A discrete element model for realistic bendable straw

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Abstract

Simulations are becoming increasingly important for the optimization of various processes. Biological variation, however, adds an extra challenge for agricultural applications. As the interactions between the crop stems and machine parts are quite complex, bulk models are often inadequate to properly describe the crop-machine interaction. Discrete element modeling (DEM) has been proposed as a better way to model the behavior of particulate systems (Tijskens et al., 2003). While DEM has already been successfully applied for modeling grain and fertilizer streams (Van Liedekerke et al, 2009), its use for simulating the flow and compression of stems has been limited, because bendable straw particles were not available in DEM softwares until very recently (Lenaerts et al, 2014). While the linear elastic models applied by Lenaerts et al. (2014) could describe the reversible bending of straw in a realistic way for small deformations, they are inadequate for describing the bending and compression behavior of the crop stems at higher compression forces where buckling phenomena become important. Therefore, new phenomenological models for the buckling behavior of crop stems during bending, inspired by the collapse of steel tubes due to ovalisation of the cross section and the formation of plastic hinges (Calladine (1989), Elchalakani et al (2002), have been implemented. Using these models virtual, bendable crop stems, with a realistic geometry, were created in the DEMeter++ software. The DEM parameters were calibrated based on three point bending tests conducted for wheat and barley straw using an Universal Testing System. The simulations were in good agreement with the measurements ($R^2 > 0.95$). This calibrated DEM model will be used in future research to simulate the processing of large numbers of virtual stems to obtain better insight in the force-deformation behavior of crop stems.

Keywords: DEM, virtual bendable crop stems, buckling

1. Introduction

Biological stem crops are processed in various agricultural machines. For optimization of these machines knowledge of both the deformation behavior of the crop and of the interaction between crop and machine is required. Many researchers have investigated the bulk deformation of stem crops and the factors influencing this process. Several (empirical) models have been proposed for describing the bulk compression, including exponential (Fabrodre and O’Callaghan, 1986; Ferrero et al., 1990; Nona et al., 2014), power law (Mewes, 1958) and polynomial forms (Sitkei, 1987).

When the interactions between individual crop stems or between stems and machine components are important bulk models are inadequate. Due to large variations in crop character-
istics and due to complex interactions between the crop particles, the estimation of bulk deformation behavior based on stem properties is nearly impossible. To the knowledge of the authors, up to date no research has been published on this subject. Discrete element modelling (DEM) has been proposed as a better way to model the behavior of particulate systems (Tijskens et al., 2003). Its use for simulating the flow and compression of stems has been limited up till now, because bendable straw particles were not available in DEM software. Very recently, the discrete element method was used to create virtual stems (Ross & Klingenberg (1997), Kattenstroth et al. (2011), Geng et al.(2011) and Lenaerts et al. (2014)). The crop stems of Lenaerts et al. (2014) were bendable and compressible in both the radial and longitudinal direction. Elementary geometric shapes, such as cylinders and spheres, were combined to produce these stems. Realistic deformation behavior was obtained by connecting the elements by linear spring-damper elements (Kelvin-Voigt elements). These (linear elastic) models could describe the reversible bending of straw particles in a realistic way for relatively small forces and deformations.

To illustrate the complexity of the deformation behavior of plant stems a typical force-deformation curve for three-point bending of a wheat stem is presented in Figure 1. It can be seen that linearity is only a good approximation for small deformations. After this initial phase the force increases at a slower rate and then drops rapidly for a further increase in deformation.

![Figure 1: A typical force-deformation curve for three point bending of wheat straw](image)

During bending of crop stems longitudinal compression forces arise on the inner side of the stem and a longitudinal tension force arises on the outer side. Both resist the applied bending moment and have a component directed towards the center of the stem. This tends to flatten the initial circular cross-section into an oval shape. This process is called ovalisation (Brazier, 1927). Under steadily increasing curvature the bending moment reaches a maximum. At this point (bending angle = θ) a kink is formed. This involves a complete local flattening of the cross-section which then offers virtually no resistance to bending (Calladine, 1989). This process is called buckling. So, for large deformations of the crop stems the behavior is highly non-linear and the DEM-model of Lenaerts et al. (2014) will no longer be valid. Therefore, the aim of this study was to extend the DEM-model of Lenaerts et al. (2014) to large deformations.

2. Materials and methods

The virtual DEM stems consist of several segments. Each segment consists of a rigid cylinder. Adjacent cylinders are connected by spherical joints. Since the cylinders are rigid, the joint is responsible for the flexibility of the tube. At each intersection between a cylinder and a joint a virtual disk is placed. Every joint consists thus of two disks. These two disks are interconnected with a number of linear, parallel spring-damper systems (Kelvin-Voigt models) (1 in Figure 2).
Figure 2: A bendable crop stalk in DEMeter++

The stiffness \((k_b)\) and the location of the springs determine the bending stiffness of the joints. The dampers \((c_b)\) prevent the joint from oscillating and stabilize the simulation. Initially, the spring-damper systems are axis-symetrically arranged (* in Figure 3). The number of segments and spring-damper systems can be chosen freely depending on the desired accuracy and the available computing capacity. A larger number will result in a more accurate simulation. The tube also experiences normal forces at the support points. To account for this, per segment and per joint, an extra set of Kelvin-Voigt systems \((k_r, c_r)\) is added in the radial direction (2 in Figure 2). The tensile stiffness of each segment is provided by an extra spring \((k_t)\) and damper \((c_t)\). They are attached to the two disks from one particular segment (3 in Figure 2).

Phenomenological models (based on the insights of ovalisation and buckling of Brazier (1927), Calladine (1989) and Elchalakani et al. (2002)) were adopted to describe the bending in crop stems. In this approach, the location of the spring-damper systems (for bending) changes as a function of the bending angle \((\theta)\). As a result, the bending stiffness also changes. Following models can be used to describe ovalisation:

\[
\xi = p_{ovalisation} \frac{D^4 \sin^2(\theta)}{4S^2}
\]

and buckling:

\[
\delta = 0 \quad \text{if } \theta < \theta_b \\
\delta = \frac{D}{2} \left(1 - \cos(b\theta - b\theta_b)\right) \quad \text{if } \theta_b < \theta < \theta_{b2}
\]

Where \(\xi\) is a dimensionless measure of the flattening in bending at the extreme fiber, \(p_{ovalisation}\) is a parameter defining ovalisation, \(D\) is the diameter of the tube, \(S\) is the segment length, \(\theta_b\) is the threshold angle for the start of buckling, \(b\) is the buckling parameter.

A problem arises when the bending angle, and thus the deformation, becomes large. The equation governing buckling is periodic. As a consequence the deformation will, after reaching a maximum, decrease again. This is physical nonsense. Although the model is thus not suitable for large deformations it remains useful for smaller deformations. The transition between both phases takes place at the threshold angle \((\theta_{b2})\). A new model is needed for the second part of buckling. An empirical model, capable of describing the change in second moment of area of the cross-section in this phase, is suggested:

\[
\delta = a_2 \frac{\theta}{\theta + b_2} + c_2 \quad \text{if } \theta_{b2} < \theta
\]

\(\theta_{b2}\) is the threshold angle defining the start of the second phase of buckling and \(b_2\) is the buckling parameter for this second phase in buckling. The values of \(a_2\) and \(c_2\) are determined by the fact that the values of \(\delta\) and \(d\delta/d\theta\) must be equal in both equations for \(\delta\) when \(\theta = \theta_{b2}\).
The equations for calculating ovalisation and buckling both start from the configuration where all spring-damper systems are arranged axis-symmetrically. The total deformation of the cross-section is the sum of ovalisation and flattening by buckling. The effect of ovalisation on the position of a spring-damper systems is applied first, and only then the effect of buckling is taken into account. For buckling to play a role the effect of flattening must be larger than that of ovalisation. The result of ovalisation (+) and buckling (o) on the location of the spring-damper systems can be seen in Figure 3. The flattening is limited to two times the wall thickness (t) (if $\delta > D - 2t$ then $\delta = D - 2t$).

Figure 3: Location of the Kelvin-Voigt elements ($N = 12$) on the virtual disk

(*) undeformed cross-section, (+) ovalised cross-section, (o) attened cross-section

When a stem has been deformed, it exhibits a different deformation behavior than stems which have not been previously deformed. Crop stems thus have a memory for the deformations they have experienced in the past. For the virtual DEM particles this behavior was also taken into account. It is generally assumed that deformations due to ovalisation are elastic and that buckling is plastic (Brazier (1927), Calladine (1989) and Elchalakani et al. (2002)). As a consequence, the changes in the location of the spring-damper systems due to ovalisation are not permanent. When the force causing the deformation is removed, the systems return to their initial axis-symmetrical position. This is not the case for a reconfiguration of the spring-damper systems due to buckling. These changes are permanent. Per joint the maximum deformation is saved. This deformation cannot decrease. It can only increase when the configuration is further flattened.

To validate the potential of the DEM model for describing the buckling of plant stems 30 wheat stems (harvested in Mechterstädt, Germany during the summer of 2012), 30 wheat stems (harvested in Leuven, Belgium during the summer of 2013) and 30 barley stems (harvested in La Luisana, Spain during the summer of 2013) were subjected to three-point bending. Subsequently, the experiments were repeated in simulation and the results were compared.

Prior to the measurements petioles and leaves were removed. The stems were cut into pieces with a length of 60 mm and were then placed on two metal supports 50 mm apart and loaded midway with a metal plunger. The plunger was rounded with a diameter corresponding to that of the diameter of the stems (4 mm). The plunger was driven at a constant speed of 1 mm/s by a universal testing system (UTS testsysteme GmbH, type UTS 5 K, Germany). The location of the plunger was recorded for each time step. The bending force was measured by a force transducer (Hottinger Baldwin Messtechnik GmbH, type U1A 10N, Germany). These experiments resulted in force-deformation profiles similar to the one displayed in Figure 1.
The dimensions of the test set-up in DEM (distance between the support points, the loading rate and the radius of the plunger and the support points) were given the same values as for the physical experiments. The virtual stems were given the same diameter, length and mass per meter as that of the real crop. A time-step (Δt) of 1.10^6 s was sufficiently small in order to obtain stable and unbiased simulations. Once a stem is created (diameter (D), segment length (S) and number of segments and spring-damper systems) the bending behavior is defined by six parameters: \(k_b\), \(\rho_{ovalisation}\), \(\theta_b\), \(b\), \(b_{02}\), and \(b_2\). These parameters should be chosen in such a way that the behavior of the virtual stems corresponds to that of real stems. Iteratively the DEM parameters for bending were varied to minimize the difference between the physical and virtual experiments. This minimization was done using Matlab (MATLAB and Optimization Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States).

3. Results and discussions

In Figure 4 typical force-deformation profiles from the DEM simulations are plotted for all three locations together with the measured data. The DEM model of a bendable straw stem is capable of describing the strong decrease in force due to ovalisation and buckling for crop stems with different physical and mechanical properties. A good agreement was found between measured data and simulations for all stems from all three locations. The \(R^2\)-values per location are displayed in Table 1.

![Figure 4: Force-deformation profiles from DEM simulations](image)

*Figure 4: Force-deformation profiles from DEM simulations (black: measured data, green: DEM simulation for data from Germany, red: DEM simulation for data from Belgium, blue: DEM simulation for data from Spain)*

| Table 1: DEM parameters (mean (\(\mu\)) and standard deviation (\(\sigma\))) |
|---------------------------|---------------------|---------------------|---------------------|
|                           | Germany (wheat)     | Belgium (wheat)     | Spain (Barley)      |
| N                         | 30                  | 30                  | 30                  |
| \(\mu\)                   | 0.955               | 0.967               | 0.975               |
| \(\sigma\)                | 0.053               | 0.0141              | 0.0135              |
| \(R^2\)                   |                     |                     |                     |

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4. Conclusions

As simulations become more important for the optimization of machines for the processing of crop stems, crop models gain in importance. Bulk models are often inadequate for describing the interactions between individual crop stems or between stems and machine components. Therefore, discrete element modelling has been proposed as a better way to model the behavior of particulate systems.

During processing of crop stems the bending of the individual stalks plays an important role. It has been shown that linear elastic models, as used in the discrete element modelling of virtual crop stems (Lenaerts, et al., 2014), are only accurate for small forces and deformations. For larger forces and deformations the behavior is highly non-linear and plastic. In this study the DEM-model of Lenaerts et al. (2014) was extended to large deformations.

When bending a crop stem two consecutive phases take place: ovalisation and buckling. New phenomenological models, inspired by the collapse of steel tubes due to ovalisation of the cross section and the formation of plastic hinges, have been implemented. These models were used to rearrange the spring-damper systems (Kelvin-Voigt models) for bending from an initial circular configuration to an ovalised and flattened configuration. In agreement with the literature ovalisation was considered elastic and flattening due to buckling plastic.

The DEM model was validated by three point bending tests on wheat and barley stems. The experiments were repeated in simulation and the buckling parameters were determined iteratively so the force-deformation profiles matched. A good agreement was found between measured data and simulations for all stems ($R^2 >0.95$). The DEM model is thus capable of accurately describing the phenomena which occur during bending of crop stems.

5. References


