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A discrete element approach for modelling bendable crop stems

Tom Leblicq *, Bart Smeets, Simon Vanmaercke, Herman Ramon, Wouter Saeys

KU Leuven – University of Leuven, Department of Biosystems (BIOSYST), Division of Mechatronics, Biostatistics and Sensors (MeBioS), Kasteelpark Arenberg 30, 3001 Leuven, Belgium

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ABSTRACT

A requirement for optimising crop processing machinery using DEM simulations is the application of virtual stems that behave realistically during deformation. In this study, data based bending models were developed for virtual segmented crop stems. These models combine realistic bending behaviour with a minimal number of model parameters. Also the effects of plastic deformation and damage were incorporated in the model. The bending model was successfully used to validate the bending behaviour of individual stems through comparison of simulations and validation measurements. It was also shown that the model is suitable for virtual stems with different numbers of segments. Moreover, based on a stem measurement it could be predicted what would happen to the same stem if it would have other dimensions or if it would be supported at different locations. Additional stem measurements were used to validate this. No significant difference ($\alpha = 0.05$) was observed between measurements and simulations. Finally, pendulum experiments showed that the deformation rate has no significant effect ($\alpha = 0.05$) on the deformation behaviour of individual crop stems.

1. Introduction

Stem crops are harvested by rotary mowers and by combine and forage harvesters. Collecting the crop residues is done with loader wagons and balers. Compressing these residues in balers makes them easier to handle and reduces storage and transport costs. A lack of knowledge on the interaction between the crop stems and the machine components results in sub-optimal designs and control strategies. Recently manufacturers of agricultural machinery are following the same path that manufacturers in other industries (e.g. automotive and aerospace) have been following for years. Optimization of (agricultural) machines is achieved, more and more, by using models and simulations. As the interactions between individual stems and machine components determine the process behaviour, a modelling framework on this level is required. Discrete Element Modelling (DEM) is a logical choice in this case, as it allows to model the behaviour of each particle (e.g. a crop stem) through its interactions with the other particles and the system elements (Tijskens et al., 2003).

1.1. Discrete element modelling of crop stems

DEM is increasingly used in agricultural applications for simulating particulate processes. The number of studies with bendable crop stems in DEM is, however, very limited. In the few studies where bendable crop stems have been considered, they have been defined by combining different segments which can move relative to each other. These segments can be spheres (Li et al., 2012; Jünemann et al., 2013), cylinders (Lenaerts et al., 2014; Leblicq et al., 2014) or capsules (Leblicq et al., 2016). The flexible particles in these studies all have linear-elastic bending behaviour.

1.2. Bending of crop stems

To assess whether the existing (linear elastic) models yield realistic results, we investigated the bending behaviour of crop stems in a previous study (Leblicq et al., 2015b). Two consecutive phases could be distinguished during the bending of stems: ovalisation and buckling. During ovalisation, the forces on the wall tend to flatten the cross section of the stem. When a stem is bent, the inner side of the stem is longitudinally compressed, whilst the outer side is stretched. Both this compression and tension result in a resistance of the stem against the bending moment. As both have a component directed towards the centre of the stem, the stresses cause a flattening of the circular cross-section into an oval shape (Leblicq et al., 2015b). This Ovalisation process is considered to be elastic. When this process continues, the flexural stiffness is reduced until the structure becomes unstable and buckles. A kink is suddenly formed and the cross-section locally completely flattens. This deformed cross section offers virtually no resistance to bending (Calladine, 1989).

* Corresponding author.
E-mail address: tom.leblicq@biw.kuleuven.be (T. Leblicq).

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1.3. Limitations of the existing bending models

The bending processes (ovalisation and buckling) result in highly non-linear and plastic deformation behaviour. After the initial linear elastic phase, the force increases at a slower rate and then drops rapidly for a further increase in deformation (Leblicq et al., 2014). Thus, whilst linear elastic DEM models can describe the reversible bending of straw stems in a realistic way for small deformations, they are inadequate for describing the bending behaviour of crop stems at larger deformations where buckling phenomena become important (Leblicq et al., 2014).

In addition, in all previous studies, the effect of plastic deformation and damaging has never been taken into account. Leblicq et al. (2016), however, showed that crop stalks respond differently to deformation when they already have been deformed plastically. The effect of deformation speed was also never taken into account. Peleg (1983), Faborode and O'Callaghan (1989), Kaliyan and Morey (2009), and Nona et al. (2014) showed that the deformation rate influences the bulk compression behaviour. However, no reports were found on the effect of plastic deformation and deformation speed on the bending behaviour of individual crop stems.

1.4. Objectives of this study

The general purpose of this study was to develop and validate a realistic DEM bending model for crop stems. The parameters of the virtual stems should be calibrated using stem measurements to ensure realistic results. The effects of deformation speed, support distance and plastic deformations should also be studied and incorporated in the bending model.

2. Material and methods

Virtual bendable stems were created in the DEMeter++ software, which was previously also used by Lenaerts et al. (2014) and Leblicq et al. (2015a). In this software, virtual segmented stems consist of connected capsules. A rotational spring is placed between two segments/capsules to create the bending resistance (Fig. 1(a)). When the stem is bent, this rotational spring (k_b) generates a moment (M) that counteracts the bending.

$$M = k_b\theta \tag{1}$$

The bending angle (θ) is chosen such that it is zero when the stem is undeformed and thus the angle increases with increasing deformation. For this, the following definition is used for the bending angle: $\theta = \pi - \phi$. where ϕ is the angle between two segments (Fig. 1(a)). An extra damper (damping constant c) is responsible for stabilizing the simulation by dissipating energy.

$$M = k_b\theta + c\dot{\theta} \tag{2}$$

In this equation $\dot{\theta}$ is the rotational velocity. In contrast to the work of Lenaerts et al. (2014) and Leblicq et al. (2015b) (who used the same software), only one rotational spring is used instead of a large number of axisymmetrically placed extensional springs. Based on the bending moment, forces (F_1 and F_2) are applied to the segments (Fig. 1(b)).

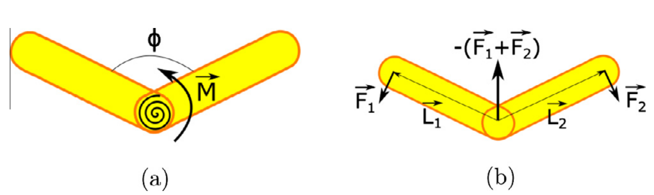

Fig. 1. Two segments of a virtual stem (a) bending moment and (b) resulting forces.

$$\vec{F_1} = \vec{M} \times \vec{L_1} \tag{3}$$

$$\vec{F_2} = -\vec{M} \times \vec{L_2} \tag{4}$$

These forces are added to the other forces acting on the segments to determine the position and velocity of the segments in the next time step.

When the rotational spring (k_b) has a constant value, the virtual stem again behaves linear elastic when bent (as was the case with the axisymmetrically placed extensional springs of Lenaerts et al. (2014) and Leblicq et al. (2016)). To create stems with realistic bending behaviour, the value of k_b should be made variable and depending on the angle and the previous deformation. To determine realistic values, a data-based approach (based on stem measurements) was used. To do this, stem bending measurements were first done.

2.1. Bending measurements

Thirty wheat stems (origination from Issoudun (France), July 2014) were measured. The stems were harvested by hand to reduce early damaging. They were then deformed by three point bending using a single column testing machine (Type LS1 Material Tester, LLoyd materials testing, West Sussex, UK) at a speed of 1 mm/s (Fig. 2). The support distance was set to 50 mm in accordance with Annoussamy et al. (2000), Nazari Galedar et al. (2008), and Tavakoli et al. (2009). In order to approximate the shape of a crop stem, the plunger consisted of a solid metal cylinder with a diameter corresponding to that of an average wheat stem (3.5 mm, Leblicq et al. (2015b)). This geometry was chosen to simulate the bending of a stem due to the interaction with a stem-shaped object. When the plunger moves down, the stem is deformed and the required force is recorded with a 50 N loadcell (Type LS Loadcell 50 N, LLoyd Instruments, West Sussex, UK). To determine the effect of plastic deformation and damaging, the procedure suggested by Leblicq et al. (2016) was used. The measurements were not performed in one run, but step-wise. In every

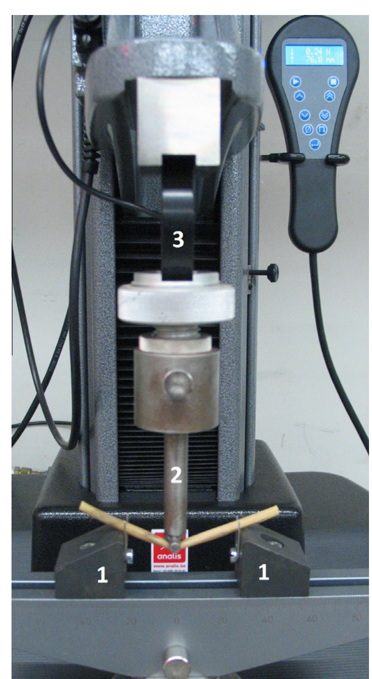

Fig. 2. Measurement set-up for three point bending of a crop stems (1) supports, (2) plunger, and (3) load cell.