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Limit values of impact energy determined from contours and surface pressure distribution of apples under impact loads

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A R T I C L E I N F O

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A B S T R A C T

During the harvest, handling, transport, sorting and other operations, apples are exposed to different static and dynamic loads. However, impact loads are the main causes of apple surface bruising and grower losses. Under impact loads, biological material has elastic characteristics. Due to this dynamic process, fluid and air in the intercellular spaces cannot move to areas with a lower load, which results in the formation of cracks and irreversible tissue damage. The mechanism of damage to the structure of apple flesh under impact loads differs qualitatively from damage generated under quasi–static loads. Therefore, it is essential to determine the critical impact energy for which deformation of the elastic apple moves toward permanent deformation. To define and determine the boundary impact energy including tissue damage, it was hypothesized that whether a permanent deformation occurs during a collision corresponds to the initial phase of maximal surface pressure stabilization. Therefore, apples with different elasticity moduli may have characteristic surface pressures above which the flesh tissue is destroyed. The maximum values for contour surface pressure are at the central point of contact. In this area, there is no evidence of flesh tissue destruction. Evaluating the maximum surface pressure over the apple surface, contours are formed near the central point of contact. This study also determined the energy required to cause permanent deformations.

1. Introduction

To produce apples with the highest quality, some important conditions and parameters, which are described in the Official Journal of the European Union, must be met (Commission Implementing Regulation (EU) No 543/2011). Improving the profitability of apple production requires moving production toward varieties intended for direct consumption. However, delicatessen varieties are more susceptible to bruising and therefore require more manual work during collection (Menesatti and Paglia, 2001; Sablani et al., 2006).

During harvest, handling, transport and sorting, ripe apples are subjected to various static and dynamic loads (Sadrnia et al., 2008). Impact damage constitutes a main cause of fruit bruising, resulting in grower loss (Bollen et al., 2017; Opara, 2007; Opara and Pathare, 2014; Paz et al., 2009; Lewis et al., 2007; Li and Colin, 2014; Li et al., 2016). During impact loads, irreversible changes occur in apple tissue internal structure, resulting in the destruction of the cell walls (Jarimopas et al., 2007). The mechanism of changes in the cellular structure of apples under impact loads differs significantly from the changes taking place under quasi–static loads (Stopa et al., 2013). For this reason, it is impossible to analyse the mechanism of bruise occurrence or to determine resistance to bruising using a simple measurement method based on a stress test (Gołacki and Rowiński, 2005; Lu et al., 2010; Herold et al., 1996). Another important factor affecting apple resistance is the elasticity of the flesh tissue. Feteke (1994) determined elasticity parameters for apples as well as for tomatoes. He investigated their firmness to determine the most precise indicator to describe biological material. What's more, Li et al. (2017) determined a mathematical model of mechanical damage of tomato. A new method for firmness evaluation was presented by Studman et al. (1997) (Fruit firmness measurement techniques – a new approach), who compared his findings with results obtained using a more traditional method.

Appearing in the literature possibility of using finite element analysis to determine the surface area and bruise volume materials of agricultural origin shows a new trend and new research opportunities (Kabas, 2010; Celik et al., 2011; Ahmadi et al., 2016; Celik, 2017). However, such analyzes must be preceded by experimental tests not only of the parenchyma tissue samples, which behaves viscoelastically,

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but also the whole test object, where the properties of the fruit skin contribute to the reduction of damage and the stress distribution inside the material should include the seed socket, which also current literature has been omitted. The lack of a combination of experimental results with the results of FEM simulation makes it impossible to determine whether the proposed model adequately maps reality.

Under impact loads, biological material is elastic. The liquid and air filling the intercellular spaces do not have enough time to move to lower-load locations, where these locations are still available (Gołacki and Rowiński, 2006; Held et al., 2015; Ahmadi el al., 2010). This situation leads to stress levels that exceed the cells' strength, causing bruises and irreversible tissue damage. At low load speeds, biological material is characterized by strong visco–elastic properties (Van Zeebroeck et al., 2004). In the initial loading phase, after gas displacement and filling of the free intercellular spaces, a liquid migration process starts inside cells, which causes deformation of the cell walls. As a result, this type of load has more destructive potential, which is greater than for impact loads (Jiangbo et al., 2011). Blahovec (1999) determined the bruise resistance coefficient (BRC) of stored apples and cherries. He proved that the abovementioned parameter depends mainly on compression distribution. An increase in load was accompanied by deformation of the apple.

In this situation, it becomes essential to determine the critical impact energy at which apple's elastic deformation transforms into permanent deformation. In elastic deformation, after the load is removed, the apples returned to their original shape; hence, a non-destructive effect on flesh tissue is observed, and as consequence, there is no risk of bruising. Bruising only appears when apple tissue is damaged through permanent deformation (Blahovec and Paprštein, 2005).

Usually, deformation measurements under impact loads are conducted by forcing a load via a free drop from a fixed height or with the use of a pendulum (Ahmadi et al., 2010; Sun et al., 2014; Komarnicki et al., 2016). The type and shape of the surface that the tested apple hits can vary. According to Sitkey (1987), these surfaces can be divided into four groups:

1. A fixed flat and rigid surface;
2. A bent and rigid surface;
3. Impact of one tested surface onto another, where one of them does not move and its centre of gravity can be moved;
4. Impact onto a fixed surface covered with absorbent plastic material.

Due to the characteristic shape of apples, contact stresses from an impact force focused on a small area must be considered. The problem of apple contact surface has been described by means of quasistatic loads. Most experimental studies have measured changes in the contact surface area between apples and loading machine elements under external forces (Herold et al., 2001; Lewis et al., 2008; Rabelo et al., 2001; Wu et al., 2012; Wenqian et al., 2015). Many interesting studies of dynamic load apples have been conducted by Acican et al. (2007), who analysed apple damage during transport in wooden boxes. Van Zeebroeck et al. (2007) conducted a study of apples using an instrument similar to a pendulum and generated models using the discrete finite element method, which allowed determination of the influence of transport on apple damage. Yuwana and Duprat (1996) use the modulus of elasticity to predict bruise volume on apples. They determined a relationship between evaluated bruise volume and predicted bruise volume. In their study, both functions were characterized by linear correlation (Yuwana and Duprat, 1996).

1.1. Goals of this study

The central aim of this study was to determine the contour and surface pressure distributions for four varieties of apples under free-impact loads with different impact energies and the critical energy values at which the first signs of flesh tissue damage are observed. Contours and surface pressure distributions were determined corresponding to elastic and permanent deformations.

The paper presents a new method for identifying parenchymal tissue damage based on the value and distribution of surface pressure, without the need for time-consuming processes like removing the skin from places where damage potentially occurred, which is necessary with the methods used until now.

This is a preliminary phase of research aiming to build a numerical model of an apple using FEM. The numerical model will allow to reduce the time-consuming experimental research. In addition, a well-built three-layer apple model (skin, parenchyma tissue and seed socket) will allow to design process lines and machines in such a way as to limit the mechanical damage of apples. To build a model should be thoroughly carried out experimental tests, which will allow the determination of the actual surface area and volume bruising and will then be used to compare with the model results.

2. Materials and methods

Tests were conducted in the Agrophysics Laboratory of the Agricultural Engineering Institute at Wroclaw University of Environmental and Life Sciences. The research material was purchased from the 'G.P.O.i.W. Trzebnickie Sady Sp.z o.o.' company. Apples were carefully selected in terms of weight, shape and dimensions. During the measurements, the apples were stored in the fridge at 3 °C and relative humidity of 90–95%. The apple cultivars selected were varieties that represent approximately 40% of all cultivated apples in 2013 in Poland: 'Idared', 'Jonagold', 'Ligol' and 'Spartan'.

The 'Idared' variety constitutes 19% of total polish production, the 'Jonagold' 10%, 'Ligol' 8%, and 'Spartan' constitutes approx. 3%. The firmness of the examined fruits was 'Idared' 76–91 N, 'Jonagold' 74–80 N, 'Ligol' 75–80 N, and 'Spartan' 73 N. Firmness was measured with the use of a manual penetrometer Facchini (type FT 327) (Rybczyński, 2007).

A schematic presentation of the measurement apparatus is shown in Fig. 1. The measurement apparatus works like a pendulum, impacting a hard and rigid plate, where the lower part is a bumper that the test subject hits. This construction allows the vibrations that occur during the testing phase to be absorbed. The pendulum arm was made from carbon fibre, which is not susceptible to resonance and was treated as weightless. Measurement of surface pressure was implemented with the use of the Tekscan® system, and recording of waveform deformation and crack propagation was done using the digital image correlation system. The apparatus allows the impact energy to be adjusted by changing the angle of the initial position of the pendulum arm and by adding additional weights to the handle area. Measurement of force and

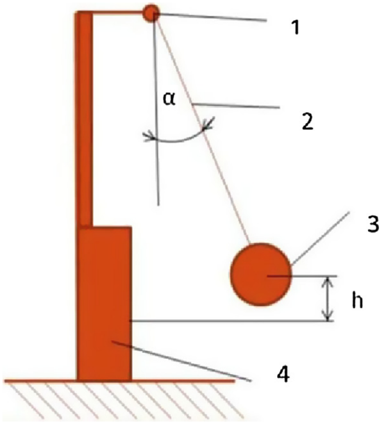

Fig. 1. Diagram of the implementation of the testing and measuring position: 1 – connection, 2 – pendulum pull, 3 – fruit in fruit holder, 4 – static bumper plate with ultra-thin pressure sensor.