Research Paper / Araştırma Makalesi

Non-linear FEM Based Compression Simulation of Pecan Fruit Kernels

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ABSTRACT

This paper introduces a finite elements method (FEM) based non-linear deformation simulation procedure for applicable nut kind of agricultural products for oil extraction. A case study was carried out on a sample pecan fruit kernel. Experimental and theoretical methods were utilised in this study. Some engineering properties to define in the FEM based engineering simulation were determined through physical compression tests. Subsequently, deformation of a kernel specimen was simulated considering non-linear simulation approach with assumption of elastic-plastic material model. Visual print-outs from the simulation results revealed a good accordance with experiments. This work contributes to further research into the usage of non-linear numerical method based deformation simulation studies for applicable nut kind of agricultural products.

Keywords: Pecan, Deformation, Compression test, Finite elements method, Simulation

Pikan Meyvesi Çekirdeklerinin Doğrusal Olmayan Sonlu Elemanlar Yöntemi Temelli Simülasyonu

ÖZ

Bu araştırmada yağı çıkartılabilir kabuklu tarım ürünlerine ait çekirdek meyvenin deformasyonu üzerine odaklanılmış ve bu ürünlerin doğrusal olmayan (non-lineer) deformasyonu için sonlu elemanlar yöntemi (FEM) temelli bir simülasyon prosedürü tanıtılmıştır. Araştırmada deneysel ve teorik yöntemler kullanılarak pikan meyvesi çekirdeği için örnek bir uygulama yürütülmüştür. FEM temelli simülasyon çalışmasında tanımlanmak üzere ürüne ait bazı fiziksel ve mekanik özellikler deneysel rijit yüzeyler arası sıkıştırma/bası testi ile belirlenmiştir. Daha sonra elastik-plastik malzeme modeli kabulü ile pikan cevizi çekirdeği deformasyonu doğrusal olmayan yaklaşımla simüle edilmiştir. Simülasyon ve fiziksel testler sonucu elde edilen görsel sonuçlar birbirleri ile oldukça uyumlu bulunmuştur. Bu araştırma, yağı çıkartılabilir kabuklu tarım ürünlerine ait çekirdek meyvenin doğrusal olmayan sayısal yöntemler ile deformasyonun belirlenmesi konusunda yapılacak ileriki çalışmalara katkıda bulunacaktır.

Anahtar Kelimeler: Pikan, Deformasyon, Bası testi, Sonlu elemanlar yöntemi, Simülasyon

INTRODUCTION

The world's most popular nuts are peanut, almond, cashew, pistachio, walnut, hazelnut, and pecan [1]. Nowadays, a considerably rise in production and consumer focus on pecan fruit can be noticed. The word "pecan" itself is of Algonquian origin and means "all nuts requiring a stone to crack." [2]. Pecan fruit *(Carya illinoinensis)* is one of the most economically important member of the *Carya* genus. In fact, it is a member of the walnut family [3, 4]. Over 98% of the world's annual Pecan fruit production is produced in the southern United States and northern Mexico. Production forecast of 2015 for Pecan fruit produced in the United States is 123 531.5 [ton] in total (approximately). This production amount hits to 72% of the world's Pecan production

(approximately) [5]. Pecan fruit are consumed for their flavour and for nutrition, and they have garnered increased attention for their numerous health benefits [4, 6, 7]. Most especially, consumers are nowadays paying more and more attention to pure cold-pressed pecan kernel oil.

Pecan oil is edible pressed oil extracted from the pecan kernel which is light weight oil and is usually pale yellow in colour. Pecan oil is neutral in flavour and takes on the flavour of whatever seasoning is being used with it. Pecan oil contains 9.5% saturated fat, which is less than in olive oil (13.5%), peanut oil (16.90%) or corn oil (12.70%). It is also used as massage oil and in aromatherapy applications [8].

In edible oil production, most manufacturers avoid the use of chemical extraction methods in order to preserve the natural nutty flavour and nutrients of oil. Therefore, mechanical extraction methods are used to extract oil. This is basically a compression process. In this process, it is important to determine mechanical properties and deformation characteristics of kernels in order to proceed optimally designed oil extraction systems. This has provided the main motivation to the present research work. Another motivation is that many studies can be found in the literature about predicting engineering properties and deformation/damage/failure characteristics of the agricultural/food products by means of linear Finite Element Method (FEM) based simulation applications [9-23]. Consideration of the non-linearity in these studies are absent or very limited. Non-linearity can now be considered in FEM based simulation codes. However, these types of non-linear works have not yet become a mainstream practice in the deformation investigation studies of agricultural products. In this content, an explicit dynamics non-linear FEM based elastic-plastic deformation simulation procedure for Pecan fruit kernel is introduced in this present study.

MATERIALS and METHODS

Experimental Procedure

Physical compression tests were carried out for Pecan fruit kernels. Major aim of these physical tests is to determine the product's physical deformation behaviour/characteristics and specific material properties such as modulus of elasticity, yield and fracture points. Some of these properties may also be defined as input parameters in the simulation studies. Sliced kernel specimens (specimen height: 6 mm) were compressed between two rigid (relative to the product) plates. Pecan fruit used in the tests were collected from Batı Akdeniz Agricultural Research Institute in Antalya (Turkey) in the harvest year of 2014 and the tests were carried out at the biological materials test laboratory of the Department of Agricultural Machinery and Techologies 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 with a single moisture content of specimens (5.20 ± 2.58 % (w.b.)) at room temperature (20ºC). Loading rate of 2.5 mm min^{-1} was set up for all tests to obtain precisely measured data [24]. Data sampling rate was 10 Hz. Ten specimens were used in physical tests. Physical testing set up and graphical demonstration of the test results which can exhibit force-deformation characteristics of kernels are shown in Figure 1.
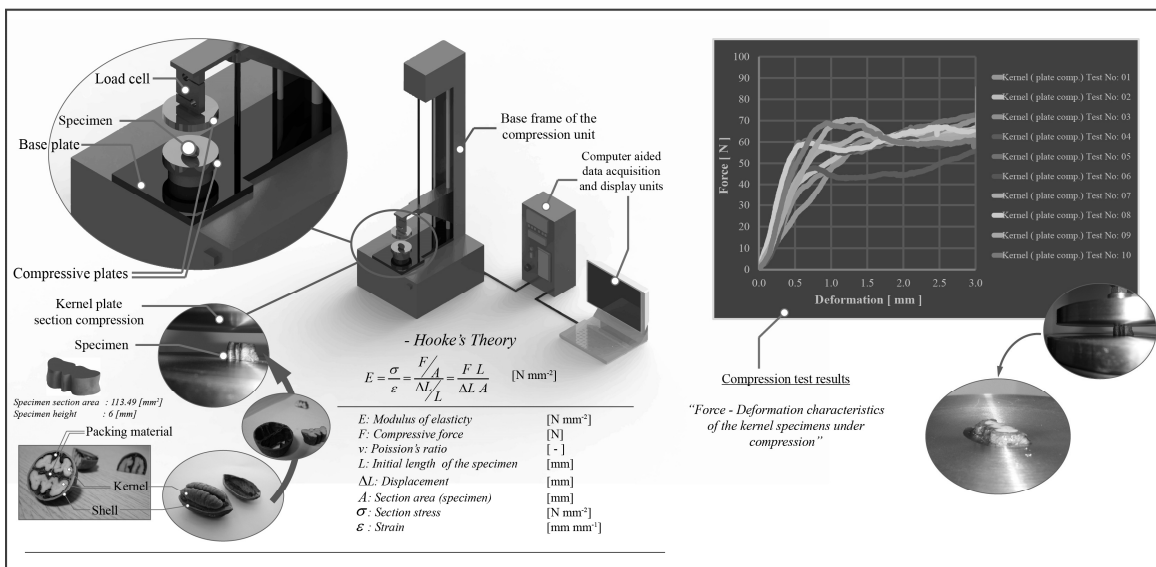

Figure 1. Compression test

Material Model

Relationship between axial loading force and deformation can be used in the calculation of modulus of elasticity, which is an important property for the determination of the linear elastic deformation of agricultural products. [25-31]. Beside, some problems involve plastic deformation. Analysis of problems involving small plastic strains allows one to design structures optimally, so that they will not fail when in service, but at the same time are not stronger than they

really need to be. In this sense, plasticity can be seen as a material failure. It is valid for most of organic materials. In fact, the classical theory of plasticity grew out of the study of metals in the late nineteenth century. It is concerned with materials which initially deform elastically, but which deform plastically upon reaching a yield stress [32]. This case may also be seen in the deformation of agricultural products. In this sense, bi-linear stress-strain relation under tensile and compression load can be drawn as shown in Figure 2.
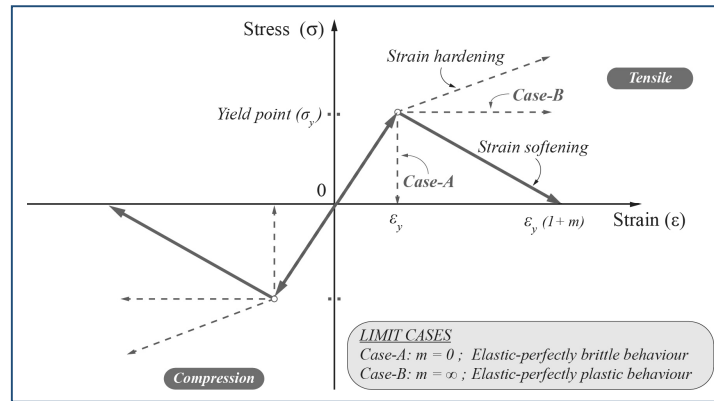

Figure 2. Bi-linear stress-strain relation

Bi-linear isotropic hardening plastic material deformation behaviour described in Figure 2 shows similarity to a kernel deformation as it can be seen from experimental deformation characteristics of the kernel (Fig. 1). Hence, it would not be wrong to make assumption of elastic-plastic material model for kernel in FEM based simulation so that deformation case can be simulated in more realistic manner. In this content, idealised material model and its properties can be described through average true stress-true strain curves of the kernel as they are given in Figure 3.

Another important parameter to be described in stress/deformation investigation for agricultural products is Poisson's ratio. Many researchers have also studied Poisson's ratio for various agricultural products [18, 26, 33-43]. Although none of these studies gives clear information for the value of Poisson's ratio of Pecan fruit kernel, some of them consider the Poisson's ratio value for soft/nut kind agricultural products as 0.4.

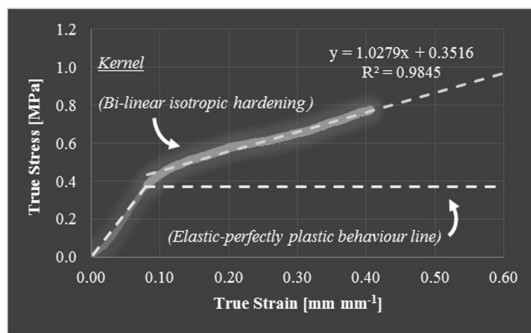| (Bi-linear isotropic hardening)	
Modulus of Elasticity [MPa]	3.881
Tangent Modulus [MPa]	1.028
Yield Point [MPa]	0.381
Force @ Yield Point [N]	39.80
Poisson's Ratio [-]	0.4
Density [kg m^{-3}]	1150

Figure 3. Idealised kernel material model and properties used in FEM simulation (Bi-linear isotropic hardening model on experimental average true stress-true strain curve of the kernel)

Non-Linear FEM Based Simulation Procedure

The practical cases (such as kernel deformation issue in this paper) in agricultural engineering mostly represent complex problems, which may be solved by numerical methods [27]. Nowadays, FEM is one of the desirable numerical methods, which can be integrated to

advanced computer aided technologies. FEM is a numerical method for solving engineering problems described by a set of partial differential equations and stress deformation field on the organic materials can be estimated using FEM in a good level of accuracy [16, 44]. Here, it should be highlighted that understanding the structural deformation behaviour of agricultural products is an important issue for high

quality kernel oil extraction and this "know-how" would lead a well-designed efficient oil extraction systems.

In the literature, most of the researchers consider homogeneous linear elastic material model assumptions to study deformation issues of agricultural products through implicit solver with static loading condition; however, the relationship between the loads and the response may become non-linear and a non-linear analysis must be performed in order to gain accurate results that reflect true to life behaviour. Here, non-linearity can be considered for material models, (for example, hyper-elasticity, plastic flows, failure), contact conditions (for example, high speed collisions and impact) or/and geometric deformation cases (for example, buckling and collapse) [45].

Compression case can be described as quasi-static loading case with highly non-linear contact conditions most especially in compression tests of agricultural products. The explicit solution method has proven valuable in solving quasi-static problems as well in addition to high velocity loading cases. The explicit dynamics system is designed to simulate nonlinear structural mechanics applications involving one or more of the following: Impact from low to very high velocity; stress wave propagation; high frequency dynamic response; large deformations and geometric nonlinearities; complex contact conditions; complex material behaviour including material damage and failure; nonlinear structural response including buckling and snap through; failure of bonds/welds/fasteners; Shock wave propagation through solids and liquids; rigid and flexible bodies. In such cases, explicit methods are more applicable and the explicit approach provides an alternative problem-solving procedure. It is essentially an incremental method. Therefore, deformation of the nut kind agricultural products may be considered as non-linear structural mechanics applications covered by the explicit dynamics system mentioned above [46-49].

The geometry is vitally significant in rheological investigations such as structural deformation, flow and heat/mass transfer analyses and their aerodynamic and hydrodynamic behaviour investigations. Therefore a proper description of the product to be realised. In this point, advances in reverse engineering (RE) technology and related applications may help researchers to obtain original digital computer aided design (CAD) models of the organic materials with their complex surface forms.

In this study, half kernel model was considered. Physical kernel geometry digitalised through 3D desktop laser scanner (Next Engine). Scanning procedure carried out for six scanning sub-steps for sample component surface in both longitudinal and transverse positions. HD resolution at macro range options was set up for the scanning process and total scanning time was 20 min approximately. SolidWorks 3D parametric design software features were used for ordering surface mesh structure and final surface refining operations of the kernel's solid model.

In the non-linear FEM simulation, explicit dynamics module of the ANSYS Workbench commercial FEM code was utilised. Physical boundary conditions with frictionless contact definition and bi-linear isotropic hardening elastic-plastic material model were defined in the set up. Bottom plate was fixed and upper plate was employed to compress the kernel. Loading rate of 2.5 mm min^{-1} was set up for upper plate. Curvature meshing approach was employed and ANSYS Workbench advanced meshing functions were used in creating mesh structure of the kernel model. Solid modelling process, boundary conditions and mesh details of the kernel model can be seen in Figure 4.
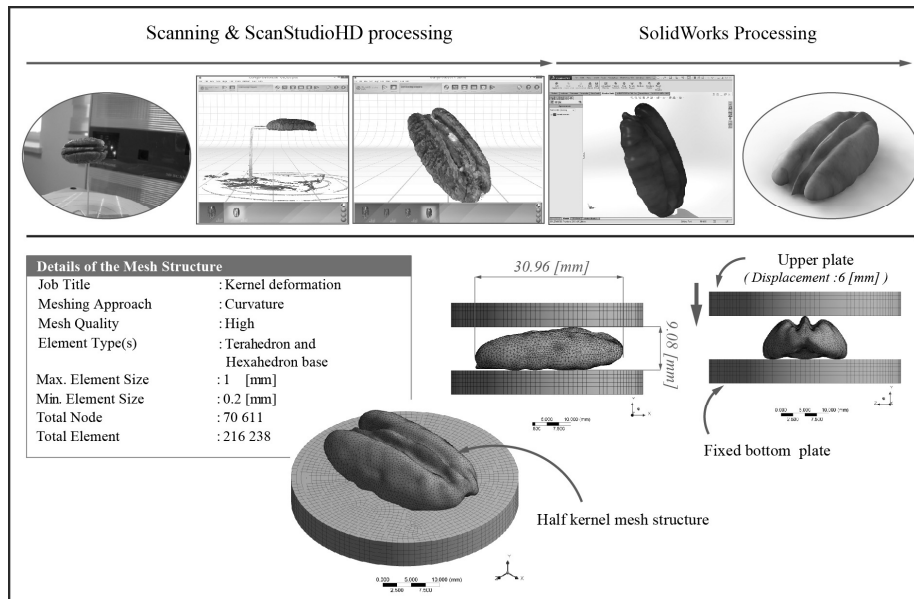

Details of the Mesh Structure	
Job Title	: Kernel deformation
Meshing Approach	: Curvature
Mesh Quality	: High
Element Type(s)	: Terahedron and Hexahedron base
Max. Element Size	: 1 [mm]
Min. Element Size	: 0.2 [mm]
Total Node	: 70 611
Total Element	: 216 238

Figure 4. Simulation set up

RESULTS and DISCUSSIONS

After pre-processor operations completed, simulation was run and results were saved. In the visual manner, results extracted from simulation exhibited a good accordance with physical deformation results. Half kernel under plate compression experienced plastic deformation at the end of simulation as it was validated in the physical case. Double axis Chart A given in Figure 5 demonstrates maximum equivalent non-linear stress and elastic-plastic deformation progressions of the half kernel against the time. Compression case run time in the simulation was 100 s. Maximum equivalent stress and deformation values in this Chart A were 1.281 MPa and 4.942 mm respectively. It was also obvious in the Chart A that deformation was considerably linear till a critical point. Beyond this point, deformation progressed plastically. The other Chart B represents simulation results of the half kernel stress-deformation progression against physical stress-deformation of the test specimen (sliced kernel specimen used in physical compression test). Although, this Chart B exhibited that there is a visible difference between numerical values of the simulation and experimental results, stress progression behaviour against deformation was quite similar in simulation and experiments. Geometry of the products under loading is a significant factor in their deformation characteristics. Therefore, this difference was obvious because of loading case of the different geometries (half kernel and sliced specimen). Different stress values should be expected because of different cross-section areas which may experience even the same compressive forces.
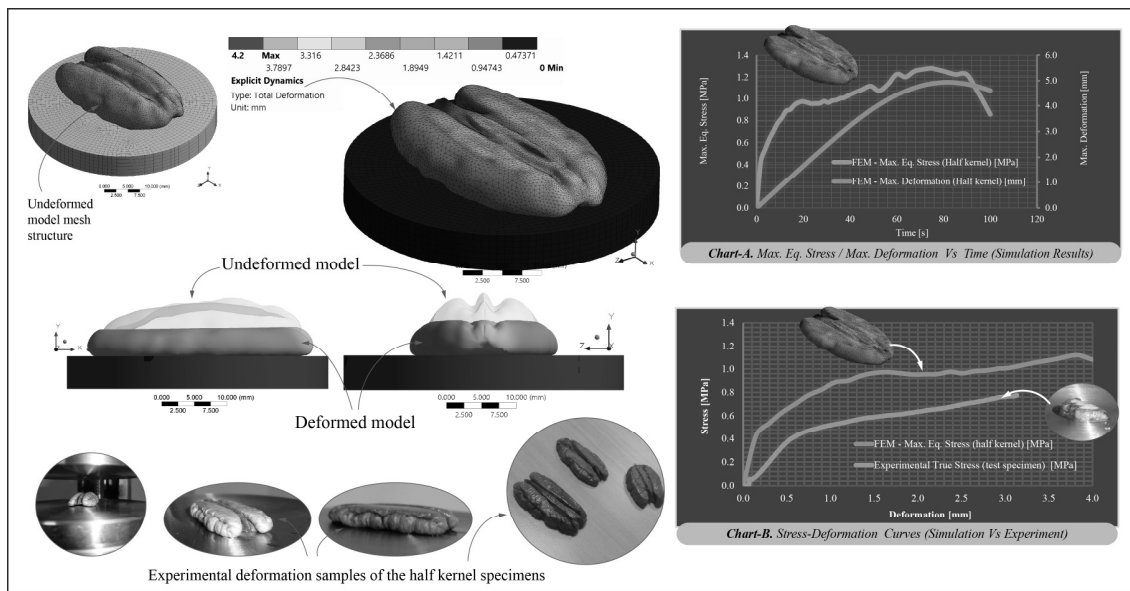

Figure 5. Simulation Results

CONCLUSION

Pecan oil is a great substitute for conventional cooking fats such as olive oil or/and butter to use in everyday cooking. Pecan oil has a very subtle nutty flavour and it contains the lowest levels of saturated fat. Therefore, there is an increase in attention for pecan oil which is mechanically extracted without chemical or thermal processes. Cold-pressing/mechanical oil extraction method is one of the essential methods to extract pure oils from nut kind products without chemical process. It is basically a compression method. In this content, determination of deformation characteristics of the target products under specific compression loading condition (pressing) plays a significant role in design of related machinery systems. Nowadays technology presents efficient engineering applications to realise productive well-designed agricultural systems. Especially, advanced engineering simulation applications are very promising. However, these type of applications have not yet become mainstream practice in design of shelled edible agricultural product processing industry. This work motivates to further research into usage of advanced numerical method based engineering simulation studies for applicable agricultural products.

Some of important points extracted from this study can be summarised as given below;
1. Physical tests for the specimens revealed the force-deformation characteristics of the pecan fruit kernel under compression loading case and important mechanical properties such as modulus of elasticity, yield and fracture points were calculated through base elasticity theories given in the related literature. Particularly, this study has provided reference data of some mechanical properties of the pecan fruit kernel to use in engineering simulation studies.
2. Physical tests for both sliced and half kernel specimens exhibited that although, the specimen deformation was linear and elastic till a critical point of deformation, plastic deformation case was seen beyond this point. This know-how is an

important parameter in design of mechanical extraction systems.

3. This elastic-plastic deformation case embedded to the material model used in the non-linear time depended FEM based simulation procedure and realistic compression simulation accomplished as it was aimed. Simulation print-outs of the deformation visuals validated by physical deformation visuals. Their deformation behaviour were seen very close each other (Figure 5).

4. Numerical results obtained from simulation also revealed that there were changes in stress-deformation values against time. In this process, maximum equivalent stress and deformation values were calculated as 1.281 MPa and 4.942 mm respectively. And it was also seen that stress progression behaviour against deformation was quite similar in simulation and physical experiments results.

In the future work perspective, it should be highlighted that in addition to geometry of the products, loading rate is one of the significant factors in their deformation characteristics under compression. In fact, it is well known issue that loading rate is also effected on the product deformation characteristics, however, there is no enough information about Pecan fruit deformation under various loading rate compression. Therefore future studies may focus on loading rate effect on deformation of the Pecan fruit components such as its shell and kernel.

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