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PREDICTION OF APPLE BRUISING BASED ON THE INSTANTANEOUS IMPACT SHEAR STRESS AND ENERGY ABSORBED*

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A b s t r a c t. Instantaneous impact shear stress together with the instantaneous energy absorbed were used to predict bruise volume in Golden Delicious apple. The prediction produced a linear relation between the predicted bruise volumes and the measured bruise volumes with a factor of proportionality (K) 1.08 and a coefficient of correlation (R) 0.949. Both the instantaneous impact shear stress and energy absorbed decreased during storage of the fruit, but the value of K was relatively constant. The value of K was also relatively constant for the impact with small drop heights, but it slightly increased with the variation of fruit mass.

K e y w o r d s: apple, instantaneous impact shear stress, instantaneous energy absorbed, predicted bruise volume, measured bruise volume

INTRODUCTION

Beginning from handling on the farm, through various stages of distribution and processing, until eating, apples are subjected to various loading conditions which lead to mechanical failure. One of the common modes of failure is bruising. Between 20-50 % of apples are bruised during handling [15].

Many theories have been explored for agricultural products [4,7,11,20-23,28] and most researchers [7,14,15,17,22,27,28] believe that failure is due to shear stress.

Bruising begins when the shear stress reaches a certain value. Because of this the critical shear stress may be defined as the current bruising strength [15]. For any material there will be limits to the normal and shear stresses it can withstand which correspond to bruising strengths. Shear failure is dependent on the maximum difference in normal stresses and independent of the absolute value of the normal stresses. Within the diagram of solid materials, for a rising load, as the stresses on the material increase, the mode of failure will be determined by the strength boundary first encountered [34]. If the size of the Mohr's circles increases, due to increasing differences in stress, and reaches first a boundary on the shear stress, bruising occurs [14].

In the case of compression tests, failure can be detected from the deflection (yield) points in the force-deformation curve. This point has been used to assess bruising [1,18,24,26]. In impact this sort of deflection is not always visible. One usually utilises other impact parameters and relates them to bruising. Maximum force [5], maximum deformation [5,6], approach energy [2], energy absorbed [2,3,6, 13,14,16,26,29,30], coefficient of restitution [8], maximum acceleration [6,32,33,34], velocity

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change [32,33], maximum value of the time rate of change of acceleration and impact time [6] have been used to predict bruising.

In the previous work [36], employing Hertz' theory, we used the modulus of elasticity together with the mass of fruit, and drop height, to predict bruise volume in apple. Because it is evident that failure is caused mainly by shear, in the present work we tried to utilise the instantaneous impact shear stress together with energy absorbed to predict bruise volume.

THEORY

Impact assessment

If an apple is considered as a sphere, assuming that i) all the mass was subjected to the same acceleration, ii) the centre of the sphere and the centre of mass remained coincident during contact and iii) the internal vibrations could be neglected; the motion of the centre of the mass of the sphere can be quantified as follows [10,19]:

- acceleration (γ, ms^{-2}):

$$\gamma = g - \frac{F}{M} \tag{1}$$

- velocity (v, ms^{-1}):

$$v = v_o - \int_o^t \gamma \, dt \tag{2}$$

- neglecting air friction, velocity of fruit at the beginning of contact v_o (ms^{-1}) can be calculated from the drop height as:

$$v_o = \sqrt{2gh}$$

- displacement (x):

$$x = \int_o^t v \, dt \tag{3}$$

where F - force measured by the transducer (N), M - mass of fruit (kg), g - gravity constant (9.81 ms^{-2}), t - time after the first contact (s) and h - drop height (m).

Figure 1 shows schematic curves of impact characteristics showing acceleration, velocity and contact area as a time function. The curve of the contact area-time function was established assuming an apple is a sphere. The instantaneous impact (normal) force is determined as follows: instantaneous contact area value is reported on the theoretical curve of contact area variations in order to determine corresponding instantaneous acceleration at time t. The instantaneous impact force is then calculated by multiplying this instantaneous acceleration by fruit mass. The instantaneous normal stress can then be expressed as:

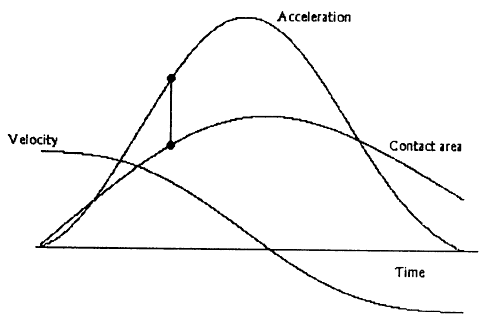

Fig. 1. Curves of impact characteristics showing acceleration, velocity and contact area versus time of contact. Example given for: apple mass 0.086 kg, maximum acceleration 63.1 G, initial velocity 0.77 ms^{-1}, final velocity -0.53 ms^{-1}, maximum contact area 1.79 10^{-6} m^2, non recoverable area 0.68 10^{-6} m^2, contact duration 4.09 10^{-3} s. Filled circles indicate measured contact area (1.39 10^{-6} m^2) and its corresponding instantaneous acceleration.

$$\sigma_t = \frac{F_t}{S_t} \tag{4}$$

where σ_t - instantaneous normal stress (Pa), F_t - instantaneous force (N), and S_t - measured contact area (m^2).

The contact area forms an ellipse so S_t can be calculated from:

$$S_t = \pi AB \tag{5}$$

where A - major ellipse radius (m), and B - minor ellipse radius (m).

The instantaneous shear stress is calculated from the relation given by Shigley [17, 25,31]:

$$\tau_t = 0.27\sigma_t \tag{6}$$

where t = instantaneous shear stress (Pa).

Up to the point of t (a point where the contact area equals to S_t), the fruit is still in compression so the energy absorbed is:

$$E_t = \frac{1}{2} M(v_o^2 - v_t^2) \qquad (7)$$

where E_t - energy absorbed up to the time of t (J), v_t - instantaneous velocity (ms^{-1}).

Bruise prediction

Within dynamic impact metal testing, the volume of the remaining indentation can be assessed by dividing the energy absorbed with the dynamic yield stress [35]. If we use this analogy and we can introduce the shear stress, and the energy absorbed, to predict the bruise volume, and write our predicting equation as follows:

$$V = \frac{E_t}{\tau_t} \qquad (8)$$

where V - bruise volume (m^3).

It should be noted that in Tabor's equation the maximum shear stress and the energy absorbed after the impact are used assuming that not all energy absorbed could be spent for plastic deformation. Here we tried to use the total energy absorbed up to time t, where t is the time when the instantaneous contact area equals the measured contact area.

MATERIAL AND METHODS

Golden Delicious apples grown in the experimental orchard, INRA Avignon, France were used in the experiments. The fruit were manually harvested and then stored at 2 °C and 95 % humidity, until they were needed for experiment. Three experiments were set up.

In the first experiment, fruit from the same category, having about the same size, were used for testing. For every test a sample of 20 apples was used. The first test was conducted five days after harvest and then every month a sample with the same size was randomly taken from storage for the next test. The fruit were followed for five months storage time. Before testing the fruit were exposed to an ambient temperature of 20 °C for 24 h. The fruit were weighted and their densities were determined by weighing them in the water. Physical data of fruit used in the first experiment are presented in Table 1. Every fruit was dropped form 0.05, 0.15, 0.25 and 0.35 m on its different equatorial parts.

Table 1. Physical data of fruit used in the first experiment

Test (storage time)	Number of fruit	Mass (kg)	Diameter (m)	Density (kg m^{-3})
I (5 days)	20	0.1937±0.0095	0.0769±0.002	789±9
II (35 days)	20	0.1891±0.0086	0.0763±0.002	782±11
III (66 days)	20	0.1920±0.0090	0.0763±0.002	783±10
IV (97 days)	20	0.1890±0.0089	0.0766±0.002	781±10
V (127 days	20	0.1881±0.0086	0.0766±0.002	778±10
VI (160 days)	20	0.1874±0.0095	0.0761±0.002	781±11

In the second experiment, 80 apples were used. Here the fruit had been stored just one week. The fruit were randomly separated into four groups designated for four different drop heights. The drop height consisted of 0.015, 0.020, 0.035 and 0.050 m.

The third experiment employed 20 fruits having a very large variation in mass considering all possible apple sizes for this variety. The fruit had been stored two weeks. In this case every fruit was dropped from 0.03, 0.06, 0.10 and 0.15 m.

Physical data for the second and the third experiments are given in Table 2.

Impact Test

Figure 2 illustrates the impact instrumentation used in the experiment. This mainly consists of a concrete block impact base equipped with an impact support, a force transducer type 9321A, an amplifier type 2626 Bruel and Kjaer and a 12 bits digital oscilloscope

Table 2. Physical data of fruit used in the second and third experiments

Experiment	Number of fruit	Mass (kg)	Diameter (m)	Density (kg m^{-3})
2	80	mean : 0.1709 min : 0.1435 max : 0.2028	mean : 0.0737 min : 0.6695 max : 0.7878	mean : 793 min : 761 max : 818
3	20	mean : 0.1562 min : 0.0830 max : 0.2430	mean : 0.0710 min : 0.0579 max : 0.0849	mean : 797 min : 767 max : 824

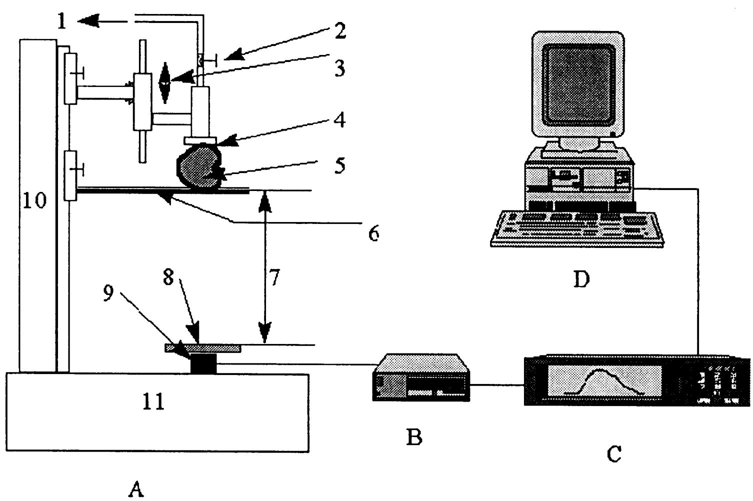

Fig. 2. Impact instrumentation showing: A - Impact device with 1) rubber pipe of the vacuum pump, 2) valve, 3) adjustable drop height to fruit diameter, 4) rubber ring 5) apple, 6) sliding metal bar adjustable to drop height, 7) drop height, 8) aluminium plate, 9) transducer, 10) stand 11) concrete block; B - Amplifier; C - Oscilloscope, and D - Computer.

Nicolet type 310 connected to an IBM computer via an interface card IEEE-488. The impact support consisted of a stand, an aluminium plate impact surface with the transducer installed below, a vacuum pump, and a sliding metal bar mounted on the stand.

During operation the fruit was held by the vacuum pump and the drop height was fixed by the metal bar and the adjusting fruit position. The fruit was then released, without initial speed, to strike against the impact surface on its cheek. The fruit was caught by hand just after striking to avoid second impact. The impact signal captured in the form of an electrostatic charge was then transformed in voltage by the amplifier. This voltage was then transmitted to the digital oscilloscope with a rate of 2 μs per point and displayed in the form of spectre in time function. This impact spectre was finally stored in the computer for further analysis.

Bruise measurement

For marking the contact area, the impact surface was smeared with blue inks made of oil and colour powder. The minor and major diameters were measured. The bruise was sectioned through its centre 24 h after impact to measure its diameter and depth. To observe the bruise zone, the bruise section was immersed in 'safranine-O' solution for 3 s. The measurement was made a few minutes after immersion to obtain the best contrast between the zone of bruised tissues and the zone of intact tissues.

Figure 3 shows a typical cross-section of the bruise showing parameters used in the calculation while Fig. 4 shows various aspects of

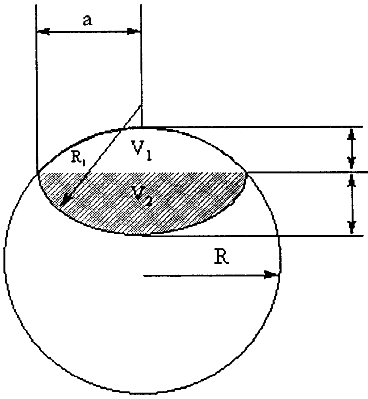

Fig. 3. Bruise section showing parameters used in bruise volume calculation.

where M - apple mass (kg) and ρ - apple density (kg m^{-3}).

Similarly, the volume of bruise below the contact plane is given by:

$$V_2 = \frac{\pi}{3} p^2 (3R_1 - p)$$

or

$$V_2 = \frac{\pi}{6} p(3a^2 + p^2) \tag{11}$$

where p - bruise depth (m) and R_l - radius of the bruising zone (m), $R_1 = \dfrac{a^2 + p^2}{2p}$.

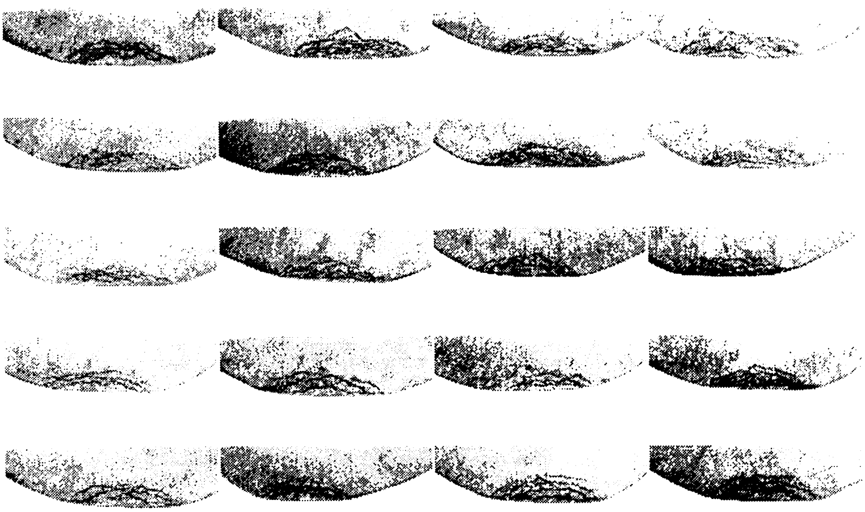

Fig. 4. Various aspects of bruising zone.

bruising zones. The bruise above the contact plane is equivalent to the volume of a spherical segment and can be calculated from:

$$V_1 = \frac{\pi}{3} h^2 (3R - h) \tag{9}$$

where h - the depth of crushed zone (m), $h{=}R{-}(R^2{-}a^2)^{1/2}$, a - bruise radius (m) and R - apple radius (m).

The radius of this sphere (apple) can be approximated by:

$$R = \left(\frac{3M}{4\pi\rho} \right)^{\frac{1}{3}} \tag{10}$$

Thus, the total bruise volume, V is the total volume of V_1 and V_2.

Data for the first experiment were first analysed globally to see the general responce and then analysed separately for every test to evaluate the change of the responce respecting the evolution of the fruit during storage. Data for the second and the third experiments were used to observe the impact of low energy and the effect of fruit mass, respectively.

RESULTS AND DISCUSSION

Observation on bruising revealed that the cells ruptured group by group commencing from the group having the weakest cell strength, which was not necessaring the cells nearest the skin. This was proved by the fact that the majority of bruises produced by the impact with a small drop height formed lines of cell ruptures at certain depths, which were not always aligned horizontally, while the cells near the skin rested intact. This kind of situation might demonstrate the heterogeneity of fruit [9]. The bruise diameter was smaller than the contact diameter. The smaller the drop height the bigger the difference between the bruise diameter and the contact diameter. For all the fruit tested the bruise diameter was on average 6.44 % smaller than its corresponding contact diameter. Based on this evidence, the bruise contact area changed little after the first groups of cell had ruptured. So using the measured contact area to estimate the normal stress should not cause significant errors in bruise prediction.

Figure 5 shows the measured bruise volumes plotted against the predicted bruise volumes using the data from the first experiments. The predicted bruise volumes linearly correlate to the measured bruise volume with a factor of proportionality (K) 1.08 and a coefficient of correlation (R) 0.949. It could be said that, in general, the prediction gave 8 % error. Comparing to the original Tabor's equation it can be noted that in the case of bio-materials (apple) most total energy absorbed was used for plastic deformation (bruising).

To see the changes in shear stress, energy absorbed, and the relation between the pre-

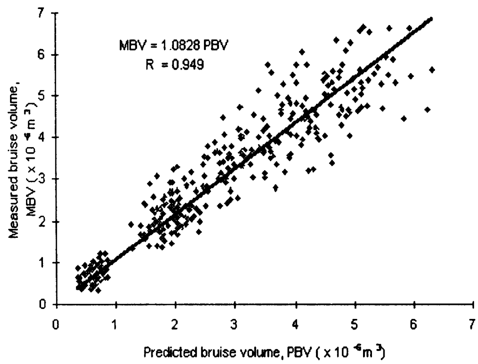

Fig. 5. Measured bruise volume plotted against predicted bruise volume for the first experiment.

dicted bruise volumes and the measured bruise volumes during storage, data were analysed for every test in the experiment. Figures 6 and 7

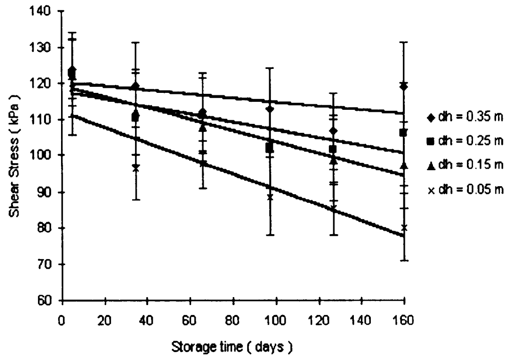

Fig. 6. Shear stress plotted against storage time (grouped according to drop height).

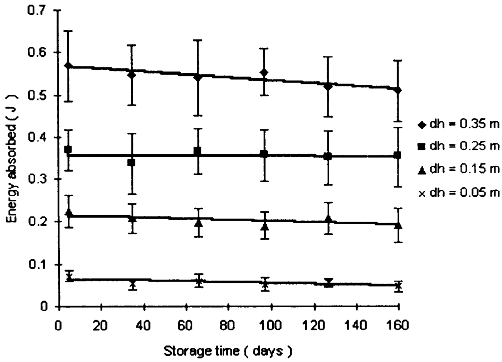

Fig. 7. Energy absorbed plotted against storage time (grouped according to drop height).

present respectively the changes in shear stress and energy absorbed during storage. Generally both the shear stress and energy absorbed decreased during storage. Table 3 gives the relationships between the predicted bruise volumes and the measured bruise volumes for each test of the first experiment.

From Table 3, it can be seen that the value of K is relatively constant during the storage period, although the shear stress and the energy absorbed decreased. This is different to the result of the previous work [36] which showed the value of K was influenced by the change in modulus of elasticity during the storage period. So, if we consider that the deviation of the K value by 1 was mainly caused by experimental errors we can conclude that the prediction of

Table 3. The relationships between the predicted bruise volumes (PBV) and the measured bruise volumes (MBV) for every test of the first experiment

Test (storage time)	Number of fruit	Equation MBV=K PBV	R
I (5 days)	20	K = 1.091	0.951
II (35 days)	20	K = 1.092	0.949
III (66 days)	20	K = 1.097	0.934
IV(97 days)	20	K = 1.010	0.951
V (127 days)	20	K = 1.114	0.966
VI(160 days)	20	K = 1.076	0.953

bruise volume based on the instantaneous shear stress and the instantaneous energy absorbed is independent of fruit firmness.

In practice, a group of fruit may be subjected to impact independently from the other groups and may experience small drop heights. The second experiment was used to explore this kind of situation. Figure 8 shows the relationship between the predicted bruise volumes and the measured bruise volumes. The linear relation produces a factor of proportionality (K) 1.163 and a coefficient of correlation (R) 0.909. Compared to the values of K in the first experiment, this K value is relatively constant. It suggests that the prediction is reliable. But attention should be paid when applying low impact energy to ensure that plastic deformation really occurs during impact.

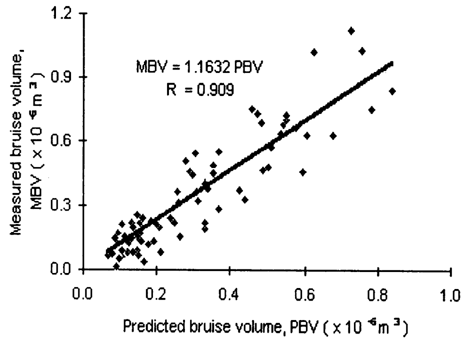

Fig. 8. Measured bruise volume plotted against predicted bruise volume for the second experiment.

The third experiment was used to observe the effect of mass variation. The sample included all possible commercial sizes of apples for this variety. The measured bruise volumes plotted against the predicted bruise volumes is shown in Fig. 9. The linear relation produces a K value of 1.346 with R value of 0.910. This suggests that the bruise prediction is influenced by the mass variation.

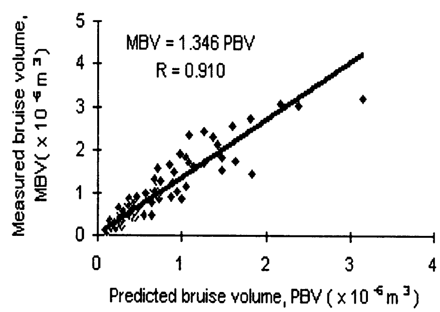

Fig. 9. Measured bruise volume plotted against predicted bruise volume for the third experiment.

CONCLUSION

The bruise prediction based on the instantaneous impact shear stress and the instantaneous energy absorbed produced a linear relation between the predicted bruise volumes and the measured bruise volumes with a factor of proportionality (K) 1.08 and a coefficient of correlation (R) 0.949. Both the instantaneous impact shear stress, and energy absorbed, decreased during the storage period of the fruit, but the value of K was relatively constant. Impact with small drop heights also produced a linear relation between the predicted bruise volumes and the measured bruise volumes with a K value of 1.163 and a R value of 0.909. With the variation of fruit mass, including all possible commercial fruit size for this apple variety, the linear relation between the predicted bruise volumes and the measured bruise volumes had a K value of 1.346 and a R value of 0.910.

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