering every combination of factors and levels (i.e., 2E’s × 2I’s × 2h_1’s × 2h_2’s × 2h_3’s × 2M’s × 2W’s × 6F’s = 768 models). Table 1 presents each of these factors and the levels of each factor. The level of each factor (i.e., the value of input parameters to the model) were based on previous studies of plant stem material properties [21, 22]. The total moment (M_{total}) at the base of the beam and the deflection at the top of the beam for each finite element model were then compared to the deflection and total moment (M_{total}) calculated using the closed form solution presented above.

Table 1: *Each input parameter (i.e., factor) and value of each input parameter (i.e., level) for the finite element analyses. The number of levels for each factor noted as (n) is presented in the bottom row of the table. The force (F) had 6 levels (0, 2, 4, 6, 8, and 10 newtons). All other factors had 2 levels (a maximum value and a minimum value). A total of 768 finite element models were evaluated (2E's × 2I's × 2h₁'s × 2h₂'s × 2h₃'s × 2M's × 2W's × 6F's = 768 models).*

Value	E (N/mm^2)	I (mm^4)	h_1 (mm)	h_2 (mm)	h_3 (mm)	M (Nmm)	W (N)	F (N)
Minimum	1.00E+03	1.00E+04	800	400	100	0	0	0
Maximum	1.00E+08	1.00E+05	1200	700	300	100	2	10
n =	2	2	2	2	2	2	2	6

Analyzing the Effect of Self-Loading on Wheat

To determine the effects of self loading on the bending strength and flexural stiffness of wheat the closed form solution method presented above was applied to vertically-partitioned wheat biomass data. Biomass data was collected from a commercially available wheat (*Triticum aestivum*) variety during the 2018 growing season in Saskatoon, Saskatchewan. As depicted in Figure 2 the biomass of wheat stems, leaves, and spikes were sampled and weighed every 10 cm along the length of the plants. Planting density was approximately 1.3 million plants per hectare with a 30.5 cm (12") row spacing.

Biomass data were gathered from a 68 cm x 68 cm square of wheat in the center of a 122 cm wide plot. The 68 cm x 68 cm square contained an average of 366 stems. A total of five samples of biomass data were taken periodically from July 27 to August 29, 2018. The same plot was used for all sampling dates with enough space left between samples to have undisturbed wheat in each subsequent sample. A square guide was placed over the middle rows of the plot to indicate the sampling area and any plants outside of the guide were then removed. Biomass was harvested in 10 cm layers measured from the ground with the highest layer collected first (topmost layer varied in size depending on total plant height). All plant matter from a single layer was harvested, weighed in the field to obtain wet-basis biomass, and bagged to be dried later. The samples were oven dried at 65°C for a minimum of 48 hours to obtain the dry-basis biomass.

Results

Comparison of Finite Element and Closed Form Solutions

As a form of data triangulation finite element models of plant stems were compared to the closed form solution presented in the methods section. In other words, the closed form solution was evaluated using the same inputs as each of the 768 finite models and the solutions from each set of input parameters were compared. The finite element models were found to be in good agreement with the closed form solutions (see Figure 3). In particular, the median error between the 768 finite element models and the corresponding closed form solutions was found to be 0.126% for displacement at the top of the specimen, and 0.0003% for the total moment at the base of the specimen. These data imply that for the ranges evaluated, the closed form solution is providing accurate results and no mistakes were made during its derivation.

Standard engineering beam equations used to derive the closed form solution presented above contain several inherit assumptions. These assumptions gradually become less valid as deflections become very large. Therefore, to determine the maximum range of applicability for the closed form solutions one additional finite element model was created and subjected to extremely large deflections. In particular, the model was created with the following input parameters: E = 5.00E+07 Nmm^2, I = 5.50E+04 , EI = 2.8E12, h_1 = 1000 mm, h_2 = 550 mm, h_3 = 200 mm, M = 1000 Nmm @ h1, W = 100 N @ h3, F = Ramped up to 5.00E+07 @ h2. It should be noted that this loading scenario exceeds the realistic range of forces and deflections a plant stem would be subjected to before breaking. This extreme model was used to investigate the extent of validity of the closed form solution for very large deflections. Agreement between this finite element model and the closed form solutions is strong at small displacements (as expected). At large displacements (greater than ~45° at the tip), geometric nonlinearities that are not captured by the closed form engineering beam equations become more influential [4]. That is to say that the closed form solution is accurate so long as the linear closed form engineering beam equations upon which it is predicated are accurate. For more discussion on this topic, see the Limitations section. Figure 4 depicts the comparison between the extremely large deflection finite element model and the closed form solution. Figure 4 displays a maximum horizontal displacement equal to the height of the stem.

A Computational Tool for Accounting for Weights

To make the closed form solutions more amenable to researchers without a structural engineering background (i.e., plant scientists, agronomists, and other end-users), an Excel (Microsoft Corporation, 2019) spreadsheet was developed, and is included as Additional File 1. The user simply inputs the flexural stiffness of the plant stem, the heights to each location of interest, the magnitude of externally applied forces and moments, and the weights at each location. Input values can be given for up to ten locations of interest along the length of the plant stem. The spreadsheet calculates the weight induced moments (M_{int}) and displacements as well as the total induced moment (M_{total}) at all locations. The spreadsheet makes the calculation both with and without self-loading considered. In addition, the error induced by ignoring the self-loading is calculated for the displacements and total induced moments. Additional instructions for using the spreadsheet can be found in the Additional File 2. Figure 5 shows an example of the spreadsheet in which 3 externally applied forces, 2 externally applied moments, and 3 weights are considered. This tool can be used by researchers to determine the necessity of including self-loading in their studies.

For example, if this spreadsheet were used to determine the necessity of including self-weight in a mechanical phenotyping study (e.g., a study using the device as presented in [6]), the following would be performed: (1) A non-destructive, small displacement, flexural test as described in [6] would be performed, to determine the specimen's flexural stiffness; (2) a destructive, large displacement bending strength test as described in [6] would then be performed on the same specimen; (3) the specimen would then be weighed and the center-of-gravity would be determined; (4) the specimen weight, center-of-gravity, and flexural stiffness as well as the magnitude and location of the load applied to the plant by the phenotyping device from the destructive bending strength test would be input into the spreadsheet; (5) the spreadsheet would report out the amount of error in the total induced moment and displacement if the weight of the specimen was ignored. This procedure would then be repeated for several representative specimens. This data could then be used to inform the researchers if self-weight induced loadings are significant and need to be accounted for in phenotyping experiments or if the amount of error introduced by neglecting self-weight is negligible. If self-weight was determined to be significant then the spreadsheet could be used to properly account for self-weight of measured samples or alternatively the researchers could use the closed form solutions presented above.

Case Study: The Effect of Self-Loading on Wheat

As a demonstrative case-study, the effect of self-loading on wheat was analyzed. The flexural stiffness of wheat was assumed to be 0.027 Nm^2 for this analysis [23]. The wheat biomass data collected as part of the current study (see methods section) was used to apply weights to the stem at every 10 cm along the length of the plant. The biomass data are shown in Additional File 3. The effect of stem weight on the stems flexural response was then analyzed using the spreadsheet described above (see Additional Files 1 and 2). Figure 6 depicts the effect of self-loading on wheat stems sampled in this study. The figure displays the contribution of self-loading to the total displacement at the top of the stem and to the total moment at the base of the stem as a percentage. The contribution of self-loading was found to increase over the growing season, and then decrease during senescence. The contribution of self-loading was found to be significantly more for wet stems than dry stems, which is to be expected. As shown in Figure 6 self-weight can account for up to 25% of the displacement of wheat stems and as much as 20% of the total moment.

Discussion

The Influence of Self-Loading

The relative contribution of self-weight to the total bending moment can be conceptualized based on two key characteristics: (1) the displacement of the stalk, and (2) the ratio of weight to flexural stiffness (EI). This is because the moment induced by the weight is directly related to its offset (i.e., displacement of the stalk), as shown in Equation 6. The offsets (i.e., stem displacement) are in turn dependent on the flexural stiffness of the stalk. This means that a stalk with high flexural stiffness that requires a larger applied force to increase its displacement will be relatively less influenced by self-weight. Conversely, a stalk with low flexural stiffness that requires a small amount of applied load to increase its displacement will be relatively more influenced by self-weight.

To aid researchers in determining if the influence of self-weight is a significant factor in a given experiment the following examples are presented. These examples pertain to common mechanical phenotyping tests used to quantify flexural stiffness [24]. In addition, we present simple correction factors for the self-weight-induced moments that are typically ignored in such experiments.

The first example loading configuration, which represents a typical flexural stiffness test for maize [6,45], applies a point load at the top of the specimen, while the stalk's center of gravity is below the loading point. The second example loading configuration, which represents a typical flexural stiffness test for wheat [25, 26], applies a point load below the grain head but near the top of the specimen. Figure 7 displays the loading diagrams for these two test configurations.

During these mechanical phenotyping tests the applied load (F) and deflection of the stem at the point of loading (δ_1) is typically recorded. Ignoring the weight of the stalk, the flexural stiffness of the stem (EI) is then calculated from the test data by rearranging the following equation to solve for EI:

$$\delta_t = \frac{F{h_t}^3}{3EI} \qquad \textbf{(15)}$$

To account for the weight of the stalk when calculating the flexural stiffness of the stem, we must modify Equation 15 to include the stalk weight (w) as discussed in the methods section. For example:

Configuration 1: Load at Top, Weight at Midspan

First, solving Equation 11 for loading configuration 1 results in:

$$\begin{bmatrix} 1 & \frac{-h_2}{2EI} \\ -w & 1 \end{bmatrix} \begin{bmatrix} \delta_2 \\ W \end{bmatrix} = \begin{bmatrix} \frac{F{h_2}^2(3h_1 - h_2)}{6EI} \\ 0 \end{bmatrix} \qquad \textbf{(16)}$$

Where the two unknowns are the displacement at the weight (δ_2) and the weight-induced moment (W). From this equation, the weight-induced moment can be calculated as:

$$W = \frac{Fh_2{}^2 w(3h_1 - h_2)}{6EI - 3wh_2{}^2} \quad \textbf{(17)}$$

Finally, we can solve Equation 5 at the point of loading (δ_1) to find a relationship between the test data and the flexural stiffness of the stem:

$$\delta_1 = \frac{Fh_1}{3EI} + \frac{Fwh_2{}^2(3h_1 - h_2)(2h_1 - h_2)}{6EI\left(2EI - wh_2{}^2\right)} \quad \textbf{(18)}$$

Where Equation 15 is shown in black, and the correction factor for the weight-induced moment is shown in blue.

Configuration 2: Load at Midspan, Weight at Top:

As before, solving Equation 11 for loading configuration 2 at the weight's location results in:

$$\begin{bmatrix} 1 & \frac{-h_1}{2EI} \\ -w & 1 \end{bmatrix} \begin{bmatrix} \delta_2 \\ W \end{bmatrix} = \begin{bmatrix} \frac{Fh_2{}^2(3h_1 - h_2)}{6EI} \\ 0 \end{bmatrix} \quad \textbf{(19)}$$

Solving for the weight-induced moment and solving for Equation 5 for the point of loading (δ_1) to find a relationship between the test data and the flexural stiffness of the stem:

$$\delta_2 = \frac{Fh_2{}^3}{3EI} + \frac{Fwh_2{}^4(3h_1 - h_2)}{6EI\left(2EI - wh_2{}^2\right)} \quad \textbf{(20)}$$

Where Equation 15 is shown in black, and the correction factor for the weight-induced moment is shown in blue.

It should be noted that Equations 18 and 20 are simply Equation 15 with the addition of a correction factor that accounts for the influence of the weight-induced bending moment. Thus by comparing the results of Equation 15 with either Equation 18 or 20, the influence of the weight-induced bending moment on the displacement of the stem can be calculated. Additionally, the results of Equation 18 and 20 (i.e., the displacements) can be input into Equation 6 to determine the magnitude of the weight-induced moment. The weight induced bending moment (W) can then be compared to the bending moment induced from the applied force (M_{ext}) to determine the effect of self-weight on the total bending moment (M_{total}) of the stem. Thus, researchers can easily determine if the weight-induced bending moments are negligible for their testing purposes, or if they need to be incorporated into the biomechanical models used in their studies.

The Influence of Self-Loading for Various Plants

As a point of reference, five plants – maize (*Zea mays*), wheat (*Triticum aestivum*), sweet sorghum (*Sorghum bicolor*), bamboo (*Bambusoideae*), and rice (*Oryza sativa*) – were analyzed to determine the impact of self-weight on plant bending moments and displacements. The values shown in Table 2 represent typical values reported in the literature for these plants. It should be noted that these are average single data points and a significant amount of variation in heights, weights, and flexural stiffnesses is expected within a given plant species. This information is presented here as an accessible reference for researchers to develop an understanding of the types of plants that are more or less affected by self-loading.

Table 2: *Self-loading related properties and the error of the induced moment at the base of the stalk if self-loading is ignored. The center of gravity of the plant is assumed to be halfway up the stem.*

Plant	Plant Height (mm)	Grain Height (mm)	Plant Weight (N)	Grain Weight (N)	Flexural Stiffness (Nm^2)	Error of M_{TOTAL} at base (%)	Error of displacement at top (%)	References
Maize	2250	1125	7.595	2.874	79.17	< 1%	< 1%	[5,22,27–29]
Wheat	638	638	0.016	0.021	0.027	12%	16%	[23,30,31]
Sweet Sorghum	2650	2650	9.64	0.346	137.1	1%	1%	[32–34]
Bamboo	10,774	N/A	138.02	N/A	229	< 1%	< 1%	[35,36]
Rice	969	969	0.0635	0.028	0.17	6%	8%	[37,38]

A key factor in determining the influence of self-loading is the ratio of the weight of a plant to its flexural stiffness. Although this parameter does not include all of the factors that influence self-loading, it can be used as a quick evaluation tool for researchers to determine the general amount of influence self-loading may have. Figure 8 depicts the influence of this ratio on the induced moment and displacement, with the plant varieties in Table 2 shown as data points. In general, it can be seen that self-weight has a negligible effect on stiff and strong stems (i.e., bamboo and maize) but becomes more influential in smaller stems (i.e., rice, wheat). It should be noted that because flexural stiffness is defined as the externally applied load divided by the displacement, the displacement and flexural stiffness relate to each other with a -1:1 ratio, e.g. a 10% increase in the displacement for a given externally applied load results in a 10% decrease in the flexural stiffness. Thus, the error of displacement at the top of stem as shown in Table 2 can also be interpreted as the error in flexural stiffness.

The Influence of Self-Loading on Stalk Lodging Resistance

The equations presented above quantify the influence of self-loading on the deflection and bending moment of plant stems. The association between deflections and bending moments and stalk lodging resistance are plant- and time-specific. For instance, in late-season lodging of maize stalks, previous studies have found that the plant experience a predominantly linear-elastic response prior to failure, and that flexural stiffness tends to strongly correlate with lodging resistance [5]. In such a case, Equation 14 demonstrates that the total moment and bending stress are directly linear, e.g. a 10% increase in the total moment will result in a 10% increase in stress. Therefore, the authors hypothesize that increasing the induced bending moment will decrease the lodging resistance at a ratio of -1:1, e.g. a 10% increase in the induced bending moment from self-loading will result in a 10% decrease in the lodging resistance of the stalk. However, for less linear material responses (e.g. during green-snap), these relationships will be less direct. For stems with nonlinear material responses, researchers will need to incorporate these self-loading equations into their biomechanical models which contain non-linear material responses.

Based on prior experience and the results presented in Table 2 and Figure 8, the authors recommend that self-weight be accounted for when testing small grain stems. Several researchers have recognized that self-weight in small grains can introduce measurement errors. To minimize these errors researchers have normalized bending strength measurements by specimen weight. This was an important first step to properly accounting for self loading. However, in the future the authors recommend the equations and excel spreadsheet presented herein be used to properly account for the effect of self-weight. The effect of self-weight on the bending strength and flexural stiffness of small grain stems is complex and is not fully captured by simply normalized bending strength measurements by specimen weight. In general, the effect of self-weight on large grain stems such as maize is minimal and for many intents and purposes is most likely negligible.

Limitations

The primary limitation of the current study is that the stalk was assumed to be in-line with the assumptions made for pure bending, including maintaining a constant cross-section with homogeneous, isotropic, linear elastic material subjected to pure bending [4]. The inclusion of the changes in cross-sectional geometry along the lengths of the stalk [22], material heterogeneity and anisotropy, or non-linear material properties would likely change the behavior of the analytical system. Further discussion of the influence of such material assumptions on equations has been investigated in a previous study by the authors [4]. These assumptions, when combined with the assumption of a single cross-section along the entire length of the stalk, results in a single flexural stiffness parameter for the entire stalk. However, the flexural stiffness of plants changes constantly along the length of the stalk (i.e., the diameter of most plant stems are large near the base of the plant and smaller near the top of the plant). The simplifying assumption of a single flexural stiffness parameter was deliberately made to allow for an easily-used generalized equation. This assumption is routinely made in phenotyping studies as well. If researchers need to incorporate changes in flexural stiffness along the length of the stalk, the approach presented in this study can be incorporated into a full Castigliano's method beam approximation [17]. Additionally, the equations used in this study assume small strains and small displacements. As such, these equations carry the same limitations as standard engineering beam bending equations, and are not suitable to predict post-failure loading conditions or displacements. When post-buckling analyses are required, non-linear finite element modeling approaches are recommended.

Finally, Equations 1, 2, and 6 assume that the maximum moment induced by self-loading is applied to the entire length of the stem below the weight, which is not accurate, and is used as a simple estimation of the moment induced by self-loading. In reality, self-loading is not a constant moment along the length of the stalk, but instead is an axial compressive load that induces a moment that varies along the length of the stalk. However, modeling loading as an axial compressive load greatly increases the complexity of the equation, to the point that the matrix equations presented in this study would not be practical. Therefore, Equation 6 presents an upper-bound of the influence of self-loading by simply applying the maximum moment along the entire length of the stem. As shown in Figure 3 and Figure 4, this assumption is reasonable for the parameter space explored.

Conclusions

The self-loading of plants plays a potentially critical role in determining the flexural stiffness and bending strength of plant stems. To the best of the authors' knowledge, this is the first study that presents a methodology for (1) incorporating the self-loading of plants with externally applied forces, (2) investigating the interconnected nature of the loading conditions placed on the plant, and (3) exploring the interconnected parameters that impact the influence of self-loading on the plant's structural integrity. Two common phenotyping configurations were presented with simplified correction factors for researchers to use in their studies. A user-friendly Microsoft Excel framework was presented that allows researchers to quickly and easily determine the relevance of self-loading to their research experiments. A survey of five self-loaded plant species was presented to enable researchers to develop an intuition on the level of influence self-loading plays on the structural integrity of various plants. It is the recommendation of the authors that self-loading be taken into account for plants such as wheat and rice that have a large ratio of weight to flexural stiffness.

Declarations

Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests

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Authors' Contributions

All authors were fully involved in the study and preparation of the manuscript. The material within has not been and will not be submitted for publication elsewhere.

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References

1. Flint-Garcia SA, Jampatong C, Darrah LL, McMullen MD. Quantitative trait locus analysis of stalk strength in four maize populations. Crop Sci. 2003;43:13–22.

2. Berry P, Sylvester-Bradley R, Berry S. Ideotype design for lodging-resistant wheat. Euphytica. 2007;154:165–79.

3. Niklas KJ, Spatz H-C. Plant physics. University of Chicago Press; 2012.

4. Stubbs C, Baban N, Robertson D, Al-Zube L, Cook D. Bending Stress in Plant Stems: Models and Assumptions. In: Geitmann A, Gril J, editors. Plant Biomechanics - From structure to function at multiple scales. Springer Verlag.; 2018. p. 49–77. Available from: https://www.springer.com/gp/book/9783319790985

5. Robertson DJ, Lee SY, Julias M, Cook DD. Maize Stalk Lodging: Flexural Stiffness Predicts Strength. Crop Sci. 2016;56:1711–8.

6. Cook DD, de la Chapelle W, Lin T-C, Lee SY, Sun W, Robertson DJ. DARLING: a device for assessing resistance to lodging in grain crops. Plant Methods. 2019;15:102.

7. Pinthus MJ. Lodging in Wheat, Barley, and Oats: The Phenomenon, its Causes, and Preventive Measures. Adv Agron [Internet]. Elsevier; 1974 [cited 2020 Jan 23]. p. 209–63. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0065211308607828

8. Robertson DJ, Julias M, Lee SY, Cook DD. Maize Stalk Lodging: Morphological Determinants of Stalk Strength. Crop Sci. 2017;57:926.

9. Zuber MS, Grogan CO. A new technique for measuring stalk strength in corn. Crop Sci. 1961;1:378–80.

10. Cloninger FD. Methods of Evaluating Stalk Quality in Corn. Phytopathology. 1970;60:295.

11. Singh TP. Association between certain stalk traits related to lodging and grain yield in maize (Zea mays L.). Euphytica. 1970;19:394–7.

12. Remison SU, Akinleye D. Relationship between Lodging, Morphological Characters and Yield of Varieties of Maize (Zea-Mays-L). J Agric Sci. 1978;91:633–8.

13. Zuber MS, Kang MS. Corn lodging slowed by sturdier stalks. Crops Soils. 1978;

14. Hondroyianni, E., et al. "Corn stalk traits related to lodging resistance in two soils of differing salinity." *Maydica* 45.2 (2000): 125-133.

15. Ma D, Xie R, Liu X, Niu X, Hou P, Wang K, et al. Lodging-Related Stalk Characteristics of Maize Varieties in China since the 1950s. Crop Sci. 2014;54:2805.

16. Wegst U, Ashby M. The structural efficiency of orthotropic stalks, stems and tubes. J Mater Sci. 2007;42:9005–14.

17. Beer FP, Johnston E, Dewolf JT. Mechanics of Materials. 3rd. McGraw-Hill; 2002.

18. Nelson N, Stubbs CJ, Larson R, Cook DD. Measurement accuracy and uncertainty in plant biomechanics. J Exp Bot. 2019;70:3649–58.

19. Hibbitt K, Karlsson BI, Sorenson EP. ABAQUS/Standard theory manual. Sorenson Inc. 2016;

20. Simulia DS. ABAQUS Analysis Manual. Provid RI. 2016;

21. Stubbs CJ, Larson R, Cook DD. Maize Stem Buckling Failure is Dominated by Morphological Factors. BioRxiv. 2019;833863.

22. Stubbs C., Seegmiller K.*, McMahan C., Sekhon R., Robertson D.J. Diverse Maize Hybrids are Structurally Inefficient at Resisting Wind Induced Bending Forces that Cause Stalk Lodging. Plant Methods. 2020;16:67.

23. HIRAI Y, INOUE E, MATSUI M, MORI K, HASHIGUCHI K. Reaction force of a wheat stalk undergoing forced displacement. J Jpn Soc Agric Mach. 2003;65:47–55.

24. Erndwein L, Cook DD, Robertson DJ, Sparks EE. Mechanical phenotyping of cereal crops to assess lodging resistance. ArXiv Prepr ArXiv190908555. 2019;

25. Berry PM, Spink JH, Gay AP, Craigon J. A comparison of root and stem lodging risks among winter wheat cultivars. J Agric Sci. 2003;141:191–202.

26. Berry PM, Spink J, Sterling M, Pickett AA. Methods for Rapidly Measuring the Lodging Resistance of Wheat Cultivars. J Agron Crop Sci. 2003;189:390–401.

27. Boon EJMC, Engels FM, Struik PC, Cone JW. Stem characteristics of two forage maize (Zea mays L.) cultivars varying in whole plant digestibility. I. Relevant morphological parameters. NJAS - Wagening J Life Sci. 2005;53:71–85.

28. Fateh M, Mohammadi S, Arbt HK, Farahvash F, Zand E. Effects of density and nitrogen fertilizer on number of ear, number of grains and grain weight in maize cultivars. Int J Biosci IJB. 2014;4:76–82.

29. Tongdi Q, Yaoming L, Jin C. Experimental study on flexural mechanical properties of corn stalks. 2011 Int Conf New Technol Agric. IEEE; 2011. p. 130–4.

30. Austenson HM, Walton PD. Relationships between initial seed weight and mature plant characters in spring wheat. Can J Plant Sci. 1970;50:53–8.

31. Zhihua Y, Yingjun L. Relationship between bending property and density of wheat stem. Agric Sci Technol. 2009;

32. Bakeer B, Taha I, El-Mously H, Shehata SA. On the characterisation of structure and properties of sorghum stalks. Ain Shams Eng J. 2013;4:265–71.

33. Ekefre DE, Mahapatra AK, Latimore Jr. M, Bellmer DD, Jena U, Whitehead GJ, et al. Evaluation of three cultivars of sweet sorghum as feedstocks for ethanol production in the Southeast United States. Heliyon. 2017;3:e00490.

34. Tsuchihashi N, Goto Y. Cultivation of sweet sorghum (Sorghum bicolor (L.) Moench) and determination of its harvest time to make use as the raw material for fermentation, practiced during rainy season in dry land of Indonesia. Plant Prod Sci. 2004;7:442–8.

35. Obataya E, Kitin P, Yamauchi H. Bending characteristics of bamboo (Phyllostachys pubescens) with respect to its fiber–foam composite structure. Wood Sci Technol. 2007;41:385–400.

36. Yen T-M. Culm height development, biomass accumulation and carbon storage in an initial growth stage for a fast-growing moso bamboo (Phyllostachy pubescens). Bot Stud. 2016;57:10.

37. Jin X, Fourcaud T, Li B, Guo Y. Towards Modeling and Analyzing Stem Lodging for Two Contrasting Rice Cultivars. 2009 Third Int Symp Plant Growth Model Simul Vis Appl [Internet]. Beijing, China: IEEE; 2009 [cited 2020 Feb 11]. p. 253–60. Available from: http://ieeexplore.ieee.org/document/5474810/

38. Chen J, Gao H, Zheng X-M, Jin M, Weng J-F, Ma J, et al. An evolutionarily conserved gene, FUWA, plays a role in determining panicle architecture, grain shape and grain weight in rice. Plant J. 2015;83:427–38.

39. van Delden SH, Vos J, Ennos AR, Stomph TJ. Analysing lodging of the panicle bearing cereal teff (Eragrostis tef). New Phytol. 2010;186:696–707.

40. Niklas KJ. The Mechanical Roles of Clasping Leaf Sheaths: Evidence fromArundinaria técta(Poaceae) Shoots Subjected to Bending and Twisting Forces. Ann Bot. 1998;81:23–34.

41. Sekhon, R.S., Joyner, C.N., Ackerman, A.J., McMahan, C.S., Cook, D.D. and Robertson, D.J., 2020. Stalk bending strength is strongly associated with maize stalk lodging incidence across multiple environments. Field Crops Research, 249, p.107737.

42. Grafius, J.E. and Brown, H.M., 1954. Lodging resistance in oats 1. Agronomy Journal, 46(9), pp.414-418.

43. Cook, D.D., de la Chapelle, W., Lin, T.C., Lee, S.Y., Sun, W. and Robertson, D.J., 2019. Stalk Lodging: A Portable Device for Phenotyping Stalk Bending Strength of Maize and Sorghum. bioRxiv, p.567578.

44. Kim, N.H., Sankar, B.V. and Kumar, A.V., 2018. Introduction to finite element analysis and design. John Wiley & Sons.

45. Sekhon, R.S., Joyner, C.N., Ackerman, A.J., McMahan, C.S., Cook, D.D. and Robertson, D.J., 2020. Stalk bending strength is strongly associated with maize stalk lodging incidence across multiple environments. Field Crops Research, 249, p.107737.

Figure 1: The loading diagram of a deflected stem, showing two loading locations with all three types of loading (an applied force, an applied moment, and a weight).

Figure 2: To obtain biomass samples a square sample area (a) was chosen and then cleared of surrounding plants. The sampling boundary height was measured (b) and then the biomass above this layer was cut and bagged. This was continued in 10 cm layers until there was no biomass left (c).

Figure 3: A comparison between the closed form solution and finite element models for the displacement at the top of the specimen (a) and the total moment at the base of the specimen (b), n= 768; A histogram of the error between the closed form solution and the finite element models

for the displacement at the top of the specimen (c) and the total moment at the base of the specimen (d), n= 768.

Figure 4: A comparison between the closed form solution and finite element model for displacements beyond loading that would typically be seen in the field. Plots depict the displacement (normalized to the height of the stem) at the top of the specimen (a) and the total moment (normalized to the maximum moment) at the base of the specimen (b); the error in the closed form displacement and total moment values for large displacements, with the finite element model displacements shown (c).

Figure 5: An example of the Excel spreadsheet in the Supplementary Data, showing loading at three locations, and calculating displacement and induced moments at four locations: the three loading locations and the base of the plant. Note that error in displacement is not calculated at the base, as displacement at the base is zero regardless of loading condition.

Figure 7: The loading diagrams for two common mechanical phenotyping test protocols used to determine flexural stiffness; a typical maize phenotyping protocol (left), and a typical wheat phenotyping protocol (right).

Figure 6: The contribution of self-loading for the displacement at the top of the stem (left) and the total moment at the base of the stem (right), for both wet and dry stems.

Figure 8: The error of displacement at the top of the stem (left) and M_{TOTAL} at the base of the stem (right), as a function of the ratio between the combined weight of the grain and plant and the flexural stiffness of the stem.