Compressive properties of Golden Delicious fruits

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Abstract. The study is aimed on the experimental evaluation of the apple cultivar Golden Delicious (*Malus domestica L.*) fruits at statical compressive loading in lateral direction. Mechanical properties such as rupture force and deformation as well as modulus of elasticity can be used to evaluate the behaviour of the fruits mechanically under the static loading. Apparent moduli of elasticity were determined on the base of elastic Hook theory and Hertz theory (ASAE, 2004). A testing machine Andilog Stentor 1000 (Andilog Technologies, Vitrolles, France) was employed for compression tests. The behaviour of the hemisphere of fruit was studied between two parallel plates and the indentation with the flat – faced cylindrical intender of diameter 8 mm and cone intender of diameter 6.4 mm and angle 60 degree was also studied.

INTRODUCTION

Mechanical properties of the apple fruits are required for the best management of the production process. Processing of apple tissue is in the many cases realized by the compress methods. Afterward material properties of the apple tissue represent very important feature of the material knowledge. The texture of apple flesh is important in assessing the eating qualities of the fruit (Khan and Vicent, 1993). Flesh firmness is a key quality parameter, since it is directly related to fruit ripeness, and is often a good indicator of shelf – life potential (De Ketelaere et al., 2006). Vozary and Meszaros (2007) interested in Idared apple cylinder of 20 mm diameter and of 15 mm length, cut out from whole apple in radial direction. The real part of impedance decreased as the deformation, or the stress increased, and the imaginary part of impedance increased under increasing stress or deformation. Extensive test have shown that if the initial part of force-deformation curves of soft biological tissues are taken into consideration, the initial part of the curves are usually concaved towards the force axis. This is exactly opposite the force-deformation curves for polymeric materials which is usually convex towards the force axis (Mohsenin, 1986).

MATERIALS AND METHODS

Samples

The apple fruits of cultivar Golden Delicious (*Malus domestica L.*) were tested. The fruits were obtained in the conventional shop and stored one day at the temperature 4°C and the air humidity (40 – 60) % in the refrigerator. Twenty samples of the fruits were collected and used for the testing. Each fruit was cut into two hemispheres. Each test was realized on the one hemisphere sample.

Methods

Statical compressive loading in lateral direction was used for the fruit testing. A testing machine Andilog Stentor 1000 (Andilog Technologies, Vitrolles, France) was employed for compression tests. The experiments were carried out at loading speed 10 mm.min^{-1}. The force F (N) and the compression D_c (m) were measured by the acquisition software RSIC ver. 4.06.
The loading curves of dependency of the force on the deformation or of the stress on the strain were realized.

Four methods were applied for testing of fruits. Ten tests were applied for each of four methods. The compression of fruit hemisphere between two parallel plates was realized. First method was based on the elastic theory and the Hook's law was used. Values of module of elasticity were calculated as the slope of the linear part of the stress – strain curves on the base of regression method. The second applied method was the determination of apparent module of elasticity realized on the base of the Hertz equations for contact stresses used in solid mechanics also at the compression of fruit hemisphere between two parallel plates. Apparent module of elasticity were determined from the equation (ASAE, 2004):

$$E_a = \frac{0.338\,K^{\frac{3}{2}} F\left(1-\mu^2\right)}{D_c^{\frac{3}{2}}}\left[\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{\frac{1}{2}}\right] \qquad (1)$$

where: E_a is the apparent modulus of elasticity, Pa,
D_c is the compression, m,
μ represents Poisson's ratio, - ,
F is the force, N,
R_U, R'_U are the minimum and the maximum radii of curvature of the convex surface of the sample at the point of contact with the upper plate, m,
K is the constant determined on the base of contact angle.

Third method was based on the penetration of fruit hemisphere by flat – ended cylindrical indenter of diameter 8 mm. Determination of the apparent module of elasticity on the base of the Hertz equations were realized from the equation (ASAE, 2004):

$$E_a = \frac{0.338\,K^{\frac{3}{2}} F\left(1-\mu^2\right)}{D_c^{\frac{3}{2}}}\left[\left(\frac{1}{R_U}+\frac{1}{R'_U}+\frac{4}{d}\right)^{\frac{1}{2}}\right] \qquad (2)$$

where: all quantities are the same as in the equation (1),
d is the indenter diameter curvature, m.

Fourth method was based on the penetration of fruit hemisphere by cone indenter of diameter 6.4 mm and angle 60 degree. Determination of the apparent module of elasticity was realized on the base of the elastic theory by the equation (McKee et al., 2011):

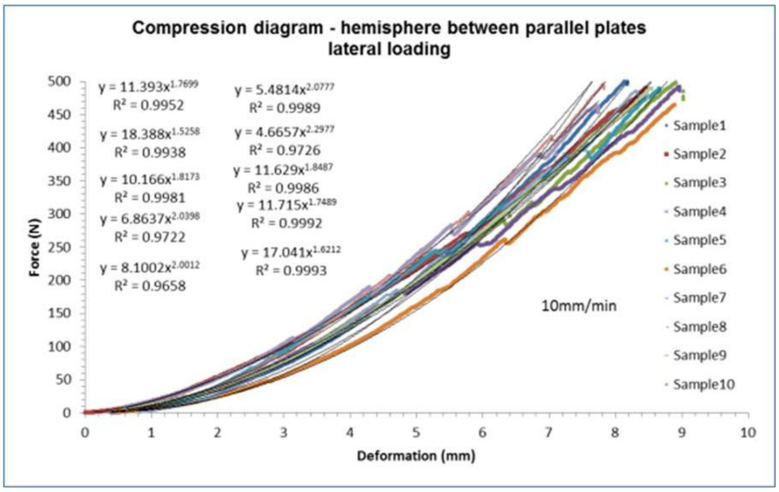
$$F = \frac{2}{\pi}\tan\alpha\,\frac{E}{(1-\mu^2)}\,D^2 \qquad (3)$$

where:
E is the modulus of elasticity, Pa,
F is force, N,
μ is Poisson' ratio, - ,
α is the half angle opening of the cone, ° ,
D is the depth of penetration deformation, mm

RESULTS AND DISCUSSION

The compression diagrams of the hemisphere fruits samples compressed between two parallel plates are presented on the Figure 1. Compression force – deformation curves (Figure 1.a.) and stress – strain curves (Figure 1.b.) of the apple fruit Golden Delicious in the lateral loading represent the nonlinear viscoelastic behaviour because the average power coefficient of the power functions applied on the force – deformation curves (Figure 1.a.) reached the value 1.875 and on the stress – strain curves (Figure 1.b.) reached the value 1.866. The elastic theory assumed the value of the power coefficient 1 and Hertz theory 1.5

a.



b.

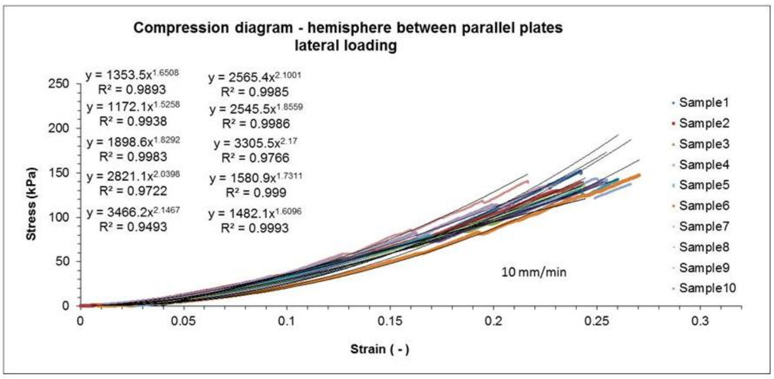


Figure 1

Compression force – deformation curves (a) and the stress – strain curves (b) of apple fruits Golden Delicious in the lateral loading – nonlinear viscoelastic characteristics

Mechanical behaviour in nonlinear curves we can describe, when we will determine the differential modulus of elasticity in the each point of the dependence. Average value of the differential modulus of elasticity obtained from the linear parts of the stress – strain curves in the Figure 1.b. by regression method (strains ranged from 0.1 to 0.3) was E = 785.536±73.597 kPa. Average value of the differential modulus in the initial region of the stress – strain curves (strains ranged from 0.04 to 0.12) reached value E = 485.845±67.591 kPa.

Apparent module of elasticity were determined from the Eq. 1. Poisson's ratio μ was assumed 0.22 (ASAE, 2004). K was the constant determined on the base of contact angle, K = 1.349. Apparent moduli of elasticity depended on value of the deformation D_c (mm). Dependencies are presented on the Figure 2. In the level of deformation from 1 mm to 9 mm, realized by the compression between two parallel plates, the experimental values of the apparent module of elasticity ranged from 500 kPa to the 2800 kPa.

Third realized method was the compress deformation of the fruit hemisphere by flat – faced cylindrical indenter of diameter 8 mm. This method enabled the measurement of mechanical properties of apple's skin with mesocarp. Compression force – deformation curves and the stress – strain curves are presented on the Figure 3.a. and Figure 3.b.

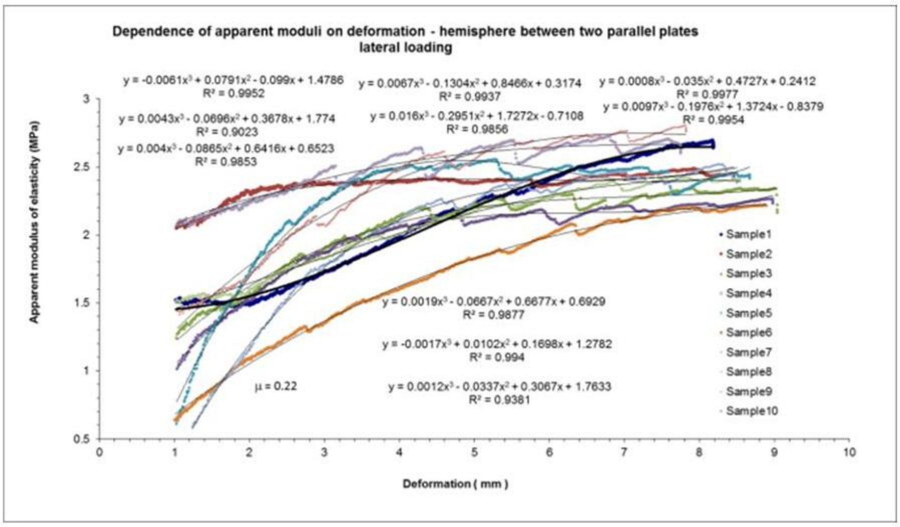


Figure 2
Dependences of the apparent module of elasticity on the deformation of apple hemisphere fruits Golden Delicious
in the lateral loading – second method – Hertz theory

a.

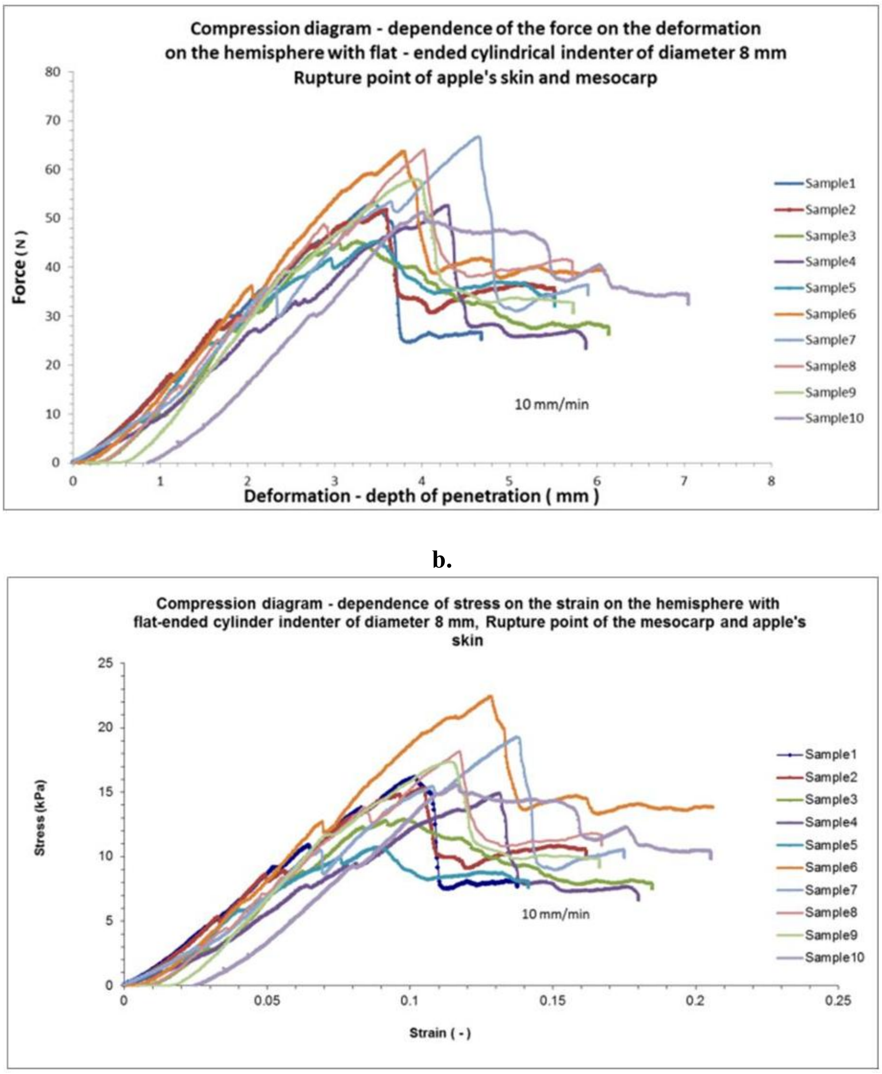


Figure 3
Compression force – deformation curves of the apple's skin fruit and mesocarp (a) and the stress – strain curves (b) of Golden Delicious fruit hemispheres in the lateral loading and the rupture points of the mesocarp and the apple fruit skin – third method

The rupture points of apple‘s skin and mesocarp (maximum of the force where apple’s skin with mesocarp is punctured by the indenter) were determined. Average value of the maximal force in the rupture point F_R=55.251±8.152 N and the maximal deformation in the rupture point D_R=3.942±0.475 mm were determined. Average value of the maximal stress in the rupture point was σ_R=16.177±3.297 kPa and the maximal strain in the rupture point was ε_R =0.113±0.016. Module of elasticity were determined on the base of Hook’s theory of elasticity from the linear part of the compression curves (deformation ranged from 0 to 2.4 mm) Average values of the module of elasticity in this region, where the strains ranged from 0.01 to 0.06, reached value E=170.168±24.273kPa. Apparent module of elasticity were determined from the Eq. 2. Poisson’s ratio μ was assumed 0.22 (ASAE, 2004). K was the constant determined on the base of contact angle, K = 1.349. Apparent modulus of elasticity depended also on value of the deformation D_c (mm). Dependencies are presented on the Figure 4. In the level of deformation from 1 mm to 7 mm the experimental values of the apparent module of elasticity obtained by the deformation of hemisphere fruits by flat – faced cylindrical indenter of diameter 8 mm, ranged from 200 kPa to the 2000 kPa.

Fourth applied method consisted in the deformation of the fruit hemispheres by the cone indenter of diameter 6.4 mm and angle 60°. The length of the cone of diameter 6.4 mm was 6 mm and then the diameter enlarged and continued as the cylinder of the diameter of 8 mm on the length 3.6 mm. Then diameter of the cylinder again continued with the diameter of 6.4 mm. The method also enabled the measurement of mechanical properties of apple‘s skin with mesocarp. Compression force – deformation curves are presented on the Figure 5. The rupture points of apple‘s skin and mesocarp were also determined. We identified two rupture points on the deformation curves. The first rupture point corresponds of the diameter 6.4 mm and the depth of penetration of 6 mm of the cone and the second point corresponds of the enlarging of the diameter of the cone on the 8 mm and the depth of the penetration from 7 mm to 9.6 mm.

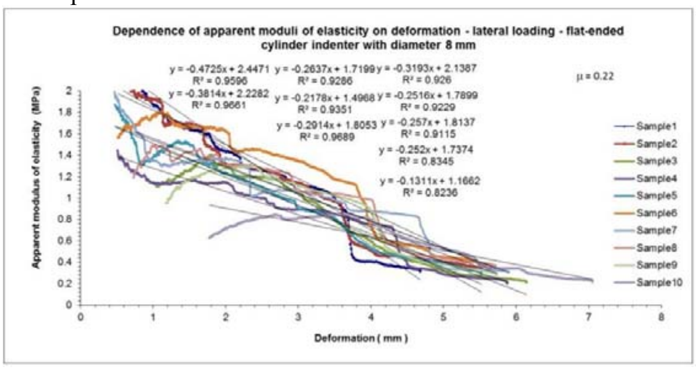


Figure 4
Dependences of apparent module of elasticity on the deformation of apple hemisphere fruits Golden Delicious in the lateral loading – third method – Hertz theory

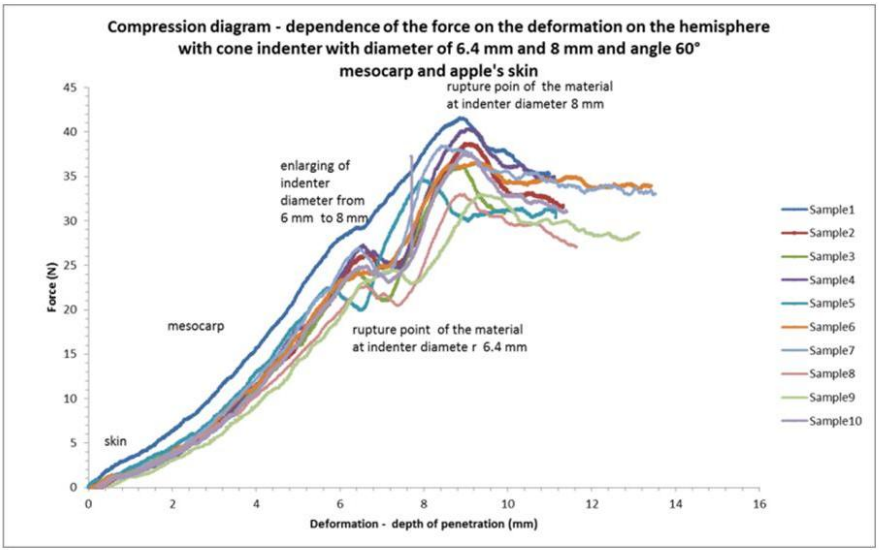


Figure 5
Compression force – deformation curves of the apple's skin fruit and mesocarp of Golden Delicious fruit hemispheres in the lateral loading and two rupture points of the mesocarp and the apple fruit skin – fourth method

Average value of the maximal force in the first rupture point F_R=24.824±0.774 N and the maximal deformation in the first rupture point D_R=6.409±0.154 mm were determined. Average value of the maximal force in the second rupture point F_R=36.826±1.016 N and the maximal deformation in the second rupture point D_R=8.838±0.142 mm were also determined. When we realized regression method by the power function model on the experimental data of the force – deformation dependencies on the Figure 5 in the range of the deformations from 1 mm to 6 mm (mesocarp of apple), we obtained very good correspondence with the Hertz theory (Figure 6). The experimental equation obtained as the average results from the ten dependencies was:

$$F= 1.443\, D^{1.540} \tag{4}$$

The coefficient 1.540 confirmed good correspondence with the Hertz theory. Apparent module of elasticity were determined from the Eq. 4. Poisson's ratio μ was assumed 0.22 (ASAE, 2004). The half angle opening of the cone was 30 °.

Apparent modulus of elasticity depended also on value of the deformation D (mm). Dependencies are presented on the Figure 7. In the level of the deformations from 2 mm to 6 mm the experimental values of the apparent module of elasticity obtained by the deformation of hemisphere fruits by the cone indenter of diameter 6.4 mm and angle 60°, ranged from 1500 kPa to the 4500 kPa.

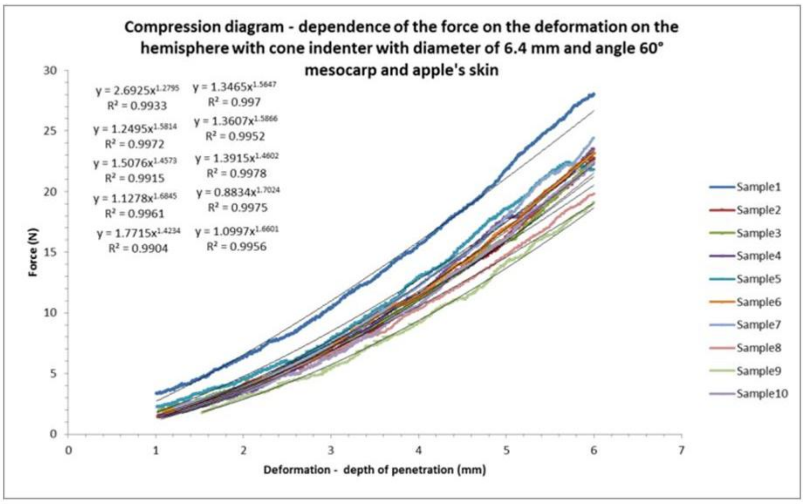


Figure 6
Compression force – deformation curves of the apple's skin fruit and the mesocarp of Golden Delicious in the lateral loading – depth of penetration from 1 to 6 mm
fourth method – Hertz model

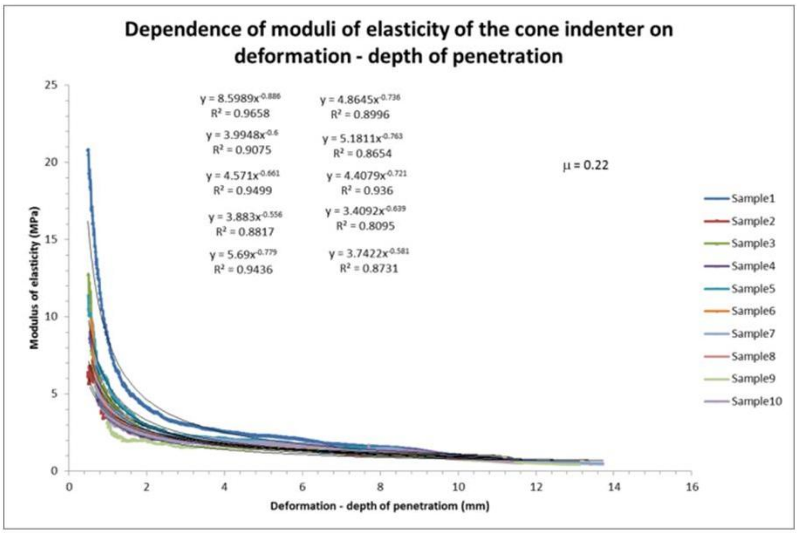


Figure 7
Dependences of apparent module of elasticity of the Golden Delicious apple fruit hemispheres on the deformation – fourth method

A lot of the authors interested in the study of the compressive properties of the apples. Cen et al. (2013) interested in the measurements of the stress – strain curves of Golden Delicious apple, which measured for each of the five storage times and reached values of the stress from 0.2 MPa to 0.45 MPa at the strain from 10% to 15%. Arnold and Mohsenin (1971) interested in the study of Yellow Delicious apple cultivars. They obtained values of the module of elasticity E = 3030 kPa and E = 4200 kPa at the compressive speed v = 2.54 mm/min. Costa et al. (2011) measured 86 apple cultivars at the compressive speed v = 100 mm/min and 300 mm/min and obtained the values of the module of elasticity from 1000 kPa to 2 000 kPa. Shirvani et al. (2014) studied the cultivars of Golden Delicious apples and on the base of the Boussinesq's theory determined the modulus of elasticity E =1530 kPa, on the base of the Hertz's theory also obtained the modulus of elasticity E =1530 kPa and on the base of the Hooke's theory determined the modulus of elasticity E =2680 kPa. Winisdorffer et al. (2015) studied 5 cultivars of the apples and reached the moduli of elasticity from 1000 kPa to 4500 kPa. Alamar et al. (2008) studied apple cultivars Braeburn and Jonagored and reached from the first part of stress-strain curve the moduli of elasticity in the range from 350 kPa to 420 kPa. They obtained the moduli of elasticity in the range from 1720 to 2010 kPa at the 80% of the stress.

CONCLUSIONS

The values of the module of elasticity of the apple fruit hemispheres which were determined on the base of the first method (Hooke's law) were not consistent with Hertz's theory. The values obtained on the base of the first method (Hooke's law) were consistent with the results of Alamar et al. (2008). The apparent module of elasticity obtained on the base of Hertz's theory for the lateral loading of the hemispheres between two parallel plates were consistent with the module determined by the cylinder flat – end indenter and the cone indenter. The values of the apparent module of elasticity depended on the deformation at which were calculated. This is indication that several of the assumptions on which the Hertz's equations are based were not completely satisfied. The apple fruit is not an ideal elastic solid body.

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