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Modeling Static Bruising in Apple Fruits: A Comparative Study, Part I: Analytical Approach

S. M. NASSIRI[1] and R. JAFARI[1*]**

[1]Department of Mechanics of Agricultural Machinery, College of Agriculture, Shiraz University, Shiraz, I. R. Iran

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ABSTRACT- Bruising degrades the quality of fresh apple fruits. Reducing bruise damage is of utmost importance in designing and developing processing equipments. The main objective of the present study was to introduce an analytical method to predict the allowable static load applicable to apple fruits. To predict the strain energy absorbed by the fruit, a point load was applied on the solid spherical object. The strain energy of the spherical element was extended to the whole body using a triple integral in the spherical domain. In order to verify the results, a series of compression tests were carried out using a universal testing machine on an apple kept at two different storage and initial fruit temperatures (zero and 25°C). The results showed a strong polynomial relation with a coefficient of determination of 0.990 between the value of the theoretical stored strain energy and the experimental one. Also, it was found that the size of the bruised area can be determined by its corresponding theoretical stored strain energy with an error less than 3.6 percent.

Keywords: Apple bruise, Bruise, Mathematical modeling

INTRODUCTION

Bruising is the main source of mechanical degrading in apple fruits. It occurs and develops in different stages from harvesting operations to consumption. A number of studies have been conducted aiming at reducing mechanical bruise formation. In some of them, the effect of static pressure has been investigated.

A numerical image technique was proposed by Roudot et al. (7) to study the damage of apple flesh caused by compression and impact loadings. It was found that two

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* Assistant Professor and Assistant Professor, respectively
** Corresponding Author

different physical phenomena were involved during impact and compression. They concluded that cell collapsing mostly occurs during impact, while cell displacement occurs during compression, and thereby, the appearance of the bruised zones was different.

Wu and Pitts (10) proposed an image processing technique to simulate a close actual cell shape for apple fruit by a three dimensional Finite Element (FE) model. The mechanical behavior of cells was studied and compared using experimental data. It was stated that the mechanical behavior of the whole body of the fruit can be estimated by cell behavior.

The behavior of Red Delicious apple tissue under dynamic axial compression (impact) was studied by Bajema et al. (1). They reported that the failure strain at the quasi-static strain rate was largest due to the occurrence of bio-yield, but not for dynamic strain rates. It was concluded that both fruit size and strain rate influenced dynamic failure properties, and thereby the type of bruised zone.

Thermal imaging was used as a non-contact bruise detection technique for apple bruise detection by Varith et al. (8). This method classified damaged and undamaged fruits by differences in thermal diffusivity of the tissues. Xing et al. (12) mentioned that the two types of bruising sources, namely compression and impact forces, influenced misclassification errors of Golden Delicious apples.

Lewis et al. (4) conducted a study to develop a testing tool for optimizing the design of harvesting and sorting equipment and packaging material to reduce apple bruise formation due to impact loads. Analytical calculations based on the Hertz contact equation were also used to compare the numerical and dynamic FE model responses.
Xing and De Baerdemaeker (11) employed VIS/NIR spectroscopy to measure the elastic modulus of apple fruits. They measured E-modulus which was used for calculating the softening index for freshly bruised spots on apple surfaces. This algorithm could separate 95% of the damaged fruits from undamaged ones.

Kim et al. (3) proposed finite element optimization algorithms to determine the viscoelastic properties of bio-materials, and to predict the mechanical behavior of such materials. The appearance of mechanical bruise which causes compression loads is a time dependent phenomenon. For this reason, online sorting for fruits which have been freshly compressed is found to be difficult.

Lewis et al. (5) used a novel ultrasonic technique to study apple contact areas and stress under static loading. Also, the finite element method was used to simulate contact stress and area. They observed that there was quite good correlation between the contact area for ultrasonic measurement and the finite element approach. Linear elastic property was assumed for materials under loading for the finite element model. It was concluded that better results may be obtained by an elastic-plastic assumption.

The aforementioned studies aimed to recognize fruit damage due to bruising, to introduce an easy way for bruise detection, especially the online type, to assess the conditions of bruise formation and to find appropriate methods of bruise reduction. By considering these studies, the present investigation was conducted to predict bruise formation by an analytical approach. This method was verified by a series of laboratory compression tests.

MATERIALS AND METHODS

The study was classified into two stages. First, an analytical model was developed to predict the bruise considering the amount of absorbed strain energy in the fruit. The simulated data were then compared to those collected from laboratory tests during the second step.

Analytical Background

Absorbed strain energy in the apple fruit during the application of an external load is a reliable criterion for studying the bruising process (5). When the absorbed total strain energy of the cells (elastic and plastic) exceeds its allowable limit, the cell collapses, and bruising occurs. Therefore, to simulate the bruising process, the amount of strain energy during static loading should be calculated.

Energy Calculation

When an external point load is applied to an apple fruit, the force distributes on a circular plane (2). The radius of the circular plane is a function of the amount of load. To simplify the problem, the shape of the apple fruit was assumed as a sphere, and point load P was applied on the contact area (Fig. 1). The height of the sectioned plane from the X-Y plane was Z=b. The normal stress on the Y-Z plane is:

$$s = \frac{P}{A} = \frac{P}{p\,(a^2 - r^2)} \tag{1}$$

When an external load is applied to a viscoelastic sphere like an apple, three phases are recognized regarding stress development. First, the apple shows elastic behavior similar to that of a linear elastic object at very low deformation (less than 5% strain). By increasing the magnitude of the load, the behavior of the viscoelastic object undergoes a change from elastic to plastic. In this stage, the object tolerates the load until total strain and energy exceed their allowable limit. In the third phase, by adding more external force, the viscous elements transfer their extra load to adjacent elements. This process is repeated for all elements. In order to model the load transfer procedure, strain energy was calculated using the following equation:

$$u_e = \frac{1}{2E}\int_v s^2\,dv \tag{2}$$

Equation 2 is substituted by 1, and can thus be written as

$$u_e = \frac{1}{2E}\iiint \frac{p^2}{p^2 (a^2 - r^2)^2}\,dv = \frac{p^2}{2Ep^2}\int_{q=0}^{2p}\int_{j=0}^{p}\int_{r=0}^{\frac{b}{\cos j}} \frac{r^2 \sin j\; dr\,dj\,dq}{(a^2 - r^2)^2} \tag{3}$$

Strain energy can be obtained by calculating the above integral in a spherical coordinate. Hence:

$$u_e = \frac{p^2}{4aEp}(a - b) \tag{4}$$

In equation 4, "a" is the radius of solid sphere and "b" is the height of the contacting plane where strain energy has been calculated (2). In the Maxwell viscoelastic material model, the modulus of elasticity is a function of time, and can be computed as:

$$E = E_0 + \sum_{i=1}^{k} E_i e^{\frac{-t}{T_i}} \quad (5)$$

where E_0 is the initial modulus of elasticity and T_i is the relaxation time for the viscous element. E_0 and T_i values were obtained by a stress relaxation test on fruit samples in different storage conditions, discussed in the next section.

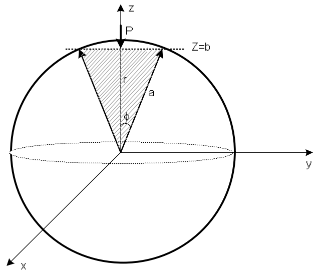

Fig. 1. A spherical object subjected to external point load

Transient strain energy in the (0, t_0) domain was calculated using the separation of variable method (t_0 is the time of exerting the load during the stress relaxation test). Hence, strain energy can be calculated as a function of time and the geometry of the apple fruits (using two time dependent elements):

$$u_e = \frac{p^2}{4ap}(a-b)\int_0^{t_0} \frac{dt}{E_0 + \sum_{i=1}^{2} E_i e^{-\frac{t}{T_i}}} \quad (6)$$

The definite integral in equation 6 was numerically calculated by Sympson's method using MATLAB software (version 7.5.0.342, The MathWorks, Inc., USA). The amount of absorbed strain energy was calculated for all samples using equation 6.

Laboratory Test

Stress Relaxation Test

Uniform size fruits were selected from a batch of Golden Delicious apples and randomly assigned to two sample groups. One group was kept at zero degree Celsius and 35% relative humidity (cold condition), and another at 25 degree Celsius and about 65% relative humidity (warm or ambient condition), so that the equilibrium moisture content was kept constant (6). Temperature and relative humidity were checked frequently by a Testo handset tester (Testo 435, Germany). The constants E_0 and T_i were obtained from the relaxation test. 10 samples from each batch were randomly selected and subjected to a compressive force by a 25 mm circular probe of the Santam machine (STM-20 model). Initial deformation was 2 mm and samples were kept under load for 7 min. To prevent any pre-relaxation phenomenon, tests were performed at a rate of 650 mm/min. The stress versus time curve was created by machine software and the corresponding data were saved. These data were used to draw out the constants using SPSS software (release 16.0.0, 2007. SPSS Inc.). The generalized Maxwell model was fitted on data and constants were obtained. This model can be expressed by the following equation:

$$\sigma(t) = \varepsilon_0\left(E_1 e^{\frac{-t}{T_1}} + E_2 e^{\frac{-t}{T_2}} + \cdots + E_n\right) \quad (7)$$

According to the fruit geometry, the above equation can be modified as follows:

$$F(t) = K(\Delta l)(E_1 e^{\frac{-t}{T_1}} + E_2 e^{\frac{-t}{T_2}} + \cdots + E_n) \tag{8}$$

where Δl is initial deformation, $K = \frac{\pi(\varphi)^2}{4D}$, φ is the probe diameter and D is the equatorial mean diameter of the fruit. The model was then verified by repeating the tests with new samples. Finally, the secured constants were substituted in equation 6.

Quasi-static Compression Test

As before, the samples were assigned to two groups: one refrigerated at zero degree Celsius and the other put in an oven at 25 degree Celsius for about 12 hours. The quasi-static compression force was then exerted on equatorial regions of samples of each group by the same probe. The samples were compressed at a constant rate of 10 mm/min. Three levels of final deformation 1.5, 3 and 4.5 mm were considered for the compression tests (Fig. 2). These levels were selected less than, equal and greater than 5% of the strain, respectively.

Fig. 2. Sample under compression test by Santam (STM-20) apparatus

Compressed samples were stored in their previous conditions for 10 days. Every day, an image was captured from the compressed zone. The vision system consisted of a flat datum and a semi-spherical cover with a white interior wall (Fig.3). Four string 12-volt-lamps with a 12 volt DC supply provided uniform and constant light intensity for tests as shown schematically in Fig.4 (10).

The sample was positioned in the centre of the test rig, where all light rays converged. The image was captured from the bruised zone, the bruised surface area being used for calculation using the image processing toolbox of MATLAB software. To verify the analytical model, the same tests were repeated.

RESULTS AND DISCUSSION

Constants of the analytical equation

As mentioned, 10 samples were used to draw out the elastic modulus and the relaxation time of viscous elements. Means of the force-deformation data were imported to SPSS software to find the best fit curve constants. Data were modeled by nonlinear regression analysis constrained to non negative constants. The minimum sum of square residuals (SSE) was the criterion for finding the best fit curve for data. Primary analysis showed that the two terms viscous element was the best model for determining the stress relaxation equation. (see Fig. 5).

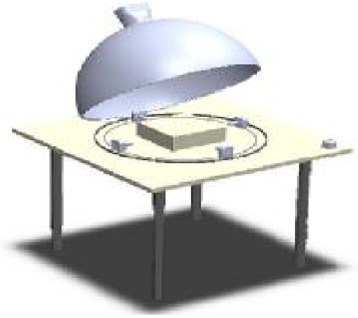

Fig. 3. Schematic view of vision system

Fig. 4. Real view of vision system

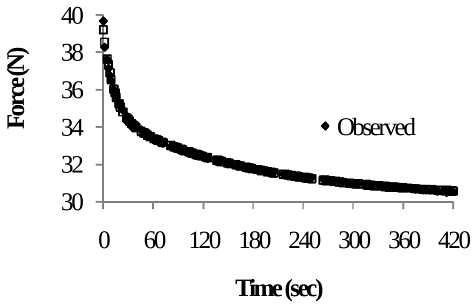

Fig. 5. Observed and modeled data for stress relaxation test when samples initially deformed 2 mm

The models were verified by a new set of data and the observed results secured the constants as shown in Figs 6 to 9. Therefore, the three terms Maxwell model was subjected on the data and the constants of equation 8 were calculated (Table 1). The same constants were used in equation 6 to calculate stored strain energy during compression. The values of the modeled strain energy were 0.29, 0.347, and 0.567 joules for initial deformations of 1.5, 3, and 4.5 mm for the cold samples, respectively. Correspondingly, they were 0.209, 0.458, and 0.810 joules at the same deformation for warm samples.

Table 1. Constants of Maxwell model with two viscous elements

Relaxation	Deformation (mm)	E_1 (N/mm^2)	E_2 (N/mm^2)	E_0 (N/mm^2)	T_1 (min)	T_2 (min)	SSR*
Cold	**2**	**0.49±0.01**	**0.49±0.01**	**3.27±0.00**	**0.21±0.05**	**2.85±0.00**	**0.71**
	4	**0.53±0.01**	**0.64±0.00**	**3.50±0.00**	**0.22±0.22**	**2.74±0.04**	**3.05**
Warm	**2**	**0.40±0.01**	**0.41±0.00**	**2.76±0.01**	**0.25±0.01**	**2.75±0.06**	**0.56**
	4	**0.55±0.01**	**0.64±0.00**	**3.83±0.01**	**0.25±0.01**	**2.99±0.06**	**3.75**

*** Sum of Square of Residuals**

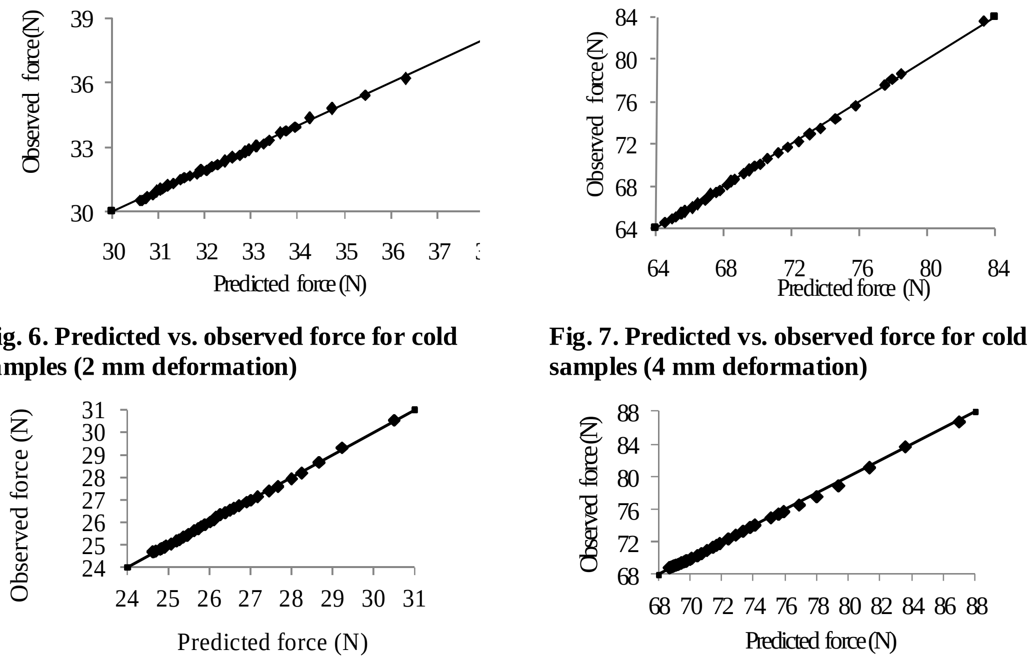

Fig. 6. Predicted vs. observed force for cold samples (2 mm deformation)

Fig. 7. Predicted vs. observed force for cold samples (4 mm deformation)

Fig. 8. Predicted vs. observed force for warm samples (2 mm deformation)

Fig. 9. Predicted vs. observed force for warm samples (4 mm deformation)

Compression tests

As mentioned, compression tests were carried out for 1.5, 3 and 4.5 mm initial deformations. Bruise formation was tracked for 10 days. Fig. 10 shows the surface area of the bruised region for every treatment. As could be seen, increasing the storage period resulted in the enlargement of the bruised region surface area. Given the suitable conditions for enzymatic reactions, the bruise developed more rapidly in the warm condition as compared to the cold one.

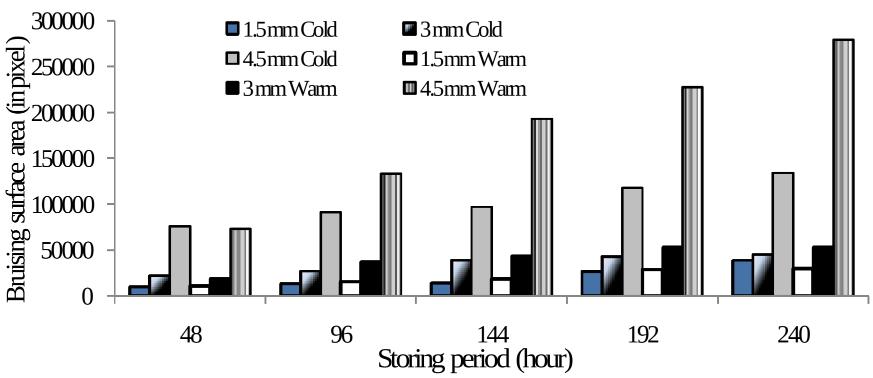

Fig. 10. Bruise development vs. storing period

In order to find out the relationship between the bruise and the modeled strain energy, first, the relation between modeled and measured strain energies was examined

(Fig. 11). The Fig. shows that cold and warm conditions followed different slopes. It might be concluded that the cold samples possessed more rigidity than the warm ones, and because of the two viscous terms, the elastic modulus has been overestimated by the model. This finding is illustrated in Fig. 12. A rapid rise can be observed in this curve at 4.5 mm initial deformation (more than 5% strain). However, both modeled and measured curves indicated that strain energy followed polynomial trends.

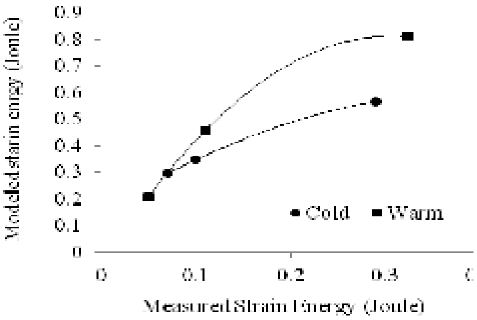

Fig. 11. Relation between modeled and measured values of the strain energy

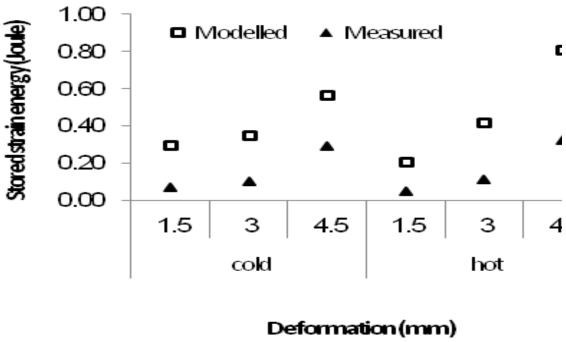

Fig. 12. Trend of strain energy at different levels of deformation

According to the main objective of the study, it was important to know whether the given amount of modeled strain energy could predict static bruise or not. For this reason, the relationship between the bruised areas' surface and the modeled strain energy was examined by computing correlation coefficients (Table 2). Cold and warm storages followed different patterns, which might be due to the differences between the strain energy trends as shown in Fig. 12. However, the same trends were observed between actual and modeled strain energies. For the warm (ambient) condition, the bruise was well correlated with both actual and modeled strain energies 4 days after storage, whereas for the cold conditions, it was two days from storage.

Table 2. The correlation coefficients between bruise surface area and stored strain energy (measured and modeled) at different storing intervals

Data	Storage condition	Storing interval (hrs)				
		48	96	144	192	240
Measured	**Cold**	**0.999**	**0.999**	**0.997**	**0.997**	**0.995**
	Warm	**0.995**	**0.999**	**0.997**	**0.995**	**0.992**
Modeled	**Cold**	**0.999**	**0.997**	**0.994**	**0.994**	**0.992**
	Warm	**0.972**	**0.984**	**0.976**	**0.971**	**0.964**

CONCLUSIONS

The proposed analytical model overestimated the amount of strain energy developed by initial deformation. The size of overestimation decreased when samples deformed more than 5% strain (4.5 mm deformation). In addition, overestimation was lower for cold samples. The study showed however, that the bruise could be detected in equal times for actual and analytical strain energies. The bruise surface area can be estimated by analytical strain energy after 2 and 4 days when fruits are stored in cold and warm conditions, respectively.

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مدل سازی قهوه ای شدن میوه های سیب تحت بارهای استاتیکی، مطالعه مقایسه ای، بخش اول: روش تحلیلی

سید مهدی نصیری[1] و رامین جعفری[1*]**

[1]بخش مکانیک ماشین های کشاورزی، دانشکده کشاورزی، دانشگاه شیراز، شیراز، ج. ا. ایران

چکیده - قهوه ای شدن سیب کیفیت میوه را کاهش می دهد. تلاش برای کاهش صدمه در اثر قهوه ای شدن اهمیت ویژه ای در طراحی و توسعه فرآیند ها و تجهیزات پس از برداشت دارد. هدف اصلی این پژوهش معرفی روش تحلیلی برای پیش بینی مقدار مجاز بارهای استاتیکی وارد بر میوه سیب بود. برای این منظور یک نیروی متمرکز بر روی یک کره شبیه سازی شده از میوه وارد شد. مقدار انرژی کرنشی کل جسم با استفاده از انتگرال سه گانه تعیین گردید. برای واسنجی نتایج تعدادی آزمون های فشاری با استفاده از دستگاه تست فشاری صورت پذیرفت. آزمون ها در دو دمای مختلف صفر و 25 درجه سانتی گراد صورت پذیرفت و سپس نمونه های بارگذاری شده در دمای مشابه نگهداری شدند. طبق نتایج بین مقدار انرژی کرنشی ذخیره شده از روش تحلیلی و مقادیر متناظر حاصل از روش آزمایشگاهی رابطه ای چند جمله ای با ضریب تبیین 0/990 برقرار است. همچنین مشخص شد که گسترش سطح قهوه ای شدن با مقدار انرژی ذخیره شده با خطایی کمتر از 3/6 درصد قابل پیش بینی است.

واژه های کلیدی: قهوه ای، قهوه ای شدن سیب، مدل سازی ریاضی

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* به ترتیب استادیار و استادیار

**مکاتبه کننده