Computers and Electronics in Agriculture 121 (2016) 1–11

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Original papers

Viscoelastic finite element analysis of the dynamic behavior of apple under impact loading with regard to its different layers

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 23 November 2015
Accepted 24 November 2015
Available online 17 December 2015

Keywords:
Apple
Dynamic behavior
FEM
Viscoelastic properties
Biophysics
Fruit texture

ABSTRACT

Annually, large quantities of apple are destroyed and suffer from quality loss because of bruising and other mechanical damages during harvesting, transportation, storage and packaging. Bruising due to impact is one of the most important reasons for the quality loss in the fresh fruit market. Regarding to the accuracy and economic justification, Finite Element Method (FEM) is one of the best ways of investigating the effective factors in bruising produced as a result of impact. In this research, FEM is used to study the dynamic impact to apple. For soft and relatively large objects like apple, the dynamic waves are absorbed by the body of the object through decreasing the kinetic energy during the impact. The amount of energy absorption is dependent upon the viscoelastic properties, geometric size of the object during the collision, and collision velocity. Therefore, in such materials, contact area and the induced stress in contact region are time dependent. In finite element modeling, a nonlinear time-dependent contact is considered. Through the use of finite element models of a typical fruit, the apple, some collision processes of the fruit were studied. The 3D FEM models were created to illustrate, as closely as possible, the typical geometrical structure of an apple fruit, containing the basic inhomogeneous structure of the fruit. In the current study, using Finite element method, the behavior of the various layers of skin, cortex and core of apple was analyzed applying impact test to collision of the fruit with a flat rigid plate as well as the collision of an apple with another apple. The different layers of apple such as skin, cortex and core have not been yet analyzed dynamically so it plays a remarkably important role. The results showed that the parameters of displacement, velocity, acceleration, stress and hydrostatic pressure in the collision of apple to apple were less than that of apple to rigid object at the velocity of 1 m/s. Also, changes of these parameters were maximum in a skin and minimum in a core.

1. Introduction

Boundary quantity issues, which involve contact in viscoelastic materials, are one of the most important issues in the industries related to solid mechanical engineering, construction, medical sciences, biosystems and the environment. In the past, mostly in the design processes, the issues related to contact mechanics because of its non-linear nature were approximately solved with certain assumptions. Nowadays, with regard to the quick expansion of modern computer technology, impact mechanisms can be numerically simulated using a tool called computational mechanics. This is due to the extensive competition which exists among researchers to utilize efficient and powerful ways for more exact simulating of the engineering issues in computational impact mechanics (Wriggers, 2002; Laursen, 2002). Damage to perishable biological materials, such as fruits due to impact, quasi-static and dynamic contact pressure, is one of the significant subjects in the domain of biosystem engineering science. Most horticultural products (like fruits) are exposed to mechanical damage as a result of bearing the contact pressure during a series of processes such as harvesting, packing, transportation, categorization, processing and storage. The main reason of quality loss in the fresh fruit market is bruising damage caused by dynamic contact. Overall, a high percentage of horticultural products are annually destroyed due to wastages in bruise (Siyami et al., 1988; Pang et al., 1992; Lewis et al., 2008). In general, bruise is defined as damage and discoloration in the surface cortex of the fruit, usually without causing a crack in the skin. In quasi-biological solids, the primary appearance of cell rupture in a small fraction of a cell system occurs from biological yield point. Yield point in biological materials plays an important role in determining their sensitivity to mechanical

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http://dx.doi.org/10.1016/j.compag.2015.11.017
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damages. Thus, how pressure as a result of contact is distributed across the joint contact area is biologically important. This is why a special attention was devoted to simulation of inelastic deformations and nonlinear modeling of contact pressure in biological productions in recent years (Sitkei, 1986; Ashrafi et al., 2008; Allan et al., 2011). To investigate how bruising is formed, many considerable empirical studies about mechanical damages of bruising on fruits have been statically and dynamically done. For example, compression tests are one of the most significant experimental ways to study bruising in apples (Lewis et al., 2008; Lu et al., 2006). Most of these empirical studies showed approximately acceptable results due to using high technology and accurate measurement machines which are available in theses laboratories. Although some studies have been conducted with simulated models and numerical analysis, the numbers of studies about numerical simulations, which can be confirmed with laboratory tests, are not considerable. In recent years, computer models have been developed to perform mechanical analysis such as the mechanical interactional modeling (Tekeste, 2009; Barauskas, 2005; Abedrabbo et al., 2006; Pramanik et al., 2007) and vibration, compression and bruise modeling of different fruits (Lu et al., 2006; Dintwa et al., 2008; Lewis et al., 2008).

Viscoelastic contact stress analysis in the industry of horticultural productions using numerical methods goes back to the first plan offered by Rumsey and Fridley (1977). In this plan, two-dimensional FEM was used and the problem was analyzed in quasi-static condition with linear shear module and constant volume index. Subsequently, no remarkable efforts were made in presenting model and numerical formulation by means of FEM for analyzing contact issues in biological solids. Lu and Abbott (1997) investigated the transient responses of apple to impact stimulation by commercial software MARC under the configuration of actual system. Researchers are always looking for the ways of developing non-destructive evaluation methods of agricultural products; and one of these ways is to use the FEM, which it has been used in areas such as heat, vibration and structural analysis.

The mechanical behavior of materials with relatively low molecular weight is discussed in terms of two kinds of special ideal materials: elastic solid and Newtonian viscous fluid. Solids have certain shapes; they transform to another balanced shape by applying external forces and return to the primary shape by removing those forces. Viscous fluids do not have certain shapes and they flow by applying external forces. One of the main characteristics of elastic behavior is the capacity to store the mechanical energy during deformation caused by loading and release it after unloading. Unlike this behavior, the mechanical energy in viscous fluid is continuously depreciating without storage. Some important engineering materials both store and depreciate simultaneously the mechanical energy while acting the applied forces. In fact, all substances in nature store and depreciate energy over the cycle of loading and unloading with different degrees. Such behavior is called viscoelastic behavior. In essence, the component equations of viscoelastic behavior consist not only of stress and strain, but also time track of stress and strain changes (Christensen, 1982). The component behavior of viscoelastic solids in contact with each other is modeled by means of linear viscoelastic and isotropic assumptions.

Apple can be modeled as a composite material with elastic quality in the axial symmetry condition, including skin, cortex and core. Measuring induced internal stresses in the apple during loading is very difficult. The appropriate alternative method is the FEM analysis to estimate the internal stresses. The FEM can also be used to model irregular and heterogeneous objects. It can solve nonlinear problems, such as changing the geometrical shape during loading, contact regions and distribution of stress and strain in fruits and vegetables (Bajema et al., 1998). This method has been mostly used for evaluating the viscoelastic properties and estimating the firmness of the fruit cortex. However, to simplify the FEM modeling, the mechanical properties of the fruit are assumed to be isotropic in most studies (Bajema and Hyde, 1998; Baritelle and Hyde, 2001). Using the software Ls-Dyna, Lewis et al. (2008) analyzed the static pressure loading between parallel plates based on FEM. They utilized a laser scanning to provide real geometrical shape of apple and considered the mechanical properties of apple to be elastic.

The results were used to determine a time limit for the mechanical damage occurrence (Lewis et al., 2008). Through the scenes video-recording with a high-frame camera, Kursat Celik et al. (2011) simulated the deformation behavior of an apple falling from different heights by FEM. Using a combination of energy analytical method and numerical modeling in finite element software ANSYS, Cherng et al. (2005) suggested a new strength index for oval-like elastic fruits. In addition to modeling the behavior of fruit as an elastic object, several researchers have studied the viscoelastic behavior of agricultural products and employed simple mechanical models combining the elastic and viscous properties to express the behavior of the object when it is under the tensile or compressive loading (De Baerdemaeker and Segerlind, 1976; Kim et al., 2008; Sadrnia et al., 2001, 2008). By finite element software MARC, Lu et al. (2006) statically analyzed the contact stress distribution resulting from the pressure of soft-bioyield probes in a compression test on apple. The effect of probes with different size, thickness and their elastic module on the contact pressure distribution on different samples of apple was investigated. In this study, apple was modeled as a composite material with a viscoelastic body and the elastic shell. Lewis et al. (2008) studied how contact stress of apple under static loading is distributed using finite element software ANSYS and ultrasonic technique. To examine the bruise, apples were modeled completely three-dimensionally and elastically. Ashrafi et al. (2008) suggested FEM by applying changes for analyzing fatigue in apple resulted from contact pressure. In this plan, the apple was modeled two-dimensionally and viscoelastically.

The main objective of the present study is to simulate the behavior of apple by viscoelastic material model and determining the behavior of different layers such as skin, cortex and core under dynamic loading. Many researchers investigated the simulation of the static behavior of apple, but no study has been conducted on the dynamic analysis considering different layers (skin, cortex and core) (Allan et al., 2011; Ashrafi et al., 2008; Hayakawa and Kuninaka, 2002; Kursat Celik et al., 2011). This is why research for more precisely examining the dynamic behavior of apple is needed and this precise analysis leads to better decision making about the dynamic impact analysis in all angles.

2. Materials and methods

2.1. Modeling the joint contact area

Two transformable figures are pressed together through applying external forces and are exposed to frictional contact with each other. The range of both figures which are in contact with each other is detached to a certain number of finite elements and tetrahedral eight-knot elements are used for constructing the finite element model (Belytschko et al., 2003; Zienkiewicz and Taylor, 2000). For numerical analysis of contact, the boundaries of two figures are assigned to three groups of prescribed transformational boundaries, prescribed traction boundaries, and contact boundaries relevant to joint contact area of two figures. By applying force, the boundary situation is continuously changing throughout the whole joint contact area. The contact condition is dependent upon