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Modeling Static Bruising in Apple Fruits: A Comparative Study, Part II: Finite Element Approach

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ABSTRACT- Mechanical damage degrades fruit quality in the chain from production to the consumption. Damage is due to static, impact and vibration loads during processes such as harvesting, transportation, sorting and bulk storage. In the present study finite element (FE) models were used to simulate the process of static bruising for apple fruits by contact of the fruit with a hard surface. Three dimensional finite element models with three different layer material models were developed. The force relation between the cortex and elastic core was simulated using a gluing mechanism. An external point load simulating the wall pressure was applied on the fruit skin. The elastic, plastic and total strain energies in apple fruits were calculated to estimate mechanical bruising. In order to validate the simulated data, compression tests were carried out using a universal testing machine. Force-deformation graphs were plotted and the area of the region restricted by the curve and deformation axis between zero and 1.5, 3 and 4.5 mm deformations were obtained at five replications to assess the stored strain energy in the fruit. Results revealed that any increase in applied external displacement increased the bruised area. A high correlation (r=0.994) was observed between bruised area and amount of stored strain energy. Other results indicated that the bruised area highly depended on skin elasticity. Increasing in skin modulus of elasticity decreased the bruised surface.

Keywords: Apple bruising, Finite element, Fruit storing

INTRODUCTION

The most prevalent symptom of damage is fruit bruising which is caused during the post harvest process. Bruise damage is produced by the impact or slow compression of the fruit against other objects. The hard wall of the fruit box and the adjacent fruits are usually two external objects that impact the apple fruit most during handling, storage

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and transportation, causing bruises on the fruit (12). Bruise is generally defined as a zone of brown tissue below the skin of the fruit. This brown tissue can reduce the quality of the fruit and the fruit's marketing potential.

Some parameters like stiffness of the rigid wall in contact with apple, thermal conditions of fruit storehouses, and the stiffness of the skin and cortex of the apple, affect the area of the bruised surface. Many researchers have focused on the nature of bruising and the effect of loading conditions on the fruit. However, only a few have considered the effect of thermal conditions of storage on bruising. Usually, bruising happens when the absorbed energy in the fruit exceeds that of its allowable limit. Measuring and predicting the energy absorption process in the fruit during static loading can be performed experimentally or theoretically. Experimental tests have disadvantages such as low accuracy, high cost and low generalizing ability. Many studies on apple bruise formation have been carried out using a variety of techniques, such as compression and drop tests (1, 3, 4, 5).

Modeling is another approach to investigate the mechanical damage to vegetative textures, especially the bruising process in fruits. Finite element analysis (FE) is a powerful theoretical method to model the process of apple bruising during the application of force. Simple models for the structure of vegetative tissue have been developed by many researchers (2, 9). In these models, fruits were assumed to have uniform and symmetric shapes (such as a sphere or cylinder). Some assumptions like homogeneity of texture and the elastic behavior of the apple were used to render an easy analysis (7, 8). As reported in previous literature, vegetative tissues usually exhibit viscoelastic behavior. However, it has been reported that the mechanical strength (modulus of elasticity and poison ratio) of the skin, cortex and core of apples are different. Changes in storing temperature can affect the viscoelastic behavior of the vegetative tissue (10).

In the present study, the finite element model was used to simulate the process of the static bruising of apple fruits during the fruits' contact with rigid surfaces at two temperature levels. The main superiority of the present study with respect to those available in the literature is the separation of the mechanical behavior of the apple fruit into three parts, namely the skin, cortex and core.

The main objectives of the present study were to:

i. develop a three-dimensional finite element model with elastic-plastic behavior of the apple fruit to simulate the bruising process.

ii. validate the FE model by comparing the theoretical results obtained from the model and the experimental data.

iii. investigate the effect of storing apple fruits on bruise propagation at two different temperature conditions.

MATERIALS AND METHODS

Finite element model was developed to simulate the behavior of apple fruits undergoing static load conditions. Some physical properties like modulus of elasticity were needed as input parameters of the simulation model. In order to determine the modulus of elasticity, a series of compression tests were carried out using Santam compression test apparatus. The compression tests were done on apples with and without skin. The difference between these two conditions was used to predict the physical properties of the apple skin. In order to determine the viscoelastic behavior of the apple, five relaxation tests were performed at two different deformation levels (2, 4 mm). All experimental tests were carried out on Golden Delicious apples which had been stored at two different temperature conditions (zero and 25 degree Celsius).

Viscoelastic Material Model

Viscoelastic materials exhibit both viscous and elastic characteristics when undergoing deformation. The Maxwell model can be represented by a damper as a viscous element and a spring as an elastic element which are connected in the series (Fig. 1).

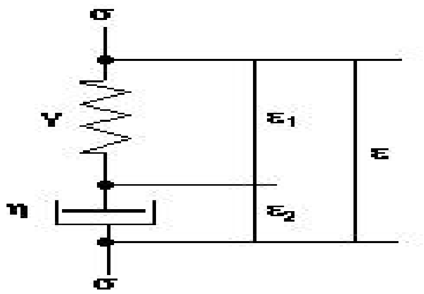

Fig. 1. The Maxwell model

The model can be represented by the following equation:

$$\frac{de_{total}}{dt} = \frac{de_1}{dt} + \frac{de_2}{dt} = \frac{s}{h} + \frac{1}{E}\frac{ds}{dt} \qquad (1)$$

In this model, if the material undergoes a constant strain, the stress gradually relaxes. First, an elastic component expands instantaneously, corresponding to the spring, and relaxes immediately upon the release of the stress. The second component, viz. viscous grows with time as long as the stress is applied. According to the Maxwell model, stress decays exponentially with time. It was found that vegetative textures follow the same behavior (10).

Stress relaxation test

As discussed by Nassiri and Jafari (11), constants E_i and T_i were obtained from the relaxation test using the generalized Maxwell model. This model can be expressed by the following equation:

$$s\,(t) = e_0(E_1 e^{-\frac{t}{T_1}} + E_2 e^{-\frac{t}{T_2}} + \ldots + E_n) \qquad (2)$$

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

$$F\,(t) = K\,(\Delta l)(E_1 e^{-\frac{t}{T_1}} + E_2 e^{-\frac{t}{T_2}} + \ldots + E_n) \qquad (3)$$

where Δl is the initial deformation and K equals $\pi\,(\varphi)^2/(4D)$. φ is the probe diameter and D is the equatorial mean diameter of the fruit. Stress relaxation tests were carried out at two levels of deformation (2 and 4 mm), and two storage conditions (zero and 25 degree Celsius). Afterwards, the model was verified by repeating the tests with new samples. Finally, the secured constants were used as input for the finite element model.

SPSS software (release 16.0.0, 2007. SPSS Inc) was used to determine the Viscoelastic model constants. The time and stress values were determined by relaxation tests in the laboratory using Santam apparatus.

Theoretical Background

Finite element analyses were carried out using ANSYS software (ANSYS, Release 12). The ANSYS program was used for solving the non linear model. This advantage supports all nonlinear material and geometric and boundary (contact, follower force or opening/closing of gaps) issues. It is important to mention that the entire experimental tests were completed in the large deformation stage (total strain more than 25%). In the present study, all sources of nonlinearity were available including the amount of large deformations as well as the property of the material. The presence of contact elements emphasizes the nonlinearity behavior as well.

Finite Element Modeling

An appropriate modeled geometry was chosen to create apple quarters. The cutting planes of the quarter were through the stem-calyx axis of the apple fruit. For the purpose of generating apple geometry, the plane polar curves of the apple with the equation $r = K(1 \pm \sin q)$ were plotted and then revolved by 90° around the stem-calyx axis of the apple fruit. Finite element models of the apple were constructed using geometry modeling and mesh generator engines of the software. The geometrical model was designed by three layers (Core, cortex and skin).

In order to establish the force relation between these layers, gluing and contact mechanisms were used (6). The main difference between glue and contact mechanism is the nature of the load transfer. The contact manager of the software was able to create the contact element with different normal and tangential stiffness. The nature of the transferring force between the two connected layers was adjusted by using the contact wizard engine and changing the normal and tangential stiffness of the contact element. The gluing mechanism could transfer the entire external load between two different layers. In the mentioned FE model, the skin was jointed to the cortex using contact elements. The cortex was glued to the apple core so that the entire internal load in the cortex-core boundary was transferred to the core. The 8 node brick element (solid 45) was used for skin and cortex meshing. The “PLANE 183” element was used to mesh the viscoelastic material (flesh). The “Cont 174” element which is able to transfer normal and tangential loads was adopted as contact element (Fig. 2).

The linear elastic property material model for the skin and cortex, and the nonlinear viscoelastic property material model for the flesh were assumed. Elastic and viscoelastic properties of the apple fruits were calculated using measured data from experimental tests. The Maxwell viscoelastic material model in the material properties engine of the ANSYS software had 95 constant inputs.

The external load was applied on the contact surface of the quarter of the modeled apple as an external displacement. The vertical displacement (along the Y axis) was exerted at three levels of 1.5, 3 and 4.5 mm. The model was constrained so that it was not free to rotate. The normal constrain was also applied on the apple fruit so that the fruit was not free to move along the Y axis. A series of FE analyses were run at various load levels. The contours of principle stress, Von misses stress, total strain energy and normal strain (along the exerted load) were plotted and their maximum values were calculated.

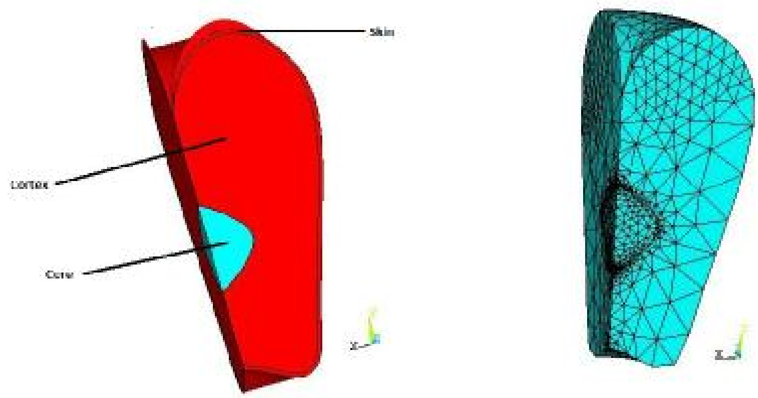

Fig. 2. Geometry and mesh of a quarter of an apple fruit

RESULTS AND DISCUSSION

Compression Tests

As mentioned earlier, compression tests were conducted at three displacement levels ($d_1 = 1.5mm, d_2 = 3mm, d_3 = 4.5mm$) and two storage conditions (cool and warm). The bruised area was measured at 48, 96, 144, 192 and 240 hours after applying the load. Increase in external displacement resulted in increasing bruised areas (11).

The force-deformation graph for each treatment was plotted and the area of the region restricted by the curve and deformation axis between zero and 1.5, 3 and 4.5 mm deformations were calculated in five replications to obtain the stored strain energy in each treatment (Fig. 3). Comparisons between the absorbed strain energy for each treatment indicated that increasing the external deformation applied on apple fruits, results in increases of total strain energy. Changing the storing condition from warm to cold increased elastic strain energy and decreased the plastic one. Results showed that total strain energy was approximately constant for each level of external displacement.

Finite Element Results

Variations of stress, strain and calculated energy by the FE method at different input levels were plotted to illustrate the effects of static loading on stress and strain propagation. Stress, strain and energy variations in an apple quarter had approximately the same contour shape. Maximum values of the aforementioned parameters were obtained in the inner layers of the fruit, near the interface of the core and the skin. Stress and strain decreased when the effect of the external force was transferred toward the apple core (Fig. 4).

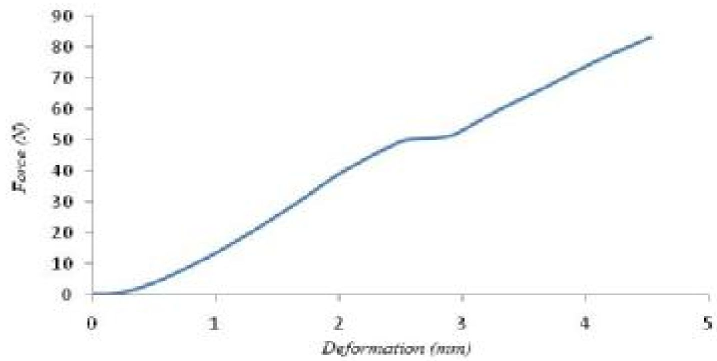

Fig. 3. A force- deformation graph sample for apple fruits subjected to 4.5 mm deformation to calculate absorbed strain energy

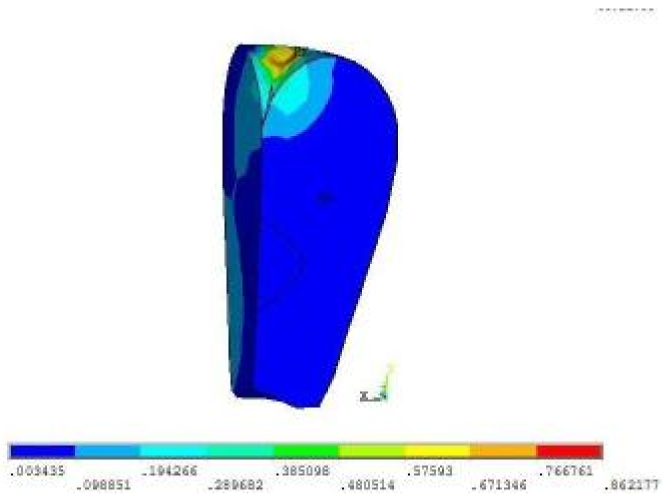

Fig. 4. Distribution of Von-Misses stress for warm storage conditions for 2mm displacement treatment

In order to find the best criterion for the formation of mechanical apple bruises, correlation coefficients between bruised areas and stress, strain and energy were calculated in different days. For all parameters, the highest correlation was observed at the 144 hour storing period (6 days after loading). Results revealed that having a correlation coefficient of less than 0.35 for all days, strain was not a good predictor of bruise formation.

The Von Misses stress graph and strain energy versus bruised area after 6 days were plotted to determine the best criterion for apple bruise prediction (Fig. 5 and 6). A nonlinear relationship (second order polynomial) was observed between the area of the bruised surface (11), and Von misses stress (Fig. 5), whereas, a linear relationship was observed between the area of bruised surface and total strain energy (Fig. 6). As depicted in Fig.

6, average strain energy in the apple fruit is the best criterion for predicting the probability of bruises. Results indicate that it is possible to predict bruising in apple fruits when the applied strain energy to the fruit exceeds its allowable limit. Fig. 7 shows that it is possible to increase the strain energy in apples up to a critical level without any mechanical bruising. This minimum level highly depends on the mechanical properties of the apple skin.

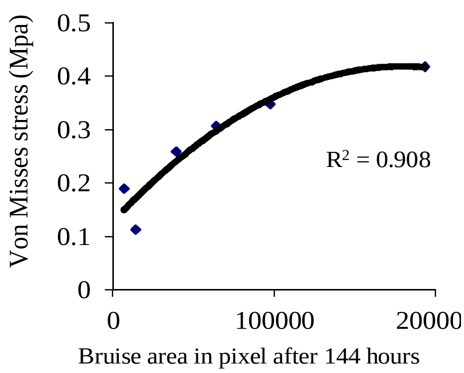

Fig. 5. Variation of bruise area versus Von Misses stress at 144 hours after loading

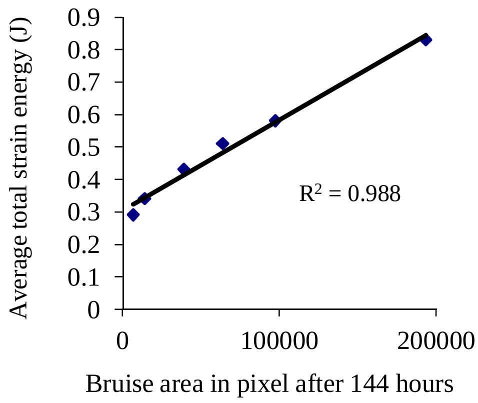

Fig. 6. Variation of bruise area versus total strain energy at 144 hours after loading

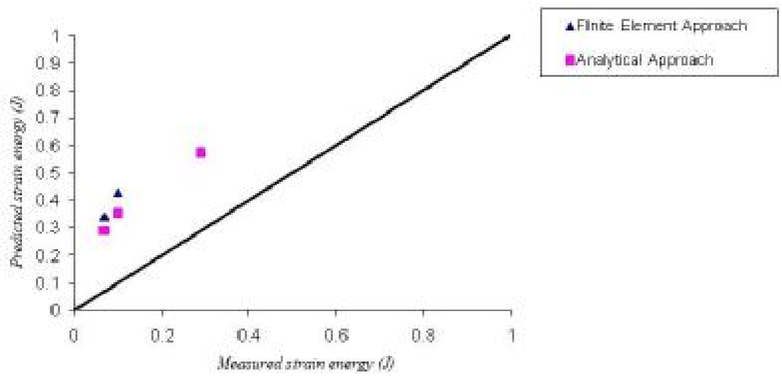

Fig. 7. Estimated strain energy by two modeling approach versus measured ones for the samples stored in cold condition

Theoretical FE results indicated that stored strain energy and consequently bruised areas were highly dependent on skin elasticity. Increases in the skin modulus of elasticity decreased the bruised area. The main reason for this phenomenon lies in the nature of the load transfer in the apple fruit. As mentioned before, the apple skin can absorb strains up to a definite level and transfer the extra load to the flesh texture. Increases in the skin modulus of elasticity decreased total skin deformation. FE results showed that the elasticity modulus of the skin is highly dependent on storage temperature. The cold storage condition resulted in increasing the elasticity modulus of the skin, thereby decreasing the bruised area.

CONCLUSIONS

Simulation results as compared to experimental ones indicated that bruising six days after loading highly correlated with stored strain energy in the apple fruit. The fruits which were stored in the refrigerator tolerated more external load than those stored at ambient storage conditions. Increases in the modulus of elasticity for apple fruits decreased bruised surface areas.

COMPARISION OF THE RESULTS (PARTS ONE AND TWO)

As describe in parts one (11) and two (the present study), analytical and finite element methods were developed to simulate the nature of the bruising process considering the amount of stored strain energy in the apple fruit. As reported previously, the absorbed strain energy in apple fruits is a reliable predictor of bruising. In order to characterize the capability of each model to predict the strain energy, data for stored strain energy predicted by two modeling methods (FE and analytical approach) versus a measured one (compression test) were plotted for various levels of external load, and compared to 1:1 line (Figs 7 and 8). As indicated by these Fig.s, both models overestimated the strain energy, which might be due to initial assumptions made about the material model behavior. In real mode, when a viscoelastic material is subjected to an external load, the mechanical properties of the material will change with variations in the load magnitude. In this case, increases in the amount of external load result in lower elasticity modulus. However, constant mechanical properties of fruits at different load magnitudes were assumed for both analytical and finite element models. Both models gave closer answers when the fruits were compressed 4.5 mm.

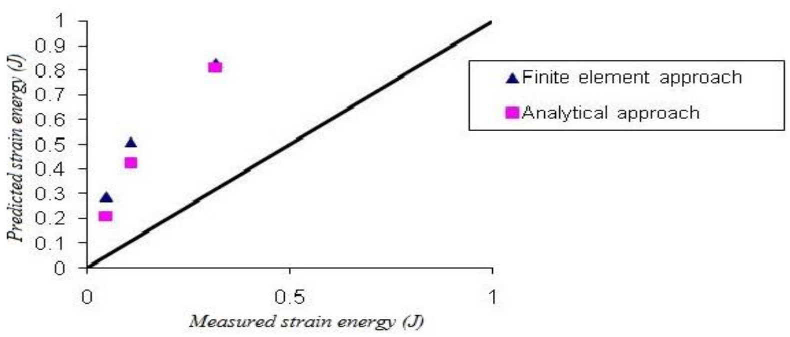

Fig. 8. Estimated strain energy by two modeling versus measured approaches for the samples stored in warm condition

As indicated in Table 1, the analytical model predicted strain energy and the consequent bruising process with less dispersion than the finite element model. Also, it was found that both models predicted strain energy better when the samples were stored in cold conditions. Keeping apples at room temperature before the tests and their consequent change in mechanical properties were the main sources of errors for predicting strain energy in both studies.

Table 1. The RMSE of two modeling approaches for predicting the absorbed strain energy at two different storage conditions

Storage condition	Modeling approach	
	Analytical	Finite Element
Cold	**0.251**	**0.297**
Warm	**0.347**	**0.399**

REFERENCES

1. Bollen, A. F., N. R. Cox, B. T. Dela and D. J. Rue. 2001. Painter, A descriptor for damage susceptibility of a population of produce. J. Agric. Eng. Res. 78 (4): 391–395.
2. Cooke, J. R., J. G. De Baerdemaeker, R. H. Rand and H. A. Mang. 1976. A finite element shell analysis of guard cell deformation. Trans. ASAE. 19: 1107–1121.
3. Garcia, J. L., M. Ruiz-Altisent and P. Barreiro. 1995. Factors influencing mechanical properties and bruise susceptibility of apples and pears. J. Agric. Eng. Res. 61: 11–18.
4. Holt, J. E. and D. Schoorl. 1997. Bruising and energy dissipation in apples, J. Textures Stud. 7: 421–432.
5. Herold, B., M. Geyer and C. J. Studman. 2001. Fruit contact pressure distributions equipment. Comp. Elec. in Agric. 32: 167–179.
6. Jafari, R., T. Tavakoli-Hashjin, S. Minaee and M. H. Raoufat. 2006. 3D Nonlinear Finite element analysis of large deformation in soil induced by tillage tools. WSEAS Trans. Math. 11(5): 1218-1226.
7. Lu, R. and J. A. Abbott. 1996. Finite element analysis of modes of vibration in apples. J. Texture Stud. 27: 265–286.
8. Lu, R. and J. A. Abbott. 1997. Finite element modeling of transient responses of apples to impulse excitation. Trans. ASAE. 40 (5): 1395–1409.
9. McLaughlin, N. B. and R. E. Pitt. 1984. Failure characteristics of apple tissue under cyclic loading. Trans. ASAE. 27: 311–320.
10. Mohsenin, N. N. 1996. Physical Properties of Plant and Animal Materials. Gordon and Breach Publisher, Canada. 890p.
11. Nassiri, S. M. and R. Jafari. 2013. Modeling static bruising in apple fruits: a comparative study, part I: analytical approach. Iran Agricultural Research. 32(2): 1-10.
12. Pang, W., C. J. Studman and G. T. Ward. 1992. Bruising damage in apple-to-apple impact. J. Agric. Eng. Res. 52: 229-240.

مدل سازی قهوه ای شدن میوه های سیب تحت بارهای استاتیکی، مطالعه مقایسه ای، بخش دوم: روش اجزای محدود

رامین جعفری[1] و سید مهدی نصیری[1*]**

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چکیده- صدمات مکانیکی وارد بر محصولات کشاورزی در مراحل مختلف از تولید تا مصرف می تواند سبب کاهش کیفیت محصول شود. صدمات می تواند به عللی چون اعمال بارهای استاتیکی و یا ارتعاشی باشد که در فرآیندهایی مانند برداشت، حمل و نقل و یا دسته بندی به محصول اعمال می شود. در پژوهش حاضر فرآیند قهوه ای شدن میوه سیب در اثرتماس میوه سیب با یک سطح صلب به کمک روش اجزای محدود شبیه سازی شد. مدل سه بعدی اجزای محدود با سه لایه مختلف طراحی گردید. قسمت گوشت سیب توسط مکانیزم اتصال چسبی در مدل اجزای محدود به هسته میانی متصل شد. نیروی نقطه ای مناسبی متناسب با فشار دیواره بر روی پوست سیب اعمال گردید. مقادیر انرژی کرنشی الاستیک، پلاستیک و کل و نیز تنش وارد بر میوه برای تخمین پدیده قهوه ای شدن مکانیکی محاسبه گردید. به منظور واسنجی داده ها از تست فشاری توسط دستگاه تست فشار استفاده شد. منحنی های نیرو- جابجایی ترسیم شد و مقدار انرژی کرنشی با محاسبه سطح زیر منحنی نیرو- جابجایی بین نقاط صفر تا 1/5، 3 و 4/5 میلی متر جابجایی در پنج تکرار محاسبه شد. نتایج مشاهده ای نشان داد که با افزایش میزان جابجایی خارجی اعمال شده به سیب، سطح منطقه قهوه ای افزایش می یابد. تطابق مناسبی بین سطح منطقه قهوه ای و میزان انرژی کرنشی ذخیره شده در میوه مشاهده گردید. سایر نتایج نشان داد که میزان قهوه ای شدن سیب تحت تأثیر مدول الاستیسیته پوست قرار دارد. با افزایش مدول الاستیسیته پوست سیب، سطح منطقه قهوه ای کاهش می یابد.

واژه های کلیدی: قهوه ای شدن سیب، اجزای محدود، نگهداری میوه

** به ترتیب استادیار و استادیا

* مکاتبه کننده