RESEARCH ARTICLE | JULY 21 2017

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AIP Conf. Proc. 1863, 520003 (2017)
https://doi.org/10.1063/1.4992667

Studying Apple Bruise Using a Finite Element Method Analysis

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Abstract. Apple bruise damage from harvesting, handling, transporting and sorting is considered to be the major source of reduced fruit quality, resulting in a loss of profits for the entire fruit industry. Bruising is defined as damage and discoloration of fruit flesh, usually with no breach of the skin. The three factors which can physically cause fruit bruising are vibration, compression load and impact. The last one is the main source of bruise damage. Therefore, prediction of the level of damage, stress distribution and deformation of the fruits under external force has become a very important task. To address these problems a finite element analysis has been developed for studying Portuguese Royal Gala apple bruise. The results obtained will be suitable to apple distributors and sellers and will allow a reduction of the impact caused by bruise damage in apple annual production.

INTRODUCTION

Apple bruise damage has been studied using experimental, analytical and numerical methods [1-5]. A number of different testing methods have been chosen to better understand the dynamic impacts of apples carried out using several techniques, such as drop and pendulum tests and with spring loaded devices to propel an apple against a counterface [5-9]. Nevertheless, according to Lewis et al. [1], the results obtained from these techniques are limited in nature and most of them are in a form that would not be suitable to apple distributors and sellers. A major work was developed by Pang et al. [9] involving dynamic impacts against different counterface materials using a pendulum device producing a series of bruising thresholds based on apple accelerations. However, these studies are experimental time consuming. Additionally, analytical methods for stress investigation are available only for a few simple cases. Nevertheless, mostly of the real problems occurring in engineering represent complex problems which can only be solved using numerical methods [3]. To address these problems several approaches were developed based on the finite element method(FEM) [1, 10-13]. Nevertheless, a numerical model to mimic accurately apple mechanical behavior is needed mainly, due to its nonlinear geometrical and material properties. In order to study this problem a biomimetic model is proposed (Fig1) and some preliminary results are presented.

MATERIALS AND METHODS

Experimental Tests

In this work the approach presented at Fig. 1 was used to study apple bruise damage. Portuguese Royal Gala apples (n=40) were dropped from heights ranging from 1 to 40 centimeters onto metal, plastic and a conveyor belt to understand apple damage as a function of height as detailed in [14]. Additionally, the mechanical characterization of the apple fruit was performed using compression tests which allowed to find and average of the Young' modulus

International Conference of Numerical Analysis and Applied Mathematics (ICNAAM 2016)
AIP Conf. Proc. 1863, 520003-1–520003-5; doi: 10.1063/1.4992667
Published by AIP Publishing. 978-0-7354-1538-6/$30.00

(E=2.0 *MPa*), the yield Stress/Strain Point (σ_y;ε_y)=(*0.4 MPa ; 0.12*), and the failure Stress/Strain Point ($\sigma^{'}$; $\varepsilon^{'}$)=(*0.4 MPa ; 0.15*) (view all details at Fig. 2b and Fig. 3c). Additionally, an average value of ρ=900 Kg/m^3 was determined for apple density. Apple's Poisson's coefficient (ν= 0.33) and the tangent modulus (G=0.6 *MPa*) were found on the literature [15].The rigid box was characterized using ρ=1240 Kg/m^3, a Young' modulus of E=2.35E3 *MPa* and a *Poisson's* coefficient of ν= 0.38.

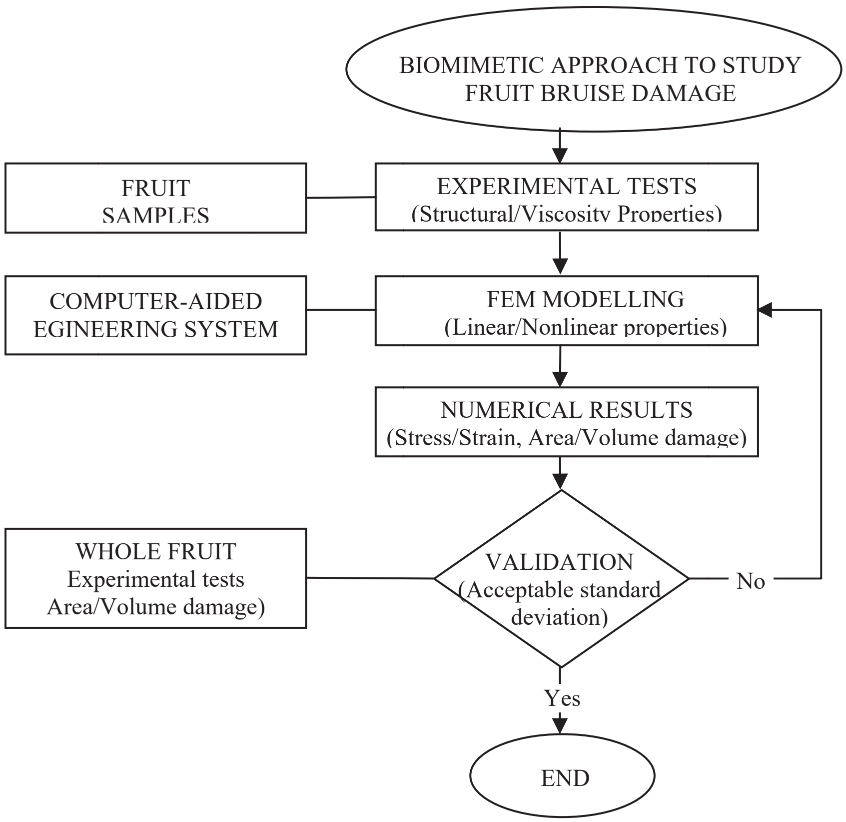


FIGURE 1. Flowchart of the biomimetic approach proposed.

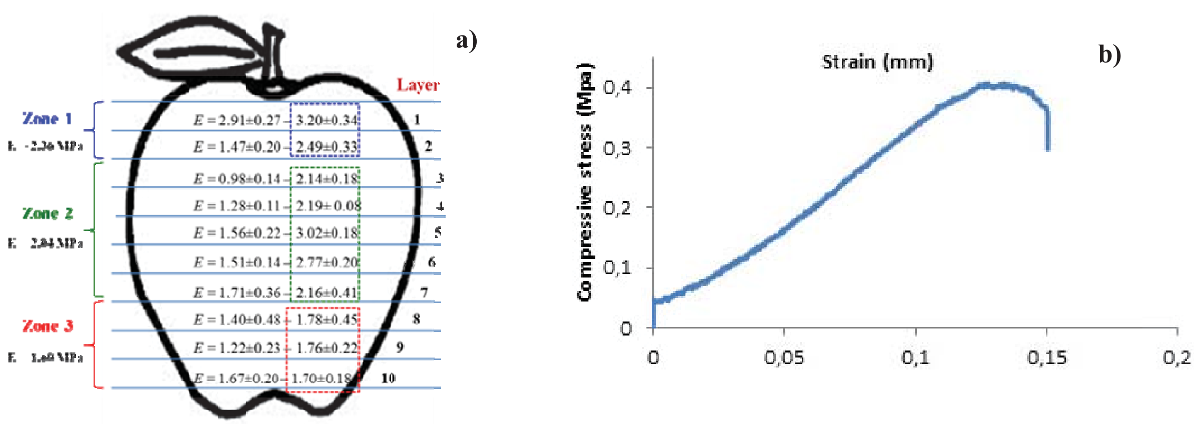


FIGURE 2. Mechanical characterization of the apple fruit using compression tests to calculate the Young' modulus, yield Stress/Strain and Failure Stress/Strain in different layers obtained by cutting the apple in layers of 5 mm and working with cubic specimens of 5 mm^3 from different regions along the apple flesh. Different results were obtained and three distinct zones 1, 2 and 3 were statistically computed 2a). Typical stress-strain curve of an apple flesh sample in a compression test 2b).

Finite Element Modeling

Problem Description and Assumptions

To modulate the free fall stage of the apple a dynamic analysis was performed using a simplified model comprising a three dimensional (3D) sphere impacting a rigid surface in ANSYS LS-DYNA software. To save computer time the analysis was made considering a sphere with a radius of 35 mm in contact with a rigid box (70x70x5 mm) (see Fig. 4). This model is considered to be a first approach to study the impact of dropping an apple trough the Y axes from different heights (1, 3, 5, 9, 13, 17, 21, 30, 40, 50, 60, 65 and 70 mm). A 3D tetrahedron and hexahedron solid elements were used to mesh both sphere and the rigid box, respectively (Fig. 4a). The initial velocity (V_i) as a function of the height (h) was applied according to the following equation:

$$V_i = \sqrt{2gh}, \quad (1)$$

where g is the acceleration due to gravity and the friction from the air was neglected.

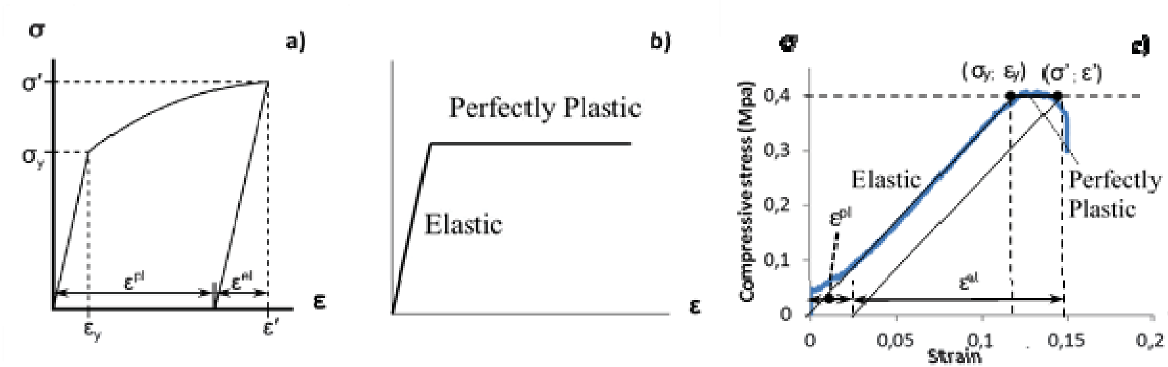


FIGURE 3. Typical stress-strain curves for an elastic-plastic material. General stress-strain curve (a). Elastic–perfectly plastic stress-strain curve (b). Elastic–perfectly plastic stress-strain curve fitted with experimental data (c).

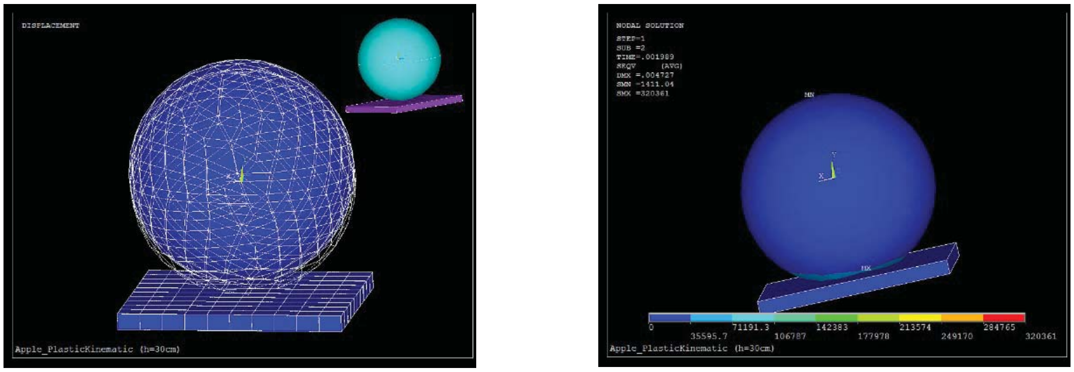
Linear/Nonlinear material modeling

The deformation of materials usually includes a permanent or plastic component that will not return to the original configuration if the load is removed and evolves in response to the deformation history. These materials also typically have an elastic behavior so that the combined deformation includes a part that is recoverable upon unloading as illustrated in Fig. 3a), where stress, strain, yield stress, yield strain, failure stress, failure strain, elastic strain and plastic strain are denoted by σ, ε, σ_y, ε_y, σ', ε', ε^{el} and ε^{pl}, respectively.

As shown in Fig. 2b), the typical mechanical behavior (strain-stress curve) of the Portuguese Royal Gala apple flesh can be described using two components, an elastic component followed by a permanent/plastic one. Therefore, the elastic–perfectly plastic material model (characterized in more detail in [16]) and presented in Fig. 3b), was used to simulate apple's mechanical behavior. Fig. 3c) presents the elastic–perfectly plastic material model fitted with the experimental data obtained from the apple flesh compression tests.

RESULTS

The finite element method was used to predict the equivalent stress (Von Mises stress -σ_{VM}) and the deformation (Def) values on apple through an explicit dynamic analysis. The elastic–perfectly plastic material model fitted with the nonlinear material behavior of the Royal Gala apple flesh. To save computer time, the analysis was carried out considering a sphere in contact with a rigid box. Thus, several velocity values were computed and applied to the sphere. Table 1 summarizes the velocity values (V_i), the equivalent stress (σ_{VM}) and deformation (Def) results as a function of the height. An increase of both equivalent stress and deformation was found as the height was considered higher. In Fig. 4b) the equivalent stress and deformation is obtained when the apple is dropped through a height of 30 cm.



a)Geometry, Mesh and deformed shape

b) Equivalent stress

FIGURE 4. The geometry (top, left a)), the mesh of the finite element model constructed to mimic the drop of 30 cm of an apple into a rigid surface and the deformed and undeformed results can be seen at 4a).Equivalent stress numerical results simulating a fall of the apple of 30 cm are presented at 4b).

TABLE 1. Velocity values (V_i), equivalent stress (σ_{VM}) and deformation (Def) results as a function of the height.

h cm)	Vel (Vi)	$\sigma_{VM\ (MPa)}$	Def (mm)
01	0.440	0.041	1.510
03	0.767	0.068	2.389
05	0.991	0.093	2.908
09	1.329	0.218	3.575
13	1.597	0.241	3.996
17	1.826	0.257	4.629
21	2.030	0.278	4.940
30	2.438	0.320	4.727
40	2.800	0.357	5.411
50	3.132	0.356	6.038
60	3.431	0.431	6.598
65	3.571	0.432	6.864
70	3.706	0.4397	7.116

CONCLUSIONS AND FUTURE WORK

Apple bruise damage causes around 25% of production losses. It has been studying using different methodologies however the results are not easily understood to apple distributors and sellers. Nevertheless, numerical simulation studies can play an essential role trying to understand the causes and finding solutions to reduce or eliminate apple bruise damage. In this paper an elastic–perfectly plastic material model that mimics accurately apple mechanical behavior is proposed and its nonlinear geometrical and material properties are considered. Equivalent stress values and a measure of the deformation was calculated. The results obtained can be used to calculate the area and the volume of apple bruise damage and compared to the one obtained experimentally in order to validate the numerical model. Additional experimental tests can be performed in order to gain some insight of the structural/viscoelastic properties of the apple that will contribute to implement more realistic apple finite element models. The methodology proposed can be used to study different fruits and also vegetables. The work proposed will contribute to add value to the agricultural sector.

The experimental results presented at Fig. 2a) were statistically grouped in three main domains suggesting that nonlinear mechanical/viscoelasticity properties must be included in a new FEM apple model, which is under development in order to mimic real apple behavior.

ACKNOWLEDGMENTS

This research work was supported by the Portuguese Foundation for Science and Technology (FCT) through the Project reference UID/Multi/04044/2013.Authors would like to thank the apple fruit company Frutus - EstaçãoFruteira de Montejunto CRL and COTHN - Centro Operativo e Tecnológico Hortofrutícula Português.

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