CRACKING SIMULATION OF HAZELNUT SHELL USING FINITE ELEMENT METHOD

ONDER KABAS

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Hazelnuts are subjected to major quality losses because of undesired physical damage during harvesting, threshing and processing. Therefore, mechanical properties and deformation behavior of the product should be determined to minimize the damage and losses during harvest and post-harvest operations. This would also help in designing agricultural machines. However, it is quite difficult to determine the amount of damage on agricultural products under dynamic loading conditions. Nowadays, one of the useful methods used in deformation analyses of the materials is the finite element analysis which has also been used in different engineering disciplines to simulate the deformation behavior of materials since the 1950's. In this study, a compression simulation was carried out for the hazelnut variety 'Tombul'. Some cracking properties were also determined using experimental and finite element analyses. As a result, it was highlighted that computer-aided simulations can help determe the behavior of biological materials under physical loading during pre-harvest and post-harvest operations.
Keywords: hazel nut, simulation, FEM (finite elements method), compression

Knack-Simulation der Haselnussschale nach der Finite-Elemente-Methode. Haselnüsse sind aufgrund unerwünschter physikalischer Beschädigungen beim Ernten, Dreschen und Verarbeiten erheblichen Qualitätsverlusten ausgesetzt. Daher sollten die mechanischen Eigenschaften und das Verformungsverhalten des Produkts bestimmt werden, um Schäden und Verluste während und nach der Ernte zu minimieren. Dies würde auch bei der Konstruktion landwirtschaftlicher Maschinen helfen. Es ist jedoch ziemlich schwierig, das Ausmaß der Beschädigung landwirtschaftlicher Erzeugnisse unter dynamischen Belastungsbedingungen zu bestimmen. Heutzutage ist eine der nützlichen Methoden bei der Verformungsanalyse von Materialien die Finite-Elemente-Analyse, die seit den 1950er-Jahren in verschiedenen technischen Disziplinen zur Simulation des Verformungsverhaltens von Materialien eingesetzt wird. In dieser Studie wurde eine Kompressionssimulation für die Haselnusssorte 'Tombul' durchgeführt. Einige Knack-Eigenschaften wurden auch unter Verwendung von experimentellen und Finite-Elemente-Analysen bestimmt. Das Ergebnis zeigte, dass computergestützte Simulationen dazu beitragen können, das Verhalten von biologischem Material unter physikalischer Belastung während Vor- und Nacherntevorgängen zu bestimmen.
Schlagwörter: Haselnuss, Simulation, FEM (Finite-Elemente-Methode), Kompression

Turkey is the leading hazelnut producer of the world. The majority of the country's production comes from the Eastern Black Sea Region. With an annual production of 600.000 tons from 705.000 hectares, Turkey yields about 70 % of the world hazelnut production (Islam, 2018) followed by Italy, Azerbaijan, USA, Georgia and Spain (Selvi, 2017). Turkey exports about 75 % of its hazelnuts, and the total export revenue from hazelnuts and hazelnut products is about 1 billion US $ annually. Therefore, hazelnuts contribute significantly to the country's economy (Ozdemir and Akinci, 2004). Besides economic value, hazelnut provides a unique and distinctive flavor as an ingredient in a variety of food products and plays a major role in human nutrition and health (Alasalvar et al., 2003).

The traditional harvesting method consists of collecting hazelnuts from the ground and a preliminary precise selection is then needed to remove stones, dirt, trash, branches, leaves, etc. (Delprete and Sesana, 2014). The physical and mechanical properties such as Poisson's ratio, yield stress point, modulus of elasticity, damage force and specific deformation, density etc. of the kernel and the shell are important parameters used in the design of processing machines. These parameters are also important for the analysis of the deformation behavior of the product during agricultural processes and operations such as handling, planting, harvesting, threshing, cleaning, sorting and drying (Patil et al., 2014). Hazelnuts are subjected to major quality loss during harvesting, threshing and processing. Since the kernel can be affected by cracking, its extraction from the shell is the most critical and delicate process in the processing of hazelnut (Kacal and Koyuncu, 2017). Shelling-induced damage greatly reduce the market value of hazelnuts. The extent and type of damage depend on the characteristics of the hazelnut variety and of the sheller. It is therefore significant to ensure accurate scientific data on the comparative characteristics of hazelnut varieties for a reliable design of the processing machines. The varieties 'Tombul' and 'Cakildak' are commonly cultivated in Turkey. They differ from each other in some properties such as shape, linear dimensions, shell thickness and hardness of kernel and shell etc. Countless studies have been assigned to textural parameters of different varieties of nuts. Shariffian and Derafshi (2008) studied the mechanical behavior of walnut under cracking conditions. Valentini et al. (2006) investigated mechanical behavior of hazelnuts used for table consumption under compression loading. Similarly, Delprate and Sesana (2013) evaluated the mechanical properties of kernel and shell of hazelnuts. Guner et al. (2003) analyzed four Turkish varieties of hazelnut under compression loading, and evaluated the effects of shell moisture and compression axis on mechanical behaviors of hazelnuts. One of the most important factors for shelling is the mechanical force applied to the hazelnut (Guner et al., 2003).

Mechanical crashing force is a hard to comprehend issue due to the biological cell structure of the product and the rapid deformation progression during the cases of dynamic and nonlinear impact. In the past sixty years, systems have been successfully implemented in which computers, software and numerical methods were integrated (Selvi and Kabas, 2017). Numerical methods can be utilized as an efficient alternative of analytical methods for prediction of the stress distribution that occurs during impact forces (Celik, 2017b). Numerical methods are powerful tools used for simulating and investigating material behavior within specified boundary conditions and Finite Element Method (FEM) is one of these methods (Salarikia et al., 2017). FEM has become a staple for predicting and simulating the physical behavior of complex engineering systems (Madenci and Guven, 2015) and some researches have applied FEM to determine the static and dynamic behavior of some agricultural products under impact loading (Xu, 2011; Petru et al., 2012; Ihueze et al., 2013; Celik, 2017b; Salarikia et al., 2017).

In this study, finite element method (FEM) was used to simulate the compression of hazelnut shell in different directions and further to predict mechanical damage of hazelnut shell. The elasticity of modulus of shell is one of the basic input parameters in deformation simulation studies. Fracture mechanism was simulated to get some engineering properties in addition to modulus of elasticity values of hazelnut shell components. Present findings may guide machine designers in optimization of key components of cracking machines for nut fruits.

MATERIAL AND METHODS

FRUIT MATERIAL

Hazelnuts were used as the sample organic material in this study to investigate deformation under compression scenarios. 'Tombul' variety nuts (*Corylus avellana*) were manually harvested in September 2016 from an orchard in Giresun, Turkey. One hundred samples (hazelnuts) were selected randomly and used in the experimental study in order to measure their mechanical and physical properties.

All physical measurements and tests were carried out at the biological material test laboratory of the Department of Agricultural Machinery and Technologies Engineering (Akdeniz University, Antalya, Turkey).

Moisture content of each hazelnut shell (8.64 ± 1.44 %, w. b.) was determined with the aid of the method described by ASAE (1983). Hazelnut samples were weighed with a precise scale (± 0.001 g), dried to a constant mass in an oven at 105 °C and reweighed. The moisture content was then calculated with the use of the following equation (Aviara et al., 2005)

$$M_{w.b} = \frac{W_i - W_f}{W_i} \times 100 \qquad (1)$$

where M_{wb} is wet-basis moisture content (%), W_i is initial mass of sample (g) and W_f is final mass of dry sample (g).

HAZELNUT PHYSICAL PROPERTIES

The physical properties of hazelnuts were determined by the following methods: Linear dimensions, i. e. length (L), width (W), and thickness (T), were determined using a CAD model geometry and shell thickness was measured with Vernier calliper (± 0.01 mm) (Celik, 2017a).

Fruit mass (M) was measured using a precise balance (± 0.001 g). Fruit density was determined using the liquid displacement method. Toluene (C_7H_8) was used instead of water, as it is absorbed by fruit to a lesser extent. Also, its surface tension is low, so that it fills even shallow dips in a fruit and its dissolution power is low (Mohsenin, 1980; Sitkei, 1986).

HAZELNUT MECHANICAL PROPERTIES

To determine mechanical properties of hazelnuts, compression tests were conducted using a computer-aided universal testing machine (Lloyd Instruments, Bognor Regis, England) with a 2000 N load cell. All of the mechanical tests were carried out for the single moisture contents of the specimens (8.64 ± 1.44 %). Compression tests of food materials are described in the ASAE standard (ASAE, 2001).

All tests about mechanical properties of hazelnuts were carried out for three orientations of the product (Longitudinal (X), Transverse (Y) and Suture (Z)) in three replications for each hazelnut sample (Fig. 1) and 2.5 mm/min loading velocity was used to compress the fruit during all tests. The data sampling rate was 10 Hz and 50 specimens were used for each of the compression tests (Celik, 2017a). The set-up for compression testing is shown in Figure 2.

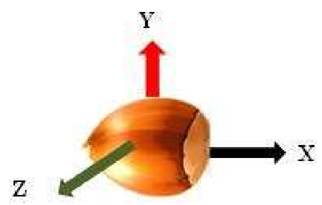

Fig. 1: Loading orientations of hazelnuts in compression test

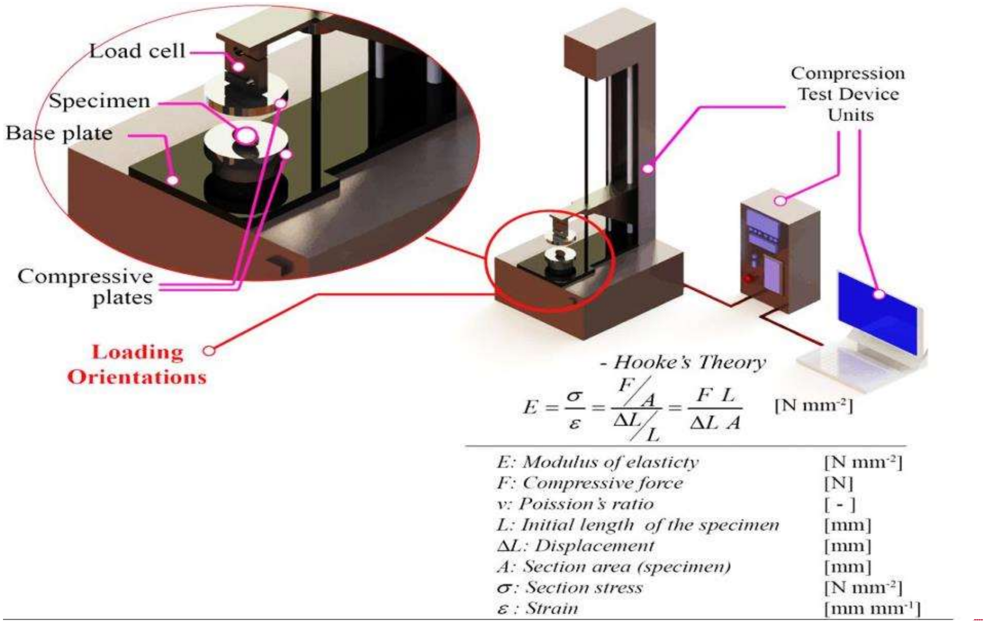

Fig. 2: Compression test setup

Poisson's ratio (λ) of the fruit was calculated using the following formula and by measuring the final diameter and length after deformation (Mohsenin, 1980)

$$\lambda = \frac{\Delta D}{\Delta L} = \frac{(D_i - D_f)}{(L_f - L_i)} \qquad (2)$$

where, D_i is the initial diameter (mm), D_f is the final diameter (mm), L_i is the initial length (mm), and L_f is the final length of the fruit (mm).

Modulus of elasticity was 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 expressed as modulus of elasticity (Ihueze and Mgbemena, 2017; Celik, 2017a).

SIMULATION SETUP

Structural static module of the ANSYS Workbench commercial FEM code was utilized to simulate the compression scenario. ANSYS Workbench is a FEM-based analysis software used to solve complex engineering problems. The software is used in industry and academic studies in order to optimize product design and reduce the cost and time of physical testing (Anonymous, 2019). In this study, the boundary conditions of hazelnut compression, linear contact definitions and idealized linear orthotropic elastic models were assumed in the simulation setup. It was assumed that the shell material was perfectly brittle. It means that the shell will show elastic material property up to a pre-defined damage point (yield point) and then will show sudden break/deformation beyond this point. In order to obtain material properties used in the simulation study, experimental force-deformation data were converted into stress-strain data (true stress-strain data), subsequently related material properties were extracted from experimental true stress-strain test data.

In the simulation scenario, the bottom plate was fixed, and the upper compressive plate was employed to compress the hazelnut product in longitudinal orientation (only shell). The upper plate was compressed by 1.5 mm. Standard earth gravity (9.81 m/s^2) was considered in the simulation. ANSYS Workbench advanced meshing functions with standard meshing approach were used in creating finite element model (mesh structure) of the product.

In creating 3D CAD data of the hazelnut shell, reverse engineering approach was utilized to obtain realistic surface form of the product. A NEXTENGINE 3D Desktop scanner (NextEngine, Inc., Santa Monica, US) was used. Scanned surfaces were ordered through the ScanStudioHD and SolidWorks 3D parametric design software and realistic solid model was obtained.

CAD modelling procedure, the simulation scenario, boundary conditions and mesh details of the models are demonstrated in Figure 3.

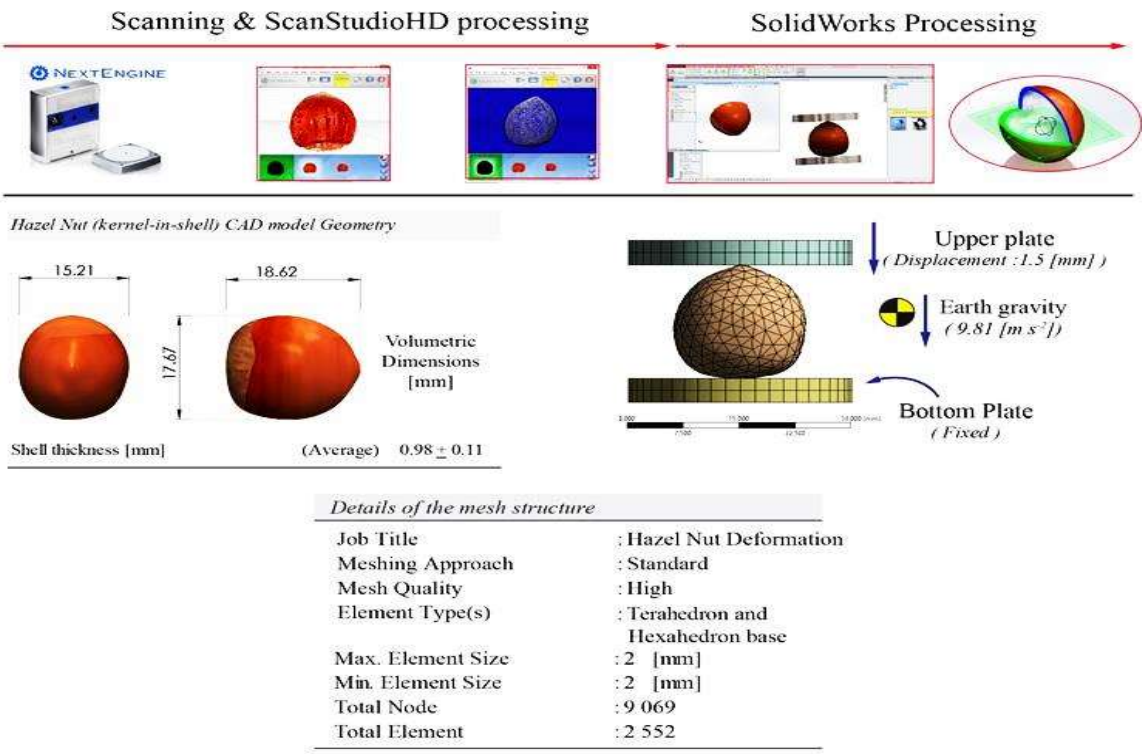

Fig. 3: Simulation setup

RESULTS AND DISCUSSIONS

The physical properties of hazelnut samples are provided in Table 1. The mean fruit length was 18.62 mm, fruit width was 17.67 mm, thickness was 15.21 mm and shell thickness was 0.98 mm. The mean mass and density of the fruit was determined as 1.705 g and 870.00 kg/m^3, respectively. These physical properties of hazelnuts were used for a solid model of a hazelnut. Present fruit mass, density and linear dimensions were within normal limits as compared to findings of previous studies (Ozdemir and Akinci, 2004).

Table 1: Physical properties of hazelnuts

	Min.	Max.	Mean	Standard Deviation
Length (mm)	16.74	19.16	18.62	0.21
Width (mm)	16.41	18.34	17.67	0.14
Thickness (mm)	14.95	16.63	15.21	0.17
Shell thickness (mm)	0.92	1.12	0,98	0.11
Mass (g)	1.691	1.781	1.705	0.034
Density (kg/m³)	809.18	901.63	870.00	7.16

The results of compression tests were used to get stress-strain and force-deformation curves of hazelnuts. The maximum force at X, Y and Z direction were measured as 138.05 N, 55.73 N and 89.23 N, respectively; modulus of elasticity at X, Y and Z directions was calculated as 86.056 MPa, 52.989 MPa and 44.037 MPa, resp., and Poisson's ratio was calculated as 0.30. Also, the force at damage point (yield point) (X, Y, Z directions) was measured as 128.44 N, 54.81 N and 87.92 N, respectively.

The present findings on deformation and cracking forces complied with the findings of earlier studies (Ozdemir and Akinci, 2004; Celik, 2017a).

In the simulation, a second order (high order) solid tetrahedral element was used for the mesh construction of 3D model of a hazelnut. A finite element mesh was generated with 9069 nodes and 2552 members (Fig. 3). To get material model properties for the hazelnut compression test, data were evaluated for 50 samples of hazelnuts. Some of mechanical properties can be seen in Table 2 and force-deformation curve is presented in Figure 4.

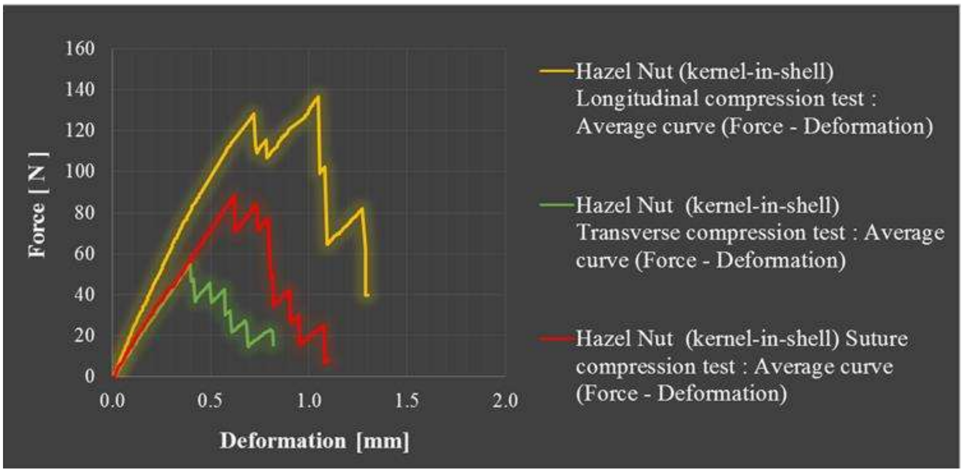

Fig. 4: Compression test results: force deformation curves (Number of the specimens used in each test: 50)

Table 2: Stress-strain test data of hazelnuts

Fruit Component	Direction of compression	Modulus of elasticity (MPa)	Poisson's ratio	Force@Damage point (compression)	Damage/Failure point
Hazelnut Shell	X	86.056 (R^2:0.9927)**	0.30	128.44*	2.470
	Y	52.989 (R^2:0.9989)**		54.81*	1.020
	Z	44.037 (R^2:0.9991)**		87.92*	1.520
Stainless Steel***	Isotropic	193 e+03	0.31		207.00

* extracted from average curves (experimental force-deformation data)
** slope of true stress-strain curve in elastic region (tan = modulus of elasticity)
*** ANSYB WB material library

After pre-processor set up, the simulation was run, and the results were recorded. The simulation results were extracted as logical visuals and numerical data related to deformation behavior of the hazelnut under pre-defined compression operation (Fig. 5).

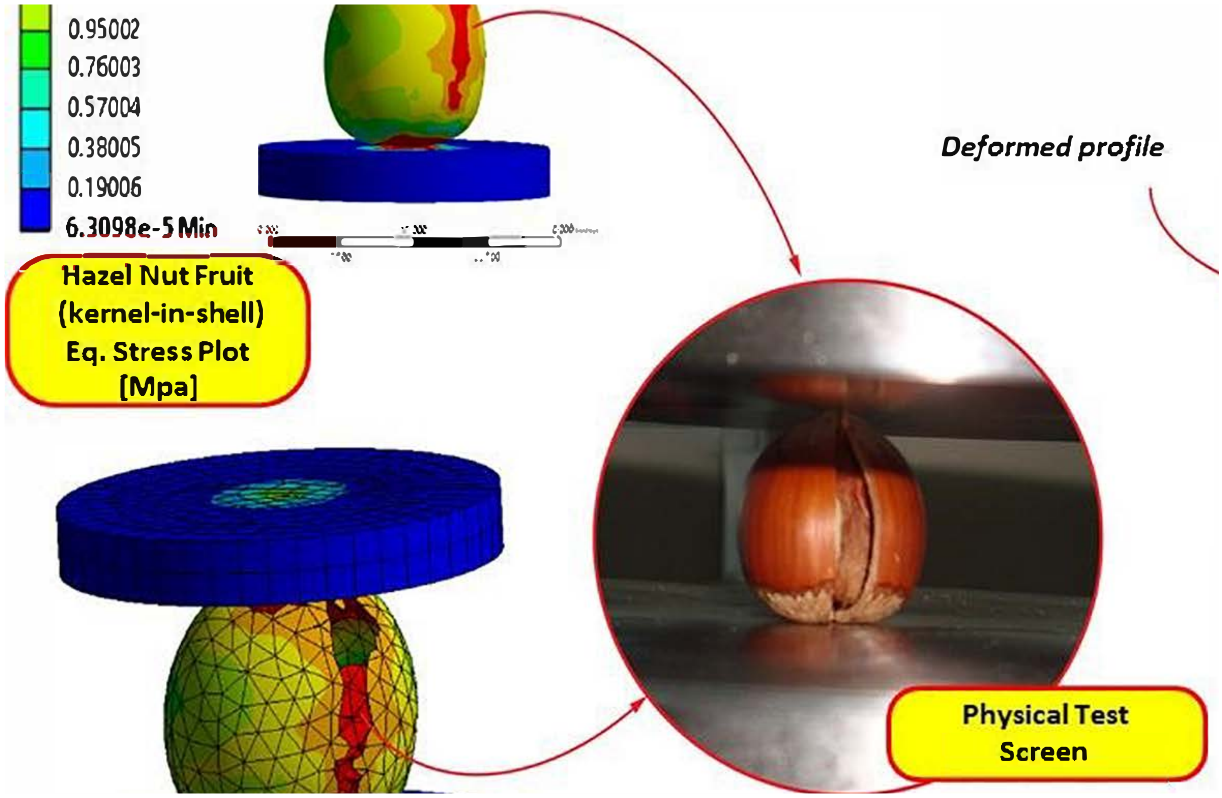

Fig. 5: Simulation results

According to simulation results, maximum equivalent stress value on the hazelnut was 10.107 MPa at the compression level of 1.5 mm. Damage point of the hazelnut was assumed to be 1.52 MPa at the orientation Z. Then, it can be commented that maximum damage started at the first contact point (sharpest contact point of the hazelnut and the plate) of the top plate and then damage on the nut continued. This damage behavior was in union with physical test screen. Therefore, it would not be wrong to say that simulation yielded a good visual representation of the physical compression case of the hazelnut. The similar deformation results might also be seen in the simulation study presented by Celik (2017a).

CONCLUSION

It is quite difficult to simulate real-time responses of organic materials under compression cases. Due to the limitations and unpredictable material characteristics and dynamic conditions, some assumptions must be made to gain approximate solutions. However, simulation results provided quite satisfactory deformation behavior in existence of these similar limitations. This indicates that computer-aided engineering (CAE) applications can help in these issues. Hence, this study focused on how the CAE applications help to simulate deformation behavior of the shelled agricultural materials during the post-harvest operations. Computer-aided simulations can help to determine the deformation behavior of biological materials when they were mechanically damaged during the pre-harvest and post-harvest operations like harvesting, handling, transportation and storage. Some key points for this study can be summarized as follows:

1) The mean fruit length, width, thickness and shell thickness, were determined as 18.62 mm, 17.67 mm, 15.21 mm and 0.98 mm, respectively. The mean mass and density of the fruit was measured as 1.705 g and 870.00 kg/m^3, respectively.
2) Crack points for the hazelnut shell (kernel-in-shell) in these test data were measured as 138.05, 55.73 and 89.23N for longitudinal, transverse and suture orientations, respectively.
3) Force in damage point was determined as 128.44, 54.81 and 87.92 N for longitudinal, transverse and suture orientations, respectively.
4) Maximum and minimum values of modulus of elasticity were calculated as 86.056 MPa (in orientation X) and 44.037 MPa (in orientation Z) in FEM simulation for the shell, respectively.
5) Maximum resistance to compressive loading of the shell was observed in the longitudinal loading orientation (orientation X). Minimum resistance against compression was observed in suture loading orientation (orientation Y).
6) Maximum equivalent stress value was 10.107 MPa at the plate deflection of 1.5 mm. Here, the damage point was defined as 1.52 MPa at the orientation Z.
7) The finite element mesh was generated with 9069 nodes and 2552 members for modelling of hazelnuts.

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