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Internal mechanical damage prediction in tomato compression using multiscale finite element models

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ABSTRACT

The mechanical damage of exocarp, mesocarp and locular gel tissues of three and four locular tomatoes subjected to an external compressive force were predicted using multiscale finite element models. The simulation factors consisted of three loading positions and five external forces. Results showed that the locular gel tissue would have mechanical damage prior to the mesocarp and exocarp tissues as force was applied to the fruit. Internal structural characteristics of the tomato had an obvious effect on the mechanical damage behavior of the tissues. The deformed displacement of the tissues was highest for four locular tomatoes compressed at a position midway between adjacent cross walls (P2) and was lowest for four locular tomatoes compressed from a position at the cross wall (P3) at the same external force. The simulated data confirmed the experimental results and were able to predict the internal mechanical damage of tomatoes.

1. Introduction

The tomato is an important fruit in people's diets. The tomato is a hierarchically and anatomically structured fruit, whose multiscale characteristics show organ (fruit) at the macro level and different types of tissues at the meso level, such as exocarp, mesocarp, endocarp and locular gel tissues. Internal tissues of the fruit subjected to an external force will have different degrees of deformation. Internal damage of the fruit occurs during mechanical handling as the applied external force exceeds a threshold for any tissue failure (Linden et al., 2006). However, the internal damage is not always immediately visible, but the fruit quality will rapidly deteriorate in a short period of time (Li et al., 2011a). Thus, understanding the internal mechanical damage of tomatoes caused by an external force is an important issue.

It is difficult to measure the internal stress distribution and damaged regions of tomatoes that are caused by applied compressive forces. Finite element methods can be utilized as an alternative solution for predicting tissue stresses (Miranda et al., 2008). Many previous studies have examined the prediction of stress distribution and damage levels in fruits and vegetables using the finite element method. Gao et al. (2008) developed a 2D finite element model (FEM) consisting of six elongated, two-force rods and predicted the relationship among applied external load, fruit deformation and skin stress (Gao et al., 2008). Kabas et al. (2008) simplified the tomato fruit into a nearly spherical solid with a single material and estimated the deformation behavior of cherry tomatoes upon drop crashing (Kabas et al., 2008). Li et al. (2011) proposed a new method for 3D parametric modeling based on the mass and height of the tomato fruit (Li et al., 2011). Wang et al. (2004) and Dintwa et al. (2011) developed a single tomato cell FEM that is treated as a liquid-filled sphere with a thin compressible wall and simulated the mechanical deformation of the single cell during a compression test (Dintwa et al., 2011; Wang et al., 2004). Van Liedekerke et al. (2010a) proposed a particle-based model to numerically study the mechanical impulse responses of these cells with subcellular detail (Van Liedekerke et al., 2010b). Van Liedekerke et al. (2010b) proposed a mesh-free particle method to simulate the micromechanics of both individual tomato cells and cell aggregates in response to external stresses (Van Liedekerke et al., 2010a). Additionally, researchers have investigated the 3D micro-structural modeling methods of fruits (Genard et al., 2007; Mebatsion et al., 2009) and the mechanical damage progression of other fruits, such as apples (Celik et al., 2011; Dintwa et al., 2008), sunflowers (Hernández and Bellés, 2007), and watermelons (Sadrnia et al., 2008), under external force by the finite element method.

To summarize, previous finite element models of the tomato fruit were developed based on continuum mechanics with a single material. These models are not in accordance with the anatomical characteristics of a tomato fruit. Thus, it is difficult to accurately

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unravel the relationship between the external loads applied to tomato fruits and the mechanical damage behavior of different types of tissues using existing finite element models. The novel multiscale finite element models of three and four locular tomato fruits were developed in this study. The objective is to investigate the mechanical damage of different types of tissues as external forces were applied to two different structural types of tomatoes.

2. Materials and methods

2.1. Experimental determination of multiscale mechanics

The tomato fruit can be considered a multibody system, which consists of exocarp, mesocarp and locular gel tissues, during modeling. The mechanical properties of different types of tissues in the tomato were taken from a previous study that used finite element analysis (Li et al., 2011b; 2012). The mechanical parameters of *Fenguan* 906 tomato tissues are shown in Table 1. Once the multiscale finite element models of the tomato fruit are created, it is necessary to validate them by the compression experimental tests of whole tomato fruits. The compression experimental data of whole tomatoes were taken from a previous study to use in the validation of models (Li et al., 2010).

2.2. Multiscale finite element modeling

2.2.1. 3D geometric modeling

Different tomato varieties have obvious differences in shape and size. The mesocarp thickness of the tomato varies from the blossom end to stem base, which is not monotonically increasing or decreasing (Fig. 1a). Thus, these tomato tissues cannot be modeled using regular geometric shapes, such as sphere, cuboid and ellipsoid. To create actual 3D geometric models of tomatoes, a *Fenguan* 906 tomato (Diameter × height: 61 × 52.5 mm) at the light red ripening stage was chosen for this research. After the fruit surface was manually cleaned and dried, the fruit was cut in half with a sharp knife along the stem–blossom axis and the middle of one fruit shoulder. We prepared an A4 paper on the desktop and set up a *XYZ* coordinate system at the center of the paper. The cutting plane of the fruit was tangent to the paper, and the blossom end was put on the origin *O* of the coordinate system. The external contour lines of exocarp and locular gel tissues on the right cutting plane were drawn with a pen on the paper, and some coordinate values of keypoints were then extracted from the drawn lines. The boundary line of the cutting plane of the locular gel tissue was created using the "Spline" option for generating geometric curves according to the coordinate values of extracted keypoints, and then, the geometric model of locular gel tissue in one locule was developed using the "areas" and "volumes" operation options in ANSYS. The modeling method was found to be suitable for irregular fruits and vegetables. It was assumed that the exocarp thickness was invariable, and the mesocarp tissue was closely linked to the exocarp and locular gel tissues. The determined thickness of the exocarp tissue was 0.3 mm. The geometric models of the exocarp and mesocarp tissues were also developed using a similar ANSYS operation procedure.

To reduce the number of FEA computations based on the structural characteristics of tomatoes, half of a three locular tomato was modeled for predicting the internal mechanical damage of fruit loaded from position 1 (P1) – locular tissue of the three locular tomato fruit (model 1, Fig. 1b2); a quarter of a four locular tomato was modeled for predicting the internal mechanical damage of the fruit loaded from position 2 (P2) – locular tissue of a four locular tomato (model 2, Fig. 1c2); and a quarter of a four locular tomato was modeled for predicting the internal mechanical damage of the fruit loaded from position 3 (P3) – cross wall tissue of the four locular tomato fruit (model 3, Fig. 1d2). The compression probe was simplified as a cuboid model with the dimensions (length × width × height) 40 × 45 × 3 mm (Fig. 1b2, c2 and d2).

2.2.2. Finite element modeling

2.2.2.1. Element type. The structural element SOLID95 was used for the exocarp tissue, and the structural element SOLID92 was used for the mesocarp and locular gel tissues. These two types of structural elements have plasticity, large deflection, and large strain capabilities and are well suited to model the curved boundaries and tolerate the irregular shapes without much loss of accuracy.

2.2.2.2. Material properties. One of the changing status nonlinear problems, or the rigid-to-flexible contact form between fruit and probe, took place as a probe compressed a tomato. Another geometric nonlinear problem, the large deformation of the tomato fruit structure, also occurred during compression. Thus, the changing statuses and geometric nonlinearities were considered in the nonlinear analysis of tomato compression in the research. The tomato tissues were regarded as linear elastic materials within the elastic deformation region and isotropic; their mechanical parameters were defined according to Table 1. The von Mises failure criterion, which was always used to estimate the yield behavior of materials (Atrens, 2006), was chosen to predict the damage behavior of different types of tomato tissues. This failure criterion was successfully used in the FEA of watermelon (Sadrnia et al., 2008), apple (Celik et al., 2011), and sunflower fruits (Hernández and Bellés, 2007).

2.2.2.3. Meshing. The element edge length of tomato exocarp and mesocarp tissues were set to 2 mm, and the element edge length of locular gel tissue was set to 1 mm. The geometric models of tomato exocarp, mesocarp and locular gel tissues were free meshed using tetrahedral elements. After the meshing operation, for toma-

Table 1
Mechanical properties of *Fenguan* 906 tomato tissues.

FEM	Tissues	Number	Elastic modulus E (kPa)	Poisson's ratio γ	Failure stress σ (kPa)	Density ρ (kg/m^3)
FEM (E_{ave})	Exocarp	1	9590	0.49	582	1000
	Mesocarp	2	726	0.45	122	1070
	Locular gel	3	124	0.45	12	1010
FEM ($E_{\max}$)	Exocarp	11	11776	0.49	610	1000
	Mesocarp	12	868	0.45	152	1070
	Locular gel	13	198	0.45	18	1010
FEM ($E_{\min}$)	Exocarp	21	7404	0.49	554	1000
	Mesocarp	22	584	0.45	92	1070
	Locular gel	23	50	0.45	6	1010

FEM – finite element model; the FEM (E_{ave}) – finite element model used the mean value of elastic modulus of each tissue, the FEM ($E_{\max}$) – finite element model used the maximum elastic modulus value of each tissue, the FEM ($E_{\min}$) – finite element model used the minimum elastic modulus value of each tissue. Poisson's ratio is dimensionless.