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Non-Linear Fem Based High-Speed Shell Shattering Simulation for Shelled Edible Agricultural Products: Pecan Fruit Shattering

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Abstract: This paper introduces an advanced engineering simulation procedure for the non-linear finite element method (FEM) based high-speed shattering case of shelled edible agricultural products. A high-speed impactor which is targeted at the Pecan fruit (kernel-in-shell) was considered in this case study. Physical compression tests were conducted on Pecan fruit specimens and experimental deformation characteristics were utilised to describe realistic material models in the FEM based engineering simulation. Subsequently, a reverse engineering approach was employed in the solid modelling stage and the Pecan shell shattering case under high-speed loading was simulated, considering the explicit dynamics approach. The effect of the high loading rate on the deformation characteristics of the Pecan fruit components was observed. Visual outputs from the simulation revealed the shattering behaviour of the Pecan fruit components under defined boundary conditions. In addition to useful visual simulation outputs, time-dependant stress distributions on the Pecan fruit under high-speed loading rates were represented using graphs. Simulation results have revealed that maximum equivalent stress values were 7.1 [MPa], 5.1 [MPa] and 0.336 [MPa] for shell, packing material and kernel respectively. Maximum reaction force at impact was calculated as 996 000 [N]. This work contributes to further research into the use of non-linear numerical method based high-speed deformation simulation studies for shelled edible agricultural products.

Keywords: Explicit dynamics, engineering simulation, High-speed shell shattering, shelled agricultural products, Pecan fruit.

Practical Application

As the industry relevance, useful deformation visuals and numerical findings related to impact shattering case of the Pecan fruit have been exhibited and the findings have been presented in a form which may be used as input parameters in design studies of shelled agricultural product processing machinery systems used in related industry.

1. Introduction

One of the most economically important members of the Carya genus is the Pecan fruit (*Carya illinoinensis*) in the Walnut family (Wood, 1994; Kotwaliwale *et al.,* 2007). The southern USA and northern Mexico are the production areas which are most well-known for Pecan fruit production. Over 98 % of the world's annual Pecan fruit production is conducted in these places. The United States Department of Agriculture (USDA) reported that the 2015 production forecast for Pecan yielded in the United States is 123,531.5 [ton] in total (USDA, 2015).

Recent years have witnessed an increase in consumer demand for Pecan fruit, particularly for its kernel because of its numerous health benefits (Kotwaliwale *et al.,* 2007; Robbins *et al.,* 2015; Bao *et al.,* 2013) most especially for pure peeled Pecan kernels which are extracted without chemical or thermal processing. Here, a mechanical shelling operation is essential to obtain the pure peeled kernel and this operation is the most critical and delicate step for achieving high-quality kernels in the shelled edible agricultural product processing industry. Efficient mechanised shelling units/systems needs to be developed/improved. In this regard, the engineering properties of shelled edible agricultural products is a pre-requisite for the design and development of cracking/shelling systems.

One of the most important experimental methods for the determination of related engineering properties and deformation characteristics of agricultural products is the compression test. This method is also the basis of current mechanical shelling systems. It is a well-known issue that compressive loading rate is an effective factor in the deformation of these products. Most existing shelling systems use low-speed compressive loading in mechanical shelling operations. Here, a question may arise: Can a design based on high-speed loading provide a faster shelling operation and allow for high-quality kernel extraction? In the literature, research related to high-speed shelling of shelled edible agricultural products is very limited (Prussia *et al.,* 1985). This has provided the main motivation for the current simulation presented in this paper.

Another motivation is that, in the literature, there are many computer aided engineering (CAE) studies related to determination of the engineering properties of shelled edible agricultural products and their focus is on predicting engineering properties and deformation/damage/failure characteristics of agricultural/food products by means of linear numerical methods based simulation applications (Chen & De Baerdemaeker, 1993; Chen *et al.,* 1996; Lu & Abbott, 1997; Hernandez & Belles, 2007; Celik *et al.,* 2008; Kabas *et al,* 2008; Fabbri *et al.,* 2011; Xu et al., 2012; Ihueze *et al.,* 2013; Petrua *et al.,* 2012; Tinoco *et al.,* 2014; Guessasma & Nouri, 2015; Fabbri & Cevoli, 2016). Most of them consider static low-speed loading with linear material model assumptions. Consideration of the high-speed loading and non-linearity in these studies are absent or very limited. Non-linearity and high-speed loading cases can now be worked in numerical method based simulation codes efficiently. However, these types of non-linear simulation have not yet become mainstream practice in research related to agricultural products deformation.

In agricultural engineering studies, many problems may become very complex (such as the high-speed shattering issue in this paper), however, they may be solved by numerical methods (Sitkei, 1986). Today's technology allows us to employ numerical methods in addressing complex problems which are very difficult to solve thorough analytical or experimental approaches. These numerical methods can be integrated to advanced CAE technologies efficiently. One of the most popular numerical methods is finite element method (FEM), which is used for solving engineering problems described by a set of partial differential equations and the deformation field on the organic materials can be estimated using FEM to a good level of accuracy (Chen & De Baerdemaeker, 1993; Celik *et al.,* 2011). Here, it should be highlighted that understanding the structural deformation behaviour of shelled agricultural products is an important issue for high quality kernel extraction and this “know-how” can lead to well-designed, efficient kernel extraction systems.

The low-speed compression scenario can be described as quasi-static loading, especially in the case of compression of agricultural products. High-speed loading considerations may change this case. In this context, highly non-linear and time dependant deformation should be considered. The explicit solution approach has proven valuable in solving high velocity loading cases. The explicit dynamics system is designed to simulate non-linear structural mechanics applications. In complicated applications, explicit methods are more applicable and the explicit approach provides an alternative problem-solving procedure. Therefore, here, it would not be wrong to say that high-speed deformation of shelled agricultural products may be considered as a non-linear structural mechanics application covered by the explicit dynamics system mentioned above (SolidWorks Doc., 2010; Wakabayashi *et al.,* 2008; Lee, 2012; Wu & Gu, 2012; ANSYS Doc., 2015).

This paper introduces a time-dependant non-linear (explicit dynamics) high-speed shell shattering simulation case study for Pecan fruit. The procedures followed in this study are detailed in the following sections.

2. Material & Methods

2.1. Physical testing

Whole Pecan fruit (kernel-in shell), its kernel and packing material were tested through compression tests separately. The main aim of these physical experiments is to determine physical deformation behaviour/characteristics and specific material properties such as modulus of elasticity, yield and fracture points of the Pecan fruit components. Some of these properties are used as input parameters in the simulation set up. Whole Pecan (kernel-in-shell), sliced kernel and packing material specimens were compressed through two rigid (relative to the product) plates and a cylindrical die (Die diameter: 2 [mm]) respectively. Three orientation loading scenarios were considered in whole kernel-in-shell fruit compression tests, namely longitudinal (Orientation-X), transverse (Orientation-Y) and suture (Orientation-Z) orientations. The Pecan fruit (Choctaw Variety) used in the tests were collected from Batı Akdeniz Agricultural Research Institute in Antalya (Turkey) in the harvest season of 2015 and the tests carried out at the biological materials test laboratory of the Department of Agricultural Machinery and Tech.' Engineering (Akdeniz University-Antalya-Turkey). A computer aided universal biological material test device (loading capacity: 2000 [N]) was utilised for the compression tests. Tests were carried out for a single moisture content of specimens (5.55 ± 1.87 % (w.b.)) at standard room temperature (20 [ºC]). Loading rate of 2.5 [mm min^{-1}] was set up for the tests to obtain accurately measured data (ASAE S368.4 W/Corr. 1 DEC 2000 (R2012)). The data sampling rate was 10 [Hz]. Ten specimens for each of the tests were utilised in this experimental study. Experimental setup, some physical measurements and graphical representation of the test results which exhibit the average force-deformation characteristics of the Pecan fruit components are shown in Figure 1, Table 1 and Figure 2 respectively.

(Figure 1. Compression test setup)

(Table 1. Some of the physical properties of the pecan fruit)

(Figure 2. Compression test results: Force-Deformation characteristics average curves (Number of specimens used in each of the tests: 10))

2.2. Description of the material models

Experimental data was used to calculate modulus of elasticity which is an essential property for determination of the deformation progression in the linear elastic loading stage of the materials (base on Hooke’s and Boussinesq’s theories – Figure 1) (Sitkei, 1986; Shelef & Mohsenin, 1967; Mohsenin, 1986; Blahovec, 1988; Blahovec, 1989; Stroshine, 1998; Ihueze & Mgbemena, 2015). Modulus of elasticity has been calculated in the linear elastic region of the stress-strain curves. The slope of the linear line in the elastic region of the force deformation curve is an indication of modulus of elasticity. The force deformation curves obtained from physical compression tests were converted to stress-strain curves for Pecan shell and kernel components to calculate modulus of elasticity.

The stage following the elastic deformation limit is known as the plastic deformation stage. This stage is accepted as the material separation stage for many brittle materials. For ductile materials, it is the transition stage to permanent shape deformation. In this context, plastic deformation of the materials may be seen as a material failure. Plasticity is concerned with materials which initially deform elastically, but which deform plastically upon reaching a yield stress (Pandey, 2016). In fact, this case is valid for most organic materials. This phenomenon may also be seen in the deformation of shelled edible agricultural products. In this sense, the bi-linear deformation characteristics of a sample material under tensile and compressive loads can be described as shown in Figure 3.

(Figure 3. Bi-linear stress-strain relation)

Figure 3 describes elastic-perfectly brittle and bi-linear strain hardening material deformation behaviours which are quite similar to the experimental deformation characteristics of the Pecan shell, packing material and kernel (Figure 2) respectively. Hence, it would not be wrong to make assumptions of orthotropic perfectly brittle and elastic-plastic (bi-linear strain hardening) material models for Pecan shells and the other components respectively in a FEM based simulation so that the deformation case can be simulated in a more realistic manner. In this regard, idealised material models and their properties can be described through experimental average true stress-true strain curves of the Pecan fruit components as described in Figure 4 and Table 2 respectively. Another important mechanical property is the Poisson's ratio in deformation analysis of the materials. In the literature, some researchers consider the Poisson's ratio values as 0.3 and 0.4 for shelled and soft/nut types of agricultural products respectively (Xu *et al.,* 2012; Mohsenin, 1986; Finney, 1963; Wang *et al.,* 1995; Cakir *et al.,* 2002; Grotte *et al.,* 2002; Burubai *et al.,* 2008; Patel *et al.,* 2008; Boac *et al.,* 2010; Khodabakhshian & Emadi, 2011; Kiani *et al.,* 2011; Khodabakhshian, 2012; Ipate *et al.,* 2013). These values were appointed in the simulation setup for the shell, the packing material and the kernel respectively.

(Figure 4. Idealised material models used in FEM simulation (Orthotropic elastic perfectly brittle and bi-linear isotropic hardening models on experimental average true stress-true strain curve of the Pecan fruit components)

(Table 2. Material properties)

2.3. *Simulation procedure*

One of the advantages of using reverse engineering (RE) technology in the agricultural research domain is that the technology allows the opportunity to obtain original/realistic digital computer aided design (CAD) models of the organic materials with their highly complex surface forms. It is significant because product geometry may have a determinant role in product deformation characteristics. Therefore the geometry should be described accurately.

In this work, the Pecan fruit (kernel-in-shell) was considered under loading of a high-speed impactor. The physical Pecan shell and kernel geometries were digitised using a Next Engine 3D desktop laser scanner. The scanning procedure was carried out for eight scanning sub-steps for the specimens in both vertical and horizontal positions. Macro range options with HD resolution was set up for the scanning process and total scanning time was 20 [min] approximately for each. SolidWorks 3D parametric solid modelling software features were used for ordering the surface mesh structure and final surface refining operations of the product's solid models.

In the simulation, a high-speed impact (hit and run) scenario in order to shatter the Pecan fruit (kernel-in-shell) was assumed. Explicit dynamics module of the ANSYS Workbench commercial FEM code was utilised to simulate the scenario. Boundary conditions with frictional contact definition (Friction coefficient between the fruit and impactor: 0.3) and idealized orthotropic elastic perfectly brittle and bi-linear isotropic hardening elastic-plastic material models were defined in the simulation setup for the shell, the packing material and the kernel respectively. The impactor was employed to hit and run the Pecan fruit (kernel-in-shell). High-speed of 10 [m s^{-1}] was appointed for the impactor loading rate. The impactor hit and run total stroke was set up as 64 [mm]. Standard earth gravity (9.81 [m s^{-2}]) was considered in the simulation. ANSYS Workbench advanced meshing functions with curvature meshing approach were used to create the mesh structure of the product components. The simulation scenario, boundary conditions and mesh structure details of the models are shown in Figure 5.

(Figure 5. Simulation setup)

3. Results & Discussions

After completion of the pre-processor steps, the simulation was run and the results were recorded. Visually, the simulation results clearly exhibited deformation behaviour of the Pecan fruit under high-speed loading condition (Figure 6). In addition to these useful visuals, numerical results based on the structural stress progression of the Pecan fruit components and reaction force progression between impactor and the fruit which are very complicated to obtain experimentally, were demonstrated through data graphs.

Double axis Graph-A and Graph-B given in Figure 6 demonstrate the maximum equivalent non-linear stress-deformation progression of the Pecan fruit components (shell, packing material and kernel) against time. Total simulation time was 6.4 10^{-3} [s]. Maximum equivalent stress values in Graph-A were 7.1 [MPa], 5.1 [MPa] and 0.336 [MPa] for Pecan shell, packing material and kernel respectively. Stress progressions in the physical tests were considerably linear until a critical damage point for the components were reached. Beyond these points, stress progressions represent plastic non-linear progression against the compression. Simulation results represented similar behaviour for the fruit components, however, for the shell, the reaction force due to initial contact was instant and this caused higher stress values than the experimental stress values obtained for the initial damage point of the shell (Graph-C). It demonstrated the loading rate effect on the material deformation. In the simulation, the case of brittle shattering was seen on the shell as a result of this instant stress progression being over the damage point of the shell material at many points during the impact action. Maximum reaction force at impact was calculated as 996 000 [N] (Graph-D). This value is a huge amount higher than experimental damage force values of the shell (see Table 2). Initial impactor contact to the fruit was instant. Therefore this very high value of force at the initial contact was experienced. However, maximum stress value of the kernel was lower than its experimental damage point (0.380 [MPa]) during the shattering case. The kernel deformation stayed within the linear deformation limits. It clearly indicates that there was no damage on the kernel: Damage-free kernel extraction in this hit and run scenario.

(Figure 6. Simulation results)

4. Conclusions

A mechanical kernel extraction method (basically applying compression) is one of the essential methods to extract kernels from shelled agricultural products without chemical and thermal processing. Most of the mechanical shelling systems have been designed in consideration of low-speed loading. However, high-speed shelling operations may be useful for faster and efficient mechanical kernel extraction operations. This paper can be considered as an initial draft research on this issue in order to achieve a well-designed mechanisation system for efficient faster agricultural production phases. This work contributes to further research into the usage of advanced engineering simulation techniques for the high-speed deformation analysis of shelled edible agricultural products.

Some of the most important points extracted from this study can be summarised as follows:

Physical tests for the specimens revealed the force-deformation characteristics of the Pecan fruit (kernel-in-shell), packing material and kernel separately under compressive loading conditions and important mechanical properties were calculated through a converted stress-strain relationship as described by Hooke's and Boussinesq's theories based modulus of the elasticity calculations.

Physical tests for the specimens revealed that, although initial deformations were linear and elastic up to a critical point, brittle and plastic deformation cases were experienced beyond these critical points, however these cases were instantaneous in the simulation for Pecan fruit components.

Experiment based material models, which were used in the non-linear time dependant FEM-based simulation procedure, were successfully described.

Realistic high-speed loading cases were successfully simulated as was intended. Simulation outputs exhibited logical structural deformation characteristics.

Simulations provided numerical results and the results revealed that there were non-linear changes in stress magnitudes against time during deformation. Maximum equivalent stress values were calculated as 7.1 [MPa], 5.1 [MPa] and 0.336 [MPa] for shell, packing material and kernel respectively. At the impact case, maximum reaction force was calculated as 996 000 [N].

Simulation outputs and numerical results indicated that damage free kernel extraction is successful in this high-speed hit and run scenario.

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FIGURE CAPTIONS

Figure 1. Compression test setup

Figure 2. Compression test results: Force Deformation characteristics average curves (Number of specimens used in each of the tests: 10)

Figure 3. Bi-linear stress-strain relation

Figure 4. Idealised material models used in FEM simulation (Orthotropic elastic perfectly brittle and bi-linear isotropic hardening models on experimental average true stress-true strain curve of the Pecan fruit components)

Figure 5. Simulation setup

Figure 6. Simulation results

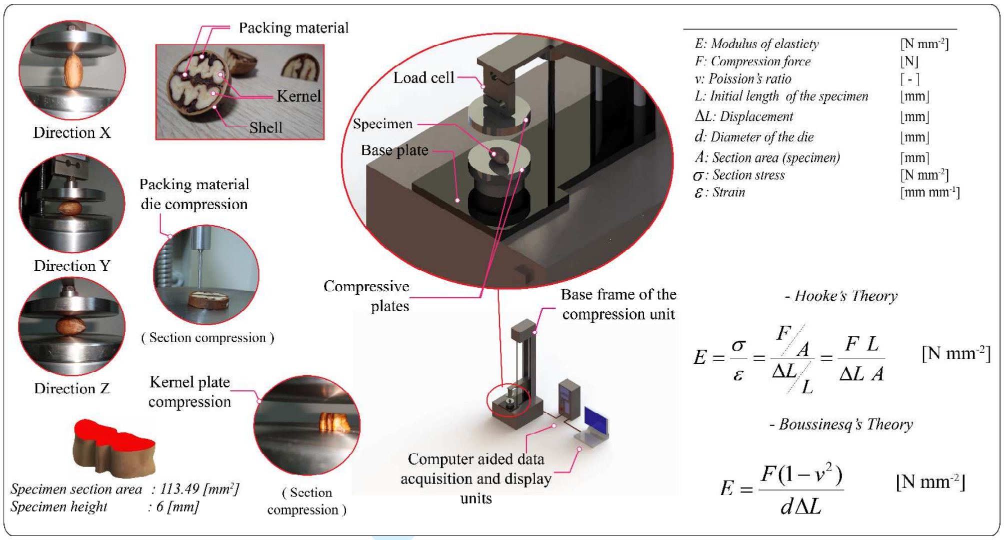


Figure 1. Compression test setup

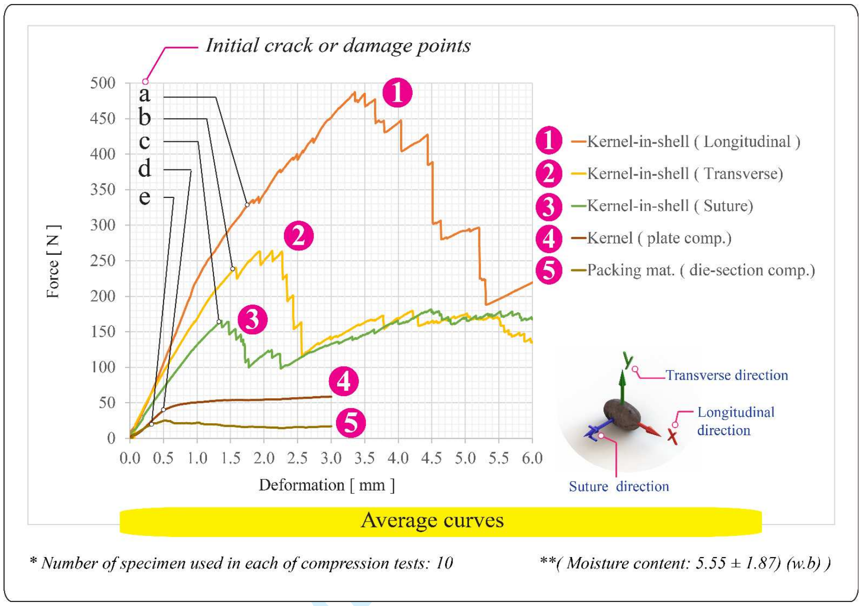


Figure 2. Compression test results: Force Deformation characteristics average curves (Number of specimens used in each of the tests: 10)

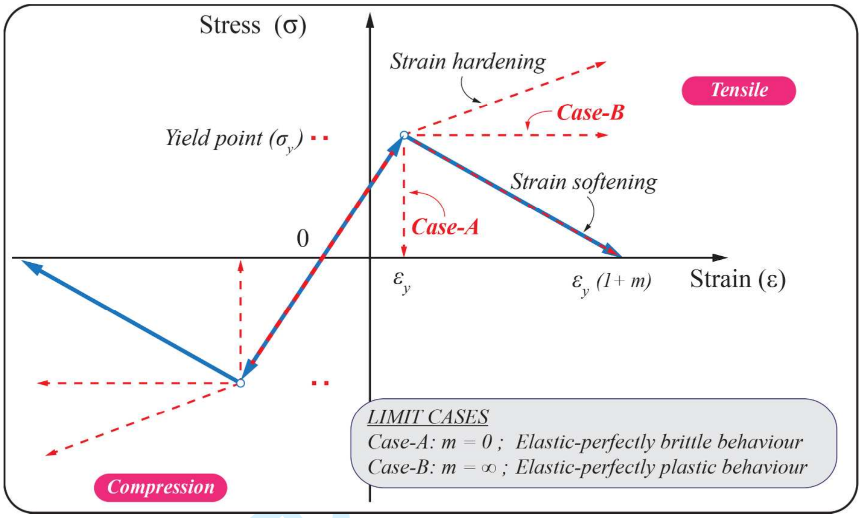


Figure 3. Bi-linear stress-strain relation

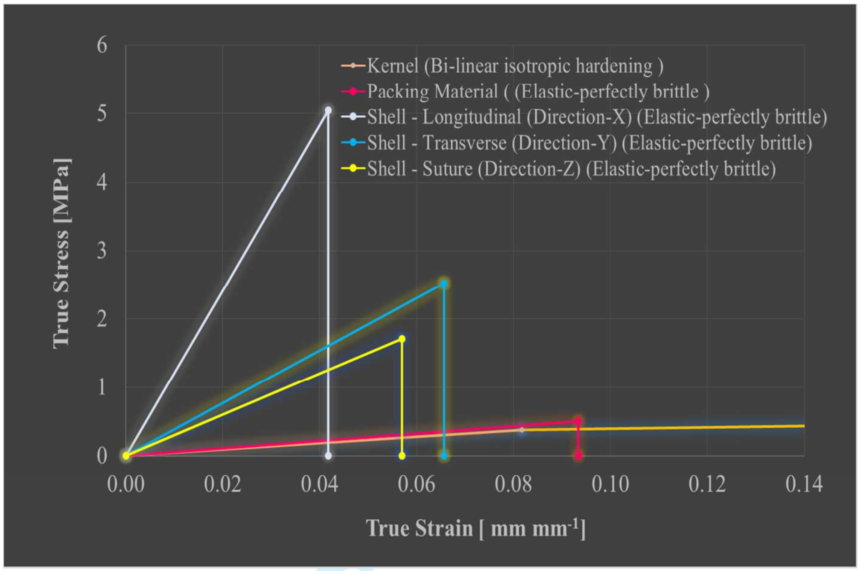
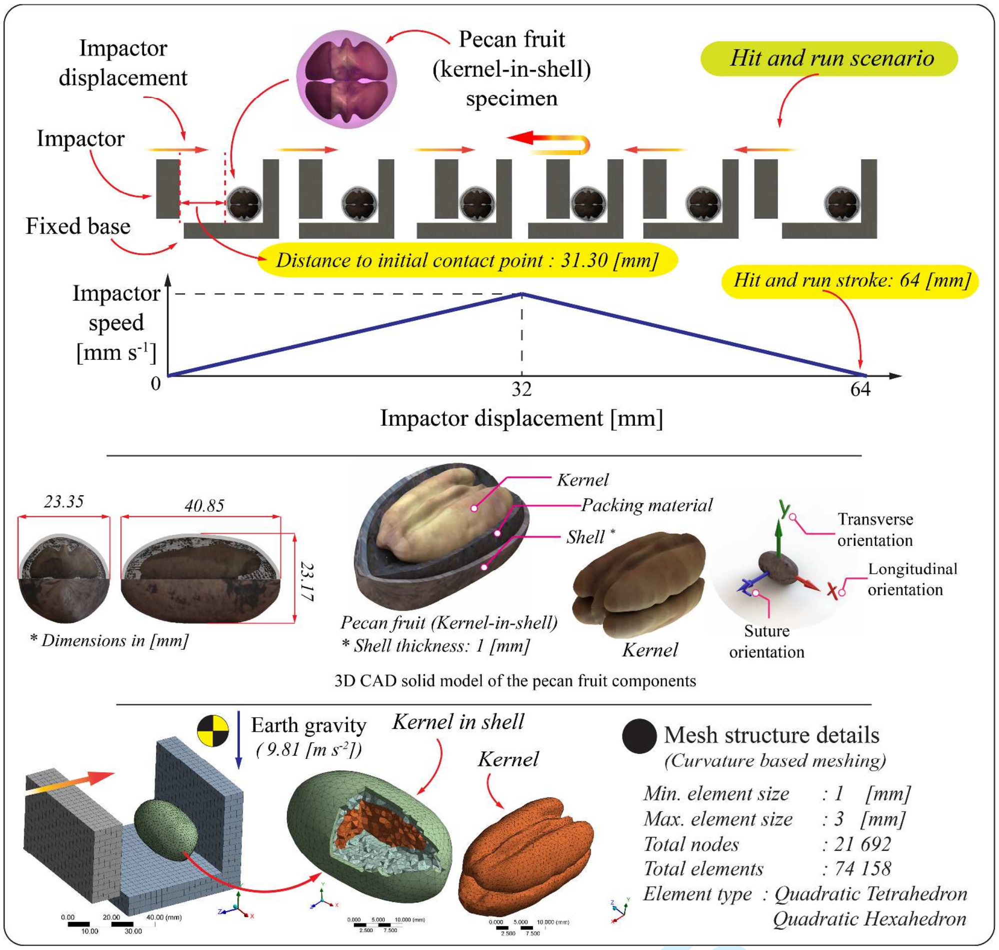
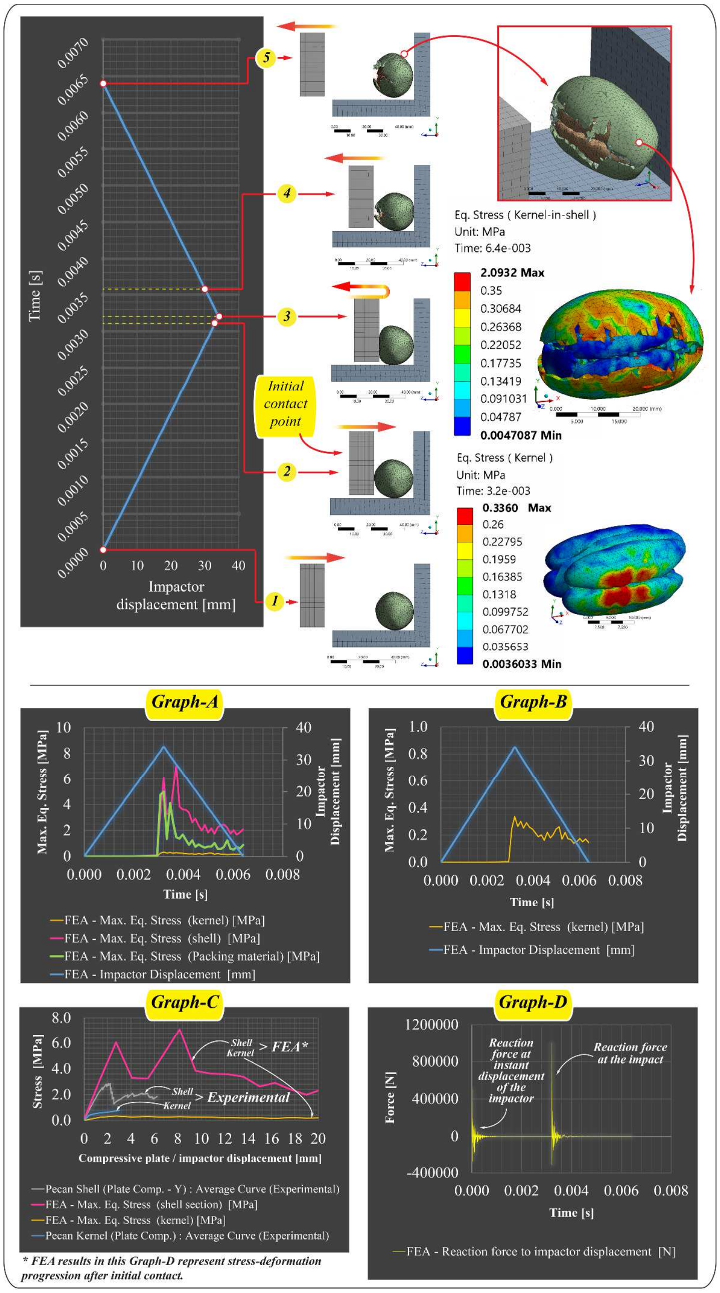


Figure 4. Idealised material models used in FEM simulation (Orthotropic elastic perfectly brittle and bi-linear isotropic hardening models on experimental average true stress-true strain curve of the Pecan fruit components)



Min. element size : 1 [mm]
Max. element size : 3 [mm]
Total nodes : 21 692
Total elements : 74 158
Element type : Quadratic Tetrahedron
Quadratic Hexahedron

Figure 5. Simulation setup



** FEA results in this Graph-D represent stress-deformation progression after initial contact.*

Figure 6. Simulation results

TABLE CAPTIONS

Table 1. Some of the physical properties of the pecan fruit

Table 2. Material properties

Table 1. Some of the physical properties of the pecan fruit

Some of the physical properties of the pecan fruit

Property[*,**]			Unit	Values
				Physical Measurements
Volumetric dimensions (Kernel-in-shell)		Longitudinal (Orientation-X)	[mm]	42.99 ± 3.12
		Transverse (Orientation-Y)		23.03 ± 2.02
		Suture (Orientation-Z)		23.31 ± 1.63
Shape index	$(y+z)/(2.x)$	(Kernel-in-shell)	[-]	0.54 ± 0.03
Geometric mean diameter	$(x.y.z)^{1/3}$		[mm]	28.43 ± 1.48
Sphericity	$((x.y.z)^{1/3}).100.x^{-1}$		[%]	66.25 ± 2.63
Shell thickness			[mm]	1.2 ± 0.37
Moisture content (w.b.)			[%]	5.55 ± 1.87

** Number of specimen used in each of physical measurements: 10*

*** Definition of the properties and related measurement methods were referenced from Mohsenin 1986, Sitkei 1986 and Stroshine 1998*

Table 2. Material properties

Material properties used in FEM based simulation

Fruit component	Compression orientation	Modulus of elasticity [MPa]	Poisson's ratio
Shell	Orientation-X	122.220 (R^2: 0.999)**	0.3
	Orientation-Y	47.614 (R^2: 0.999)**	
	Orientation-Z	34.251 (R^2: 0.999)**	
Kernel	Normal to section	3.881 (R^2: 0.986)**	0.4
Packing Material	Normal to section	29.712***	0.3

Fruit component	Density [kg m^{-3}]	Force @ Damage point (Compression) [N]	Damage/Failure point [MPa]
Shell	1100	335.62*	5.045
		239.42*	2.530
		165.03*	1.710
Kernel	1150	39.80*	0.380
Packing Material	330	24.53*	0.500

** Extracted from average curves(Experimental force-deformation data)*

*** Based on Hooke's theory, slope of the true stress-strain curve in elastic region (tanα = modulus of elasticity)*

**** Based on Boussinesq's theory (Cylindirical die comp.)*