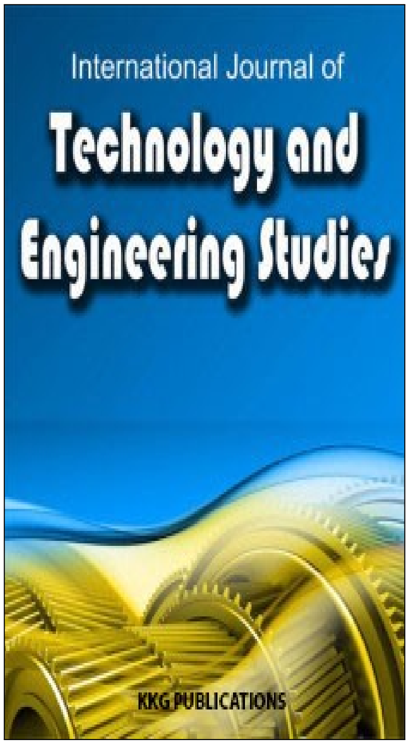

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H. KURSAT CELIK [1], GOKHAN KUNT [2], ALLAN E. W. RENNIE [3], IBRAHIM AKINCI [4]

[1, 2, 4] Faculty of Agriculture, Akdeniz University, Antalya, Turkey
[3] Engineering Department, Lancaster University, Lancaster, UK

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NON-LINEAR FEM-BASED SHATTERING SIMULATION OF SHELLED EDIBLE AGRICULTURAL PRODUCTS: WALNUT SHATTERING BY NUT CRACKER HAND TOOL

H. KURSAT CELIK [1]*, GOKHAN KUNT [2], ALLAN E. W. RENNIE [3], IBRAHIM AKINCI [4]

[1, 2, 4] Faculty of Agriculture, Akdeniz University, Antalya, Turkey

[3] Engineering Department, Lancaster University, Lancaster, United Kingdom

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Abstract. This paper presents a case study for non-linear Finite Element Method (FEM) based shattering simulation of shelled edible agricultural products. Walnut shell shattering using a simple nutcracker hand tool was considered in this case study. Some engineering properties were determined through physical compression tests to describe material models used in the FEM-based engineering simulation. Subsequently, a reverse engineering approach was employed in the solid modeling stage. The Walnut shell shattering case using a simple nutcracker hand tool was simulated considering non-linearity (explicit dynamics approach). Visual print-outs from simulation results revealed the shattering behavior of the walnut under defined boundary conditions. In addition to useful simulation print-outs of the shattering case, the time-dependent deformation behavior of the walnut during shattering was represented through charts. This work contributes to further research into the usage of non-linear numerical method-based deformation simulation studies for shelled edible agricultural products.

INTRODUCTION

Walnut fruit is one of the oldest cultivated fruits in the world. The Walnut fruits kernel is consumed for its flavour and for nutritional reasons. It is a highly appreciated type of nut product because of its unique organoleptic characteristics and good sources of dietary fibre, various vitamins and minerals [1], [2]. They have garnered increased attention for their numerous health benefits. A considerable rise in production and consumer focus on walnut fruit has also been witnessed. The Food and Agriculture Organization of the United Nations (FAO) statistics indicate that the total production amount in the world in 2013 (FAOSTAT data May 2015) for Walnut fruit (kernel in shell) was 3,467,015.532 [tonnes], with the top five walnut producing countries being China (49.1%), Iran (13.1%), United States of America (12.1%), Turkey (6.1%) and Ukraine (3.3%). Most especially, consumers are paying more and more attention to the peeled Walnut kernel. To obtain the peeled kernel, a shelling operation is necessary. The shelling operation is the most critical and delicate step for achieving high quality kernels. Here, the mechanical properties of shelled agricultural products is a pre requisite for the design and development of cracking/shelling systems. Besides industrial shelling systems, domestic consumers use simple hand tools to extract the kernel. This is a basic compression process. In consideration of this, it is important to determine the mechanical properties and deformation characteristics/behaviour of the walnut in order to progress optimally designed kernel extraction systems for both domestic users and industrial bulk production. This has provided the main motivation for the current simulations presented here. Another motivation is that there are many studies in the literature which are focused on predicting engineering properties and deformation/damage/failure characteristics of the agricultural/food products by means of linear FEM based simulation applications [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. Consideration of the non linearity in these studies is absent or very limited. Non linearity can now be worked in FEM-based simulation codes efficiently. However, these types of non linear simulation have not yet become mainstream practice in research related to agricultural products' deformation.

The practical cases (such as the Walnut shell shattering issue in this paper) occurring in agricultural engineering mostly represent complex problems, which may be solved by numerical methods [18]. Nowadays, FEM is one of the popular 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 with a good level of accuracy

*Corresponding author: H. Kursat Celik
†Email: hkcelik@akdeniz.edu.tr

[3], [19]. 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" would lead to well designed, efficient kernel extraction systems. In the literature, most of the studies are constructed on homogeneous linear elastic material model assumptions, considering deformation issues of agricultural products through implicit solvers with static loading conditions, however, the relationship between the loads and deformation may become non linear and at that point a non linear analysis should be undertaken in order to gain realistic results that reflect true-to-life behaviour. Non linearity can be divided into three aspects: Material models, (for example, hyper-elasticity, plastic flows, failure) (1); Contact conditions (for example, non linear contact conditions at high/low speed collisions and impact between elements) (2); and/or geometric deformation cases (for example, buckling and collapse) (3) [20]. The compression case can be described as a quasi static loading case with highly non linear contact conditions, especially in the case of compression of agricultural products. The explicit solution approach has proven valuable in solving quasi static problems, in addition to 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, it would not be wrong to say that deformation of the shelled agricultural products may be considered as non linear structural mechanics applications covered by the explicit dynamics system mentioned above [21], [22], [23], [24]. As mentioned above, this paper introduces an explicit dynamics non-linear FEM-based deformation simulation case study for Walnut shell shattering using a simple nut cracker hand tool.

METHOD AND MATERIALS

Experimental Procedure

Physical compression tests were carried out for the Walnut (kernel-in-shell) and its kernel separately. Experimental procedures were set up in order to determine their physical deformation behaviour/characteristics and specific material properties such as modulus of elasticity, yield and fracture points. Some of these properties were also essential as input parameters in the simulation studies. Whole Walnut (kernel in shell) and sliced cubic kernel specimens (kernel specimen dimensions: 4x4x5 [mm]) were compressed between two rigid (relative to the product) plates. Three orientation loading scenarios were considered in whole walnut compression tests, namely longitudinal (Direction X), transverse (Direction Y) and suture (Direction Z) orientations. The Walnut type used in the tests were imported American Walnuts and they were collected from a commercial market shelf randomly in January 2016. All tests and measurements were carried out at the biological materials test laboratory of the Dept. 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.

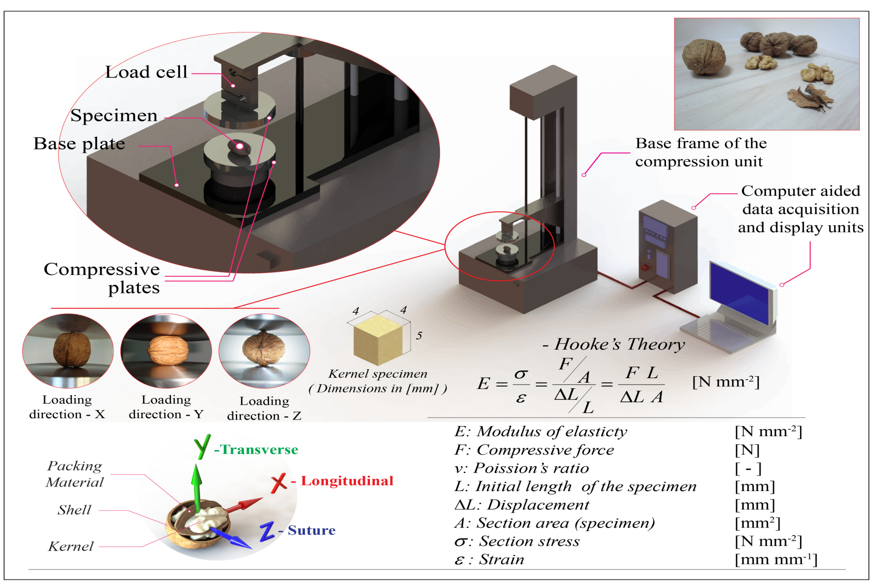

Fig. 1. Compression test setup

Tests were carried out for single moisture content of specimens (6.86 ± 0.22% (w.b.)) at standard room temperature (20 [^{o}C]). Loading rate of 2.5 [mm min 1] was set up for the tests to obtain precisely 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 and graphical representation of the test results which exhibit the average force deformation characteristics of the Walnut (kernel in shell) and kernel specimens are shown in Fig. 1 and Fig. 2 respectively.

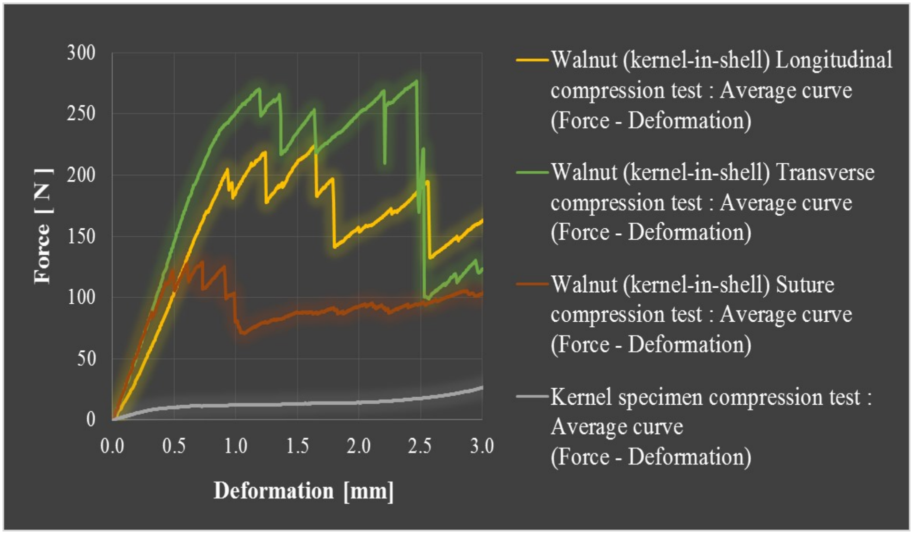

Fig. 2. Compression test results: Force Deformation characteristics average curves
(Number of the specimens used in each of the tests: 10)

Material Model

True stress-strain data were converted from experimental force deformation data. They were used to calculate modulus of elasticity which is an essential property for determination of the deformation in the linear elastic loading stage of the materials [18], [25], [26], [27], [28], [29], [30]. Behind the elastic deformation, some problems may involve plastic deformation cases. Plastic deformation of the materials may be seen as a material failure. In fact, it is valid for most organic materials. Plasticity is concerned with materials which initially deform elastically, but which deform plastically upon reaching a yield stress [31]. This phenomenon may also be seen in deformation of agricultural products. In this sense, the bi linear stress-strain relation under tensile and compression load can be drawn as shown in Fig. 3.

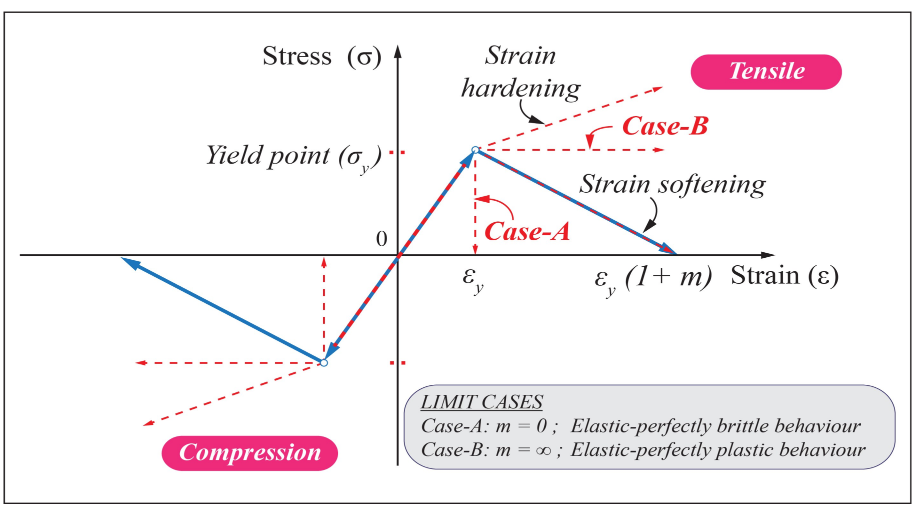

Fig. 3. Bi-linear stress-strain relation

Elastic perfectly brittle and bi linear strain hardening material deformation behaviours are described in Fig. 3, which are quite similar behaviours to the experimental deformation characteristics of the Walnut shell and kernel (Fig. 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 Walnut shell and kernel respectively in a FEM-based simulation so that the deformation case can be simulated in a more realistic manner. Same material model was defined for packing material. The material model for the hand cracker tool was also assumed as an elastic plastic (bi linear strain hardening) material model (stainless steel from FEM code's non linear material library). In this regard, idealised material models and their properties can be described through experimental average true stress true strain curves of the Walnut shell and the kernel, as given in Fig. 4 and Table 1 respectively. Poisson's ratio is another important parameter which is essential in deformation investigations of agricultural products. Poisson's ratio has been studied for various agricultural products by a large number of researchers. Some of them consider the Poisson's ratio values as 0.3 and 0.4 for shelled and soft/nut types of agricultural products respectively [12], [26], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42].

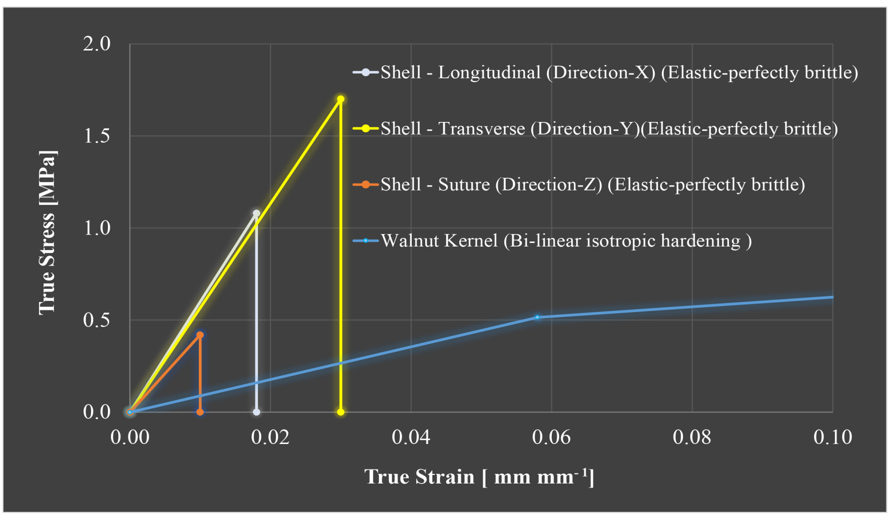

Fig. 4. Idealised Walnut shell and kernel material models used in FEM simulation (Orthotropic elastic perfectly brittle and bi-linear isotropic hardening models on experimental average true stress-true strain curve of the Walnut components)

TABLE 1
MATERIAL PROPERTIES

Material Properties	Shell (Longitudinal)	Shell (Transverse)	Shell (Suture)	Kernel	Stainless Steel
Modulus of Elasticity* [MPa]	63.916	71.783	42.770	9.335	193 x 10^3
Tangent Modulus** [MPa]	-	-	-	2.235	1.8 x 10^3
Yield Point (Damage) [MPa]	1.080	1.700	0.420	0.515	210
Force @ Yield Point [N]	162.640	229.574	83.707	7.770	-
Poisson's Ratio [-]	0.30	0.30	0.30	0.40	0.31
Density [kg m^{-3}]	1044	1044	1044	958	7750

* Slope of the average true stress-strain curve in elastic region (tan α = modulus of elasticity)

**Slope of the average true stress-strain curve in plastic region (tan β =Tangent Modulus)

Non Linear FEM-Based Simulation Procedure

To obtain more realistic and accurate deformation results, a realistic description of the product geometry should be used in the structural analysis, because product geometry plays a significant role in rheological investigations. One of the most useful methods of obtaining original/realistic digital Computer Aided Design (CAD) models of the organic materials with their complex surface forms is to use advanced Reverse Engineering

(RE) tools. In this work, the whole Walnut (kernel in shell) model was considered. The physical Walnut 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 30 [min] approximately. SolidWorks 3D parametric solid modelling software features were used for ordering surface mesh structure and final surface refining operations of the product's solid models. In addition, solid models of the Walnut components and a simple nut cracker hand tool design were realised specifically for this study.

In the non linear FEM simulation, a hand tool compression scenario in order to shatter the Walnut fruit (kernel in shell) was assumed. Explicit dynamics module of the ANSYS Workbench commercial FEM code was utilised to simulate the scenario. Physical boundary conditions with frictional contact definition and idealized orthotropic elastic perfectly brittle and bi-linear isotropic hardening elastic-plastic material models were defined in the simulation setup. The bottom handle was fixed and the upper handle of the tool was employed to compress the Walnut fruit (kernel in shell).

An exaggerated loading rate of 2 [m s $^{-1}$] was assumed for upper plate compression in order to gain the physical solution time. The upper handle was compressed by 10 [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 in creating the mesh structure of the product components. The simulation scenario, boundary conditions and mesh details of the models are demonstrated in Fig. 5.

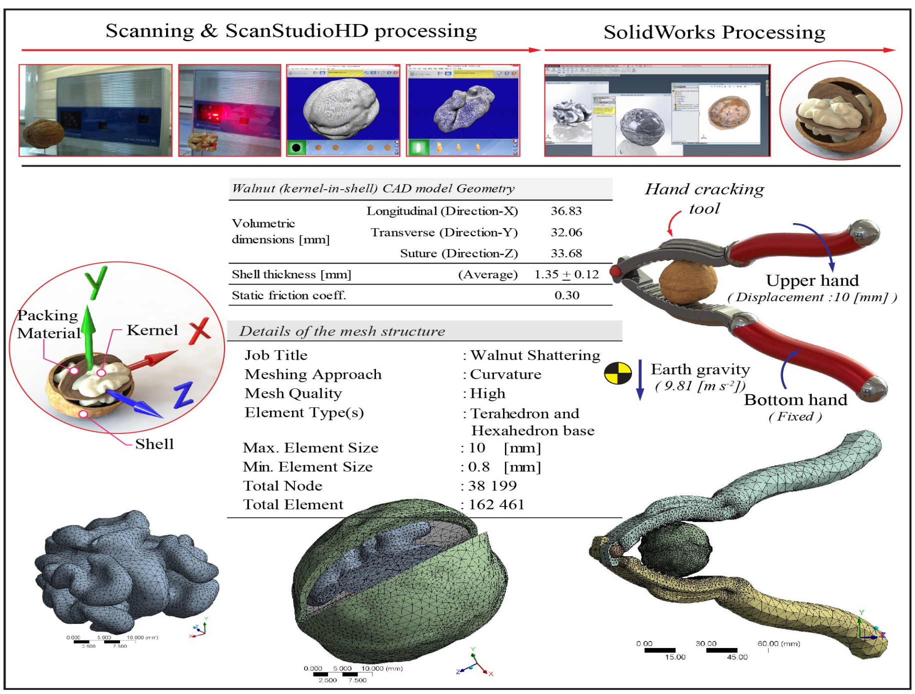

Fig. 5. Simulation set up

RESULTS AND DISCUSSION

After completion of the simulation solve time, the results were recorded. Visually, the simulation results extracted show logical physical deformation behaviour for the Walnut fruit and the hand tool under defined boundary conditions (Fig. 6). In addition to these useful visuals, numerical results based on the structural stress progression of the Walnut components, which are very complicated to obtain experimentally, were exhibited through data graphs.

Double axis chart A given in Fig. 6 demonstrates the maximum equivalent non linear stress deformation progression of the Walnut fruit components (whole fruit, shell and kernel) against time. Total simulation time was 0.005 [s]. Maximum equivalent stress values in this chart A were 5.370 [MPa] and 0.274 [MPa] for Walnut shell and kernel respectively. Whole Walnut (kernel in shell) stress progression can also be seen in this chart A. Stress progressions are considerably linear until a critical damage point for the shell is reached. Beyond these points, stress progressions represent non linear progression against linear compression. The case of shattering was seen on the shell as a result of the stress progression being over the damage point of the shell material at many points during the compression action. Here, there can be seen differences in the stress progression between the shell and whole Walnut (kernel in shell). After deformation time of 0.002 [s] (approximately), the kernel started to make a contribution to the resistance against the compressive tool, which caused higher stress values for the whole walnut as is seen in the chart, however, the kernel deformation stayed within the linear deformation limits (damage point: 0.515 [MPa]). It clearly indicates that there was no damage on the kernel: Damage-free kernel extraction. The other chart B represents stress deformation progression of the nut cracker hand tool against time. At first sight, maximum equivalent stress value of 288 [MPa] on the tool was beyond the defined yield point of the tool material (210 [MPa]). This indicated a plastic deformation failure on the tool. Geometry of the products under loading is a significant factor in deformation characteristics. This result highlights that a design change on the tool geometry should be realised.

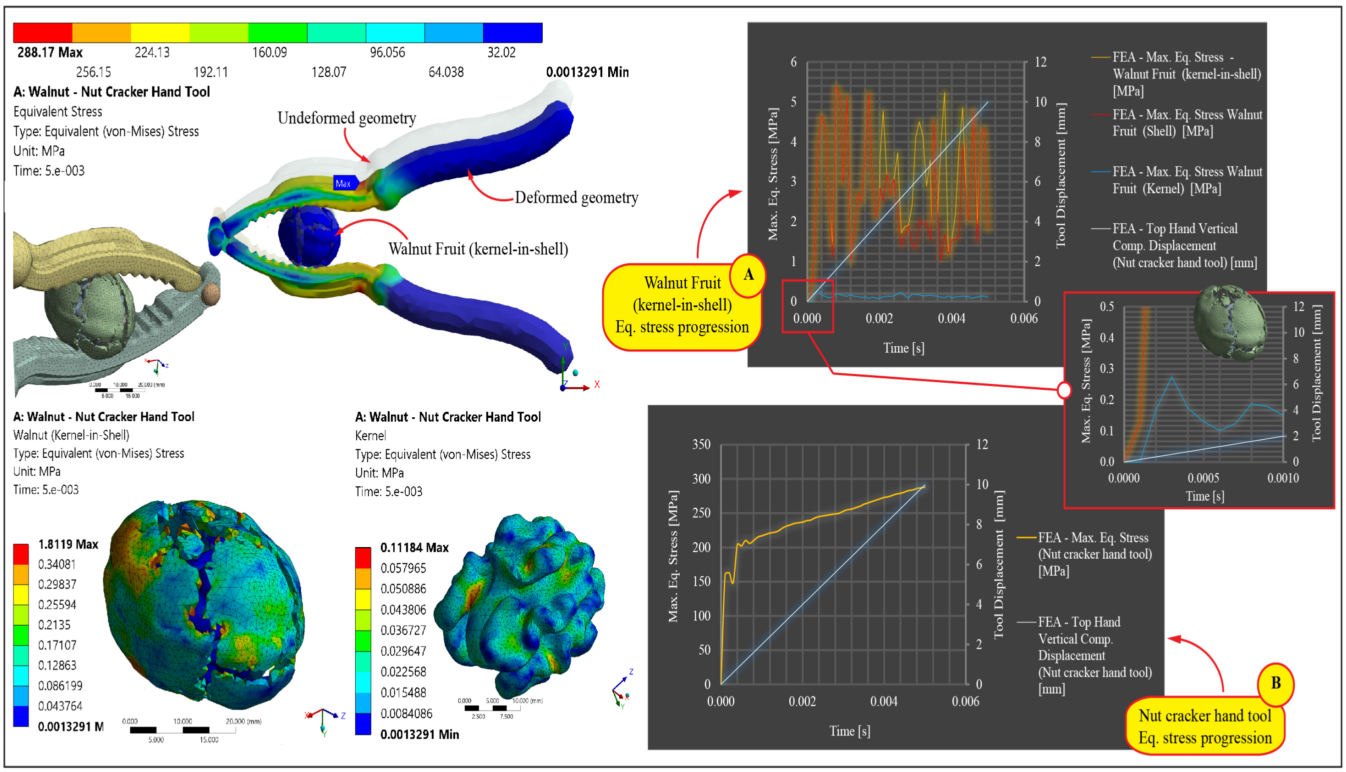

Fig. 6. Simulation results

CONCLUSION AND RECOMMENDATIONS

Mechanical kernel extraction method (basically applying compression) is one of the essential methods to extract kernels from shelled agricultural products without chemical processing. In this context, determination of the deformation characteristics of the target products under specific compression loading condition plays a significant role in the design of kernel extraction systems. Nowadays, technology allows for the realisation of productive, well designed mechanisation systems for efficient agricultural production phases. Most especially, advanced engineering simulation applications exhibit great promise for efficient product processing and these applications will inevitably become mainstream practice in the design of the agricultural product processing industry. Some of the most important points extracted from this study can be summarised as follows:

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

2. 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 in the tests for Walnut shell and kernel respectively.

3. Experienced deformation cases were embedded into the material models which were used in the non linear time dependant FEM-based simulation procedure, and realistic compression simulations were accomplished as was intended. Simulation print outs exhibited logical physical deformation/characteristics.

4. Numerical results obtained from simulations also revealed that there were non linear changes in stress magnitudes against time during deformation. Maximum equivalent stress values were calculated as 5.370 [MPa], 0.274 [MPa] and 288 [MPa] for shell, kernel and the hand tool respectively.

5. Simulation results revealed plastic deformation failure on the nut cracker hand tool. This indicates that a design change could be necessary on the tool geometry for failure-free nut cracking operations.

One of the well known issues, which has affected the product deformation characteristics, is loading rate. Change of the loading rate may cause a different deformation response of the product under compression. In this study, a quick shattering case was considered in order to gain a physical simulation run-time. In future work, the focus may be on the loading rate effect on the deformation of Walnut fruit components under various loading rate conditions. This work contributes to further research into the usage of advanced numerical method-based engineering simulation studies for edible shelled agricultural products.

Declaration of Conflicting Interests

There are no associated conflicts of interest.

Acknowledgment

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