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A multiscale finite element model for mechanical response of tomato fruits

Zhiguo Li[a,b,*], Yuqing Wang[b]

[a] School of Chemical Engineering, University of Birmingham, B15 2TT Birmingham, UK
[b] School of Mechanical and Power Engineering, Henan Polytechnic University, 454003 Jiaozuo, China

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ABSTRACT

A multiscale finite element model, which included three parts: cuticle, pericarp frame and septal tissues, and a nearly incompressible surface-based fluid-filled locule, was developed to simulate the compressive mechanical response of a tomato fruit. In the model, the cuticle was bonded to the outer surface of a frame of pericarp tissue; the tissue frame was meshed into hexahedral tissue (cell aggregate) elements so that the macroscopic fruit could be linked to microscopic cell aggregates. The contact between the fruit and compression probe was defined as a hard contact pressure-overclosure relationship and followed a Coulomb friction model. Assuming elastic-plastic constitutive behavior for the cuticle and the cell aggregate elements and water-like fluid in the locule, the simulated compression force mainly depended on the elastic modulus of the cell aggregates. Increasing the modulus of the cell and cuticle resulted in coupling effects between the fruit tissue structure and the fluid inside the locule that gradually intensified with increasing percentage deformation. Using previously determined material parameters of pericarp cells and cuticle, the model was found to be remarkably capable of reproducing the macroscopic force-deformation behavior of a tomato fruit in compression up to 10% deformation. The model can be used to predict the mechanics of the cuticle if the mechanics of the pericarp are known, or *vice versa*. In this way, the elastic modulus, yield strength and Poisson's ratio of *Delyca* tomato cuticle at 5 mm/s loading speed was eventually predicted to be 800 MPa, 50 MPa and 0.49 respectively. The multiscale modeling method might also be used for other fruits.

1. Introduction

Production of tomatoes in Europe in 2014 was about 16.8 million tonnes, 9th in terms of agricultural production value (latest data, http://ec.europa.eu/eurostat/). Unfortunately, fresh fruit is very susceptible to internal mechanical damage during harvesting, packaging and transport, and the quality can be substantially reduced by poor handling. Internal damage may lead to accelerated rot of a whole fruit (Li and Thomas, 2014, 2016), which is a food safety and economic issue. Thus, understanding the internal mechanical deformation or damage of tomatoes caused by an external force is an important issue.

An emerging approach is to estimate the internal mechanical response (e.g. damage) of tomatoes using finite element (FE) models. Previous studies relating the application of FE models applications to postharvest estimation of internal mechanical behaviors of fruits and vegetables are abundant. Work concerning finite element modelling of fruits has modelled them as multi-tissue systems relating macro- to meso-mechanics (Dintwa et al., 2008; Hernández and Bellés, 2007; Li et al., 2013; Sadrnia et al., 2008) or has related meso- to micro-mechanics (Ghysels et al., 2009; Van Liedekerke et al., 2010) or has sought correlations between single cell mechanics and those of its components, usually the cell wall (Dintwa et al., 2011 Wu and Pitts, 1999). Additionally, several two- and three-dimensional multiscale models have been developed to predict the viscoelastic deformation of, water loss from, and gas exchange in fruit tissues (Ho et al., 2011, 2013; Aregawi et al., 2014).

Tomatoes are hierarchically structured at the macroscale, which can be regarded as consisting of cuticle and cells at the microscale and several fluid-filled locules. Mechanical damage to fruit, manifested at the macro scale, is caused by failure of single cells and cuticle at the microscale. To understand this requires 3D multiscale FE model linking the macroscopic (whole fruit or organ) scale through the mesoscopic (tissue) scale to the microscopic

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[*] Corresponding author at: School of Chemical Engineering, University of Birmingham, B15 2TT Birmingham, UK.
E-mail address: lizhiguo0821@163.com (Z. Li).

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(cuticle and cell) scale, in order to simulate the mechanical compression behaviors of whole fruits. However, current virtual tomato fruit, tissue or cell models cannot do this because a tomato fruit has many single cells, and the computational task of solving a fruit model based on single cells is impractical. Additionally, the effect of fluid inside the locules on the mechanical response of the whole fruit has also not been investigated so far. An alternative method is to develop a finite element model in which the pericarp tissues are considered to consist of notional aggregates of cells, namely tiny blocks of several adherent cells. The cuticle is considered separately. In this approach, the cell aggregates are represented by corresponding elements in finite element modeling and are considered to have the mechanical properties of single cells, as previously determined by Li et al. (2016). Therefore, the objective of this study was to develop such a model in order to simulate the compressive mechanical response of tomato fruits, using data from Li et al. (2011) to approximate the anatomical characteristics of a real tomato fruit, Li et al. (2016) for single cell mechanical properties and Espana et al. (2014) for cuticle mechanical properties.

2. Material and methods

2.1. Experimental mechanical data of whole fruit

Two package of fresh-market vine *Delyca* (BioSabor company, Spain) tomatoes (10 samples) was bought from a supermarket for this study. Whole fruit mechanical data of tomatoes was determined by vertical compression tests along the blossom-stem axis direction at 5 mm/s. Each fruit was compressed to 10% deformation between the metal base plate and the moving flat-end probe of a TA-Xi2 Texture analyzer (Fig. 1a and b). Force-deformation data were recorded in real time during loading, and then force-displacement data of 5 tomato samples at 20 compression levels with a step increment of 0.5% deformation were averaged for validating the multi-scale finite element model of whole fruit by simulating compression tests described in Section 2.2.4.

2.2. Multiscale FE model

2.2.1. Geometrical modeling

Firstly, a two-locule tomato sample (diameter × height: 51 × 50 mm) was cut in half with a sharp knife along the blossom-stem axis and photographs of the section were captured using a digital camera (Canon 95IS, Photo size: 3648 × 2736 pixels), as shown in Fig. 1b. Coordinate values of 30 key points on the left external boundary line of the fruit pericarp section were extracted by image processing, and then the external boundary line of the pericarp frame was created using these coordinate data by the operation command "create spline curve". Because the pericarp and septal tissues in a fruit are not of uniform thickness, 10 points in each tissue were chosen randomly for thickness measurement. The average thickness of pericarp and septa of *Delyca* tomato fruits, namely 7.5 mm and 7 mm respectively, were used to create the geometrical frame of the pericarp and septal tissues. To reduce the number of FE computations based on the structural characteristics of a two-locule tomato fruit, only a quarter of the fruit was geometrical modeled by a series of operation commands such as revolution and extrusion in Abaqus 6.14/CAE (Dassault Systemes Simulia Corp., USA). Subsequently, a "skin reinforcement" technology in Abaqus/CAE was used to define a cuticle with 10 μm thickness (measured by SEM, data not published) that is bonded to the outer surface of the frame of pericarp tissue. For simplicity, the upper-plate compression probe and bottom-plate metal base of the Texture analyzer (Section 2.1) were geometrically modeled as being 3D analytically rigid and were associated with respective reference points whose motion governs the motion of the rigid surface. Finally, a 3D compression simulation system (Fig. 1c), which included a virtual tissue frame model of 1/4 tomato fruit, an up-plate probe and a bottom-plate base, was developed.

2.2.2. Interaction definition

2.2.2.1. Hydraulic fluid model. The locule of the tomato fruit was modeled into a surface-based fluid-filled cavity. The contact surfaces between fluid and cavity, namely the boundary surfaces of the fluid locule, were defined by element-based surfaces with normals pointing to the inside of the locule. The surface definition provided the coupling between the deformation of the fluid-filled locule structure and the pressure exerted by the contained fluid on the cavity boundary of the locule structure. A reference point was associated with the fluid inside the locule to calculate the changes of volume and pressure of fluid inside the locule during whole fruit simulation. The fluid inside the locule was defined by a hydraulic fluid model in Eq. (1), which followed some assumptions: (1) nearly incompressible; (2) had a linear pressure-volume relationship during compression; (3) the fluid density did not depend on its temperature; (4) initial gauge pressure was 0; and (5) with similar properties to water (density $\rho_f = 1$-1.07×10^3 kgm^{-3}; bulk modulus $E_f = 2 \times 10^3$ MPa) (Li et al., 2011; Dintwa et al., 2011). As the fluid inside the locule is nearly incompressible, there could be a big change in pressure even if the volume does not change very much. The use of gauge pressure is not relevant – it just means everything is measured against (above) atmospheric pressure and is appropriate if the pressure differences are being considered.

$$P_f = -E_f(V_p/V_0 - 1) = -E_f\left(\rho_0/\rho_p - 1\right) \tag{1}$$

where P_f–current gauge pressure of fluid, E_f –bulk modulus of fluid, V_0 –fluid volume at initial zero gauge pressure, V_p- fluid

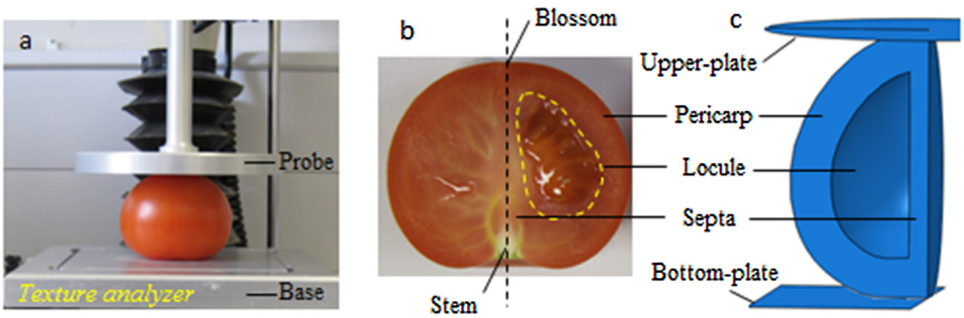

Fig. 1. Whole fruit compression test and multiscale geometrical modeling.