Modelling of maize plant by the discrete element method

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1 Introduction, Research Scope and Objectives

The perpetual goals of agricultural machine design and development are optimizing the energy consumption, increasing the working quality and reducing the losses of machineries. One of the most efficient analysis methods for agricultural machinery designers is the time honoured in-situ test of the latest prototypes. However, due to the seasonal characteristic of agricultural processes and products these tests are limited in time, difficult to observe in detail and often proved to be very expensive.

Numerical modelling of agricultural crops is becoming more common year by year. First, studies relating the mechanical behaviour of bulk crop assemblies were conducted by using the discrete element method (DEM). DEM is capable of modelling contacts and bonds among separate particles, making it an effective tool to analyse complex loading and breaking conditions of plant parts and to expand beyond the limitations of in-situ tests. Thus, researchers are turning to the modelling of fibrous agricultural materials (stalks and stems), however, due to its complex nature there is still no suitable simulation method and crop model that could predict the interactions among fibrous agricultural materials and machine parts.

Maize (Zea mays L.) is one of the most cultivated crops of the world: almost 1050 million metric tons of maize were produced in 2017, while it also played an important role in Hungary’s agricultural industry: 6.8 million metric tons were harvested in 2017. Based on the forecast of the Food and Agriculture Organization of the United Nations, approximately 1200 million metric tons will be harvested from almost 200 million hectares in 2050. The main parts of a maize plant are the root system, stalk, leaves, tassel, shank and maize ear. The stalk, the strongest part of maize plant, is constituted of nodes and internodes, both have the same skin-core (rind-pith) structure. Furthermore, there is a difference between the orientation of tissues in nodes and internodes as well: the orientation of the tissues is non-uniform while in internodes the tissues are oriented in longitudinal direction of the stalk. Accordingly, the biological structure of maize, especially the structure of the stalk, is suitable for our study. Consequently, maize has been chosen for the interest of the current study due to its importance in agriculture and its biological structure.

The current project resolves to explore the suggestion that the DEM can be exploited to reproduce the mechanical behaviour and breakage of fibrous agricultural materials, such as maize plant. The primary objective of this thesis is to contribute to understanding of DEM modelling of fibrous agricultural materials and provide a model that represents the physical and mechanical existence of maize.

2 A Brief Literature Overview

Based on the literature review, several studies on the mechanical properties of maize stalks were conducted through transversal compression, three-point bending and cutting tests, but no studies related to the maize ear detachment and collision was...
found. The previous studies were carried out on different maize varieties from different parts of the world in different growing seasons. On the other hand, experiments were usually conducted on dried or deep-frozen samples and, therefore, the condition of these samples was not related to the harvested material. Furthermore, the mechanical behaviour of samples was estimated through small deformation loading cases, while large deformation of samples occurs during harvesting by a combine harvester with a maize head.

Less studies were found regarding the physical and morphological properties of the maize plant. The effect of reducing the moisture content or freezing on the mechanical behaviour are not known and, moreover, in the real processes, mainly virgin plants with 60-80% w.b. moisture content are involved. Thus, the analysis of virgin plants is evident in order to obtain results related to the real agricultural process. The diameter, length, mass and moisture content of each internodal section of the stalk and the position, shape, diameter, length and mass of the maize ear play the most important role during harvesting. Therefore, these properties must be measured and observed during the harvesting period when they are stabilized.

It is common knowledge that the environmental conditions during the different growing stages of maize have a significant effect on the properties of the fully developed plant, but only a few studies provided detailed meteorological data about the experimental plot regarding the actual growing season.

The primary purpose of the previously described discrete element models was to simulate the response of stems in a special loading case: bending, compression, impact load or collision between a stem and a flat plate. Thus, most of them cannot predict a detailed mechanical behaviour and breakage of stems during the complex loading situation of maize harvesting. Furthermore, the previous DEM models about stems and stalks were less detailed to analyse effectively the working quality of agricultural process.

3 Materials and Methods

Maize, variety Sufavor FAO360, was planted in the central region of Hungary on 15 April 2016. The plant density was 70,000 pieces ha\(^{-1}\) and the distance between the rows and plants was 0.75 m and 0.2 m, respectively. On the same day, the experimental plot, approximately 100 rows width and 500 plants long, was appointed in the middle of the non-irrigated field after taking into consideration its geographical properties for a homogeneous experimental plot.

Daily meteorological data were collected from the nearest meteorological station to the experimental plot by the Hungarian National Meteorological Service (OMSZ).

At the experimental plot, a general observation on the structure of maize was carried out by using 100 virgin maize plants. On 20 maize plants, the location of the maize ears was observed and its centre of mass was estimated from the soil surface and from the centre of the stalk by using a measuring tape.
During the **sample collection**, healthy plants without any observable damage, disease or mutation were systematically selected to provide uniform sample collection. For the laboratorial tests, plants were cut off right above the soil surface, and the leaves and tassel were carefully removed to secure the virginity of the samples. By using maize stalks, bunches were created and transported to the laboratory.

As to the **physical and morphological properties** (Figure 3.1), the minor and major dimensions of nodal and internodal cross-sections were measured on 10 stalks by a digital calliper. Ten stalks were cut into internodal sections by a bandsaw and their wet-mass was measured by a digital balance. The diameter and length of the shank and maize ears were measured on 20 maize ears by a digital calliper and measuring tape, respectively. The diameter of the ears was measured in one point in the middle section of the ear, where it is nearly constant. The total mass was measured on 20 samples by a digital balance. An image, parallel to the longitudinal axis of the ear, was taken in front of a white background. Afterwards, the background was completely removed by an image processing software. In the next step, the pictures were transformed into binary images with luminance factor 0.95, so the profile of the images (shape of ears) could be easily estimated.
Chapter 3. Materials and Methods

Figure 3.2: Experiments on the mechanical behaviour.

Generally, all the mechanical experiments (Figure 3.2) in the current study focused on the internodal sections of the stalk because the likelihood of loading on an internodal section of the stalk is higher than on the nodal section, moreover, previous studies justified that the physical and mechanical properties are roughly the same along the internodal region of the stalk. During all the experiments, the minor axis of the internodes was the direction of load and force-displacement data were collected at 100 Hz by the universal testing machine, while high-resolution videos were recorded on each sample with 30 frames per second. Two types of transversal compression tests; sectional transversal compression between flat plates and local transversal compression between a flat plate and an edge; were conducted on each internode of 10 maize stalks with deformation velocity of 300 mm min\(^{-1}\). Three-point and cantilever bending experiments on each internode of 10 maize stalks were conducted with a deformation speed of 300 mm min\(^{-1}\), while the bending tool and the supports had a cylindrical shape with a diameter of 10 mm. For the dynamic cutting experiments, a pendulum impact machine was modified by replacing the hammer with a cutting blade unit in such a way that the gap between the blade and supports was approximately 6 mm on both sides. The cutting test was carried out
on each internode of 10 maize stalks. For the ear-detachment experiment, a special apparatus was developed based on the process of maize harvesting and the general design of deck plates in a maize header. The stalk section with the maize ear was fixed in a clamp while the cross head of the universal testing machine with the apparatus moved upwards with a velocity of 600 mm min$^{-1}$. Through the ear-collision experiment, the coefficient of restitution among maize ears and steel (S235, EN 10027) and plastic (Polyethylene, PE) sheets were measured in longitudinal and radial directions of the maize ear.

The discrete element model of the maize stalk and the experiments were created and analysed in the commercial DEM software EDEM® (DEM Solutions Ltd, Edinburgh, Scotland, UK). During the model formation a complex solid-, solid-, hollow- and chain of spheres geometrical structures were used to create each parts of the virtual plant. Based on the importance and role of maize parts during harvesting, their
geometrical structure is more or less detailed, as shown on Figure 3.3.

Figure 3.4 shows the complex solid geometrical structure of the 4\textsuperscript{th} internodal section that was inspired by the real fibrous mechanical structure (skin-core) of a maize stalk. To reproduce this structure five different particle types were defined: particle types P41 and P42 form the skin; particle types P40 and P50 form the nodes and particle type P43 forms the core. In the skin, types P41 and P42 form a special composition: each cross-section contains 38 particles, 19 P41 particles and 19 P42 particles alternately. Thus, longitudinal fibres can be formed by aligning the cross-sectional layers. In the nodes, a solid cross-section is formed by using 19 particles of types P40 and P50 respectively. Finally, the inner volume is made up by using randomly generated particles type P43 with porosity of 60\% and the diameter of the core particles shows a normal (Gaussian) distribution. By using a non-structured particle distribution in the core, the disadvantages of the well-structured skin can be compensated, namely: the influence of the artificially created breaking planes of the skin on the breakage of the internodal section and the dependency of the loading direction can be reduced. The stalk parts in Section B were formed by following the same logic, however, 18 particles were used to form the skin in a cross-sectional layer and the poly-disperse core was neglected.

![Figure 3.4: DEM geometrical model of the 4\textsuperscript{th} internodal section of a maize stalk.](image)

After taking into consideration the existing DEM bonded models the Timoshenko Beam Bond Model (EDEM\textsuperscript{\textregistered}, DEM Solutions Ltd, Edinburgh, UK) was chosen for
this study because the Timoshenko beam theory takes into account the shear deformation that is essential for analysis on short, stubby beams, moreover, this bonded model enables a stochastic variation for the strength parameters that reflects the natural diversification of the real material.

Figure 3.5 shows the bond structure of the $4^{th}$ internodal section of the virtual maize stalk. To ensure the transversely isotropic mechanical behaviour of the model, different bonded parameters were used in the bonds that are oriented in different directions. In the skin, bonds among the specially composed particles P41-P41 and P42-P42 provide the mechanical behaviour in longitudinal direction, while, bonds among the particles P41-P42 provide the mechanical behaviour in transversal direction. In the core, the bonds among the randomly generated particles P43-P43 provide an isotropic mechanical behaviour, while, the bonds among the particles P43-P41 and the P43-P42 provide the contact among the skin and core in transversal direction. Bonds among the nodal particles P40-P40 and P50-P50 provide the mechanical behaviour of the node in transversal direction, while, bonds among the particles P40-P43, P40-P41, P40-42, P50-P43, P50-P41 and P50-42 provide the contact among the nodes, the skin and the core. The bonded structure of the stalk parts in Section B were formed by following the same logic but without the poly-disperse core.

**Figure 3.5:** DEM bond structure of the $4^{th}$ internodal section of a maize stalk.

The geometrical model of the maize ear is one particle in which the ideal shape of the maize ear was approached by 23 spherical surfaces, while the shank consists
of 10 spherical particles with diameter of 10.5 mm. The maize ear with the shank was situated beside the 6th internodal section in such a way that its centre of the mass was 93.99 cm and 9.42 cm from the virtual soil surface and the centre of the stalk, respectively. As to the bonded structure of the shank with the maize ear, it is necessary to note that it is impossible to model the real, broken condition of the shank so a curved shape with unbroken bonds among the particles was modelled. In this model there is only one type of bond among the particles along the axial direction of the shank, thus its mechanical behaviour in transversal direction is provided by the stiffness of the particles.

The influence of the bonded, non-bonded, bond-fabric and the numerical model parameters on the DEM simulated mechanical behaviour of the model was analysed by using a virtual representation of each laboratory experiment. To find an optimal set of the model parameters an optimization loop was determined based on the observed qualitative and measured quantitative characteristics of the investigated samples.

4 Theses

The following theses can be drawn based on the experiments on the maize plant:

Thesis 1:

The mechanical resistance of the internodal stalk sections decreases as the equivalent internodal diameter decreases:

Thesis 1.a: An exponential relationship with a higher correlation coefficient than 0.95 between the mechanical work \( W \) and the equivalent internodal diameter \( d_{IN} \) was determined for sectional (Eq. 4.1) and local (Eq. 4.2) transversal compression, and for three-point bending (Eq. 4.3):

\[
W^{SC} = 0.506 \cdot e^{0.1402 \cdot d_{IN}} \quad (d_{IN} = 5 - 25 \text{ mm}) \quad (4.1)
\]

\[
W^{LC} = 0.058 \cdot e^{0.2031 \cdot d_{IN}} \quad (d_{IN} = 5 - 25 \text{ mm}) \quad (4.2)
\]

\[
W^{TB} = 0.0459 \cdot e^{0.2376 \cdot d_{IN}} \quad (d_{IN} = 5 - 25 \text{ mm}) \quad (4.3)
\]

Thesis 1.b: Taking into account the average diameter of the first node \( \bar{d}_{N1} = 28.5 \pm 1.4 \text{ mm} \) and the bi-linear (Eq. 4.4 and 4.5) decreasing of the equivalent internodal diameter \( d_{IN} \) from the bottom to the top of the stalk, more than 75% of the total mechanical work \( (p = 1 - 10) \) is required to process the first five internodal sections \( (p = 1 - 5) \), Equation 4.6:

\[
d_{IN} = (-0.0594 \cdot p + 0.8673) \cdot \bar{d}_{N1} \quad (p = 1 - 5), \quad (4.4)
\]

\[
d_{IN} = (-0.0632 \cdot p + 0.8640) \cdot \bar{d}_{N1} \quad (p = 6 - 10), \quad (4.5)
\]
\[ W_{\%} = \frac{\sum_{p=1}^{10} W - \sum_{p=6}^{10} W}{\sum_{p=1}^{10} W} \cdot 100\% \geq 75\%. \]  

**(Thesis 2):**

Based on the field observations on the harvest-ready maize plant, two different structural conditions of the shank can be determined:

- buckled, when a plastic joint was formed at one point of the shank;
- healthy, when there is no observable change on the shank.

A statistical two-sample t-test on the collected data justified that the detachment force required to separate the harvest-ready maize ear from the stalk is independent of the structural condition of the shank. Thus, an average detachment force of \( 457.3 \pm 58.2 \) N was determined by using all the collected data regardless the structural condition of the shank.

**Related publications:** [1]; [3]; [11]; [16].

**(Thesis 3):**

The coefficient of restitution among the harvest-ready maize ear, steel (S235, EN 10027) and plastic (Polyethylene, PE) plates is independent of the analysed directions of collision relative to the maize ear: axial and radial, as shown in Table 4.1:

<table>
<thead>
<tr>
<th></th>
<th>Radial</th>
<th>Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (S235, EN 10027)</td>
<td>( 0.34 \pm 0.05 )</td>
<td>( 0.34 \pm 0.04 )</td>
</tr>
<tr>
<td>Polymer (Polyethylene, PE)</td>
<td>( 0.42 \pm 0.03 )</td>
<td>( 0.41 \pm 0.09 )</td>
</tr>
</tbody>
</table>

**Related publications:** [3]; [8]; [11]; [16].

The following theses can be drawn based on the discrete element simulations on the maize plant:

**(Thesis 4):**

Based on the biological structure of the maize plant, a special discrete element model was created that consists of spherical particles that are organized into complex (well-structured skin and poly-disperse core); hollow (well-structured skin) and chain of spheres geometrical substructures:

**Thesis 4.a:** A calibration method was established (Figure 4.1) to determine a possible combination of numerical parameters of the bonded (Timoshenko Beam Bond Model, TBBM) and non-bonded (Hertz-Mindlin Contact Model,
HMCM) contact models describing the mechanical behaviour of the numerical maize plant. By using this combination of the numerical parameters it was justified that the mechanical behaviour of the model (stiffness, strength and breakage) is in a good agreement with the mechanical behaviour of the real maize plant in case of the applied experiments: sectional and local transversal compression; three-point bending; dynamic cutting; ear detachment and collision.

**Thesis 4.b:** It was justified that the experimentally validated complex discrete element model, that consists of spherical particles organized into a well-structured skin and a poly-disperse core, is capable of analysing the complex biological structure of the real stalk (*epidermis, cortex, medulla* L.) in case of quasi-static mechanical loadings resulting in residual deformation, when the internal structure plays an important role.

*Related publications:* [4]; [5]; [6]; [7]; [8]; [10]; [12]; [14]; [15].

**FIGURE 4.1:** Calibration and validation method for the virtual maize plant.
Thesis 5:
The influence of the location and direction of the external load, and the influence of the contact model parameters on the mechanical behaviour of the virtual maize plant were examined through a detailed sensitivity analysis:

Thesis 5.a: It was justified that the poly-disperse structure of the core compensates the loading direction dependency of the well-structured skin in the analysed loading cases, because the response of the model was identical in case of:

- compressing on the top, middle and bottom region of the internodal section during sectional transversal compression;
- cutting on a particle and between two particles of the skin during dynamic cutting;
- compressing and bending in different radial directions around the longitudinal axis ($0^\circ$ – $45^\circ$ – $90^\circ$ – $135^\circ$) of the internodal section during sectional transversal compression and three-point bending.

### Table 4.2: Range of the analysed contact model parameters.

<table>
<thead>
<tr>
<th>Parameters of the bonded contact model (TBBM)</th>
<th>$E_B[MPa]$</th>
<th>$\nu_B[-]$</th>
<th>$S_T[MPa]$</th>
<th>$S_S[MPa]$</th>
<th>$\zeta[-]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skinning, long.</td>
<td>2000-6000 $\bigstar$</td>
<td>0.1-0.4 $\bigstar$</td>
<td>100-1000 $\bigstar$</td>
<td>10-100 $\bigstar$</td>
<td>0.1-0.9 $\bigstar$</td>
</tr>
<tr>
<td>Skin, tr.</td>
<td>600-1800 $\bigstar$</td>
<td>0.1-0.4 $\bigstar$</td>
<td>10-100 $\bigstar$</td>
<td>5-15 $\bigstar$</td>
<td>0.1-0.9 $\bigstar$</td>
</tr>
<tr>
<td>Core</td>
<td>2-6 $\bigstar$</td>
<td>0.1-0.4 $\bigstar$</td>
<td>1-8 $\bigstar$</td>
<td>-</td>
<td>0.1-0.9 $\bigstar$</td>
</tr>
<tr>
<td>Ear &amp; shank</td>
<td>200-600 $\bigstar$</td>
<td>-</td>
<td>20-60 $\bigstar$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of the non-bonded contact model (HMCM)</th>
<th>$E_P[MPa]$</th>
<th>$\theta_{P-P}[-]$</th>
<th>$\theta_{P-G}[-]$</th>
<th>$e_{P-G}[-]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin, core &amp; shank</td>
<td>67.5-540 $\bigstar$</td>
<td>0.1-0.9 $\bigstar$</td>
<td>0.1-0.9 $\bigstar$</td>
<td>0.2-1.0 $\bigstar$</td>
</tr>
<tr>
<td>Ear</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5-0.9 $\bigstar$</td>
</tr>
</tbody>
</table>

Analysed by $\bigstar$ transversal compression; $\bigstar$ three-point bending; $\bigstar$ dynamic cutting; $\bigstar$ ear-detachment and $\bigstar$ ear-collision.

Thesis 5.b: The analysed range of the bonded contact model parameters (Timoshenko Beam Bond Model, TBBM) are shown in Table 4.2. The main influence of the bonded parameters on the mechanical behaviour of the virtual maize plant is determined in the following statements:

- In case of the sectional transversal compression experiment:
  - as the Young’s modulus ($E_B$) increases, the initial stiffness increases, the number of broken bonds increases and after the breakage of the skin the mechanical resistance of the internodal section is higher;
- as the mean tensile strength in transversal direction of the skin \((S_{T}^{S,\text{tr.}})\) increases, the number of broken bonds decreases in the skin;
- as the mean tensile strength in the core \((S_{C}^{T})\) increases, the number of broken bonds decreases in the core, thus, the mechanical resistance of the internodal section is higher after the breakage of the skin;
- as the coefficient of variation of strength \((\xi)\) increases, the number of broken bonds increases in the skin, thus, the transition between the initial and exponential sections of the force response is smoother.

- In case of the three-point bending experiment:
  - as the Young’s modulus in longitudinal direction of the skin \((E_{B}^{S,\text{long.}})\) increases, the initial stiffness increases, the peak resistance force increases, the peak resistance force appears at lower displacement, the resistance of the bended cross-section is higher after the breakage and the number of longitudinal cracks in the skin increases;
  - as the mean shear strength in transversal direction of the skin \((S_{S}^{S,\text{tr.}})\) increases, the peak resistance force increases, the resistance of the bended cross-section is higher after the breakage and the number of longitudinal cracks in the skin decreases.

- In case of the dynamic cutting experiment:
  - as the mean tensile strength in longitudinal direction of the skin \((S_{T}^{S,\text{long.}})\) increases, the peak cutting force increases, the required cutting work increases, the bending resistance after cutting was higher and the resulted cutting surface is less even;
  - as the mean shear strength in longitudinal direction of the skin \((S_{S}^{S,\text{long.}})\) increases, the peak cutting force decreases, the required cutting work increases and the resulted cutting surface is less even.

- In case of the ear detachment experiment:
  - as the Young’s modulus in longitudinal direction of the shank \((E_{B}^{S\text{H}})\) increases, the stiffness of the shank increases, while the detachment takes place at lower displacement;
  - as the mean tensile strength between the shank and ear \((S_{T}^{S\text{H}&\text{ME}})\) increases, the ear detachment force increases, while the the detachment takes place at higher displacement.

**Thesis 5.c:** The analysed range of the non-bonded contact model parameters (Hertz-Mindlin Contact Model, HMCM) are shown in Table 4.2. The main influence of the non-bonded parameters on the mechanical behaviour of the virtual maize plant is determined in the following statements:

- as the particle-particle Young’s modulus \((E_{P})\) and the particle-particle coefficient of static friction \((\theta_{P-P})\) increases, the mechanical resistance of the internodal section is higher after the breakage of the skin in case of sectional transversal compression;
– as the particle-geometry coefficient of static friction ($\theta_{P-G}$) increases, the mechanical resistance is higher after the breakage of the bended cross-section in case of three-point bending;

– in case of the ear collision test, the relationship between the bounce height of the ear ($E_{ME} = 27$ GPa, $\rho_{St} = 930$ kg $\cdot$ m$^{-3}$) and the particle-geometry coefficient of restitution ($e_{P-G} = 0.5 - 1.0$) can be determined with a higher correlation coefficient than 0.95 as:

- a second order function (4.7) for steel ($E_{St} = 200$ GPa, $\rho_{St} = 7850$ kg $\cdot$ m$^{-3}$) plate:

$$H_{St} = 1284.1 \cdot (e_{P-G}^{ME})^2 - 1336.5 \cdot (e_{P-G}^{ME}) + 385.14 \quad (4.7)$$

- a third order function (4.8) for polyethylene ($E_{St} = 0.7$ GPa, $\rho_{St} = 950$ kg $\cdot$ m$^{-3}$) plate:

$$H_{Pl} = 3303.5 \cdot (e_{P-G}^{ME})^3 - 5489 \cdot (e_{P-G}^{ME})^2 + 3090 \cdot (e_{P-G}^{ME}) - 557.66 \quad (4.8)$$

5 Related Publications


