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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

# A discrete element model (DEM) for predicting apple damage during handling

Otto C. Scheffler [a], Corné J. Coetzee [a,*], Umezuruike L. Opara [b,c]

[a] Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa
[b] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Horticultural Sciences, Faculty of AgriSciences, Stellenbosch University, South Africa
[c] Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Department of Food Science, Faculty of AgriSciences, Stellenbosch University, South Africa

ARTICLE INFO

*Article history:*
Received 24 January 2018
Received in revised form
11 May 2018
Accepted 30 May 2018

*Keywords:*
Discrete element method
Apples
Pendulum device
Bruise damage
Overlapping bruises
Multiple impacts

Apples can suffer from significant mechanical injury in the form of bruise damage. The discrete element method (DEM) allows for individual particle contacts and the dynamic behaviour of a group of particles to be studied. Successfully applying this method to apples allows for future investigations into postharvest mechanical damage to be performed on a range of fruit and vegetables. A contact model that closely replicated the visco-elastic nature of apples was used and the material properties were successfully determined using a pendulum device. Bruise damage models (in the form of bruise volume, bruise area and bruise depth) were coupled to the peak impact forces available through DEM. Bruise formations resulting from multiple impacts and variable time durations between impacts were studied. A detailed multi-sphere particle shape representation along with a realistic contact point loading scheme was implemented. Overlapping bruises were studied and accounted for on a post process level. The resulting DEM model was successfully validated and extended to include run-time bruise visualisation. Qualitatively the model accurately predicted the dynamic bulk behaviour of the apples. Quantitatively, the model succeeded in predicting the contact forces experienced by apples to within 11%. The model predicted the mean bruise damage of a single apple for realistic situations within an accuracy of 47% in terms of mean bruise volume, 35% for bruise area and 30% for bruise depth.



## 1. Introduction

World trade in fruit accounts for approximately 12% of the world's total annual agricultural production (Vigneault, Thompson, Wu, Hui, & LeBlanc, 2009). The postharvest handling of produce does however still introduce mechanical damage of which bruising damage is considered to be the principal form (Van Zeebroeck et al., 2007). Decreasing the amount of postharvest mechanical damage can improve profits for fruit growers and assist in food security.

* Corresponding author.
E-mail address: ccoetzee@sun.ac.za (C.J. Coetzee).
https://doi.org/10.1016/j.biosystemseng.2018.05.015
1537-5110/

**Nomenclature**

| | |
|---|---|
| $c_n$ | Normal Damping Constant, s |
| $c_n^*$ | Effective Normal Damping Constant, s |
| $d_b$ | Full Depth of Bruise, mm |
| $d_t$ | Depth from Fruit Surface to Top of Bruise, mm |
| $E$ | Apparent Elastic Modulus, MPa |
| $E^*$ | Equivalent Elastic Modulus, MPa |
| $E_{1,2}$ | Elastic Moduli of the Two Impacting Bodies, MPa |
| $F_n$ | Normal Contact Force, N |
| $F_t$ | Tangential Contact Force, N |
| $G$ | Apparent Shear Modulus, MPa |
| $G^*$ | Equivalent Shear Modulus, MPa |
| $G_{1,2}$ | Shear Moduli of Impacting Spheres, MPa |
| $k_n$ | Normal Elastic Constant, N $m^{-3/2}$ |
| $k_t$ | Tangential Elastic Constant, N $m^{-1}$ |
| $R^*$ | Effective Radius of Curvature, m |
| $R_{1,2}$ | Radii of the Impacting Spheres, m |
| $V$ | Bruise Volume, $mm^3$ |
| $V_i$ | Initial Impact Velocity, m $s^{-1}$ |
| $w_{1,2}$ | Bruise Widths across Major & Minor Axis, mm |
| $\overline{w}$ | Mean Bruise Width, mm |
| $\delta_n$ | Normal Deformation, m |
| $\dot{\delta}_n$ | Normal Deformation Rate, m $s^{-1}$ |
| $\delta_t$ | Tangential Deformation, m |
| $\mu_d$ | Dynamic Friction Coefficient |
| $\nu$ | Poisson's Ratio |
| $\upsilon^*$ | Effective Poisson's Ratio of Impacting Bodies |
| $\upsilon_{1,2}$ | Poisson's Ratio of Two Impacting Bodies |

*Abbreviations*

| | |
|---|---|
| BA | Bruise Area |
| BD | Bruise Depth |
| BV | Bruise Volume |
| CHMI | Constant-Height Multiple-Impacts |
| DEM | Discrete Element Modelling |
| IHMI | Increasing-Height Multiple-Impact |
| KK | Kuwabara and Kono Model |
| PF | Peak Force |
| RH | Relative Humidity |
| SD | Standard Deviation |
| VEP | Visco-Elastoplastic Pressure-Based Model |

One of the most widely cultivated of all fruit is apples. They particularly appeal to customers due to a relatively long postharvest life, distinct flavour and their nutritional value. Mechanical damage does however accelerate the processes that lead to spoilage and a loss in nutritional value (Opara & Pathare, 2014).

The use of the discrete element method (DEM) is increasingly moving outside of its original application – particularly the agricultural industry. This is due to the method's versatility as a numerical technique that simulates the dynamic behaviour of discrete particles (Tijskens, Ramon, & De Baerdemarker, 2003). DEM thus provides an excellent means for investigating various stages of the postharvest handling chain.

### 1.1. *Objectives*

A bruise prediction model was developed and implemented in DEM, using the commercial DEM package, *PFC3D* from Itasca Consulting Group, Inc. Minneapolis, MN, USA (PFC3D, 2016). The objectives are:

1. Design of an experimental set-up to determine the contact model parameter values and to quantify bruise damage.
2. The development of a bruise prediction model in the DEM environment, including multiple impacts and bruise overlap.
3. Validation of the developed DEM model through physical and numerical simulation.

### 1.2. *Previous studies using DEM*

The only significant prior investigation into the use of DEM for the prediction of apple damage (and other fruit and vegetables in general) is that of Van Zeebroeck (2005). However, the study by Van Zeebroeck only made use of simple spheres to represent the apples. Using a more representative shape will in general lead to an improvement in the modelled dynamics of the particles at both a single particle level, and at a bulk level (Höhner, Wirtz, & Scherer, 2013). Compared to spherical particles, a much-improved particle shape representation is possible with the use of clumps (i.e. multi-sphere particles) in *PFC3D*. The use of clumps is efficient since the fast and robust algorithms established for spherical particle contact detection can be readily used (Lu, Third, & Müller, 2015).

A disadvantage of clumps is that the size of the comprising spheres (called pebbles in *PFC3D*) is imposed by the particle shape and volume and if the radii of these spheres are used to define the local curvature, it might not be accurate if it is used in the contact force model. Another disadvantage is that multiple simultaneous contacts between particles might occur due to the large number of comprising spheres. Kruggel-Emden, Rickelt, Wirtz, and Scherer (2008) and Höhner, Wirtz, Kruggel-Emden, and Scherer (2011) showed that the contact behaviour of a clump dropped onto a wall with multiple contacts was different from that of a spherical particle with the same properties and a single contact.

The disadvantages of spheres and clumps motivated Smeets et al. (2014) to make use of faceted particles represented by triangulated surface meshes to calculate contact forces by integrating the Hertz pressure over the contact area between two rounded shapes. This method obtained an improved shape representation and each facet was associated with a local radius of curvature. The results converged to that of the Hertz contact upon mesh refinement and good results were achieved by compressing a single pear-shaped particle using a rubber-like material. To demonstrate the applicability of the approach, the bulk behaviour of a number of spheres, pears and “gummy bear-shaped” particles was modelled in a shaking box under gravity loading. However, these results were not validated, and bruise damage not modelled. A direct comparison of faceted particles and clumps to predict fruit