Scientia Horticulturae 245 (2019) 39–46

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

FEM-based simulation of the mechanical behavior of grapefruit under compressive loading

Seyed-Hassan Miraei Ashtiani*, Hassan Sadrnia, Hamid Mohammadinezhad, Mohammad Hossein Aghkhani, Mehdi Khojastehpour, Mohammad Hossein Abbaspour-Fard

Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

ARTICLE INFO

Keywords:
Bruise damage
Compression axis
Packing
Stress distribution
Tissue

ABSTRACT

Bruising in fresh crops is a major challenge of the horticulture industry, which can cause quality degradation and losses throughout the pre-harvest to the post-harvest stages. A visual understanding and/or detailed description of the mechanical behavior of fruits under different loading scenarios using analytical and physical experiments are complicated topics. This is particularly more complicated in fruits with a thicker peel. Vulnerability of grapefruits to mechanical damage under an external compression force was predicted in this study using the finite element method. The simulation results showed that the internal texture reach the yield point at 9.55 and 13.7 mm of longitudinal and transverse displacements, respectively, although the peel showed no sign of damage under these displacement values. However, according to the experimental data, the samples needed 29.47 and 36.55 mm displacements at the both longitudinal and transverse directions before reaching the complete yield and failure limits. Based on Newton's second law, a total of 25 and 31 grapefruits in the longitudinal and transverse directions were needed to create the forces (60 and 75 N) required for developing the yield displacements in the fruit pulp. Finite element results showed that the method is capable of contributing to the prediction and knowledge of internal mechanical damages of grapefruits and equally other horticultural products.

1. Introduction

Citrus fruits are economically the most important horticultural product in the world (Navarro et al., 2015). From a commercial perspective, grapefruit (*Citrus paradisi* Macf.) is the fourth most produced citrus in the world with an annual production of about 6.18 million tons (Sharma et al., 2016). It is qualitatively characterized by a unique shape, pleasant taste, and long shelf life that are appealing for consumers. In addition, it is a rich source of nutrients and phytochemicals that help maintain a healthy diet. Since it can reduce the risk of special chronic diseases like obesity, cancers, and cardiovascular diseases, there is a growing demand for supply and consumption of fresh and, at the same time, quality grapefruits (Zheng et al., 2016).

Fruits are subjected to different (static and dynamic) forces and thus damages during a broad farm-to-table cycle spanning various harvest, grading, packaging, handling, transportation, and storage operations (Miraei Ashtiani et al., 2016a; Hu et al., 2016; Stopa et al., 2017). According to Opara and Fadiji (2018), fruits are exposed to compression due to multiple reasons like contact forces from the picker, branches, and other fruits in overfilled bulk bins or boxes, and from stacked boxes, or from placing boxes in a tight spot together. In a poorly designed packaging system, bins are either overfilled or overstacked in the postharvest journey of fresh horticultural commodities from growers to end consumers. As a result, the static forces of products in one bin can lead to the rupture of cell walls and membranes of packed horticultural produce, particularly in lower rows (Hussein et al., 2018; Opara and Fadiji, 2018). Even in a storage facility or refrigerator, where the statistic forces of stacked boxes are tried to be kept away from the products inside them, there is still the chance of damage to the commodities. For example, in the packaging industry of horticultural produce, 40% of the packages are made of paper or paperboard. Environmental factors such as temperature and relative humidity also affect their fiber network and can cause the degradation of the cartons or, on a larger scale, the collapse of the stacked bin column. As a result, the commodities will be exposed to forces that may cause internal bruising (Fadiji et al., 2018). A review of field and research observations during the past 40 years revealed that between 40 and 50% of the horticultural production is lost to large mechanical damages, water loss, and subsequent spoilage in the post-harvest handling system, before reaching the consumer (Ahmad and Siddiqui, 2015). Mechanical damages, even at a small

* Corresponding author.
E-mail address: se_mi139@mail.um.ac.ir (S.-H. Miraei Ashtiani).

https://doi.org/10.1016/j.scienta.2018.10.006
Received 7 May 2018; Received in revised form 3 October 2018; Accepted 4 October 2018
0304-4238/

scale, speed up fruit softening leaving them prone to fungal infestation that in turn reduces the fruit-industry revenues and can even pose health threats to the consumer (Hu et al., 2016). In fact, most decay pathogens such as bacteria and fungi can easily infiltrate the dead or damaged tissues, which are suitable for their growth, and from there, they start to infect the rest of the fruits or vegetables during their storage and transportation in long distances (Pholpho et al., 2011).

From a marketing point of view, the appearance of fruits is a fundamental criterion for consumers to decide about and judge their quality (Kim and House, 2012). Unlike surface damages that can be noticed by peel discoloration, internal damages cannot be detected quickly, especially in fruits with a thick peel (Sadrnia et al., 2008) like grapefruits. An internal damage can rapidly exacerbate the fruit quality within a very short period (Li et al., 2013). As a result, in the modern horticultural management, prediction of damage level, stress distribution, and displacement in biological materials exposed to different external forces has turned to an important topic (Khodabakhshian and Emadi, 2015). Grapefruits are vulnerable to bruising due to the type of their internal tissue and high moisture content. Therefore, it is important to understand the mechanical behavior of grapefruit under compressive loading in order to improve harvest and post-harvest practices for this fruit.

A fruit is made of different types of cells. Cellulose and polysaccharides are the main constituents of cells and can give different levels of adhesiveness, wall thickness and elasticity to them (Reeve, 1970;Param and Zoffoli, 2016). This complex cellular structure of agricultural products makes it highly difficult to calculate the stresses developed under the peel (inner stresses) due to an external force (Seyedabadi et al., 2015; Sadrnia et al., 2008). Useful information can be extracted from a mechanical analysis of agricultural products to optimize the design of farm machinery (Miraei Ashtiani et al., 2016b; Celik, 2017) to keep the forces acting on the product lower than its yield force (Yilmaz and Yildirim, 2016).

Besides the advances in the laboratory instrument production, the development of software and computer industries has provided a platform for engineers to use computer-aided design (CAD) and numerical methods to simulate material behaviors under different boundary conditions (Kabas and Vladut, 2015; Salarikia et al., 2017). The analytical methods are applicable to a limited number of cases for stress analysis purposes. Most mechanical phenomena that occur within the agriculture sector present complicated problems, which can only be solved by numerical methods as an alternative solution (Celik et al., 2011). One of these methods that is both highly robust and efficient in predicting internal stress distribution and detecting damaged areas from compression load in biological products is the Finite Element Method (FEM) (Li et al., 2013; Seyedabadi et al., 2015). Since it is very laborious to solve partial differential equations and integral using analytical methods, the FEM approach can be used as a numerical computation technique for approximation. In fact, FEM splits a complicated problem into several smaller units and solve these simpler equations (Nowak, 2016). Numerous authors have reported the use of FEM in the prediction of behavior of agricultural products subjected to mechanical loads. Cardenas-Weber et al. (1991) analyzed the mechanical properties and internal stresses of melon using FEM. Their simulation model worked with a relative error of 11% showing good approximation compared to empirical data. Kim et al. (2008) modeled stress distribution inside a whole apple compressed between two parallel plates in an FEM environment. Sadrnia et al. (2008) reported FEM-based prediction of bruising in watermelon samples. They found a good fitness between the simulation and experimental results. An FEM model was used to explain the mechanical behavior of *Jatropha curcas* L. seeds under compression loading (Petrů et al., 2012). It was reported that FEM was useful for optimizing pressing machines. The internal mechanical damage of tomatoes subjected to compression loading was predicted using the FEM approach (Li et al., 2013). Results suggested that the simulation results were consistent with the experimental data. Seyedabadi et al. (2015) used FEM to study the mechanical properties of cantaloupe under compression loading from two parallel plates. It was found that FEM can predict the experimental results with a high accuracy. Authors have also used FEM to analyze the mechanical damage progression caused by an external force in fruits such as grapes (Rong et al., 2004), orange (Ihueze and Mgbemena, 2017), and carrot root (Stopa et al., 2017).

The literature review revealed that numerical methods have not been used in combination with other methods for prediction of mechanical behavior of grapefruits. The internal stress distribution of grapefruit subjected to the external compressive force was thus analyzed here using FEM simulation to compare its results with experimental measurements.

2. Materials and methods

2.1. Grapefruit samples

Fresh mature seedless grapefruits (var. Ghermez) were manually harvested (approximately 210 days after full bloom) from 12-year-old trees of a research orchard in Jiroft, Kerman, Iran (longitude: 57°73′E and latitude: 28°56′N) during late November 2017. Samples were homogeneous in terms of dimensions, shape and peel color. Each grapefruit sample was kept in a separate sterile plastic bag and were immediately transferred in a ventilated vehicle to the Post-harvest Physiology Laboratory of the Ferdowsi University of Mashhad, Iran. Samples were re-examined for visible damages and abnormalities. The sample surfaces were washed with a slow stream of cold water (about 4 °C) and were wiped dry with a cotton cloth. Twenty samples were then selected randomly for measuring moisture content and physical parameters. They were weighed by a digital scale (SP402, Ohaus, USA, ± 0.01 g accuracy), and their geometry was measured by a digital caliper (Mitutoyo, Japan, ± 0.01 mm accuracy). A geometric model was developed by measuring peel thickness of multiple spots. The moisture content of grapefruit samples was measured separately for peel and pulp using the method proposed by Miraei Ashtiani et al. (2014). The remaining fruits (80 samples) were kept at the conditions recommended by Lado et al. (2015) (*i.e.* 12 ± 1 °C and 80–85% RH) during the experiments (2 days). Prior to the experiments, the required samples were left at room temperature for about 1 h. Similarly, all analyses were done at room temperature (20 °C).

2.2. Whole grapefruit compression experiment

A texture analyzer (H5KS, Tinius Olsen, England) with a 1 kN load cell was selected for the flat-plate compression test. An aluminum flat plate (Ø = 10 cm) connected to a load cell was used for compressing the samples. A constant-rate compression load (20 mm/min) was applied to the samples (ASABE Standards, 2008). For each test, the sample was placed on the lower flat plate and was compressed until reaching its failure point by the downward movement of the parallel plate. The real-time force-displacement data from each loading stage were stored in a computer connected to the device. Consequently, some of the mechanical properties such as the rupture force and deformation at rupture were extracted from each curve.

The two loading positions (longitudinal and transverse axes) for testing are shown in Figs. 1 and 2 is a typical force-deformation curve for the response of a grapefruit under the compression test. The blue circles mark the maximum compression strength points beyond which the sample would take damage (Opara and Fadiji, 2018). Each loading position was carried out in twenty replications.

2.3. Mechanical properties of pulp and peel tissues

Given the different cellular structure of the fruit's peel and pulp, it was necessary to analyze their mechanical properties separately before