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# Influence of Apple Region and Variety on the Mechanical Properties and Bruise Threshold of Apples

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**Abstract:** In this study, the effect of apple region on some mechanical properties of cylindrical apple tissue samples that have 10 mm diameter and 15 mm length was investigated. The values of failure stress, failure strain, modulus of elasticity and tissue toughness were determined for two apple varieties (Golden Delicious and Fuji), and changes of mechanical properties as a function of apple region and variety were analyzed by using the analyses of variance and the t-test. The compression tests were performed on Golden Delicious and Fuji apple tissue samples using Universal Testing Machine Tissue samples were extracted from apple region throughout stem, cheek and calyx axis. Furthermore, skin rupture properties of apples were determined by using quasi-static compression test with 8 mm diameter cylindrical probe. In this test condition, loading rate of 10 mm min$^{-1}$ was used. In the second step of this study, apple bruise thresholds were calculated by using the mechanical properties, radius of curvature and apple mass. Apple bruise thresholds were predicted for three apple region from stem to calyx axis. According to t-test results, significant difference was found between Golden Delicious and Fuji apples for failure stress, modulus of elasticity and tissue toughness. Mechanical properties and apple bruise threshold values showed that when apple was dropped on a cheek axis and stem axis for Golden Delicious and Fuji apples, respectively apples could be more resistant to impact damage in impact condition.
**Key words:** Mechanical properties, apple region, bruise threshold, cylindrical apple tissue

## Elmaların Zedelenme Sınırı ve Mekanik Özellikleri Üzerine Çeşit ve Elma Bölgesinin Etkisi

**Özet:** Bu çalışmada, 10 mm çapa ve 15 mm yüksekliğe sahip silindirik elma doku örneklerinin bazı mekanik özellikleri üzerine elma bölgesinin etkisi araştırılmıştır. Bozulma gerilimi, bozulma deformasyonu, elastisite modülü ve doku sertliği değerleri iki elma çeşidi (Golden Delicious ve Fuji) için belirlenmiş ve elma bölgesi ve çeşidin bir fonksiyonu olarak mekanik özelliklerdeki değişimler varyans analizi ve t testi ile ortaya konmuştur. Golden Delicious ve Fuji elma doku örnekleri üzerinde materyal test cihazı kullanılarak sıkıştırma işlemi uygulanmıştır. Doku örnekleri elmaların sap, karın ve çiçek ekseni boyunca elma bölgelerinden çıkartılmıştır. Ayrıca, elmaların kabuk yırtılma dirençleri 8 mm lik çapa sahip silindirik uç ile statik sıkıştırma testi kullanılarak yapılmıştır. Bu test koşulunda, 10 mm min$^{-1}$ lık yükleme hızı kullanılmıştır. Bu çalışmanın ikinci aşamasında, elma zedelenme sınır eşikleri elmaların mekanik özellikler, eğrilik yarıçapları ve kütleleri kullanılarak hesaplanmıştır. Elmaların zedelenme sınır eşikleri çiçek-sap ekseni boyunca üç elma bölgesi için tahmin edilmiştir. Yapılan t-testi sonuçlarına göre, bozulma gerilimi, elastisite modülü ve doku sertliği özellikleri için Golden Delicious ve Fuji elma çeşitleri arasında önemli farklılıklar bulunmuştur. Mekanik özellikler ve elma zedelenme sınır eşik değerleri Golden Delicious ve Fuji elma çeşitlerinin sırasıyla karın ve sap bölgesinden düşürülmesi durumunda çarpma zedelenmelerine karşı daha dirençli olabileceğini göstermiştir.
**Anahtar kelimeler:** Mekanik özellikler, elma bölgesi, zedelenme sınırı, silindirik elma dokusu

## INTRODUCTION

Knowledge of the mechanical properties of fruit flesh and intact fruit is needed to grade, store and transport fruit with less damage. Due to the complex structure of fruits, the mechanical properties and firmness measurements are influenced by factors such as shape or size, variety, growing conditions, fruit orientation as well as the planting design in orchard, tree structure and pruning, soil chemical and physical conditions, soil management, nutrients available and water balance (Wang, 2003; Pasini et al., 2004). Force-deformation curves are commonly used to determine the mechanical properties of fruits and vegetables. From this curves, elastic limit, bio-yield and rupture point is especially important to calculate the some mechanical parameters. For instance, Mohsenin (1980) described the bio-yield point as a point on the force-deformation or stress-strain curve at which there arises an increase in deformation with a decrease or no change of force. In addition to this description, rupture point was defined as a point on the force-deformation or stress-strain curve at which the axially loaded specimen ruptures under a load. In some agricultural materials such as apple, pear and potato, the presence of this bio-yield point is an indication of initial cell rupture in the cellular structure of the material. Furthermore, in biological materials, rupture may cause puncture of skin or shell, cracking or fracture planes. It may be stated that a "bio-yield point" in this materials corresponds to a failure in the microstructure while a "bio rupture point" corresponds to a failure in the macrostructure of the material.

Mechanical properties influence the sensitivity to damage definitively for certain fruits and vegetables. In avoiding damage to fruit species the permissible falling height and permissible static pressure are of great importance. The permissible falling height can be explained by using the term such as bruise threshold and bruise resistance. Bruise threshold is the drop height at which bruising just begins to occur while bruise resistance is the size of a bruise for a given drop height and defined as a ratio of bruise volume and loading energy (Sitkei, 1986; Holt and Schoorl, 1983 and 1984; Blahovec et al., 2002). Several researchers have also reported other indices of fruit potential to damage such as bruise probability (Bollen, 2002), bruise resistance coefficient (Holt and Schoorl, 1977), bruise index (Blahovec and Mares, 2003), specific bruise susceptibility (Opara, 2007), and bruise harmonic index (Blahovec and Paprstein, 2005). To predict the bruise threshold, mechanical properties related to fruit tissue, fruit mass, radius of curvature for impacts on a flat and rigid surface and impact surface are used. All the factors mentioned above influences the bruise threshold and bruise resistance. Mechanical properties of fruit tissue obtained during the quasi-static and dynamic loading are the failure stress, failure strain, poisson's ratio, toughness and modulus of elasticity (Bajeme, 1995). To reduce impact bruising requires reducing the impact-induced failure stress and, or increasing failure stress of fruit tissue. Handling system improvement can reduce impact-induced failure stress can be reduced by reducing the effective drop height. In this case, peak impact force reduces. Furthermore, adding the cushioning materials on impact surface reduces peak force and distributes forces over a greater area of the commodity specimen surface (Baritelle and Hyde, 2001). Baritelle and Hyde (2000) and Baritelle and Hyde (2001) reported that reducing relative turgor could reduce tissue elastic modulus which can in turn make a specimen more self-cushioned by distributing a given force over a large area of the specimen's curved surface. Murase et al. (1980) showed similar results for quasi static loading, reporting young's modulus in compression increased more or less linearly with increasing water potential in potato tuber tissue. Lewis et al. (2007) reported the elastic properties of the apple flesh varied according to load orientation and position. Typical values of failure stress were around 0.40-0.51 MPa in their study.

Wang (2004) studied on mechanical properties of pear tissue as a function of location and orientation and found that the differences of the four mechanical properties (failure stress, failure strain, young's modulus and failure energy) did significantly differed between top (stem) and middle (cheek), tangential and radial, nearer the core and nearer the skin. Varith et al. (2001) used a technique to measure the bruise threshold namely paired-height multiple impacting (PIHM). This technique detected the bruise threshold in individual apples by comparing force profile pairs from successively higher drops of the specimen on the same specimen location onto a rigid surface.

The objectives of this study are (1) to measure the mechanical properties of apple flesh for three apple regions and two apple varieties, and (2) to predict the apple bruise threshold by using those mechanical properties and theory of elasticity.

## MATERIALS and METHODS

### Materials

Golden Delicious and Fuji apple varieties were used as a test material during the experimental study. The apples were purchased from a local market and uniform and undamaged apples were used. The average weight and diameter of Golden Delicious and Fuji apples were 186 g and 68.85 mm, and 195 g and 73.23 mm, respectively. The radius curvature of two apple varieties was measured by using a radius of curvature meter (ASAE, 2001; Vursavuş and Özgüven, 2003). The size and mass measurement was made with a digital caliper and electronic balance of a sensitive 0.01 mm and 0.001 g sensitivity, respectively.

### Methods

#### *Determination of mechanical properties*

The mechanical properties of apples were evaluated using cylindrical specimens taken from three region of apple tissue, namely stem, cheek and calyx. To determine the variation of mechanical properties (failure stress, failure strain, modulus of elasticity and tissue toughness) from the stem to the calyx, cylindrical tissue samples were used. Cylindrical specimens used during the all tests were 10 mm in diameter and 15 mm in length. Due to the fact that the Magness-Taylor test is typically applied radially, the test for detailed effects of apple region for two apple varieties was conducted on radial samples only (Figure 1).

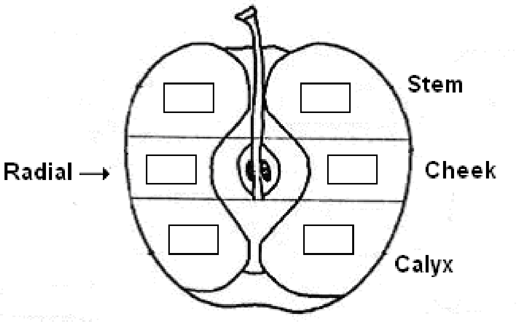

**Figure 1. Scheme of apple regions used for extracting apple tissue**

Compression tests on flesh apple samples were performed on a universal testing machine, Lloyd model made in England, with a maximum loading sense of 5 kN in Çukurova University, Agriculture Machinery Laboratory. Cylindrical tissue samples were prepared using the methods proposed by Bajema et al. (1998) and Mas'oudi et al. (2005). Long samples were cut to 10 by 15 mm size with a sharp knife.

Cylindrical samples were placed between two plate of the universal testing machine and they were loaded and force- deformation curve was recorded by a computer (Figure 2). Failure stress, failure strain, modulus of elasticity and toughness were determined from this curve. In each test condition, constant loading rate of 100 mm min$^{-1}$ was used.

Modulus of elasticity was determined from the Hook's law as shown in Equation (1). The cross sectional area of the apple tissue and the initial length of the sample were used to calculate the failure stress and failure strain. The length difference before and after the test, $\Delta$L was calculated by using the initial length of the sample and deformation at the failure point (Mohsenin, 1980; Mas'oudi, 2005).

$$E = \frac{FL}{A\Delta L} \qquad (1)$$

Where: E is the modulus of elasticity in MPa, F is the force at failure point in N, $\Delta$L is the length difference in mm, A is the average sample cross sectional area in mm$^2$.

Failure stress was determined as the failure force divided by failure plan area as in Equation (2).

$$\sigma = \frac{F}{A} = \frac{4F}{\pi d^2} \qquad (2)$$

Where: $\sigma$ is the failure stress in MPa, and d is the diameter of the cylindrical tissue sample in mm.

Failure strain ($\varepsilon$) was determined from length reduction variation divided by the initial length of sample (15 mm) as seen in Equation (3).

$$\varepsilon = \frac{\Delta L}{L} \qquad (3)$$

Toughness used as a parameter of tissue mechanical properties was determined by using Equation (4) (Mohsenin, 1980; Bajema et al., 2000).

$$Q = \frac{1}{2}\sigma.\varepsilon \qquad (4)$$

Where: $Q$ is the measure of tissue toughness in MPa.

For puncture tests, halved section of apple was compressed with an 8 mm diameter spherical indenter as described ASAE testing standards (No. S368.4) (ASAE, 2001). In this test condition, loading rate of 10 mm min$^{-1}$ was used and force-deformation curve was recorded by a computer. By using this curve, force (N) and deformation (mm) at bio-yield and rupture point was read and rupture energy (N mm) and firmness (N mm$^{-1}$) was calculated. The detailed information related to puncture test was given in the results.

Radius of curvature of two apple varieties was measured by using radius curvature meter from stem to calyx axis as can be seen in Figure 3. In this measurement, methods and equations of radius of curvature proposed by Mohsenin (1980) and ASAE testing standards (ASAE, 2001) were used.

### *Prediction of apple bruise threshold*

Bruises occur under impact loading when the stress (force/area) induced in the fruit by an impact exceeds the failure stress of the fruit tissue. If we know the strength (failure stress) and stiffness of the tissue, and the size (mass) and shape (smallest radius of curvature) of the fruit, we can predict bruise threshold using a recently developed equation.

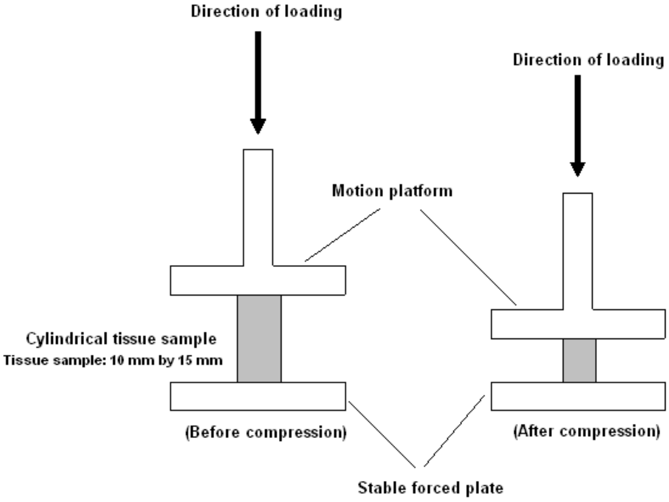

**Figure 2. Compression test of cylindrical tissue samples**

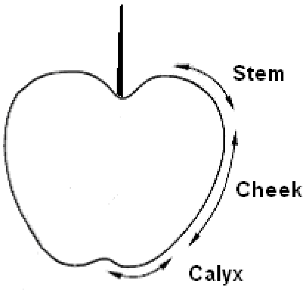

**Figure 3. Radius of curvature measurement points for two apple varieties**

Researches indicate that all of the variables such as fruit mass, radius of curvature, failure stress, and failure strain can be used to predict bruise threshold.

Specimen impact damage (bruising) occurs when impact-induced stress exceeds tissue failure stress ($\delta_i \geq \delta_f$). At that point the bruise threshold was exceeded. Bruise threshold is the drop height at which bruising just begins to occur for a given specimen mass, radius of curvature, and impact surface. $\delta_f$ is dependent parameters on commodity, strain rate, turgor, temperature and other factors. $\delta_i$ (impact-induced stress) is a function of impact energy, colliding body curvatures and colliding body elastic modulus (Hyde and Baritelle, 2000; Hyde et al., 2001; Baritelle and Hyde, 2001) .

$$\delta_i = \frac{2}{3}(mgh)^{1/5}(E)^{4/5}(1/R)^{3/5} \qquad (5)$$

Where: $\delta_i$ is average induced compressive stress in MPa; m is mass of specimen in kg; g is acceleration due to gravity in m $s^{-2}$; h is drop height in m; E is modulus of elasticity of specimen in MPa and R is radius of curvature of specimen in impact point in m.

At bruise threshold (failure), impact-induced stress ($\delta_i$) equals to failure stress ($\delta_f$) measured in fruit tissue. In this case,

$$\delta_f = \frac{2}{3}(mgh)^{1/5}(E)^{4/5}(1/R)^{3/5} \qquad (6)$$

And at failure, h is bruise threshold drop height and solving Equation (6) for h yields:

$$h = \frac{(\frac{3}{2})^5(\delta_f)^5 R^3}{(E^4 mg)} \qquad (7)$$

Also at failure, E = $\delta_f/\varepsilon_f$, where: $\varepsilon_f$ is failure strain; so, Equation 8 can be used to predict the bruise threshold in impact condition by taking into consideration the defined parameters

$$h = \frac{(\frac{3}{2})^5 \delta_f {\varepsilon_f}^4 R^3}{mg} \qquad (8)$$

where: h is bruise threshold in mm; $\delta_f$ is failure stress in MPa; $\varepsilon_f$ is failure strain; *R* is radius of curvature of apple in impact point in m; *m* is individual fruit mass in kg and *g* is acceleration due to gravity in m $s^{-2}$.

### *Experimental Design and Analysis*

Experiments were conducted for twenty replicates at room temperature for each test. For each replication, all specimens from the stem to the calyx were taken from the same apple so that the error due to apple to apple variability can be reduced. For two varieties, apples were halved and two halves were used in order to take tissue samples as seen in Figure 1. Two replicates from the stem to the calyx were carried out for one apple. Consequently, a total of 30 apples and 60 apple tissue samples were tested. Single factor completely randomized design was used to find the effect of three apple regions (stem, cheek and calyx) in Golden Delicious and Fuji apple varieties under compression loading. Furthermore, the effect of apple variety on failure stress, failure strain, modulus of elasticity and toughness was examined using the generalized t-test on the difference of mean values and Duncan’s multiple range test was used to compare the means.

## RESULTS and DISCUSSION

### *Mechanical properties*

The results of the comparison between the some mechanical properties for two apple varieties are shown in Table 1. Skin puncture force at bio-yield and rupture point, and firmness at bio-yield point was lower for Golden Delicious apple when compared with Fuji apple variety. Increase in the force and decrease in the deformation at bio-yield point for Fuji apple automatically increased the firmness value. This shows that Fuji apple variety has more resistance than that of the Golden Delicious apple. Therefore, there could be greater bruise susceptibility in impact condition for Golden Delicious apple. Similar trend was also observed by Aydın and Öğüt (1992) for skin puncture tests of Golden, Straking and Amasya apple varieties.

As described in method section, failure stress, failure strain, modulus of elasticity and toughness of apple tissue was calculated and given in Table 2 and Figure 3.

Failure stress increased from stem to calyx axis significantly (probability $P<0.05$) in Golden Delicious apple. However, the failure stress value in Fuji apple was found to be statistically insignificant for three apple regions according to analyses of variance results, in spite of the fact that there was a decreasing tendency. Failure stress values in Golden Delicious and Fuji apples from stem to calyx axis were found to be from 0.265 to 0.309 MPa and from 0.617 to 0.556 MPa, respectively. This is consistent with the finding of Abbot and Lu (1996) that the calyx apple region of Golden Delicious had higher failure stress than the stem and cheek apple region. According to t-test, the failure stress difference between Golden Delicious and Fuji apples was found to be significant (probability $P<0.05$) (Table 2). All the values and Duncan test results were given in Figure 4a.

Failure strain of Golden Delicious and Fuji apple varieties as a function of apple region is shown in Figure 4b. Even though failure strain increased from stem to calyx axis slightly, there was no significantly difference among them (probability $P>0.05$) according to analyses of variance results. The effect of apple region on failure strain in Fuji apple variety is also shown in Figure 4b. In spite of the fact that failure strain calculated on stem axis for Fuji apple was higher than that of the other two axes, analyses of variance results showed that the difference among them was not significant statistically ($P>0.05$). The t-test results reveal that no significant difference exists between failure strain in Golden Delicious and Fuji apples. The mean values and Duncan's test results were given in Figure 4b. As can be seen in Equation 8, failure strain is the 4th power. This power means that failure strain factor plays an important role in determining the bruise threshold than are the tissue failure stress and fruit mass.

**Table 1. Some mechanical properties of two apple varieties for skin puncture test under quasi-static loading (loading rate: 10 mm/min, diameter of cylindrical probe: 8 mm)**

| **Properties** | **Golden Delicious** | **Fuji** |
|---|---|---|
| Force at bio-yield point(N) | 26.38 (8.20) | 27.54 (7.02) |
| Deformation at bio-yield point (mm) | 2.64 (0.69) | 2.03 (0.60) |
| Force at rupture point (N) | 41.27 (10.14) | 43.57 (10.94) |
| Deformation at rupture point (mm) | 3.97 (0.80) | 3.28 (0.74) |
| Rupture energy (N mm) | 84.76 (33.61) | 74.08 (31.52) |
| Firmness at bio-yield point (N mm$^{-1}$) | 10.13 (2.28) | 14.06 (2.79) |

**Table 2. Failure stress ($\delta$), failure strain ($\varepsilon$), toughness ($Q$) and modulus of elasticity ($E$) of apple tissue for two varieties with respect to the apple region (loading rate: 100 mm/min)**

| **Region** | **Golden Delicious** | | | | **Fuji** | | | |
|---|---|---|---|---|---|---|---|---|
| | $\delta$ (MPa) | $\varepsilon$ (-) | $Q$ (KPa) | $E$ (MPa) | $\delta$ (MPa) | $\varepsilon$ (-) | $Q$ (KPa) | $E$ (MPa) |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Stem | 0.265 | 0.149 | 19.81 | 1.92 | 0.617 | 0.173 | 53.31 | 3.77 |
| | (0.053) | (0.032) | (6.61) | (0.985) | (0.103) | (0.039) | (14.86) | (1.11) |
| Cheek | 0.282 | 0.151 | 21.75 | 1.89 | 0.562 | 0.150 | 42.06 | 4.12 |
| | (0.049) | (0.026) | (5.74) | (0.496) | (0.943) | (0.039) | (13.19) | (1.81) |
| Calyx | 0.309 | 0.154 | 23.51 | 2.094 | 0.556 | 0.154 | 44.10 | 3.90 |
| | (0.049) | (0.026) | (6.08) | (0.418) | (0.099) | (0.05) | (19.49) | (1.10) |

**Note:**

- The numerical value in the parenthesis is standard deviation.
- ANOVA indicated significant effect of apple region on the values shown in the columns 1 and 8 at $P < 0.05$, and non-significant effect on the values shown in columns 2, 3, 4, 5, 6 and 7.
- The t-test indicated non-significant difference between the columns 2 and 6 $P > 0.05$, and significant difference between columns 1 and 5, 3 and 7, 4 and 8 at $P<0.05$.

Modulus of elasticity did not change as a function of apple region from stem to calyx axis for Golden Delicious apple. In the measurement, the highest modulus of elasticity was found on the calyx apple region. This agrees with Abbot and Lu's (1996) finding that calyx region of Golden Delicious apple had higher modulus of elasticity than the other two regions In Fuji apple variety, cheek region of apple had higher modulus of elasticity than that of the other two regions with a value of 4.12 MPa. According to analyses of variance results, the effect of apple region on modulus of elasticity of apple tissue was found to be statistically insignificant (probability P>0.05) for both apple varieties as can be seen in Table 2 and Figure 4c. Further, the t-test results reveal that significant difference existed between Golden Delicious and Fuji apples due to environmental and cultivar conditions, and orchard management practices. As shown in Figure 4c, modulus of elasticity of Fuji apple tissue was found more than twofold when compared with Golden Delicious apple. This means that Fuji apple tissue is firmer than Golden Delicious apple tissue. The mean values and Duncan's test results were given in Figure 4c.

The effect of apple region on tissue toughness for two varieties is presented in Figure 4d. Toughness values in Golden Delicious apple from stem to calyx axis was found from 19.81 to 23.51 KPa. Corresponding values for Fuji apple were from 53.31 to 44.10 KPa. According to analyses of variance results, the effect of apple region on tissue toughness was found to be statistically insignificant (probability P>0.05) for Golden apple but, found to be significant for Fuji apple (probability P<0.05) as can be seen in Table 2 and Figure 4d.

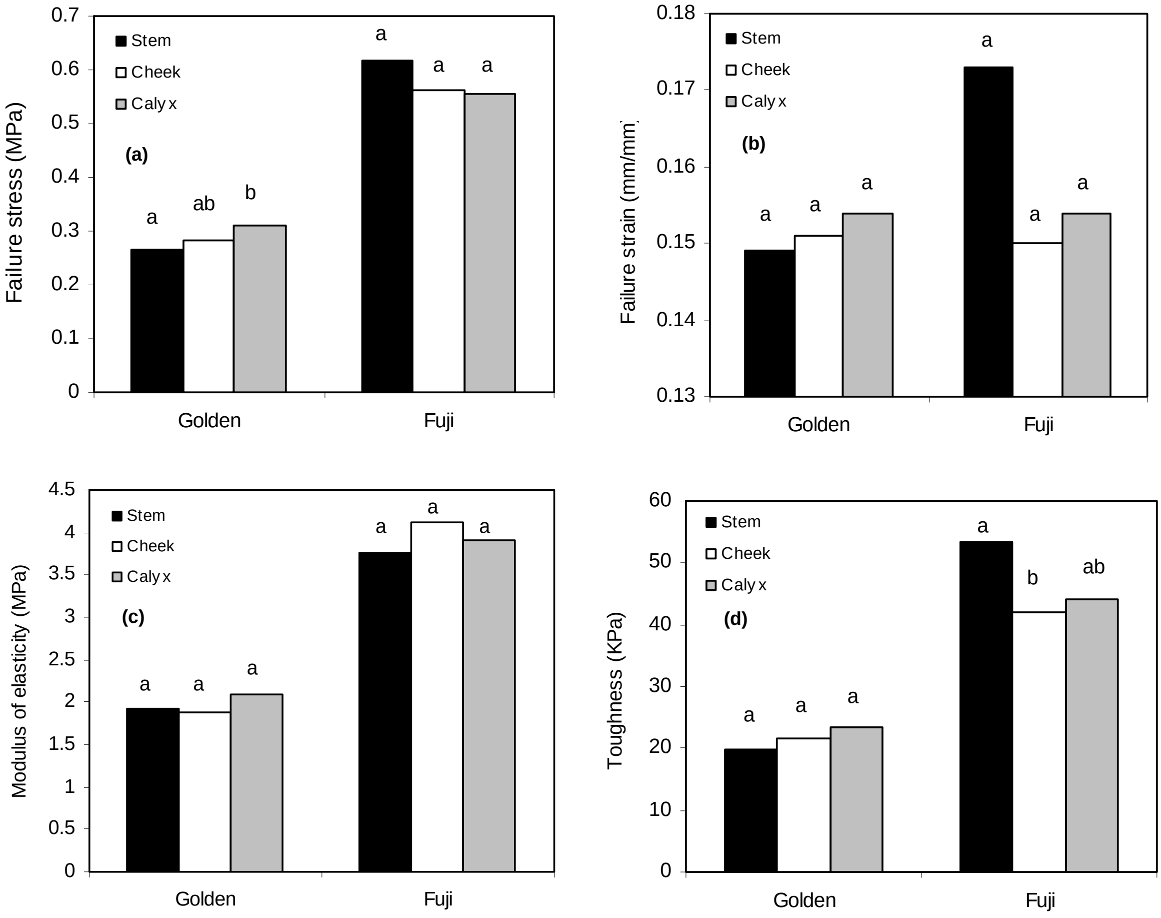

**Figure 4. Mechanical properties of Golden Delicious and Fuji apple tissues versus apple**

Furthermore, the t-test results show that significant difference existed between tissue toughness in Golden Delicious and Fuji apples. The mean values of tissue toughness and Duncan's test results were given in Figure 4d and Table 2.

All of the mechanical properties obtained from the compression tests showed that Golden Delicious and Fuji apples have relatively uniform mechanical properties around the apple region because the mechanical properties values are insignificant statistically. But, the anisotropic properties of the apples were more pronounced in the Fuji apple due to the fact that the difference in the mechanical parameters was higher. Therefore, it will be necessary to consider the anisotropic properties of apples not only in designing firmness instruments and but also in the determining dynamic behaviour of apples such as bruise susceptibility and bruise threshold.

### *Bruise threshold for Golden Delicious and Fuji apples*

Radius of curvature values from stem to calyx axis are used in order to calculate the predicted bruise threshold. Therefore, radius of curvature was measured by using the curvature meter and the values were given in Figure 5. This parameter is important to predict the bruise threshold because of the fact that radius of curvature is the 3rd power as can be seen in Equation 8 and is much more important in determining the bruise threshold than are the tissue failure stress and fruit mass.

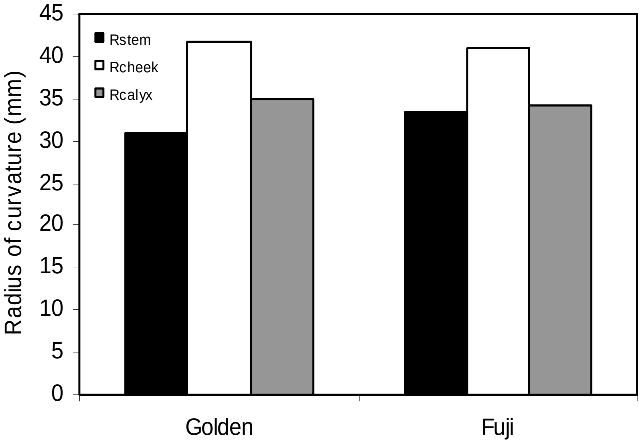

**Figure 5. Radius of curvature values measured on apple regions**

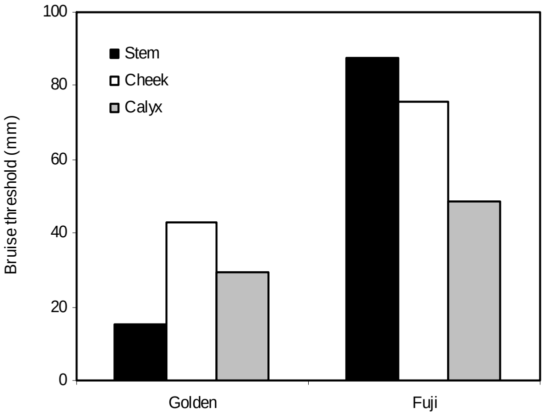

**Figure 6. Predicted bruise threshold by variety and apple region**

Figure 6 shows bruise threshold changes with apple region for Golden Delicious and Fuji apples. As mentioned earlier, failure strain and radius of curvature are much more important to predict the bruise threshold levels than are the tissue failure stress because of the fact that failure strain and radius of curvature 4th and 3rd power, respectively. As can be seen in Figure 6, bruise threshold values that were predicted by using the parameters such as failure stress, failure strain, radius of curvature and apple mass were found different because of the change in the mechanical properties of apple region (stem, cheek, calyx) for two apple varieties.

Bruise threshold values for Golden Delicious and Fuji apples were 15.45 mm and 87.62 mm on stem axis, respectively. For calyx axis, these values were found to be 29.58 mm and 48.59 mm for Golden Delicious and Fuji apples, respectively. As seen in the values calculated by using the Equation (8) and in Figure 6, Fuji apple bruise threshold values were higher than those of the Golden Delicious apple. This means that Fuji apple has higher bruise resistance in impact condition than that of the Golden Delicious apple. In our study, the failure stress used in order to predict the bruise threshold played an important role because there was significant difference between failure stress values for two apple varieties whereas failure strain and radius of curvature were found to be insignificant for two apple varieties according to t- test results.

## CONCLUSIONS

Mechanical properties such as failure stress, failure strain, modulus of elasticity and tissue toughness were measured as a function of tissue specimen from stem to calyx apple region in Golden Delicious and Fuji apples. Fuji apple had higher failure stress, modulus of elasticity and tissue toughness than Golden Delicious apple. This means that Fuji apple had higher strength than that of Golden Delicious in three apple regions. Therefore, this variety will show more strength against mechanical harvest, impact and the other post harvest handling. All of the mechanical parameters for Golden Delicious had low values which show less strength against external forces and stresses.

The relationship presented in order to predict the bruise threshold does not provide precise absolute values of bruise threshold, but if references on elasticity theory are correct, it provides useful estimate of trends in that variable with change in failure stress, failure strain, mass, and radius of curvature. According to predicted bruise threshold, we can reveal that Fuji apple has higher bruise resistance in impact conditions because bruise threshold values are higher.

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