Determination of contact stresses in the potato tuber upon impact

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Abstract: *Determination of contact stresses in the potato tuber upon impact.* The aim of the study was to determine the surface stress upon impact of a potato tuber against a flat panel as a result of freefall, based on registered parameters of impact and the tuber's size and shape characteristics. The courses of force and displacement during impact of the tuber against the flat panel were used to determine the maximum force and corresponding displacement, and allowed identification of their dependence on impact energy. The dependencies are described with the use of regression equations. Maximum stresses were determined considering two methods of identification of the contact area – based on the course of deformation and based on actual measurement. Lower stress values were obtained in the method involving determination of the contact area than in the alternative method. A constant value of maximum stresses was determined for the analysed range of impact energy.

Key words: potato tuber, surface stress, impact force

INTRODUCTION

Most of mechanical damage occurs during activities connected with harvesting, transport, reloading and packing of vegetables and fruit. The damage results from dynamic loads generated during impact of the material against working elements of machines, fall from a height and mutual collisions [Waszkiewicz et al. 1992, Gołacki and Rowiński 2006, Waszkiewicz et al. 2007, Stopa 2010]. In case of potatoes, damage usually occurs at the place of contact of tubers with cylindrical or flat surfaces [Sypuła 2013]. The severity and kind of damage is determined by shape of the product and contact loads, characterised with the influence of force onto a small area. The loads are very dangerous, as even an insignificant force may result in exceeding the acceptable stress level in the material, which causes damage to its inner structure [Herold et al. 2001, Komarnicki et al. 2013].

In case of applying methods which involve dropping of spherically shaped bodies onto the flat surface of the force sensor, there appears a problem resulting from the fact that the impact force greatly depends on weight of the body, height it is dropped from, body curvature radius and the body's resilience properties [Gołacki and Rowiński 2006]. High variability of these parameters has unfavourable influence onto damage evaluation accuracy.

Whereas determination of force is not a problem nowadays thanks to the use of piezoelectric sensors, determination of the contact area is always burdened with the risk of measurement error. The contact area surface changes depending on the value of pressing forces, which changes the values and distribution of stresses, deformations and dislocation in the contact area.

The literature usually contains proposals for resolving precise contact area measurements with the use of a static

load [Frączak and Wróbel 2003, 2007, Komarnicki et al. 2013], which turns out to be very time consuming and difficult to measure. Formulas based on the theory of elasticity, developed by Hertz, were frequently used to calculate surface stresses. Assumptions made in this theory exclude the possibility to apply them to vegetal materials. However, despite limitations, some researchers used Hertz's theory to determine the relations between the time of contact and surface pressures [Siyami et al. 1988, Kamiński et al. 2011]. As far as measurement of the surface area is concerned, Herold et al. [2001] applied a Tekscan sensor in the form of a thin matrix. Measurement was performed by registering the location of contact points of electrodes from two foils, caused by pressure from bodies touching each other; the area was measured as a grid of squares with defined dimensions. Thanks to a semiconductor between the electrodes, measurement of the stress force was also possible at the intersection of the electrodes. A weakness of this system is that measurement of surface pressures takes place through a layer located between the electrodes touching each other, which influences the conditions of contact.

It has been believed so far that maximum surface pressures occurred nearby the central point of the contact area, but in the investigations of Herold et al. [2001] and Stopa et al. [2013] using the Tekscan system, maximum pressures occurred at the edges of the contact area of the apple with the flat panel, which was explained with loss of carrying capacity by damaged apple cells in the central point of contact. However, Lewis et al. [2008] believe that this results from addition of the measurement layer between the apple and the panel. The authors proposed their own method of measurement of the contact area for determination of surface pressures in apples compressed with two panels, based on the ultrasound technology. As a result of these investigations, a distribution of surface pressures in the function of force and distribution of pressures along the contact area was obtained. Lewis et al. [2008] demonstrated that maximum pressure values occurred at the central point of contact of the fruit with the panel and, moreover, demonstrated the relation between the contact area of the loading element with the apple and the area of actual bruising.

In the investigations conducted under impact load, Stopa et al. [2013] measured surface pressures of Ligol apples using a pendulum. In order to correctly determine pressure stresses in the conditions of dynamic load, it was necessary to simultaneously measure the force and surface of the contact area of the apple with the surface of the pendulum. To achieve that, the force and contact area during impact was registered using the Tekscan High-Speed system. It was determined that growth in the impact energy influenced the value and distribution of surface pressures. In the investigation using a pendulum as the hitting element and measurement apparatuses with piezoelectric sensors, Bajema et al. [1998] determined the forces, dislocations and stresses upon impact, which allowed obtaining most reliable results regarding characteristics of dynamic stresses upon impact of a potato tuber.

The aim of the investigation is to determine surface stresses upon impact of a potato tuber against a flat panel as a re-

sult of free fall of the potato tuber, based on registered impact parameters, as well as size and shape related characteristics of the potato tuber.

MATERIAL AND METHODS

The investigation was carried out in laboratory conditions at the Department of Agricultural and Forest Machinery of Warsaw University of Life Sciences – SGGW. The object of investigation were tubers of the Hermes potato variety with starch content of nearly 16% and density of $1,090 \, kg \cdot m^{-3}$. The tubers were dropped from various heights so that the required impact energy could be obtained for the selected tuber with the known weight. In case of free fall of a potato tuber, impact energy was changed by 0.1 J within the range of 0.3–0.9 J.

The measurement station (Fig. 1), which consisted of a steel frame and a stand, movable platform for determination of fall height and panel with a pie-zoelectric force sensor, which was hit by the falling tuber, was used for performing the measurements. During the tests, tubers were held by a suction cup under the influence of underpressure created by the vacuum cleaner, whereas the height of tuber fall (drop) was adjusted and determined by means of a metal measurement strip. The fall height was assumed to be the distance between the flat surface of the impact panel and the plane tangent to the lower convex tuber surface.

Upon disappearance of underpressure, free fall of the tuber onto the steel panel surface occurred. This manner of dropping the tubers limited rotation while falling on the impact panel which was previously covered with an ink layer to obtain an impression reflecting the contact area on the tuber surface (Fig. 2). Subsequently, the area was determined with the Multi-Scan imaging analysis programme. To avoid repeated impact, the tuber was caught with the hand after first bounce from the impact panel.
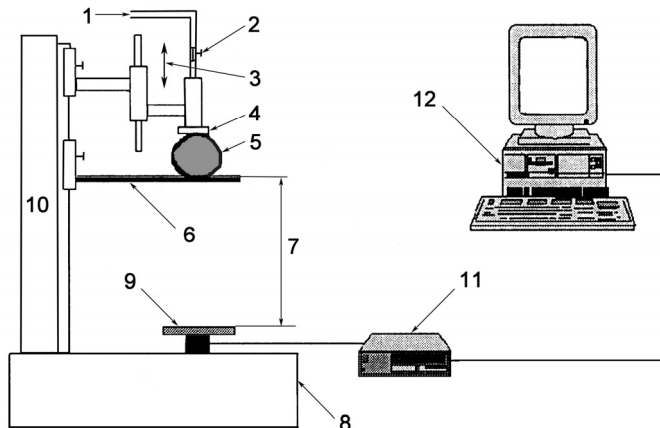

FIGURE 1. Test station for determination of tuber stress and deformation: 1 – underpressure vacuum cleaner duct, 2 – shut-off valve, 3 – indicator of fall height depending on tuber size, 4 – suction cup, 5 – tuber, 6 – fall height determination strip, 7 – fall height, 8 – frame, 9 – panel with force converter, 10 – stand, 11 – measurement amplifier, 12 – computer

FIGURE 2. Image of the contact area on the potato tuber after impact

Registered signal from the force sensor, in the form of electric force, was transformed by the amplifier into voltage. The voltage signal was transferred into the measurement system with an analogue to digital converter characterised with the sampling frequency of 30,000 Hz. All data from the measurement system were recorded on the computer drive. Based on recorded results, the courses of force and dislocation upon impact of the tuber against a flat metal panel (Fig. 3) were determined using the ESAM 3 software. Calculations for these courses were conducted with the use of numeric integration methods.

Upon impact, normal stress changes along with changes in momentary force and area of tuber contact with the panel according to the following formula:

$$\sigma(t) = \frac{F(t)}{S(t)} \qquad (1)$$

where:
$\sigma(t)$ – normal stress [MPa];
$F(t)$ – impact force [N];
$S(t)$ – momentary contact area [m^2].

Thus, maximum surface stresses are defined as:

$$\sigma_{max} = \frac{F_{max}}{S_{F\,max}} \qquad (2)$$

where:
σ_{max} – maximum surface stresses [MPa];
F_{max} – maximum force upon impact [N];
$S_{F max}$ – contact area of the tuber upon maximum force [m^2].

For the assumed tuber shape, the area of its contact with the panel has the shape
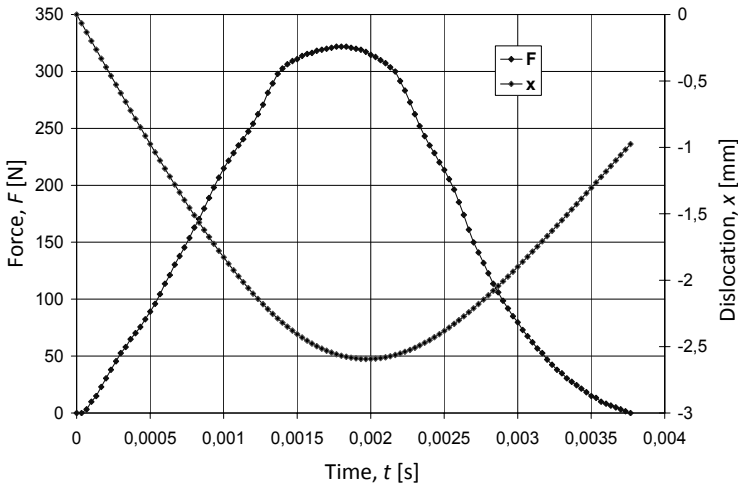

FIGURE 3. Exemplary course of the parameters of impact of a potato tuber against the panel during the phenomenon: $F(t)$ – force, $x(t)$ – displacement [m]

of an ellipse and is described by the following formula:

$$S(t) = \pi b_1(t) b_2(t) \qquad (3)$$

where:
$S(t)$ – momentary contact area [m^2];
$b_1(t)$ – large semi-axis of the ellipse [m];
$b_2(t)$ – small semi-axis of the ellipse [m].

Semi-axes of the ellipse upon impact $b_1(t)$ and $b_2(t)$ were conditioned upon tuber displacement $x(t)$ and tuber curvature radiuses R_1 and R_2 at the place of contact, measured in planes perpendicular to each other and to the tangent surface of the tuber curvature:

$$b_1(t) = \sqrt{2R_1 x(t) - \left(x(t)\right)^2} \qquad (4)$$

$$b_2(t) = \sqrt{2R_2 x(t) - \left(x(t)\right)^2} \qquad (5)$$

where:
R_1, R_2 – tuber curvature radiuses [m];
$x(t)$ – tuber displacement [m].

Upon impact, ellipsis semi-axes $b_1(t)$ and $b_2(t)$ are increased with growth in displacement and, pursuant to Figure 3,

the largest contact area occurs with maximum displacement.

The tuber curvature radius in the area of impact was determined with a digital spherometer (Fig. 4) according to the following formula [ASAE 2011]:

$$R = \frac{y^2}{8c} + \frac{c}{2} \qquad (6)$$

where:
R – tuber curvature radius [m];
c – arrow value [m];
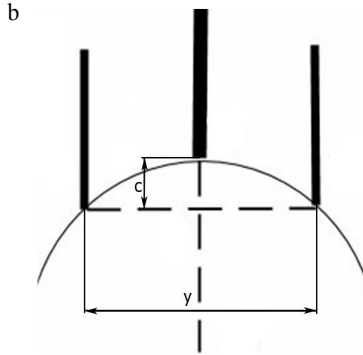y – distance between spherometer bolts [m].

FIGURE 4. Measurement of tuber curvature radius: (a) spherometer, (b) measurement principle

Shape of the tuber at the place of contact with the impact surface was determined by way of measurement of two curvature radiuses R_1 and R_2, in mutually perpendicular planes. Results of the surface area of the impact mark, processed in the Multi-Scan programme, were used for verification of the contact area determined as above.

RESULTS AND DISCUSSION

The courses of force and displacement upon impact of the tuber against a flat panel (Fig. 3) were used for determina-

tion of the maximum force and corresponding displacement connected with potato deformation, which allowed evaluation of predefined impact energy onto their values.

Based on conducted trials regarding impact of a potato tuber against a flat panel, it can be concluded that the maximum impact force increases in a linear manner along with growth in impact energy (Fig. 5a). Energy growth by 0.1 J causes growth in maximum impact force by 36 N. This is in line with results of the investigations conducted by Fluck and Ahmed [1973] who observed that the result of growing impact energy in fruit impact tests was maximum force growth.

Upon impact, nearly all kinetic energy is changed into deformation energy.

Tuber deformation visible in the impact area is analysed as dislocation. The dislocation-time curves were determined by double integration of the acceleration-time curves with calculated initial speed from the conservation of energy right.

With impact energy growth, there occurs linear increase in the values of maximum dislocations, and the character of its changes is similar to that in the case of maximum forces (Fig. 5b).

In case of energy growth in the area of tuber deformation by 0.1 J, the increase of maximum displacement is equal to 0.2 mm. The largest maximum displacement take place at the energy level of 0.9 J and reach about 3.5 mm.

Based on the courses of force and displacement upon impact of the tuber against the panel (Fig. 3), it can be
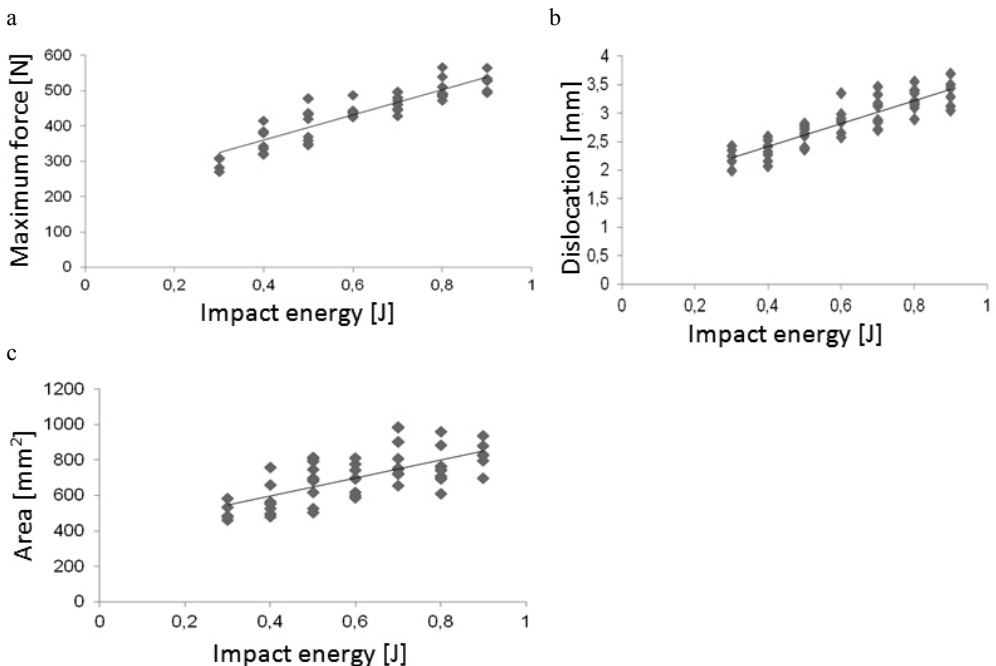

FIGURE 5. Influence of impact energy on: (a) maximum force, (b) displacement, (c) maximum contact area

observed that the maximum force value occurs before the tuber experiences maximum displacement. The occurred time shift results from greater speed of propagation of the stress wave in the tuber than the displacement speed [Bajema et al. 1998, Stropek and Gołacki 2015]. Because of this, the values of displacement at the time of occurrence of the maximum force were considered in calculations of the contact area and maximum contact stress upon impact.

The relations between maximum values of force, displacement, contact area and the impact energy were described with the following regression equations:
– maximum force:

$$F_{\max} = 357.7E_z + 216.6;\ r^2 = 0.80;$$

– maximum displacement:

$$x_{F\max} = 2.0E_z + 1.61;\ r^2 = 0.77;$$

– maximum contact area:

$$S_{F\max} = 504E_z + 397;\ r^2 = 0.47.$$

Poorer matching of the model to the contact area of the tuber with the panel results from the fact that, pursuant to formulas (3)–(5), the area depends on displacement and tuber curvature radiuses R_1 and R_2, which were variable for individual tubers.

Results of the contact area calculated based on the curve of displacement course were verified against the results concerning area of the mark obtained upon contact with the impact panel (Fig. 6).

By way of statistical analysis it was concluded that the calculated area significantly differed from the area of the obtained mark, creating two separate homogenous groups (Table 1).

The difference between average contact areas from the calculations and determined based on direct measurements was equal to 19%. Determination of the contact area, in particular upon impact, is quite difficult and bears the risk of inaccuracy, with errors in evaluation of the contact area – according to Siyami et al. (1988) – potentially as high as 20%.

Linear growth of maximum force and contact area (Fig. 5) along with energy growth indicates that maximum contact stresses may take similar values for all analysed energy levels. The variance analysis demonstrated that differences between average stress values are statis-
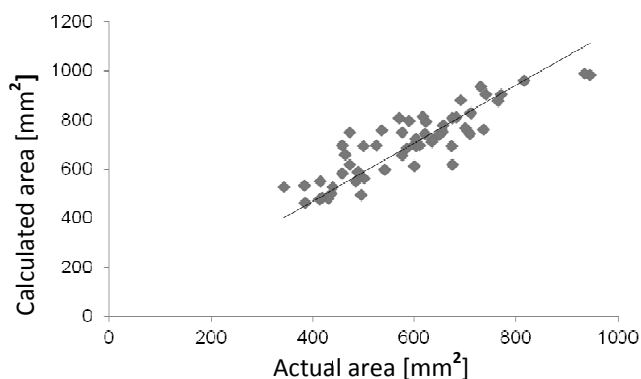

FIGURE 6. Relation between the area of the impact surface from calculations and area measured based on the mark after contact of the tuber with the panel

TABLE 1. Results of statistical analysis of the contact area, with division into homogenous groups according to the method of determination

Area	Number of samples	Average [mm^2]	Standard error	Homogenous group	
Calculated	57	705.9	17.9	x	
Measured	57	592.2	17.9		x

TABLE 2. Results of variance analysis covering influence of impact energy onto maximum stress

Factor	Sum of square values	Number of degrees of freedom	Average square value	Coefficient F_{emp}	Critical relevance level
Stress based on area calculations					
Impact energy	0.0833787	6	0.0138964	2.04	0.078
Stress based on determined area					
Impact energy	0.11046	6	0.0184099	1.32	0.265

tically insignificant for the impact energy from the analysed range (Table 2).

The constant value of maximum stresses for the analysed levels of impact energy may evidence that the energy of 0.3 J will already cause damage to the tuber tissues. Based on this reasoning, one may assume the threshold value of

TABLE 3. Stress values for analysed variables

Determination method	Impact energy [J]	Peak stress value [MPa]			Standard deviation [MPa]	Coefficient of variation [%]
		min	max	average		
Based on area calculations	0.3	0.562	0.648	0.599	0.034	5.70
	0.4	0.517	0.809	0.672	0.102	14.31
	0.5	0.397	0.757	0.625	0.117	18.72
	0.6	0.618	0.768	0.677	0.063	9.35
	0.7	0.500	0.733	0.619	0.073	11.75
	0.8	0.593	0.858	0.713	0.075	10.55
	0.9	0.625	0.747	0.688	0.051	7.39
	total	0.397	0.858	0.657	0.087	11.11
Based on determined area	0.3	0.629	0.806	0.715	0.067	9.43
	0.4	0.638	0.931	0.776	0.120	14.54
	0.5	0.576	1.079	0.782	0.178	22.76
	0.6	0.489	0.895	0.775	0.095	12.22
	0.7	0.667	0.797	0.673	0.101	14.96
	0.8	0.667	0.809	0.742	0.054	7.33
	0.9	0.687	1.07	0.814	0.149	11.17
	total	0.489	1.079	0.752	0.120	13.20

0.6 MPa as causing tissue damage (Table 3 and Fig. 7). For the analysed variety of potato, the average value of maximum stress fell within the range of 0.599–0.713 MPa, for the method in which the contact area was determined based on the course of deformation.

The value of average maximum stress for the method involving determination of area by means of contact surface impression fell within the range of 0.637––0.814 MPa, with the average value 14.5% higher than in the former method.

The obtained stress values are slightly lower than provided by Bajema and Hyde [1999], who provided the values of dynamic stress for five potato varieties (0.99–1.21 MPa), but those were defined as the maximum pressure which did not involve further tissue destruction as a result of plastic deformations. On the other hand, Kamiński et al. [2011] demonstrated that the values of surface pressures in carrot roots in case of radial compression were even three times lower than calculated based on Hertz's formulas.

In the authors' opinion, significant differences in the value of stress evidence that individual tubers have slightly different mechanical and resistance properties, and constitute the result of specific impacts. Different kinds of tuber damage may occur upon impact. For low impact energies, tissue damage will usually cause development of dark stains, whereas in the case of high impact energies, potato flesh may break. The kind of flesh damage will influence propagation of stress waves and stress values at the place of contact with the impact surface.

CONCLUSIONS

1. Based on the courses of impact force and familiarity with the potato tuber weight and curvature radiuses, contact stresses occurring upon impact may be determined.
2. The average value of maximum stress for the method where the area was determined by means of impact impression was by 14.5% higher than in the method where the contact area was determined based on the course of deformation.
3. Constant value of maximum stresses in the analysed range of impact energy may already indicate occurrence of tissue damage in tubers and will
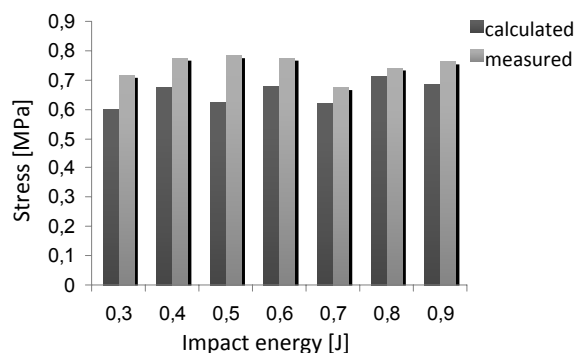

FIGURE 7. Maximum surface stress values upon potato tuber impact against a flat panel, depending on energy level

allow determination of the threshold stress level to reflect severity of damage.

4. Significant differences in stress values may result from potato tuber anisotropy and kind of damage occurred upon impact.

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Streszczenie: *Określenie naprężeń kontaktowych w bulwie ziemniaka podczas zderzenia.* Celem badań było określenie naprężeń powierzchniowych podczas zderzenia bulwy ziemniaka z płaską płytką w wyniku jej swobodnego spadku na pod-

stawie zarejestrowanych parametrów zderzenia i cechy bulwy związane z wielkością i kształtem. Przebiegi siły i przemieszczenia podczas zderzenia bulwy z płytą płaską posłużyły do wyznaczenia maksymalnej siły i odpowiadającemu jej przemieszczeniu oraz pozwoliły określić ich zależność od energii zderzenia. Zależności te zostały opisane za pomocą równań regresyjnych. Określono maksymalne naprężenia, uwzględniając dwie metody wyznaczania powierzchni kontaktu na podstawie przebiegu odkształcenia oraz za pomocą rzeczywistego jej pomiaru. Dla metody wyznaczania powierzchni kontaktu na podstawie przebiegu odkształcenia uzyskano mniejsze wartości naprężeń niż w metodzie alternatywnej. Stwierdzono stałą wartość maksymalnych naprężeń dla badanego zakresu energii zderzenia.

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