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Mathematical modelling of mechanical damage to tomato fruits

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ABSTRACT

A 3D virtual model was developed of compression of a whole tomato fruit to 10% deformation. This included a 1/4 geometrical model of the fruit, an up-plate probe and a bottom-plate base. The fruit model included the cuticle, a pericarp frame and septal tissues, and a nearly incompressible surface-based water-filled locule. The cuticle was meshed into quadrilateral membrane elements whilst the pericarp frame and septal tissues were meshed into hexahedral brick elements with an edge size of 0.4 mm, approximating cells in the fruit. Assuming elastic-plastic constitutive behaviour and von Mises yield criterion for the cuticle and cell elements, the cuticle did not yield during simulation whilst the cells that had yielded were mainly distributed inside the pericarp tissues and near the stem-blossom axis. The vertical compression resulted in a main local deformation response in the contact area and a minor equatorial structural response. The internal damage volume increased from 0 to 6672 mm^3 when a vertical force from 0 to 6.5 N was applied and the corresponding deformation of the model fruit ranged from 0 to 10%. The relationship between internal damage volume and percentage deformation (or compression force) followed the 4-parameter sigmoidal model. Tiny internal damage of fruit at the microscale began from the start of the compression but was not easily observed when the fruit deformation was <3%. This mathematical modelling method to find the internal damage volume might also be used for other fruits.

1. Introduction

Tomato fruits are an important component of many human diets and therefore their quality is also important. Unfortunately, fresh fruit is very susceptible to mechanical damage during harvesting, packaging and transport, and the quality can be substantially reduced by poor handling. Internal mechanical damage may lead to accelerated rot of a whole fruit. Many fruits with apparently little damage during harvesting are subsequent discarded and losses in the harvest-consumption system might be as high as 51% (FAO, 2003), which is a serious food safety and economic issue.

Food security and agricultural efficiency require that urgent action is taken to minimize such losses. Previous research only relates to surface damage or bruising, assessment of which typically requires storage for several days and then a sensory (touch/visual) evaluation (Idah and Yisa, 2007; Van Linden et al., 2006a,b; Li, 2013), because browning of damaged tomato tissues is not obvious (unlike apple, for example). There are other methods to evaluate the degree of mechanical damage to tomatoes, for example by evaluating bruise susceptibility using related impact mechanical parameters: absorbed energy (Van Zeebroeck et al., 2007a; Babarinsa and Ige, 2012) or peak contact force (Desmet et al., 2002) on impact; or by predicting the internal mechanical damage distribution of fruits by finite element simulation (Kabas et al., 2008; Li et al., 2013). Additionally, there is some research on calculation of the volume of mechanical damage of young coconut (Kitthawee et al., 2011), apple (Van Zeebroeck et al., 2007b; Zarifneshat et al., 2010), peach (Ahmadi et al., 2010) and pear (Maness et al., 1992) fruits by visible anatomical measurement, but this is not suitable for tomato fruits because of the similar colour of damaged and undamaged tissues.

To sum up, a quantitative assessment of internal damage of tomatoes is still far from being realized. As a result it is difficult to investigate accurately the effect on internal damage of factors such as the application of external forces during harvesting, packaging and transport; and it is unachievable for agro-industry producers, especially in fruit packaging factories, to sort handled tomato fruits into different damage grades for immediate or optional handling (i.e. not storable or storable) based on internal damage severity.

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Furthermore, tomatoes are hierarchically structured at the macro-scale, consisting of different types of tissue at the meso-scale, each of which is a highly structured arrangement of cells at the micro-scale (Li and Thomas, 2015, 2016). Mechanical damage to fruit, manifested at the macro-scale, is caused by failure of cells at the micro-scale (Li and Thomas, 2014). The current finite element models of tomato fruits cannot relate the behaviour of the macroscopic fruit to that of the microscopic cells. Therefore, the objective of this study was to develop a 3D finite element model relating macro-fruit to micro-cells, to allow internal and surface mechanical damage caused by external forces to be simulated at the cellular level and to investigate quantitatively the effect of fruit deformation/external forces on the extent (volume) and nature of the damage. It was expected that the damage volume of tomato fruit could be calculated by in depth consideration of the simulation results. This is the first time a method was attempted to assess quantitatively the mechanical damage of tomato fruits based on the results of FEA.

2. Material and methods

2.1. Virtual modelling of whole fruit compression system

In order to simulate the mechanical response of a tomato fruit in compression up to 10% deformation in a Texture analyser (Fig. 1a), a 3D geometrical model of a whole fruit compression system (Fig. 1b) was developed, which included a 1/4 geometrical model of fruit and an up-plate and a bottom-plate. The fruit model included three parts: cuticle, pericarp frame and septal tissues, and a nearly incompressible surface-based water-filled locule. The definition of symmetry boundary conditions and the geometrical modelling method were the same as with the previous model developed by Li and Wang (2016). The 10 μm thickness of cuticle was bonded to the outer surface of a frame of pericarp tissue by a "skin reinforcement" technology in Abaqus 6.14/CAE (Dassault Systemes Simulia Corp., USA). The up- and bottom-plate in the model respective referred to the simplified up-plate compression probe and bottom-plate metal base of the Texture analyser (Fig. 1a) and were associated with respective reference points whose motion governed the motion of the rigid surface. The locule of the tomato fruit was modeled into a surface-based water-filled cavity. The contact surface between water and cavity, namely the boundary surface of the fluid locule, was defined by element-based surface with normals pointing to the inside of the locule. A reference point was associated with the water inside the locule to calculate the changes of volume and pressure of water inside the locule during simulation of the whole fruit compression. The contact between the fruit and the up-/bottom-plate was defined as a hard contact pressure-overclosure relationship and followed a Coulomb friction model. These methods are described more fully in the manual of Abaqus 6.14/CAE.

In the FE model of fruit (Fig. 1c), the cuticle was meshed into 4-node M3D4R membrane elements and the pericarp frame and septal tissues were meshed into 8-node hexahedral C3D8IH cell elements with the edge size of 0.4 mm (approximating the average size of tomato cells as described by Li et al. (2016)) so that the macroscopic fruit could be linked to microscopic cells. In the outer layer of the model, the M3D4R cuticle elements shared 4 nodes (common nodes) with the underlying 8-node C3D8IH cell elements (Fig. 1d). Inside the pericarp frame and septal tissues,

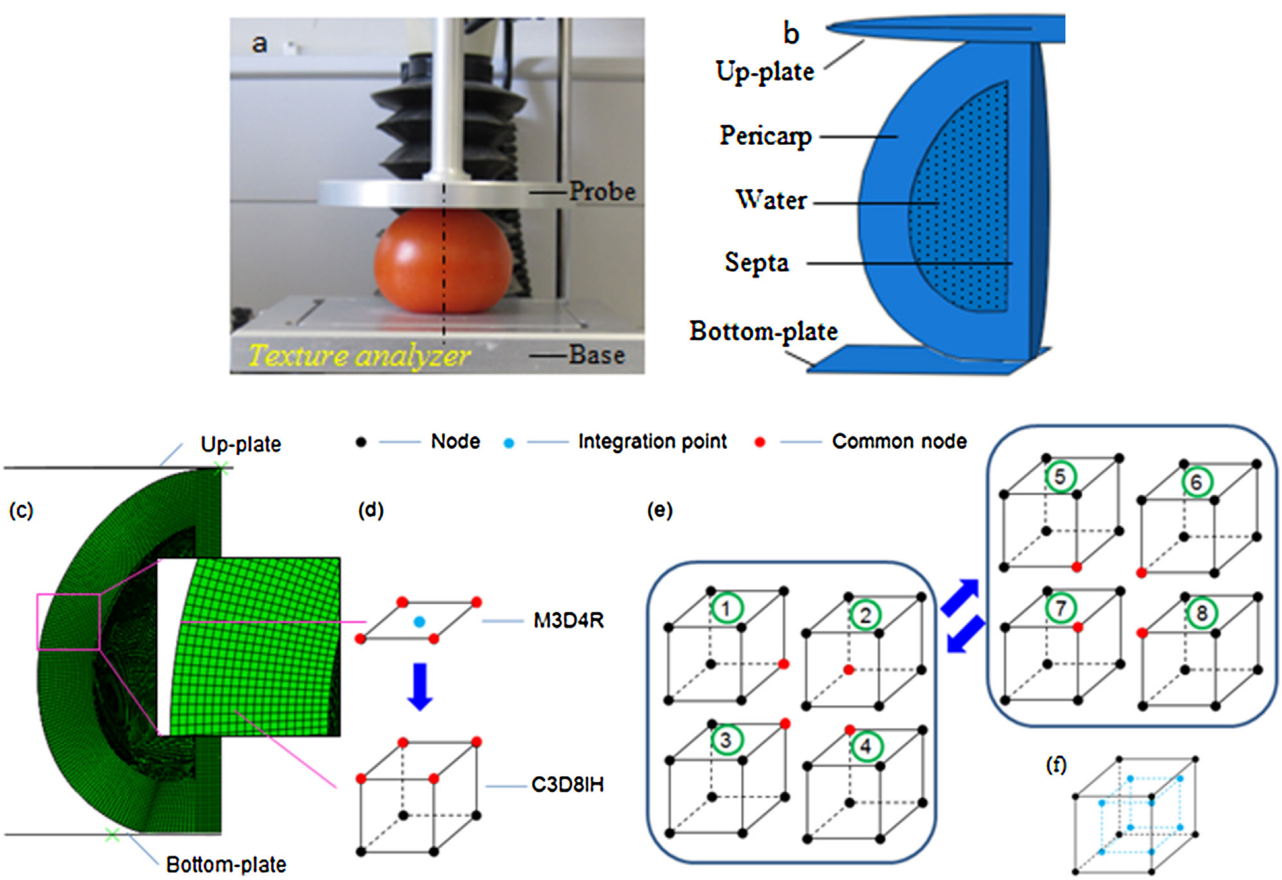

Fig 1. Whole fruit compression test and 3D virtual FE model. (a) Compression test of a whole fruit (diameter × height: 51 × 50 mm) using TA-Xi2 Texture analyser (Li and Wang, 2016); (b) 3D geometrical model of whole fruit compression system (Li and Wang, 2016); (c) Finite element model; (d) Connecting case of M3D4R and C3D8IH elements in the surface of fruit model; (e) Connecting case of C3D8IH elements inside the fruit model; (f) 8-integration point C3D8IH element.