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Determination of bruise susceptibility of pears (Ankara variety) to impact load by means of FEM-based explicit dynamics simulation

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ABSTRACT

This study focuses on determining bruise susceptibility and the realistic representation of time-dependent nonlinear deformation behaviour of pears (Ankara variety) under various impact cases. A reverse engineering approach, physical material tests and finite element method (FEM)-based explicit dynamics simulations were utilised to investigate impact deformation characteristics of the fruit. Three impact heights (0.25, 0.5 and 1 m), three impact surfaces (steel, wood and rubber-based materials) and three impact orientations of the fruit (vertical, horizontal and at a 45° angle) were considered in the impact simulation scenarios. Useful numerical data and deformation visuals were obtained from the simulation results. These results revealed that maximum bruise susceptibility magnitude on the fruit was experienced for the case of impact on the wood-based platform (impact height: 1 m; impact orientation: 0°) and minimum bruise susceptibility magnitude was calculated for the case of impact on the rubber-based impact platform (impact height: 1 m; impact orientation: 45°). In addition to this, numerical results related to fruit bruising were analysed through response surface analysis approach and prediction models were successfully described with a reasonable coefficient of determination (R^2) values. Verification checks of the prediction models also indicated that the relative differences between the results of simulation and the empirical model were in agreement (max. 7.03%). These models can describe the bruise susceptibility magnitudes of the fruit for various impact cases on specific impact platforms. This study contributes to further research on the usage of numerical-methods-based nonlinear explicit dynamics simulation techniques in complicated deformation and bruising investigations and industrial applications related to agricultural and food products.

Industrial relevance

This work aims to represent and simulate time-dependent impact deformation of pears. Time-dependent impact deformation is a very difficult phenomenon to describe through physical experiments and/or mathematical expressions. As a further step beyond other researchers, a novel, realistic time-dependent nonlinear deformation simulation study based on experimental data has been introduced. Empirical models with specific perspectives have also been developed to estimate bruise susceptibility magnitudes of the fruit under a very wide range of impact events. Useful deformation visuals and numerical findings related to impact bruising of the fruit have been exhibited and these findings have been presented in a form which may be used as input parameters in design studies of agricultural and food product processing machinery systems used in related industries.

1. Introduction

The major aim in designing optimal agricultural equipment or food product processing systems used in the production phases of harvesting and post-harvesting is to provide the ability to harvest, transport, grade, process and pack the products with no bruises. Bruises are the most common type of mechanical damage seen on agricultural products, particularly on fruit such as pears which are highly sensitive to mechanical damage (Berardinelli et al., 2005; Eissa et al., 2012). Most mechanical damage of fruit is caused by mechanical impact cases that occur in many agricultural processes such as harvest, transportation and post-harvest operations and the fruit industry suffers considerable economic losses due to this type of mechanical damage (García et al., 1995; Van Zeebroeck et al., 2003, 2007; Berardinelli et al., 2005; Prusky, 2011; Abedi and Ahmadi, 2013a; Komarnicki et al., 2016). Therefore, impact

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phenomena and bruise damage measurement deserve special attention (Sarig, 1991). In this regard, prediction of the level of damage, stress distribution and/or deformation behaviour of the fruit under impact cases has become a very important issue in order to develop optimal machinery systems for related fruit production and processing industries. At the initial design phases of these types of systems, some related features (as design parameters), such as engineering properties, deformation behaviour and bruise susceptibility of the products under pre-defined loading cases, should be clearly described; however, this may become very complicated.

Opara and Pathare (2014) have published an enlightening review work on bruise damage measurement and analysis of fresh horticultural produce. They underline that among the research and industry there are currently no agreed criteria by which to assess the amount or susceptibility to bruising of the products; bruise volume, however, is the most commonly reported measure of the amount of bruise damage. Additionally, different objective indices exist for quantifying the potential of bruise damage occurring on the products under mechanical loading, but bruise susceptibility expressed as the amount of damage per unit of absorbed impact/compression energy is the most widely reported. In addition to image-processing-based non-destructive bruise detection methods, some analytical calculation methods based on physical experiments, such as pendulum and/or physical drop tests, are available today to determine bruise level or bruise susceptibility of fruit under impact (Van Zeebroeck et al., 2003; Van Linden et al., 2006; Opara et al., 2007; Eissa et al., 2012; Lu and Tang, 2012; Polat et al., 2012; Abedi and Ahmadi, 2013b; Opara and Pathare, 2014; Komarnicki et al., 2016). These methods, however, may not be efficient modes of describing proper deformation behaviour or internal stress progression, which may be considered the main cause of the cell structure failure of the products during impact. Consequently, their applications may be considered as limited for dynamic impact damage cases.

In fact, a bruise is a type of subcutaneous tissue failure without rupture of the skin of fruit-like products (Mohsenin, 1986). In this regard, the major reason for the bruises – plastic deformation which is seen behind the material elastic deformation limit (yield point) due to the internal stress progression during mechanical loading – may be considered a material failure. Here, it should also be highlighted that measuring or/and describing internal stresses which are associated with mechanical impact forces, is a very difficult phenomenon due to the biological cell structure of fruit and the rapid deformation progression during cases of dynamic and nonlinear impact. In light of this, numerical methods can be utilised as an efficient alternative solution for prediction of the stress distribution that occurs during impact. Numerical methods have been used in various engineering disciplines since the 1950s. These methods have furthermore been indicated as part of an effective, unique solution to the practical, complex problems experienced in agricultural engineering (such as impact cases of agricultural products) (Sitkei, 1986).

Nowadays, one of the most common numerical methods in use is the finite element method (FEM) which is utilised for obtaining approximate solutions to partial differential equations; the method has been applied successfully in many areas of engineering sciences to study, model, and predict the behaviour of structures (Khoei, 2015). The theoretical aspects of computer integration of the method were resolved in the 1960s and 1970s, and have resulted in a large body of scientific papers in various engineering fields (Munjiza et al., 2015). The method has also been found useful in the research field of agricultural engineering in the context of the deformation of agricultural products, and many studies have been conducted to estimate complex stress field of organic materials under various boundary conditions (Cardenas and Stroshine, 1991; Chen and De Baerdemaeker, 1993a,b; Chen et al., 1996; Lu and Abbott, 1997; Hernández and Bellés, 2007; Celik et al., 2008, 2011; Fabbri et al., 2011; Xu et al., 2011; Petrů et al., 2012; Ihueze et al., 2013; Tinoco et al., 2014; Guessasma and Nouri, 2015; Fabbri and Cevoli, 2016). Here, it should be highlighted that most of these studies have been conducted under considerations of static or quasi-static loading cases, small strain deformation and linear contact with linear elastic material model assumptions through implicit solvers. Consideration of the nonlinearity in part contact and plasticity in material models (particularly in drop or impact cases) in these type of studies is absent or very limited. Arguably, the small-strain and small-displacement-based FEM solution is not of much use in today's modern scientific, engineering and technological applications (Munjiza et al., 2015). The relationship between the loads and deformation may become nonlinear and at that point a nonlinear analysis should be undertaken in order to gain realistic results that reflect true-to-life behaviour.

In this context, the explicit solution approach has been pointed out as being valuable in solving loading cases such as impact/crash and drop test events. The explicit dynamics system is designed to simulate nonlinear structural mechanics applications. In complicated applications, explicit methods are more applicable and the explicit approach provides an alternative problem-solving procedure (Wakabayashi et al., 2008; SolidWorks Doc. 2010; Lee, 2012; Wu and Gu, 2012; ANSYS Doc. 2016). Therefore, here, it would not be wrong to say that deformation due to cases of impact of the fruit may be considered as nonlinear structural mechanics applications covered by the explicit dynamics system mentioned above. Today's technology allows us to work nonlinearity and time-dependent impact loading cases by means of numerical-methods-based simulation codes efficiently. However, these types of nonlinearity (geometry, contact and/or material nonlinearity) including explicit dynamics simulations have not yet become mainstream practices in the research related to the deformation of agricultural products due to impact. This has provided the main motivation for the current simulations presented here, in addition to the experimental work to reveal some engineering properties of a specific agricultural product (the Ankara variety of pears).

The determination of some engineering properties and bruise damage levels of pears under various loading conditions, including impact cases, has been studied by various researchers. Some of these researchers have investigated bruise damage levels and/or bruise susceptibility of pears through physical experiments such as pendulum/impact and axial compression tests. The common approach is to calculate the bruise volume by measuring physical bruise dimensions (bruise depth and bruise surface area). Here, the main drawback of physical experiments based analytical solutions is that they are not very accurate for describing complex bruise volumes with irregular geometry and nonsmooth boundaries. (García et al., 1995; Blahovec et al., 2002, 2004; Blahovec and Paprštein, 2005; Yurtlu and Erdoğan, 2005; Ozturk et al., 2009; Eissa et al., 2012; Komarnicki et al., 2016).

Other researchers have considered numerical method based simulation techniques in addition to physical experiments in their studies. Dewulf et al. (1999) and Song et al. (2006) have investigated the dynamic behaviour and vibration characteristics of a pear and their correlation with material characteristics by using FEM based modal analysis simulations. They assumed dynamic loading conditions and linear elastic material properties in their FEM simulations. Fenyvesi et al. (2013) have conducted a stress analysis study of fruit samples (apple and pear). FEM based simulations have been utilised to determine the stress state of the fruit' flesh, skin, core and seed components under static loading condition by assuming linear elastic material properties. In the area of impact phenomena, Yousefi et al. (2016) have studied drop