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STOCHASTIC VARIATION IN DISCRETE ELEMENT METHOD (DEM) FOR AGRICULTURAL SIMULATIONS

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Abstract

The diversity of physical and mechanical properties of agricultural materials makes them a good object for analysis, using stochastic variation during the discrete element modelling (DEM) of fibrous agricultural materials. Consequently, our study focuses on the use of coefficient of variation in agricultural DEM simulations. Laboratorial three-point bending, sideward compression and dynamic cutting tests were conducted to define the main mechanical parameters and behaviour of corn stalks. The effects of the different variations of coefficients (between 0.0 – 1.0 by 0.2 increments) on the quantitative and qualitative simulation results were analysed. The results of the study clearly demonstrate that the coefficients of the variation could be advantageously utilised.

Keywords

Discrete element method (DEM), stochastic variation, corn stalk.

1. Introduction

Thanks to the natural diversity of physical and mechanical properties of agricultural materials, the accurate numerical modelling of these materials provides a huge challenge for researchers. In most cases during the laboratorial or in situ tests, the parameters of interest usually show a wide confidence interval around the mean values. Nonetheless, these parameters could inordinately change in the same sample as well. To handle this problem a stochastic variation, as in the natural structures, should be used during the numerical simulations.

From the different numerical methods the discrete element method (DEM) with the Timoshenko-Beam-

Bond-Model (TBBM) has the most potential for development [1]. Consequently, our study focuses on the using of the coefficient of variation in TBBM for agricultural DEM simulations.

DEM is used to investigate bulk agricultural materials widely. Keppler et al. calibrated the micromechanical parameters of a sunflower DEM model based on odometer tests so that the model can sufficiently approach the macro mechanical behaviour of the real bulk material [2]. Földesi et al. investigated the pressure relations of an oil press by DEM simulations [3]. Tamás et al. examined the soil-tool interaction and the relations in cohesive soil by using the DEM [4].

In connection with fibrous materials fewer literatures can be found. Kemper et al. investigated the iteration among grass stalk and rotation mower by DEM [5]. A special solid geometrical structure of DEM was analysed for corn stalks in quantitative and qualitative ways by Kovács et al. [6]. Several possible DEM geometrical structures for modelling of fibrous agricultural materials were compared by Kovács et al. [7]

To calibrate a DEM model, in situ and laboratorial tests are indispensable. Qin Tongdi et al. investigated the effect of different production fields on three point bending behaviour of the same maize species [8]. Sun Zhong-Zhen et al. examined the effect of moisture content on three point bending behaviour of maize stalks [9]. M. Azadbakht et al. accomplished in situ dynamic cutting test by a modified Charpy impact test to analyse the resistance against dynamic cutting force of maize stalks [10].

The results of the study clearly demonstrate that the coefficient of variation could be advantageously utilised during the simulations of agricultural materials.

2. Theory and background

Discrete element method (DEM) is developed to investigate bulk materials which contain separate parts. The definition of a DEM model is the following [11]: It contains separated, discrete particles which have independent degrees of freedom and the model can simulate the finite rotations and translations, connections can break and new connections can come about in the model.

In the field of discrete element modelling there are not so many contact models that are adaptable to modelling fibrous agricultural materials, moreover, the different DEM software products provide different contact models. In our study EDEM 2.7 (DEM Solutions Ltd.) and Timoshenko-Beam-Bond-Model (TBBM) by Nicholas J. Brown, Jian-Fei Chen, and Jin Y. Ooi were used [1].

During the bond formation a cylindrical beam is created between the predefined particles. This beam has no real volume and mass, but its mechanical behaviour follows the Timoshenko beam theory, so it can transmit forces and moments among the particles. This kind of contact can break if one of the stresses meets the predefined maximum stresses (compressive stress, tensile stress or shear stress). From the point of view of agricultural materials, the stochastic variation of the bond strength in TBBM is one of the most important features [1].

In the contact model three coefficients of variation (CoV) for the three strengths could be used [1.]:

– ζ_C : coefficient of variation for compressive strength (σ_C);

– ζ_T : coefficient of variation for tensile strength (σ_T);

– ζ_S : coefficient of variation for shear strength (τ).

Through the initializing of the bonds the maximum stresses are calculated with the following equations:

$$\sigma_C = S_C \cdot ((\zeta_C \cdot N) + 1) \quad (1)$$

$$\sigma_T = S_T \cdot ((\zeta_T \cdot N) + 1) \quad (2)$$

$$\tau = S_S \cdot ((\zeta_S \cdot N) + 1) \quad (3)$$

where S_C , S_T and S_S the mean compressive, tensile and shear strength of the bonds, respectively; N is a random number from standard normal distribution [1].

With modification of coefficients of variation in range from 0.0 to 1.0 the initialized strengths of bonds show different distributions. In the following example the mean tensile strength was assumed 500 MPa and the figure shows the distribution of the bond strengths with different coefficient of variations on Figure 1.

In this study the effect of the stochastic variation of the bond strength on the simulation quantitative and qualitative results were analysed.

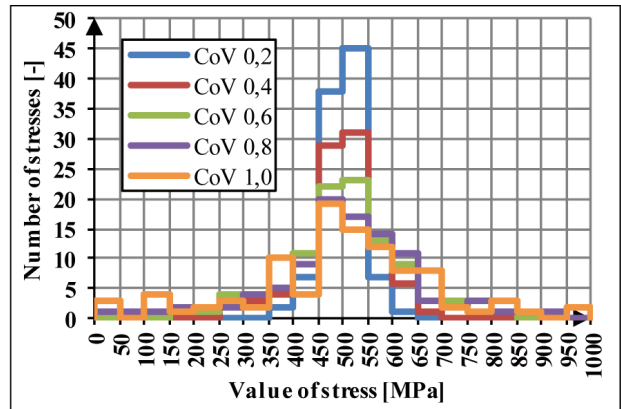


Figure 1. Initialized bond strengths with different coefficients of variations

3. Material and methods

Based on harvest and product processes of harvest-ready corn stalks the main loads (three-point bending, sideward compression, dynamic cutting) were determined. Root leaves and ears of the plant were neglected in our study so these parts were removed from the stalk before the measures.

First of all, the physical properties of the stalks (mass, moisture content, length, diameter, shape) were measured and taken down. After that laboratorial three-point bending, sideward compression and dynamic cutting tests were conducted to define the main mechanical parameters and behaviour of corn stalks. The results of the measures weren't directly usable for the modelling method so suitable data and graphs were calculated with mathematical and statistical methods for the numerical modelling.

Based on our previous study a hollow DEM geometrical structure with 18 particles was chosen for the study [7]. This geometrical model ensures detailed investigations with low computational costs. After that the DEM models of three-point bending, sideward compression and dynamic cutting were simulated with 0.0; 0.2; 0.4; 0.6; 0.8 and 1.0 coefficients of variation. The models had to be recalibrated in every case of the coefficients of variations because of the new distribution of bond strengths.

The simulation results were evaluated by quantitative and qualitative ways in order to find a right coefficient of variation that can simulate the mechanical properties and behaviour of the real plant more accurately.

4. Measures

Before each measure the necessary specimens were prepared. During the preparation, leaves and ears were pruned from the stalk and the necessary physical parameters were measured. Finally, the stalks were cut to the right size for the mechanical measures.

Analyses were conducted for the fourth internode hence the results of the study are in relation to the fourth internode. During the measurement of the physical parameters 10 plants were investigated. Water based moisture content, diameter, length and mass of the fourth internode were measured (Table 1.).

Table 1. Physical parameters of the fourth internode.

Parameters	Results
Average moisture content	51,68 %
Average diameter	18.2 mm
Average length	123.9 mm
Average mass	32.9 gr

The aim of the three-point bending test was to define the resistance against bending of the first internode. The bending diagram has three different sections: the linear section where the relation is linear between the force and displacement, the contraction section where the diagram reaches the maximum force and the bended cross-section of the internode is flattening, and finally, the plastic joint section where the bended cross-section is crashed so the resistance against the bending is decreasing gradually until the end of the bending test (Figure 2.).

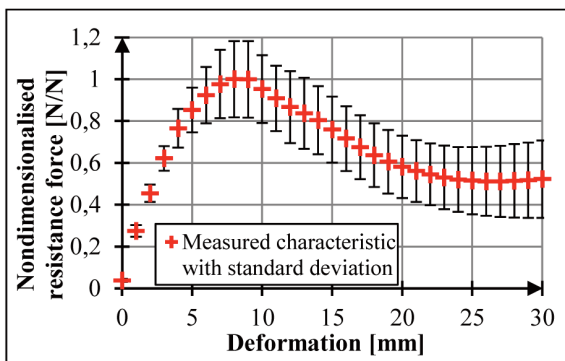


Figure 2. The characteristics of three-point bending of the fourth internode

The aim of the compression test was to determine the side pressing resistance of the fourth internode and the crossway and residual sideways deformation over the stalk length. The compression diagram has two different sections: the constant section which goes up to 35% deflection where the resistance force is close to constant, the exponential section that goes

from 35% to 75% deflection where the resistance force is exponentially increasing (Figure 3.).

The aim of the dynamic cutting test was to determine the cutting work of the first internode. Ten specimens were investigated, and based on the evaluation of the results the average cutting work with standard deviation of the fourth internode was 21.92 ± 6.8 J.

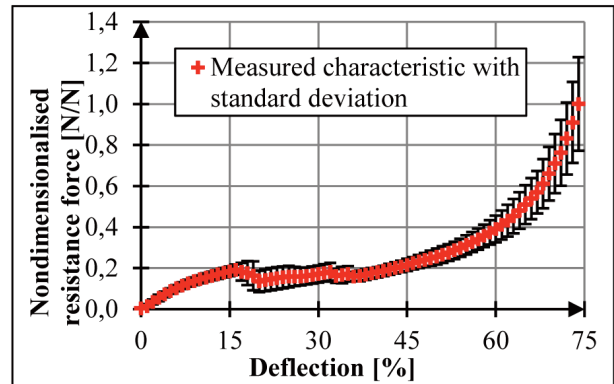


Figure 3. The characteristics of sideward compression of the fourth internode

5. Model calibration and variation

Thanks to the randomization during the bond formations, different bond strength distributions come about in different simulations despite the same set of input model parameters. Consequently, in the beginning of our study the effect of the coefficients of variation on the model calibration was analysed.

When the coefficient of variation value was 0.2; nine simulations were conducted with the same set of input model parameters: three simulations of three-point bending test, sideward compression and dynamic cutting, respectively. After the simulations the characteristics of three-point bending, sideward compression and the results of dynamic cutting work were compared.

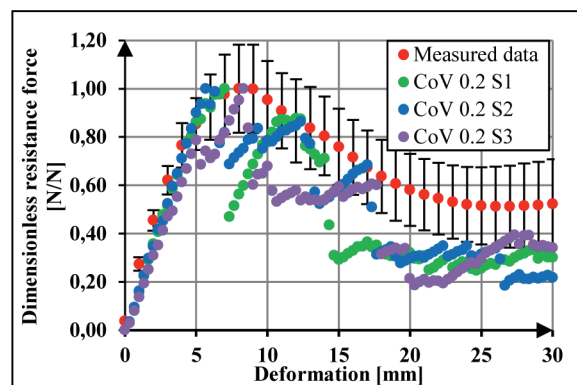


Figure 4. Simulated characteristics of three-point bending test with different distribution of bond strengths

In the course of three-point bending simulations, all three characteristics (CoV 0.2 S1; CoV 0.2 S2; CoV 0.2 S3) coincide very-well with the linear stage of the measured curve. In the middle section of the simulation process, all the simulated diagrams show sharp changes, but at the right end of the chart all of them show a nearly constant resistance force. (Figure 4.)

Based on these results, it could be declared that on the simulated characteristics of the three-point bending test significant differences could not be observed despite the different distribution of the bond strengths.

In case of the modelling sideward compression two characteristics, the CoV 0.2 S1 and the CoV 0.2 S2, provided nearly the same results. After the beginning section of the curve, both of them have two sharp drops between 10% and 25% deflections and after 25% deflection the resistance force is close to zero to 55% deflection. After that, both of them have an ascending section until the end of the simulation. The characteristic of CoV 0.2 S2 differs from the mentioned characteristics only in the beginning stage because it has one big drop, about 20% deflection, instead of two smaller ones. (Figure 5.)

Based on these results, it could be declared that on the simulated characteristics of sideward compression test significant differences could not be observed despite the different distribution of the bond strengths.

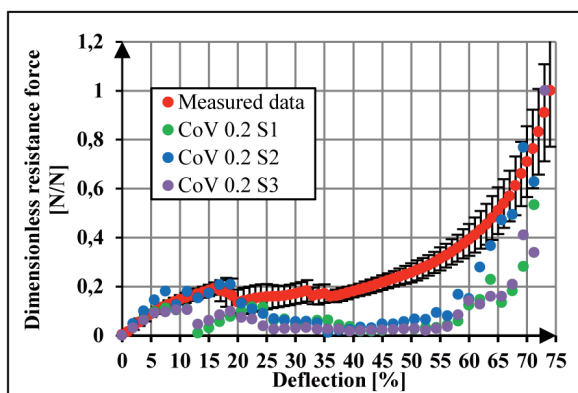


Figure 5. Simulated characteristics of sideward compression test with different distribution of bond strengths

During the comparison of simulations of dynamic cutting, only the value of dynamic cutting work could be compared.

Based on the results, it is clear that there are no significant differences among the results of simulated dynamic cutting works despite the different distribution of the bond strengths. (Figure 6.)

The simulation results clearly demonstrate that there are no significant differences among the

simulated results in cases of different distributions of bond strengths.

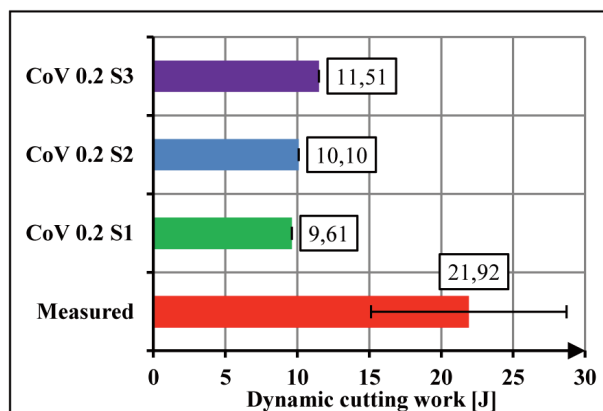


Figure 6. Simulated results of dynamic cutting test with different distribution of bond strengths

6. Quantitative results

The model was evaluated with quantitative and qualitative methods. During the quantitative method the real measure diagrams and results, from the three-point bending, sideward compression and dynamic cutting were compared with the simulation diagrams and results.

During the comparison of quantitative simulation results of three-point bending and sideward comparison the curve with best fit and smoother characteristic was searched for and naturally, through the characteristics the right CoV was searched for as well.

Based on the simulated characteristics of the three-point bending test, the following observations can be established:

- characteristics from CoV 0.0 and 0.2 present a very unsmooth curve and a very inaccurate fit except the linear stage of the curves (Figure 7.);

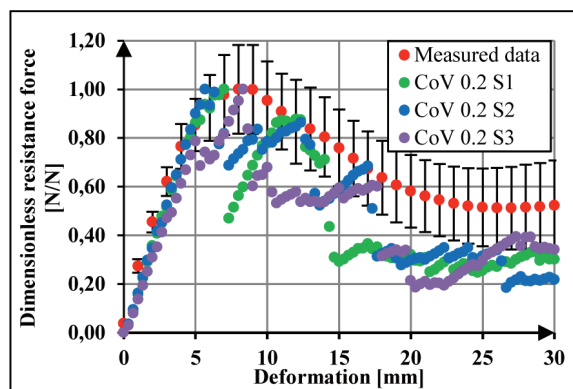


Figure 7. Simulated characteristics of three-point bending test from CoV 0.0 and 0.2

- characteristic from CoV 0.4 shows smaller drops and the most accurate fit with the measured data (Figure 8.);

–characteristic from CoV 0.6 presents a curve with smaller drops and high inaccuracy in its middle stage (Figure 8.);

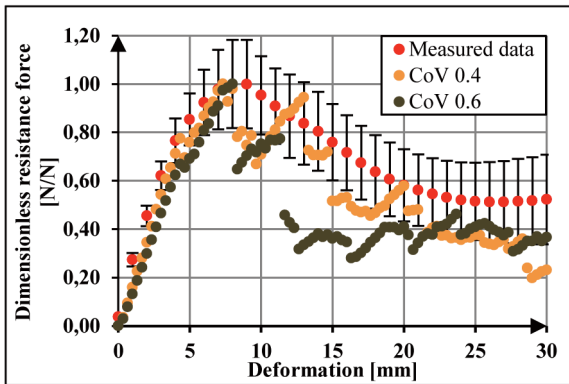


Figure 8. Simulated characteristics of three-point bending test from CoV 0.4 and 0.6

–characteristics from CoV 0.8 and 1.0 shows one or two recordable drops only and has an acceptable accuracy in all its stages (Figure 9.).

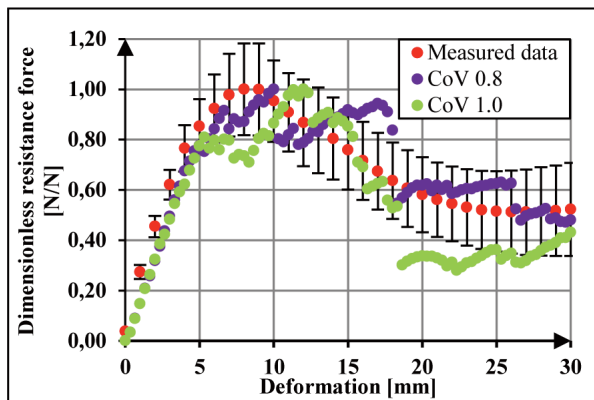


Figure 9. Simulated characteristics of three-point bending test from CoV 0.8 and 1.0

Based on the simulated characteristics of the sideward compression test, the following observations can be established:

–characteristics from CoV 0.0 and 0.2 present a very unsmooth and inaccurate curve (Figure 10.);

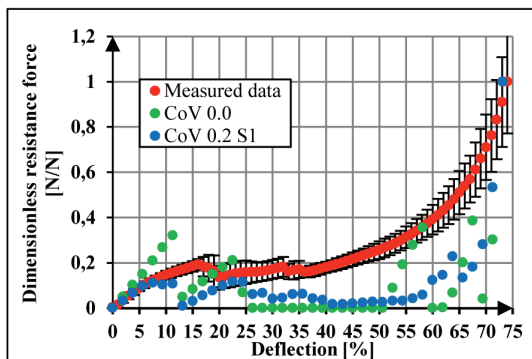


Figure 10. Simulated characteristics of sideward compression test from CoV 0.0 and 0.2

–characteristics from CoV 0.4 and 0.6 show smoother curves and they approach the measured data from below (Figure 11.);

–characteristics from CoV 0.8 and 1.0 present the smoothest and the best fit with the measured chart (Figure 12.).

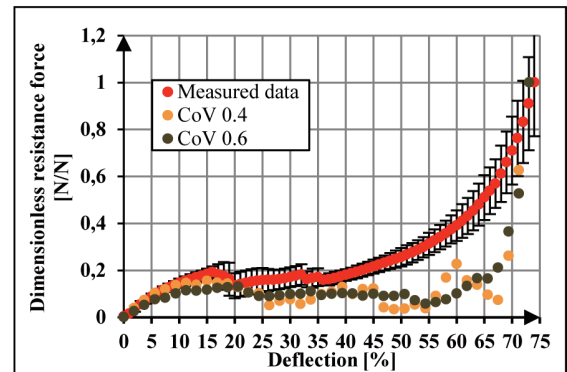


Figure 11. Simulated characteristics of sideward compression test from CoV 0.4 and 0.6

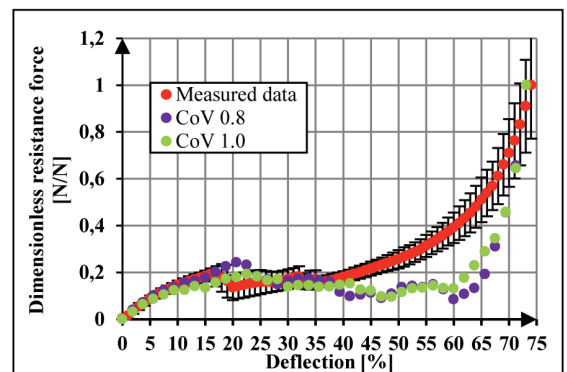


Figure 12. Simulated characteristics of sideward compression test from CoV 0.8 and 1.0

During the comparison of quantitative simulation results of dynamic cutting the most accurate result was searched for and naturally, through this result the right CoV was searched for as well.

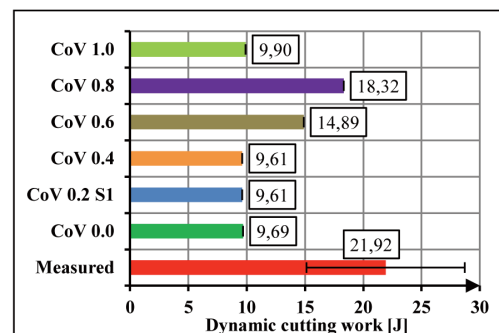


Figure 13. Simulated results of dynamic cutting test from CoV 0.0 - 1.0

Based on the simulated results of the dynamic cutting test, the following observations can be established:

- results from CoV 0.0; 0.2; 0.4 and 1.0 are practically the same with more than 50% inaccuracy (Figure 13.);
- result from CoV 0.6 is near to the lower limit of the measured dynamic cutting work (Figure 13.);
- result from CoV 0.8 is the only one that is situated between the limits of the measured dynamic cutting work (Figure 13.).

To sum up this chapter, the simulation characteristics and results from CoV 0.8 presented the best fit with the measured characteristics and results.

7. Qualitative results

During the qualitative evaluation cross-section deformations, crashes, breaks of the model were compared with the observed experiences of the real specimens.

Unfortunately, in most cases there were no noticeable differences among the qualitative results from different CoVs. From this reason in the following chapter the qualitative results from CoV 0.0 and 0.8 will be compared because simulation with CoV 0.8 provided the most accurate quantitative results.

In course of the qualitative evaluation of simulation results of three-point bending test, the shape of the modelled sample with the real specimen at the point of maximum deformation and the residual deformation of modelled sample with the real specimen was compared.

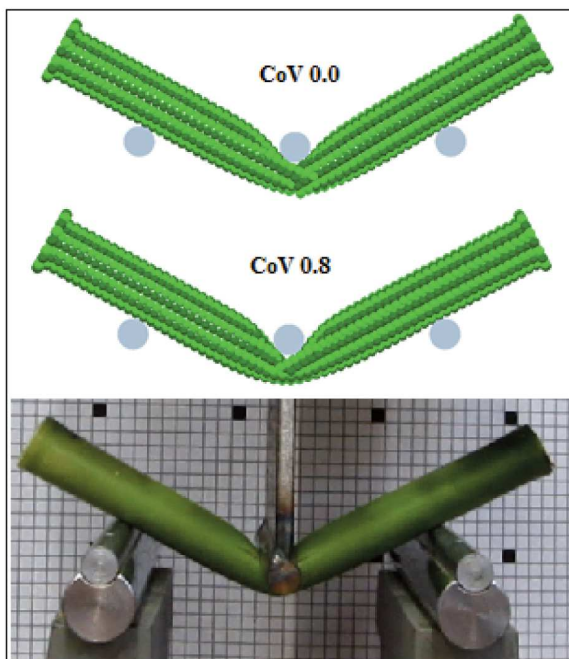


Figure 14. Simulated and real shape of specimens at the point of maximum deformation during the three-point bending test

Based on the observations during the measure, the following statements can be formed for the simulated specimens at point of maximum deformation:

- in all cases, the bended cross-sections of the modelled specimens were crashed under the loading anvil just as the real specimen (Figure 14.);
- in all cases, the bended shapes of the modelled specimens were near the same as the real specimen (Figure 14.).

Based on the observations during the measure, the following statements could be formed for the residual deformations of the simulated specimens after the process of three-point bending:

- the bended cross-section of the modelled specimen with CoV 0.0 shows less residual crash than the modelled specimen with CoV 0.8, but none of them present such a large buckle in the bending zone as the real specimen (Figure 15.);
- the residual shape of the specimen with CoV 0.0 was fully straight, in turn, the residual shape of the specimen with CoV 0.8 bended a little back (thanks to the more extended crashed zone) after the simulated bending process (Figure 15.).

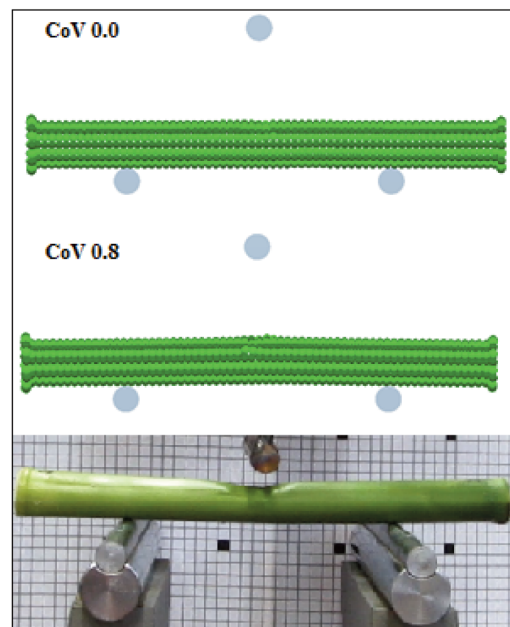


Figure 15. Simulated and real residual shape of specimens in the end of the three-point bending test

In the case of the qualitative evaluation of the sideward compression test the deformations and the damages of the cross-section were analysed.

The following statements can be formulated with the comparison of the models:

- in the first stage, the initial shape of the specimens can be observed (Figure 16.);
- in the second stage, elastic deformation took place until the first break appeared in vertical direction,

the model with CoV 0.0 could mimic the real specimen better (Figure 16.);

- in the third stage, another break appeared in horizontal direction, the vertical and the horizontal breaks could be observed clearly in the model with CoV 0.0, in turn, the breaks could not be realized in the model with CoV 0.8 (Figure 16.);
- in the fourth stage, that is the end of the compression process, the model with CoV 0.8 could better mimic the state of the real specimen (Figure 16.);

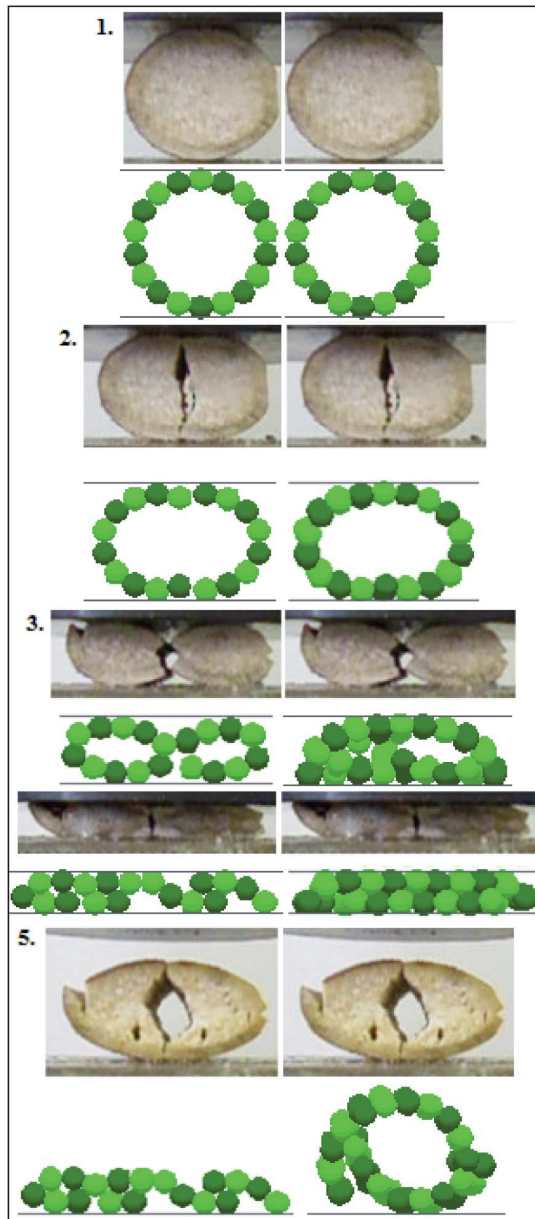


Figure 16. Simulated and real deformations and crashes of specimens during the sideward compression test, CoV 0.0 on the left side, CoV 0.8 on the right side

- in the last stage, compression clamps returned to the starting point and an elastic deformation was conducted in the real and in the model with CoV

0.8 as well, in turn, the model with CoV 0.0 showed only a minimal elastic deformation. (Figure. 16.)

During the qualitative evaluation of the dynamic cutting test the surface of cut was analysed.

The following statements can be formulated with the comparison of the models and the real specimen:

- in the models the cutting knife broke out the bottom part of the specimens, in turn, on the real specimen this phenomena was not observed (Figure 17.);
- in the model with CoV 0.0 the cutting trace has a form of “L”; in the other model it is straight aside from some fibres; the real sample had a fully straight surface of cut with some fibres as well, so from this point of view the model with CoV 0.8 mimics better the behaviour of the real specimen (Figure 17.).

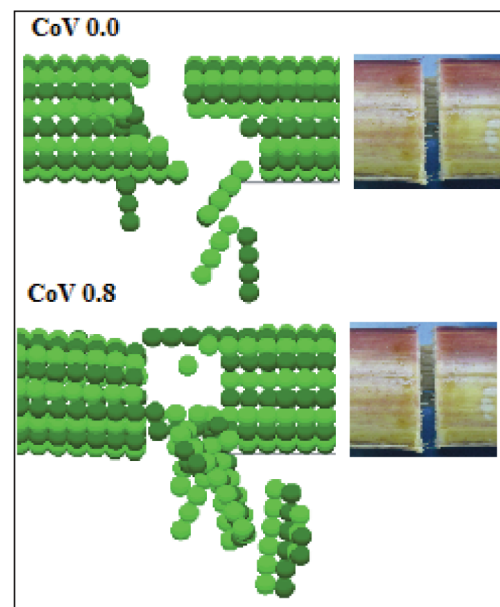


Figure 17. Simulated and real surfaces of dynamic cutting test

8. Conclusion

In our study the effect of coefficients of variation of the Timoshenko-Beam-Bond-Model was investigated in connection with discrete element modelling of fibrous agricultural materials.

After laboratorial three-point bending, sideward compression and dynamic cutting tests the necessary characteristics and results were calculated for the discrete element model.

During the model formation a hollow geometrical structure with 18 particles was chosen for the study, based on our previous research [7].

The DEM models of three-point bending, sideward compression and dynamic cutting were simulated with 0.0; 0.2; 0.4; 0.6; 0.8 and 1.0 coefficients of variation.

Based on the quantitative and qualitative evaluation of the models, the following conclusions can be formulated:

- during the calibration, there are no significant differences among the simulated results in case of different distributions of bond strengths;
- during the quantitative evaluation of all the simulated laboratorial tests, the simulation results from CoV 0.8 provided the smoothest curves and the most accurate results;
- during the qualitative evaluation of the simulated three-point bending test, significant differences between the simulation results from CoV 0.0 and 0.8 were not observed;
- during the qualitative evaluation of the simulated sideward compression test, in the first three investigated stages the simulation results from CoV 0.0 presented better coincidence with the real specimen, in turn, within the last two investigated stages the simulation results from CoV 0.8 mimics were better regarding the behaviour of real specimen;
- during the qualitative evaluation of the dynamic cutting test, the simulation results from CoV 0.8 mimics were better considering the surface of cut of the real specimen.

To sum up, the results of the study clearly demonstrate that the coefficient of variation could be advantageously utilised during the simulations of agricultural materials.

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