

1 **The Effect of Plant Weight on Estimations of Stalk Lodging Resistance**

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15 **Abstract**

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

25 **Results:** A mathematical methodology for properly accounting for the interconnected relationship
26 between self-loading and external loading of plants stems is presented. The method was compared
27 to numerous finite element models of plants stems and found to be highly accurate. The resulting
28 interconnected set of equations from the derivation were used to produce user-friendly applications
29 by presenting (1) simplified self-loading correction factors for common loading configurations of
30 plants, and (2) a generalized Microsoft Excel framework that calculates the influence of self-
31 loading on crop stems. Results indicate that ignoring the effects of self-loading when calculating
32 stalk flexural stiffness is appropriate for large and stiff plants such as maize, bamboo, and sorghum.
33 However, significant errors result when ignoring the effects of self-loading in smaller plants with
34 larger relative grain sizes, such as rice (8% error) and wheat (16% error).

35 **Conclusions:** Properly accounting for self-weight can be critical to determining the structural
36 response of plant stems. Equations and tools provided herein enable researchers to properly
37 account for the plant's weight during mechanical phenotyping experiments used to determine stalk
38 lodging resistance.

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40 **Keywords:** bending, flexural, plant, lodging, stalk, stem, stiffness, strength, weight

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42 **Background**

43 Yield losses due to stalk lodging (breakage of crop stems or stalks prior to harvest) are
44 estimated to range from 5-20% annually [1,2] resulting in billions of dollars of lost revenue. *Stalk*
45 *flexural stiffness* and *stalk bending strength* (see box 1 for definitions) are key mechanical
46 phenotypes that govern stalk lodging resistance [3–7, 22]. These key phenotypes are measured
47 with the aid of mechanical phenotyping devices [24]. However, a method to properly account for
48 plant weight when measuring *stalk flexural stiffness* and *stalk bending strength* has not been
49 presented. Consequently, the effect of self-weight is typically neglected in mechanical tests used
50 to quantify these phenotypes. Neglecting self-weight during mechanical phenotyping experiments
51 can introduce significant errors in *stalk flexural stiffness* and *stalk bending strength* measurements
52 which in turn result in inaccurate predictions of stalk lodging resistance.

53 Properly accounting for self-weight during mechanical phenotyping experiments requires
54 (1) a basic understanding of the types of mechanical forces plants experience, (2) clear definitions
55 of the mechanical phenotypes being measured and (3) a conceptual understanding of how
56 mechanical phenotyping devices work and the types of forces present during mechanical
57 phenotyping experiments. Each of these three requirements is discussed in the paragraphs that
58 follow. An explanation of the basic types of forces plants experience is presented first, followed
59 by definitions for *stalk flexural stiffness* and *stalk bending strength*. Finally, a discussion of the
60 basic principles of mechanical phenotyping devices used to measure *stalk flexural stiffness* and
61 *stalk bending strength* is presented.

62 ***Types of Forces experienced by Plants***

63 Plants are subjected to three principle types of forces, namely: (1) *Contact Forces*, (2)
 64 *Surface Forces* and (3) *Body Forces*. *Contact Forces* occur when solid materials ‘contact’ (i.e.,
 65 push on) one another. Most mechanical phenotyping devices impart *Contact Forces* (i.e., they
 66 physically contact and push on the plant). *Contact Forces* can also occur when an adjacent plant
 67 or a researcher contacts a plant and pushes on it. *Surface Forces* are forces that are distributed
 68 across a plants surface. The wind is an example of a *Surface Force*. Both *Contact Forces* and
 69 *Surface Forces* are commonly referred to as *External Forces* or externally applied loads as they
 70 originate from external objects. The last type of mechanical force plants are subjected to is *Body*
 71 *Forces*. *Body Forces* are forces due to gravity (i.e., the plants weight). It is important to note that
 72 all plants are constantly subjected to *Body Forces* whereas they are only intermittently subjected
 73 to *External Forces* (e.g., *Contact Forces* and *Surface Forces*). In other words, *Body Forces* (i.e.,
 74 self-weight) are always present in any mechanical phenotyping test and as such need to be
 75 accounted for.

76 ***Box 1: Glossary of Terms***

| Term | Definition |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bending Moment | The result of multiplying a force by the perpendicular distance from the force to the axis about which the bending moment is being calculated. Conceptually can be thought of as a torque. |
| Bending Stress | A measure of the force experienced by the plant tissues that is normalized to size and geometry. |
| <i>Body Forces</i> | Forces acting on the plant due to the gravity. |
| <i>Contact Forces</i> | Forces that occur when other solid materials contact the plant. |
| <i>External Forces</i> | Forces that are applied to the plant from an external source (e.g. <i>Contact Forces</i> or <i>Surface Forces</i>). <i>Body Forces</i> are <u>not</u> an <i>External Force</i> . |
| <i>Stalk Flexural Stiffness</i> | Flexural stiffness is a standard structural engineering quantity for measuring the flexural (i.e., bending) deformability of objects. It is equal to the elastic |

| | |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | modulus of the material multiplied by the moment of inertia (a geometric term which quantifies the distribution of mass about the object's centroid). During mechanical phenotyping tests of plant stalks flexural stiffness is typically calculated by applying a force, measuring deflection and using Castigliano's energy method to indirectly solve for flexural stiffness. |
| <i>Stalk Bending Strength</i> | The maximum bending moment the plant can support before structural failure occurs (i.e., before breaking). |
| <i>Surface Forces</i> | Forces that are distributed across the plant's surface. |

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78 ***Bending Strength and Flexural Stiffness Definitions***

79 Determining the bending strength and flexural stiffness of plant stems requires the
80 calculation of “bending moments” (see [17] for a complete discussion of bending moments).
81 Bending moments arise from any force (either *External Forces* or *Body Forces*) that cause a plant
82 to bend or flex and can be conceptually thought of as a torque. A bending moment is calculated
83 by multiplying a force by the perpendicular distance from the force to the axis about which the
84 bending moment is being calculated. In most plant studies bending moments are typically
85 calculated about the base of the plant (i.e., at the stalk – soil interface) as this is where bending
86 moments are the largest. Both *External Forces* and *Body Forces* (i.e., self-weight) create bending
87 moments in plant stems.

88 We now proceed to provide definitions for *stalk bending strength* and *stalk flexural*
89 *stiffness*. Note these terms are sometimes used incorrectly and interchangeably in the mechanical
90 plant phenotyping literature. However, they are structural engineering terms with precise and
91 distinct definitions. The *stalk bending strength* of a plant is defined as the maximum bending
92 moment the plant stalk can support before structural failure occurs (i.e., before breaking). In
93 contrast *stalk flexural stiffness* is a measurement of the flexural (i.e., bending) deformability of the

94 plant. In other words, *stalk flexural stiffness* is a measure of a plant's resistance to bending
95 deformations, whereas *stalk bending strength* is a measure of a plants resistance to breaking. The
96 flexural stiffness of standard engineering structures is defined as the elastic modulus of the material
97 the structure is composed of multiplied by the moment of inertia of the structure. The moment of
98 inertia is a geometric term that quantifies the distribution of mass about an object's centroid [17].
99 However, plant stalks are often composed of multiple materials and are non-prismatic (i.e.,
100 tapered) thus their moment of inertia changes as a function of length along the stalk. This
101 complicates the calculation of *stalk flexural stiffness*. Consequently, most studies utilize
102 engineering beam equations to indirectly solve for *stalk flexural stiffness* (e.g., [4,17]). The process
103 of indirectly solving for *stalk flexural stiffness* is explained in detail in the methods section.

104 ***Mechanical Phenotyping Principles***

105 Several mechanical phenotyping devices have been developed to measure *stalk flexural*
106 *stiffness* and / or *stalk bending strength* [6,22,24,42,43]. A review of these devices is presented in
107 [24]. In general, all these devices apply an external load (e.g., a *contact force*) to either a single
108 plant or to a group of plants and measure the accompanying deflection of the plant stem(s).
109 Standard engineering beam equations are then used to calculate the *flexural stiffness* and *bending*
110 *strength* of the plant sample (e.g. [6,24]). However, the standard engineering beam equations used
111 in these analyses ignore the effect of *Body Forces* (i.e. self-weight) and are therefore error prone.

112 It is important to note that the bending moments induced from *Body Forces* are inextricably
113 connected to *External Forces*. In particular, the bending moment induced from *Body Forces* (i.e.,
114 self-weight) is a function of the distance between the plant's base and its center of gravity. As
115 *External Forces* from a phenotyping device displace the center of gravity of the plant away from

116 the base of the stem, the bending moment induced from *Body Forces* increases. Previous studies
117 have examined the influence of *Body Forces* (i.e., self-weight) on *stalk bending strength* in the
118 absence of *External Forces* while others have examined the influence of *External Forces* on *stalk*
119 *bending strength* while ignoring *Body Forces* [3,4,8–15]. However, a method for simultaneously
120 accounting for both *External Forces* and *Body Forces* during mechanical phenotyping experiments
121 has not been presented. Consequently, *Body Forces* are ignored in mechanical phenotyping studies
122 which leads to inaccuracies in stalk lodging resistance predictions.

123 The purpose of this paper is to provide a generalized framework to simultaneously account
124 for both *Body Forces* and *External Forces* when taking measurements of *stalk flexural stiffness*
125 and *stalk bending strength*. A derivation of the governing engineering equations used to calculate
126 these mechanical phenotypes is presented. The derivation is validated by comparing its results to
127 the results of several nonlinear finite element models of plant stems. In addition, a user-friendly
128 Microsoft Excel spreadsheet is developed and presented to aid researchers in determining the effect
129 of self-weight in mechanical phenotyping experiments. The spreadsheet does not require an
130 advanced understanding of engineering mechanics. It was developed to aid researchers from non-
131 engineering disciplines to determine the necessity of accounting for plant weight in mechanical
132 phenotyping experiments. Finally, several case studies are presented to demonstrate the type of
133 error present in mechanical phenotyping tests that do not account for *Body Forces*.

134

135 **Methods**

| Term | Definition |
|--------------------|-----------------------------------------------------------------------|
| δ | Horizontal deflection (mm) |
| EI | Flexural stiffness (Nmm 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 moment induced from externally applied forces and moments (Nmm) |
| M_{body} | Total moment induced from self-loading (Nmm) |
| M_{TOTAL} | Total applied moment (sum of M_{ext} and M_{int}) (Nmm) |
| 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) |

137

138 The sections that follow detail the methods used to investigate the effect of self-weight on
139 measurements of *stalk flexural stiffness* and *stalk bending strength* of plant stems. For clarity, the
140 methods are broken into five distinct subsections. First, the traditional approach (which ignores
141 *Body Forces*) to calculate bending strength and flexural stiffness is presented, and its limitations
142 are discussed. Second, a derivation of a more accurate approach to calculating bending strength
143 and flexural stiffness that simultaneously accounts for both *Body Forces* and *External Forces* is
144 presented. The derivation is predicated upon engineering solid mechanics theory. The third section
145 describes how this new approach was parametrically investigated and validated by comparing its
146 results to those of engineering finite element models of plant stems. In the fourth section, the
147 development of a user-friendly Excel spreadsheet is explained. The spreadsheet was developed to
148 help researchers without a background in engineering mechanics successfully apply the new

149 approach to calculating *stalk bending strength* and *stalk flexural stiffness*. The last section explains
150 a series of three case studies. These case studies were conducted to illustrate how the equations
151 presented in the current work can be applied to investigate the effects of self-weight.

152 ***Traditional Solution (Ignoring Body Forces)***

153 Traditionally, the bending strength of a plant stem is calculated as the maximum externally
154 applied moment (M_{ext}) (applied from a phenotyping device) that the stem can withstand prior to
155 structural failure, i.e., bending strength = Maximum (M_{ext}). Using traditional methods, the flexural
156 stiffness (EI) of a plant is solved for indirectly by relating the externally applied moment (M_{ext})
157 induced by a phenotyping device to the resulting deflection of the stem (δ) using Castigliano's
158 energy method [24,42,43]. In this way, the deflection of the plant is equal to the partial derivative
159 of the internal potential energy of the system with respect to the applied load (F) from the
160 phenotyping device [17]:

$$161 \quad EI = \frac{\int M_{ext} \frac{dM_{ext}}{dF} dx}{2\delta} \quad (1)$$

162 Unfortunately, the effect of *Body Forces* is ignored in these traditional approaches. In other
163 words, these analyses consider only the external bending moment (M_{ext}) applied by the
164 phenotyping device. In reality the total bending moment (M_{TOTAL}) which is the combination of
165 both the externally applied bending moment (M_{ext}) and the bending moment resulting from *Body*
166 *Forces* (M_{body}) should be considered (i.e., $M_{TOTAL} = M_{ext} + M_{body}$). Thus, to more accurately
167 quantify *stalk flexural stiffness* and *stalk bending strength* the traditional approach must be
168 modified to use M_{TOTAL} , and not just M_{ext} .

169 ***Derivation of New Approach That Accounts for Both Body Forces and External Forces***

170 Properly accounting for *Body Forces* when calculating *stalk bending strength* and *stalk*
171 *flexural stiffness* requires derivation of a closed form solution for the total bending moment of the
172 stem (M_{TOTAL}). The derivation is presented in this section for completeness. However, it should be
173 noted that the derivation is based upon engineering solid mechanics theory and those from a non-
174 engineering background may therefore find parts of the derivation difficult to follow. For this
175 reason, the authors have incorporated the resulting sets of equations from the derivation into a
176 user-friendly excel spreadsheet that can be used by the plant research community. The derivation
177 is presented below followed by an explanation of the excel spreadsheet.

178 Consider Figure 1, which depicts the free body diagram of a plant stem with an arbitrary
179 loading applied at two locations. The figure depicts two weights (w) (e.g. stem weight, grain
180 weight), as well as two externally applied *Contact Forces* (F) and two externally applied moments
181 (M). Note that as mentioned before the externally applied loads and moments can be arise from
182 any external object. Commons sources of externally applied forces include phenotyping devices,
183 wind, and adjacent plants.

184 Bending moments induced from self-weight (i.e., *Body Forces*) will increase with
185 increased stem deflection. For the weight (w) at each location, we can calculate the induced
186 bending moment from self-weight (W) as the product of the weight and the weight's offset (i.e.,
187 the deflection of the stem at the location of the weight (δ)). Thus for the two locations shown in
188 Figure 1, we have:

$$189 \quad W_1 = \delta_1 w_1 \quad (2)$$

$$190 \quad W_2 = \delta_2 w_2 \quad (3)$$

191 It should be noted that Equations 2 and 3 assume that the maximum bending moment
 192 induced by self-loading is applied to the entire length of the stem. Details regarding this
 193 assumption are presented in the Limitations section.

194 The offsets (δ_1 and δ_2) used in equations 2 and 3 to calculate the bending moments
 195 induced from self-weight are unknowns and are a function of the externally applied moments and
 196 forces. Using engineering theory for beam deflection and the theory of superposition of loading
 197 [17], we can calculate the deflection of the stem at height h_1 (i.e., location 1) as a function of the
 198 applied forces, applied moments, and weight-induced moments. Equation 4 shows this
 199 calculation, where the first row of equation 4 concerns loads, moments and weights at location 1
 200 (i.e., at height h_1) and the second row of equation 4 concerns forces, moments and weights at
 201 location 2 (i.e., at height h_2).

| | Applied Forces | + | Applied Moments | + | Weight-Induced Moments | |
|--------------|----------------------------------|---|-----------------------------------|---|-----------------------------------|---------|
| $\delta_1 =$ | $F_1 \cdot \frac{h_1^3}{3EI}$ | | $M_1 \cdot \frac{h_1^2}{2EI}$ | | $W_1 \cdot \frac{h_1^2}{2EI}$ | Loc. #1 |
| | $F_2 \frac{3h_1h_2 - h_2^2}{EI}$ | | $M_2 \frac{2h_1h_2 - h_2^2}{2EI}$ | | $W_2 \frac{2h_1h_2 - h_2^2}{2EI}$ | Loc. #2 |
| 202 | (4) | | | | | |

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

| | Applied Forces | + | Applied Moments | + | Weight-Induced Moments | |
|--------------|----------------------------------------------------|---|----------------------------------------|---|----------------------------------------|---------|
| $\delta_2 =$ | $\mathbf{F}_1 \cdot \frac{h_1^2(3h_1 - h_2)}{6EI}$ | | $\mathbf{M}_1 \cdot \frac{h_2^2}{2EI}$ | | $\mathbf{W}_1 \cdot \frac{h_1^2}{2EI}$ | Loc. #1 |
| | + | | $\mathbf{M}_2 \cdot \frac{h_2^2}{2EI}$ | | $\mathbf{W}_2 \cdot \frac{h_2^2}{2EI}$ | Loc. #2 |
| 204 | | | | | | (5) |

205

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

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

213
$$\mathbf{W}_L = \delta_L \mathbf{W}_L$$
 (6)

214 Next, Equations 4 and 5 can be generalized by noting that each force, moment or weight (F, M, or
 215 W, shown in bold in Equations 4 and 5) is multiplied by a geometric coefficient. The geometric
 216 coefficient for each term is a function of the height where the deflection is measured and the height
 217 at which the loading is applied. This geometric coefficient can be denoted as either f_F (for forces)
 218 or f_M (for externally applied moments or internal weight-induced moments). As such, for any
 219 vertical location Z at a height of h_Z , the deflection δ_Z is calculated by summing the product of each
 220 load, moment or weight (F, M, or W) and its corresponding geometric coefficient (f_F or f_M) at every
 221 loading location (from L=1 to L=n). Note that this geometric coefficient assumes a constant

222 flexural stiffness (EI), as discussed in the Limitations section. Thus, the generalized form of
 223 Equations 4 and 5 can be written as:

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

224
 225 Where “location 1” is the most apical location of interest and “location L” is the most basal location
 226 of interest. Equation 7 can now be consolidated into a fully generalized form of:

$$\delta_p = \sum_{L=1}^n F_L f_F(Z, L) + \sum_{L=1}^n M_L f_M(Z, L) + \sum_{L=1}^n W_L f_M(Z, L) \tag{8}$$

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

$$f_F(P, L) = \begin{cases} 3h_L h_p^2 - \frac{(h_L - h_p)^3}{6EI}, & h_p \geq h_L \\ \frac{h_L^2 (3h_L - h_p)}{6EI}, & h_p < h_L \end{cases} \tag{9}$$

229

$$f_M(P, L) = \begin{cases} \frac{h_L(2h_P - h_L)}{2EI}, & h_P \geq h_L \\ \frac{h_P^2}{2EI}, & h_P < h_L \end{cases} \quad (10)$$

230

231 Equations 6 through 9 can also be put into a generalized matrix form. From Equations 6

232 and 8 we see that for any number of weights at any number of locations (n), we will have 2n

233 unknown values ($\delta_1, \delta_2, \dots, \delta_n, W_1, W_2, \dots, W_n$), and 2n linearly independent equations. By

234 rearranging these equations and converting them to matrix notation we can write:

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

235

236 Where the first matrix in the equation is a square matrix of size 2n x 2n, and the second and third

237 matrices in the equation are column matrices of size 2n x 1. Within the square matrix, the top

238 left and bottom right n x n submatrices (shown in green text) are identity matrices, the bottom

239 left n x n submatrix (shown in blue text) is a diagonal matrix of the negative weights (-w), and

240 the top right n x n submatrix (shown in orange text) is the negative geometric coefficients of the

241 weight-induced moments, as calculated by Equation 10. We can then solve this matrix equation

242 by taking the inverse of the multi-colored matrix and multiplying by the right-most vector to

243 calculate the deflections and moments induced by *Body Forces*:

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

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

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

249 Now that we have derived a closed form solution for M_{TOTAL} (eq 13) we can calculate the *stalk*
250 *flexural stiffness* and the *stalk bending strength* of the plant stem. Additionally, we can now
251 calculate the value of bending stress. Bending stress is a useful measure of the loading of the
252 plant tissue that is normalized to size and geometry. The larger the bending stress in the tissue,
253 the closer it is to tissue fracture and structural failure. We can write the bending stress in the
254 stem in this case as a function of the total bending moment and the section modulus of the cross-
255 section ($S(h_L)$):

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

257 Note that “section modulus” is an engineering term used to quantify the cross-sectional distribution
 258 of mass about its centroid and can be used in making *stalk flexural stiffness* and *stalk bending*
 259 *strength* predictions [17]. It should be noted that the section modulus is constant for a given plant
 260 stem cross-section. Therefore, there exists a 1:1 correlation between the total bending moment,
 261 and the bending stress. As such, all comparisons performed between total bending moments can
 262 also be conceptualized as being comparisons in *stalk bending strength* or bending stress.

263 Table 1 shows a comparison between the equations used to calculate *stalk flexural stiffness*,
 264 *stalk bending strength* and bending stress for the new method, which accounts for *Body Forces*
 265 and the traditional method which does not account for *Body Forces*.

266

267 **Table 1:** Comparison of equations used to calculate *stalk flexural stiffness*, *stalk bending*
 268 *strength* and bending stress for the traditional method and the new approach derived in this
 269 study

| | Traditional Method | New Approach |
|---------------------------------|-------------------------------|---------------------------------|
| <i>Stalk Flexural Stiffness</i> | $\frac{M_{ext}}{\delta}$ | $\frac{M_{TOTAL}}{\delta}$ |
| <i>Stalk Bending Strength</i> | $\max (M_{ext})$ | $\max (M_{TOTAL})$ |
| Bending Stress | $\frac{M_{ext}(h_p)}{S(h_p)}$ | $\frac{M_{TOTAL}(h_p)}{S(h_p)}$ |

270

271 ***Finite Element Modeling to Confirm Accuracy of New Closed Form Solution Method***

272 The new approach to calculating *stalk flexural stiffness* and *stalk bending strength* outlined
273 in the previous section was derived based on governing physical principles and well-established
274 engineering equations. Special care was taken to ensure no algebraic mistakes were made during
275 the derivation and that any assumptions were properly considered. Nonetheless, as a form of data
276 triangulation [18] to confirm the accuracy of the new approach it was compared to a series of
277 nonlinear finite element models of plant stems. A basic description of the Finite Element Method
278 and the construction of the specific finite element models of plant stems used in this study are
279 presented below.

280 The Finite Element Method is a standard numerical technique used by engineers to quantify
281 the detailed mechanical response of complex structures and materials [44]. Finite Element Models
282 are commonly used calculate the flexural stiffness of complex structures which violate basic
283 assumptions made in closed form engineering equations. It should be noted that nonlinear finite
284 element models (i.e. “large deflection” simulations) are valid for both small and large deflections.
285 Comparing the new closed form solution approach which accounts for *Body Forces* to nonlinear
286 finite models of plant stems thus enables us to check the accuracy of the new approach.

287 To this end, a series of 768 non-linear finite element models of plant stems were developed,
288 analyzed, and compared to the new approach derived in the previous section. The models were
289 developed in Abaqus/CAE 2019 [19,20] and analyzed in Abaqus/Standard 2019 using a direct, full
290 Newton solver [19,20]. A mesh convergence study was performed to ensure adequate mesh
291 density of all models. Analyses were run non-linearly, recalculating the system stiffness matrix at
292 each solution increment. In other words, the models were fully capable of accounting for nonlinear

293 effects due to large deformations. Model development and post-processing were automated
294 through a series of custom Python scripts, which can be obtained upon reasonable request to the
295 authors. A brief description of the models is given below.

296 In these simulations the stems were modeled as 2-noded linear beam elements in a 2-
297 dimensional analysis [19,20]. In each of these models the bottom node of the stem was fixed in all
298 degrees of freedom ($U1 = U2 = UR3 = 0$). Stems were modeled with a weight at height h_1 , applied
299 force at height h_2 , and applied moment at height h_3 . It should be noted that because 2-noded beam
300 elements were used, the model was partitioned at h_3 so that moments could be directly applied to
301 nodes. The plant stem was modeled with the radius values such that that the resulting moments of
302 inertia were as presented in Table 2 using the equation $I = \frac{\pi}{4} r^4$ [17]. As the models allowed free
303 expansion in the radial direction, Poisson's ratio was found to be negligible based on preliminary
304 parametric analyses and was set to a value of 0.3 for all analyses.

305 A factorial design of experiments was used to compare the results of the new approach
306 derived above to the results of the finite element models. In particular, the *stalk flexural stiffness*
307 and *stalk bending strength* of each finite element model was compared to the corresponding values
308 calculated using the new approach derived in the previous section. A full parametric sweep of all
309 relevant input parameters (i.e. factors) was conducted to ensure the accuracy of new approach for
310 a broad range of plant species. In particular, a factorial design of experiments was utilized with 8
311 factors to compare the two methods. The factors were the elastic moduli of the stem (E), the
312 moment of inertia (I) of the stem, the heights of the applied moments, forces and weights (h_1 , h_2
313 and h_3), the magnitude of the applied moment (M), the magnitude of self-weight (W), and the
314 magnitude of the applied force (F). The moduli, moment of inertia, heights, weights, and moments

315 were evaluated at two different levels. The force was evaluated at 6 levels. Thus a total of 768
 316 unique models were constructed covering every combination of factors and levels (i.e., $2E's \times 2I's$
 317 $\times 2h_1's \times 2h_2's \times 2h_3's \times 2M's \times 2W's \times 6F's = 768$ models). Table 2 presents each of these factors
 318 and the levels of each factor used in the experiment. The level of each factor (i.e., the value of
 319 input parameters to the model) were based on previous studies of plant stem material properties
 320 [21, 22].

321 **Table 2:** Each input parameter (i.e., factor) and value of each input parameter (i.e., level) for the
 322 finite element analyses. The number of levels for each factor noted as (n) is presented in the
 323 bottom row of the table. The force (F) had 6 levels (0, 2, 4, 6, 8, and 10 Newtons). All other
 324 factors had 2 levels (a maximum value and a minimum value). A total of 768 finite element
 325 models were evaluated ($2E's \times 2I's \times 2h_1's \times 2h_2's \times 2h_3's \times 2M's \times 2W's \times 6F's = 768$
 326 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 |

327
 328

329 **Development of Excel Spreadsheet to Calculate Stalk Flexural Stiffness and Stalk Bending**
 330 **Strength**

331 An Excel spreadsheet (Microsoft Corporation, 2019) was developed to help researchers
 332 without a background in engineering mechanics successfully apply the new approach to
 333 calculating *stalk flexural stiffness* and *stalk bending strength*. The spreadsheet was developed

334 using the equations presented in Table 1 and is included as Additional File 1. The spreadsheet
335 allows the user to input the flexural stiffness of the plant stem as well as the magnitude of
336 externally applied forces and moments, and weights. Input values can be given for up to ten
337 locations of interest along the length of the plant stem. The spreadsheet calculates the weight
338 induced moments (M_{body}) and deflections, as well as the total induced moment (M_{total}) at all
339 locations. The spreadsheet makes the calculation both with and without self-loading
340 considered. In addition, the error induced by ignoring self-loading is calculated for the
341 deflections and total induced moments. More details about the spreadsheet and use instructions
342 are provided in Additional File 2.

343 *Case Studies*

344 To provide further insights and to demonstrate how to effectively use the equations
345 derived above three separate case studies were conducted. The primary purpose of the first case
346 study was to demonstrate how researchers can determine if the influence of self-weight is a
347 significant factor in a given experiment. In this case study, two loading configurations commonly
348 used to measure *stalk bending strength* and *stalk flexural stiffness* are presented [24]. Figure 2
349 displays these two test configurations. The equations derived above are applied to each test
350 configuration and are used to develop simple correction factors to account for the moments
351 induced by *Body Forces* that are typically ignored in mechanical phenotyping experiments.
352 These correction factors can be used to determine the magnitude of error introduced if *Body*
353 *Forces* are ignored.

354 To provide general insights into the effect of *Body Forces* on several plant species a
355 second more generalized case study was conducted. Five plants species were included in this

356 case study: maize (*Zea mays*), wheat (*Triticum aestivum*), sweet sorghum (*Sorghum bicolor*),
357 bamboo (*Bambusoideae*), and rice (*Oryza sativa*). Average mechanical properties and biomass
358 distributions for each plant species were attained from the literature and were used as inputs to
359 the Excel spreadsheet provided in Additional File 1. The spreadsheet was then used to determine
360 the impact of self-weight on measurements of *stalk flexural stiffness* and *stalk bending strength*
361 (i.e., to quantify the amount of error introduced when *Body Forces* are ignored).

362 For the third case study a detailed experimental analysis of a commercially available
363 wheat variety was conducted. In this study, the Excel spreadsheet provided in Additional File 1
364 was used to determine the effects of self-loading on the flexural response of wheat stems
365 throughout a growing season. The methods and results of this third case study are presented in
366 Additional File 3.

367

368 **Results**

369 *Comparison of Finite Element and Closed Form Solutions*

370 As a form of data triangulation finite element models of plant stems were compared to the new
371 closed form solution which accounts for *Body Forces* that is presented in the methods section. In
372 other words, the closed form solution was evaluated using the same inputs as each of the 768 finite
373 models and the solutions from the closed form equations and the finite element models were
374 compared. The finite element models were found to be in good agreement with the closed form
375 solutions. In particular, the median error between the 768 finite element models and the closed
376 form equations was found to be 0.126% for deflection at the top of the specimen, and 0.0003% for
377 the total bending moment at the base of the specimen. Figure 3 displays these comparisons in terms

378 of calculations of *stalk bending strength* and *stalk flexural stiffness*. As shown in the figure the
379 closed form solution method can accurately account for both *Body Forces* and *External Forces*
380 when calculating *stalk flexural stiffness* and *stalk bending strength*. These data imply that for the
381 ranges evaluated, the closed form solution is providing accurate results and no mistakes were made
382 during its derivation.

383 However, it should be noted that as shown in Figure 3a, the error in measured *stalk*
384 *flexural stiffness* is relatively high in analyses with very small deflections. This was expected. The
385 error in *stalk flexural stiffness* measurements that occurs at near-zero deflections is caused by
386 simplifying assumptions made in the derivation of the closed form solution. Researchers should
387 therefore avoid using the closed form solution method to analyze plant samples undergoing very
388 small (near-zero) deflections. A deflection of approximately 2.5% - 20% of the stalk height (i.e.,
389 a deflection angle of $\sim 6^\circ$) is generally a good starting point to employ in mechanical phenotyping
390 experiments used to measure *stalk flexural stiffness*.

391 As mentioned previously, the engineering theory used to derive the closed form solution
392 presented above contains several inherent assumptions. These assumptions gradually become less
393 valid as deflections become very large. Therefore, to determine the maximum range of
394 applicability for the closed form solutions one additional finite element model was created and
395 subjected to extremely large deflections. In particular, the model was created with the following
396 input parameters: $E = 5.00E+07 \text{ N/mm}^2$, $I = 5.50E+04 \text{ mm}^4$, $EI = 2.8E12 \text{ Nmm}^2$, $h_1 = 1000 \text{ mm}$,
397 $h_2 = 550 \text{ mm}$, $h_3 = 200 \text{ mm}$, $M = 1000 \text{ Nmm @ } h_1$, $W = 100 \text{ N @ } h_3$, $F = \text{Ramped up to } 5.00E+07$
398 $\text{N @ } h_2$. It should be noted that this loading scenario exceeds the realistic range of forces and
399 deflections a plant stem would be subjected to. In other words structural failure of the stem would
400 occur far before such high forces and deflections could be achieved. This extreme model was used

401 to investigate the extent of validity of the closed form solution for very large
402 deflections. Agreement between this finite element model and the closed form solutions is strong
403 at small deflections (as expected). At very large deflections (greater than $\sim 45^\circ$ angle at the tip of
404 the stem), geometric nonlinearities that are not captured by the closed form engineering beam
405 equations become more influential [4]. That is to say that the closed form solution is accurate so
406 long as the linear closed form engineering beam equations upon which it is predicated are
407 accurate. For more discussion on this topic, see the Limitations section. Figure 4 depicts the
408 comparison between the extremely large deflection finite element model and the closed form
409 solution. Figure 4 displays a maximum horizontal deflection equal to the height of the stem.

410

411 ***A Computational Tool for Accounting for Weights***

412 To make the closed form solutions derived in the methods section more amenable to
413 researchers without a structural engineering background (i.e., plant scientists, agronomists, and
414 other end-users), an Excel (Microsoft Corporation, 2019) spreadsheet was developed, and is
415 included as Additional File 1. The user simply inputs the *stalk flexural stiffness* of the plant
416 stem, the heights to each location of interest, the magnitude of externally applied forces and
417 moments, and the weights at each location. The spreadsheet calculates the weight induced
418 moments (M_{body}) and deflections as well as the total induced moment (M_{total}) at all locations. The
419 spreadsheet makes the calculation both with and without self-loading considered. In addition,
420 the error induced by ignoring self-loading is calculated. Figure 5 shows an example of the
421 spreadsheet in which 3 externally applied forces, 2 externally applied moments, and 3 weights
422 are considered. This tool can be used by researchers to determine the necessity of including self-
423 loading in their studies.

424 For example, if this spreadsheet were used to determine the necessity of including self-
425 weight in a mechanical phenotyping study (e.g., a study using the device as presented in [6]), the
426 following would be performed: (1) A non-destructive, small deflection, flexural test as described
427 in [6] would be performed, to determine the specimen's *stalk flexural stiffness*; (2) a destructive,
428 large deflection bending strength test as described in [6] would then be performed on the same
429 specimen; (3) the specimen would then be weighed and the center-of-gravity would be
430 determined; (4) the specimen weight, center-of-gravity, and *stalk flexural stiffness* as well as the
431 magnitude and location of the load applied to the plant by the phenotyping device from the
432 destructive bending strength test would be input into the spreadsheet; (5) the spreadsheet would
433 report out the amount of error present in *stalk flexural stiffness* and *stalk bending strength*
434 calculations if the weight of the specimen was ignored. This procedure would then be repeated
435 for several representative specimens. This data could then be used to inform the researchers if
436 self-weight induced loadings are significant and need to be accounted for in phenotyping
437 experiments or if the amount of error introduced by neglecting self-weight is negligible. If self-
438 weight was determined to be significant then the spreadsheet could be used to properly account
439 for the self-weight of measured samples.

440 ***Case Study Results***

441 Results from the first and second case studies are presented below. Results from the third
442 case study (experimental analysis of wheat throughout a growing season) are found in Additional
443 File 3.

444 With regards to the first case study, Figure 2 displays two common loading
445 configurations used during mechanical phenotyping experiments. The first test configuration
446 represents a typical *stalk flexural stiffness* test for maize [6,45] and applies a *Contact Force* at

447 the top of the specimen, while the stalk's center of gravity is below the loading point. The
 448 second test configuration shown in Figure 2 represents a typical *stalk flexural stiffness* test for
 449 wheat [25, 26] and applies a *Contact Force* below the grain head but near the top of the
 450 specimen.

451 During these types of mechanical phenotyping tests the *Contact Force* (F) applied by a
 452 phenotyping device and the deflection of the stem at the point of loading (δ_t) are
 453 recorded. Ignoring the weight of the stalk, the *stalk flexural stiffness* (EI) is then typically
 454 calculated from the test data by rearranging the following engineering beam equation to solve for
 455 EI:

$$\delta_t = \frac{Fh_t^3}{3EI} \quad (15)$$

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

459 *Configuration 1: Load at Top, Weight at Midspan*
 460

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

$$\begin{bmatrix} 1 & \frac{-h_2}{2EI} \\ -w & 1 \end{bmatrix} \begin{bmatrix} \delta_2 \\ W \end{bmatrix} = \begin{bmatrix} \frac{Fh_2^2(3h_1 - h_2)}{6EI} \\ 0 \end{bmatrix} \quad (16)$$

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

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

466 Finally, we can solve Equation 5 at the point of loading (δ) to find a relationship between
 467 the test data and the deflection:

$$468 \delta_1 = \frac{Fh_1}{3EI} + \frac{Fwh_2^2(3h_1 - h_2)(2h_1 - h_2)}{6EI(2EI - wh_2^2)} \quad (18)$$

470 Where Equation 15 is shown in black, and the correction factor for the weight-induced moment
 471 is shown in blue. This newly calculated deflection can then be substituted into the corresponding
 472 equation in Table 1 to calculate the corrected *stalk flexural stiffness*.

473
 474 *Configuration 2: Load at Midspan, Weight at Top:*

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

$$477 \begin{bmatrix} 1 & \frac{-h_1}{2EI} \\ -w & 1 \end{bmatrix} \begin{bmatrix} \delta_2 \\ W \end{bmatrix} = \begin{bmatrix} \frac{Fh_2^2(3h_1 - h_2)}{6EI} \\ 0 \end{bmatrix} \quad (19)$$

478 Solving for the weight-induced moment and solving for Equation 5 for the point of loading (δ)
 479 to find a relationship between the test data and the deflection:

$$480 \delta_2 = \frac{Fh_2^3}{3EI} + \frac{Fwh_2^4(3h_1 - h_2)}{6EI(2EI - wh_2^2)} \quad (20)$$

481 Where Equation 15 is shown in black, and the correction factor for the weight-induced moment
 482 is shown in blue. This newly calculated deflection can then be substituted into the corresponding
 483 equation in Table 1 to calculate the corrected *stalk flexural stiffness*.

484 It should be noted that Equations 18 and 20 are simply Equation 15 with the addition of a
 485 correction factor that accounts for the influence of the weight-induced bending moment. Thus by

486 comparing the results of Equation 15 with either Equation 18 or 20, the influence of the weight-
 487 induced bending moment on the deflection of the stem can be calculated. Additionally, the
 488 results of Equation 18 and 20 (i.e., the deflections) can be input into Equation 6 to determine the
 489 magnitude of the weight-induced moment. The weight induced bending moment (W) can then
 490 be compared to the bending moment induced from the applied force (M_{ext}) to determine the
 491 effect of self-weight on the *stalk bending strength*. Using the methods presented in this case
 492 study researchers can easily determine if weight-induced bending moments are negligible or if
 493 they need to be incorporated into their mechanical phenotyping studies.

494
 495 A second case study was conducted to determine the general influence of *Body Forces* on
 496 several plant species. The values shown in Table 3 represent typical values reported in the
 497 literature for the five plants species included in this case study. It should be noted that these are
 498 average single data points and a significant amount of variation in heights, weights, and flexural
 499 stiffnesses is expected within a given plant species. This information is presented here as an
 500 accessible reference for researchers to develop an understanding of the types of plants that are
 501 more or less affected by self-loading.

502
 503 **Table 3:** *Self-loading related properties and the % error introduced when self-loading is ignored*
 504 *in calculations of stalk bending strength and stalk flexural stiffness. The center of gravity of the*
 505 *plant was 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 Stalk Bending Strength (%) | Error of Stalk Flexural Stiffness (%) | 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] |

506

507 A key factor in determining the influence of *Body Forces* in different plant species is the
508 ratio of the weight of a plant to its *flexural stiffness*. While this ratio does not include all of the
509 factors that influence self-loading, it can be used as a quick evaluation tool for researchers to
510 determine the general amount of influence self-loading may have. Figure 6 depicts the influence
511 of this ratio on *stalk flexural stiffness* and *stalk bending strength*, with the plant varieties in Table
512 3 shown as data points. In general, it can be seen from the figure that *Body Forces* (i.e., self-
513 weight) has a negligible effect on stiff and strong stems (i.e., bamboo and maize) but becomes
514 more influential in smaller stems (i.e., rice, wheat).

515

516 **Discussion**

517 Mechanical measurements of plants have been used to investigate stalk lodging resistance
518 for over a century. However, engineers or mechanical measurement experts have typically not
519 been involved in past studies. Consequently, very few previous studies have attempted to
520 account for the complex influence of the plant's own weight (i.e., *Body Forces*) on mechanical
521 measurements. The studies that have attempted to account for self-weight typically normalized
522 bending strength measurements by specimen weight [e.g., 46,47]. This was an important first
523 step and raised general awareness of the need to somehow account for self-weight during

524 mechanical phenotyping studies. However, the effect of self-weight on *stalk bending strength*
525 and *stalk flexural stiffness* is complex and is not fully captured by normalizing *stalk bending*
526 *strength* measurements by specimen weight.

527 This is the first report the authors are aware of that presents a method to properly account
528 for plant weight when calculating *stalk bending strength* and *stalk flexural stiffness*. Results
529 demonstrate the equations derived herein to account for the complex effects of self-weight
530 during mechanical phenotyping experiments are accurate. The authors therefore recommend that
531 future studies utilize the equations, corrections factors and Excel spreadsheet presented herein to
532 account for the effects of self-weight during mechanical phenotyping experiments. More
533 specifically, based on prior experience and the results presented in Table 3 and Figure 6, the
534 authors recommend that self-weight be accounted for when testing small grain stems. However,
535 the effect of self-weight on large grain stems that possess a small ratio of plant weight to *stalk*
536 *flexural stiffness* (e.g., mature maize stalks) is minimal and for many intents and purposes is most
537 likely negligible.

538 More broadly the authors would advocate for increased collaboration between plant
539 scientist and engineers. The mechanical response of plant stems is complex and requires specific
540 expertise to fully understand. While the Excel spreadsheet and equations derived above have
541 been made as approachable as is feasible to non-experts, they will be most useful to engineers
542 and structural mechanics experts who fully comprehend the inherent assumptions and limitations
543 of the tools.

544 Finally, it should be noted that the association between *stalk flexural stiffness*, *stalk*
545 *bending strength*, and stalk lodging resistance are plant- and time-specific. For instance, in late-
546 season lodging of maize stalks, previous studies have found that plants experience a

547 predominantly linear-elastic response prior to failure, and that *stalk flexural stiffness* tends to
548 strongly correlate with lodging resistance [5]. In such a case, Equation 14 demonstrates that the
549 total bending moment and bending stress are directly linear, e.g. a 10% increase in the total
550 bending moment will result in a 10% increase in stress. Therefore, the authors hypothesize that
551 increasing the *stalk bending strength* will decrease the lodging resistance at a ratio of -1:1, e.g. a
552 10% increase in the induced bending moment from self-loading will result in a 10% decrease in
553 the lodging resistance of the stalk. However, for less linear material responses (e.g. during
554 green-snap), these relationships will be less direct. For stems with nonlinear material responses,
555 researchers will need to incorporate these self-loading equations into their biomechanical models
556 which contain non-linear material responses.

557

558 ***Limitations***

559 The primary limitation of the current study is that the stalk was assumed to be in-line with
560 the assumptions made for pure bending, including maintaining a constant cross-section with
561 homogeneous, isotropic, linear elastic material subjected to pure bending [4]. It should be noted
562 that the finite element models were also only valid for linear elastic materials. Inclusion of changes
563 in cross-sectional geometry along the length of the stalks [22], material heterogeneity and
564 anisotropy, and non-linear material properties would likely change the behavior of the analytical
565 system. A discussion of the influence of these factors has been presented in a previous study by
566 the authors [4]. The simplifying assumptions made in the derivation of the closed form solutions
567 combined with the assumption of a single cross-section along the entire length of the stalk, results
568 in a single flexural stiffness parameter for the entire stalk. However, the flexural stiffness of plants
569 changes constantly along the length of the stalk (i.e., the diameter of most plant stems are large

570 near the base of the plant and smaller near the top of the plant). The simplifying assumption of a
571 single flexural stiffness parameter was deliberately made to allow for an easily-used generalized
572 equation. This assumption is routinely made in phenotyping studies as well. If researchers need
573 to incorporate changes in flexural stiffness along the length of the stalk, the approach presented in
574 this study can be incorporated into a full Castigliano's method beam approximation
575 [17]. Additionally, the equations used in this study assume small strains and small deflections. As
576 such, these equations carry the same limitations as standard engineering beam bending equations,
577 and are not suitable to predict post-failure loading conditions or deflections. When post-buckling
578 analyses are required, non-linear finite element modeling approaches are recommended. In
579 summary, the analyses in this study are only valid for conditions in which traditional phenotyping
580 methods are considered valid.

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

591 **Conclusions**

592 Equations were derived to account for the influence of self-loading on measurements of
593 *stalk flexural stiffness* and *stalk bending strength* of plant stems. The derived equations were
594 parametrically validated against hundreds of nonlinear finite element models of plant stems. The
595 closed form equations are accurate and showed good agreement with the finite element models
596 (median error < 0.2%). The equations were incorporated into a user-friendly spreadsheet that can
597 be used by the research community to account for self-loading of plants during mechanical
598 phenotyping studies. Results indicate that ignoring self-weight can lead to significant errors in
599 phenotyping measurements of small grains (e.g. 16% error in *stalk flexural stiffness* for wheat).
600 It is the recommendation of the authors that self-loading be taken into account for plants such as
601 wheat and rice that have a large ratio of weight to flexural stiffness. In addition, to minimize
602 error, a deflection of 2.5% to 20% of the stalk height (a deflection angle of around 6°) is
603 recommended for mechanical phenotyping tests used to characterize *stalk flexural stiffness*.

604 **Declarations**

605 **Ethics Approval and Consent to Participate**

606 Not applicable

607 **Consent for Publication**

608 Not applicable.

609 **Availability of Data and Materials**

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

612 **Competing Interests**

613 The authors declare that they have no competing interests

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619 **Authors' Contributions**

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

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

737 **Figure 2:** The loading diagrams for two common mechanical phenotyping test protocols used to
738 determine flexural stiffness; a typical maize phenotyping protocol (left), and a typical wheat
739 phenotyping protocol (right).

740 **Figure 3:** A comparison between the closed form solution and the solution of finite element models
741 for *stalk flexural stiffness* (a) and for *stalk bending strength* (b), $n=768$, as a function of deflection
742 normalized by plant height. Histograms of the error between the closed form solution and the finite
743 element models for *stalk flexural stiffness* (c) and for *stalk bending strength* (d), $n=768$. Panel (a)
744 demonstrates that significant errors can occur at very small (near-zero) deflections. A deflection
745 of 2.5% to 20% of the stalk height is recommended to minimize error during *stalk flexural stiffness*
746 phenotyping experiments.

747 **Figure 4:** A comparison between the closed form solution and the finite element model solution
748 (FEM) for very large deflections (i.e., for deflections and loads beyond what would typically be
749 seen in the field). Plots depict the deflection at the tip of the stalk (a) and the maximum moment
750 at the base of the stalk (b); the % error between the finite element model and the closed form
751 calculation of *stalk flexural stiffness* and *stalk bending strength* are shown as a function of stalk
752 deflection normalized by stalk height (c).

753 **Figure 5:** An example of the Excel spreadsheet (see Additional File 1), showing loading at three
754 locations, and calculating deflection and induced moments at four locations: the three loading
755 locations and the base of the plant. Note that the error in deflection is not calculated at the base,
756 as deflection at the base is zero regardless of loading condition.

757 **Figure 6:** The error of *stalk flexural stiffness* (left) and *stalk bending strength* (right), as a function
758 of the ratio between the combined weight of the grain and plant and *stalk flexural stiffness*.