

Effect of Impact Level and Fruit Properties on Golden Delicious Apple Bruising

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Abstract: Problem statement: Bruise damage is a major cause of fruit quality loss. Bruises occur under dynamic and static loading when stress induced in the fruit exceeds the failure stress of the fruit tissue. Statistical bruise estimation models were constructed to calculate Golden Delicious apple bruise volume with respect to fruit properties. **Approach:** The regression models were built based upon impact force and impact energy as main independent variable with other parameters including fruit curvature radius, temperature and acoustical stiffness. An instrumented pendulum was constructed as a tool to perform three levels of controlled impact on apple fruit. **Results:** Significant effects of acoustical stiffness, temperature and the curvature radius and some interactions on bruising were obtained at 5% probability level with the coefficient of determination of 0.93 and 0.98 for force model and energy model respectively. **Conclusion:** It was demonstrated that increasing the temperature and curvature radius and lowering acoustical stiffness will reduce the bruise damage of the golden delicious apple fruit.

Key words: Bruise volume, golden delicious apple, impact, fruit properties, regression models

INTRODUCTION

Apple consumers increasingly demand better quality fruits. Mechanical damages such as bruises, abrasions, cuts and punctures are irreversible and are accumulated damages during the handling process. The inevitable consequence of mechanical damage is low grade and low quality fruits, hence less income to both growers and packers (Timm *et al.*, 1996; Abbott and Lu, 1996). The factors affecting damage severity are fruit fall height, contact energy, the number of contact, the kind of contact surface and the size and ripeness stage of the fruit (Lin and Brusewitz, 1994; Roth *et al.*, 2005). Identifying the impact situation which can create bruises are necessary to improve harvesting, transporting, grading procedures and equipments (Lin and Brusewitz, 1994; Ragni and Berardinelli, 2001; Van Linden *et al.*, 2006). Bruising may be intensified

by some other factors such as texture, variety, maturity stage, water content, fruit shape, temperature, firmness, size and a series of fruit interior factors such as modulus of elasticity, strength of cell walls and, internal structure and cell shape (Studman *et al.*, 1997; Van Linden *et al.*, 2006).

Detailed information about bruise estimation models for Golden Delicious apple is limited. The statistical models contain contact energy or impact force as the main independent variable (Van Zeebroeck *et al.*, 2007a). These models have advantages and disadvantages. The impact force models are advantageous, because they can be generalized to impacts of materials with different material properties and curvature radius. The impact force is the influential factor in explicating the apples bruising when impacted by various materials. The bruise estimation models, containing impact energy that was constructed for

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metal-apple indenter contact, cannot be applied to apple-apple contact because in both situations the impact energy is the same (Pang *et al.*, 1992; Van Zeebroeck *et al.*, 2007c). Nevertheless, a drawback of exploiting impact force regression model is high probability of impact force to be influenced by fruit properties (e.g., temperature and maturity). In opposite, the energy of impact is not affected by the fruit characteristics, which present a privilege of impact energy over impact force models. As a result, contact energy models are superior to inquire the effect of fruit characteristics on bruise damage (Van Zeebroeck *et al.*, 2007a; 2007b; 2007c).

Bruise estimation models for apples (especially for Golden Delicious apple) reported in the references are limited to the effect of two properties of fruit (either maturity or temperature of fruit) and these models are unstable (Studman *et al.*, 1997). The objective of the present work was to evolve bruise estimation models for Golden Delicious apple contain parameters namely impact force, impact energy, fruit acoustical stiffness, curvature radius and temperature.

MATERIALS AND METHODS

Experimental details: The apples used in this study were Golden Delicious variety. The apples were harvested in 2008 from “Shabestar” district, Tabriz, Iran. Apples were hand-picked at a commercial orchard to insure their freshness and avoid damage during harvesting and transporting. Fruits were stored in a cool storage with controlled atmosphere (85% RH, 3°C). All measurements were performed within maximum two days. Fruits were kept at desired temperature for 10 h prior to measurement. Samples at 3°C were measured during 15 min to reduce apple warming in the measuring room at 20°C. Apples were placed on a pendulum equipped with a force sensor (type AC20, AP Tech, Netherlands; Sensitivity: 1.87 mV N⁻¹) and an encoder equipment (RON 275, Heidenhain; Resolution: 0.005°) to measure energy of impact and impact velocity (Van Zeebroeck *et al.*, 2003). The samples then were hit by a spherical metal impact or with radius of 25 mm (Fig. 1).

The dependent variable that used in the bruise estimation models was the bruise damage volume. The bruise volume was recorded 48 h after contact and determined based on:

$$BV = \frac{\pi}{6} dD^2 \quad (1)$$

Bruise estimation models had either the impact energy (kinetic energy of pendulum rod just before collision) or the impact force as independent variables along with other variables. Used independent variables in the regression models consist of:

- Impact Energy (E) (J)
- Impact Force (F) (N)
- Fruit Temperatures (T)
- Curvature Radius of apple (R) at the contact location (mm)
- Fruit acoustical Stiffness (S) (s⁻² kg^{2/3})

Three contact levels were used as summarized in Table 1. The applied impact energy levels were chosen above the critical impact level of Golden Delicious apple. The lower limit of applied impact level was based on the measured impact force during handling and transporting but the higher impact level was in apple mechanical harvesting and sorting. For each impact the exact impact energy and impact force were recorded. The lowest impact level was close to the detection limit of bruise damage and other levels (2 and 3) exposed obviously visible damages and were easily perceivable.

The curvature radius was measured at the fruit contact area by means of a non-commercial radius meter because a proper measuring device was not available. It was, therefore, constructed on an analog height meter base (Fig. 2a).



Fig. 1: General view of the pendulum device for measuring impact force and impact velocity of the apple fruit

Table 1: Overview of different impact levels applied on the apple fruit

Impact levels	Impact energy (J)		Impact force (N)	
	Average	SD ^a (%)	Average	SD ^a (%)
1	0.05	3.60	25.80	1.8
2	0.10	4.23	66.24	2.1
3	0.19	1.82	101.50	1.6

^a: Standard deviation as percent of the average

The curvature radius was determined using the following equation (Mohsenin, 1986) (Fig. 2b):

$$\text{RADIUS} = \frac{(\text{AC})^2}{8(\text{BD})} + \frac{(\text{BD})}{2} \quad (2)$$

Since apple cannot be considered completely spherical, the harmonic average ($2RR'/(R + R')$) was chosen based on circumferential (R) and meridian curvature Radius (R'). Based on Hertz theory the use of harmonic mean is more acceptable than the computational mean, due to its accuracy on estimation of smaller curvature radius, which participate more to the maximum contact pressure.

The acoustical stiffness of apple was calculated based on acoustical impulse- response method (Schotte *et al.*, 1999; Van Zeebroeck *et al.*, 2007b). The apple was positioned with the stalk end on a rubber pad. A microphone was fixed on a support at a few millimeters off the apple and was directed upward. The fruit was stimulated by tapping it on the equator at the opposing side of the microphone by a rigid plastic bar. Acoustical measurements were taken with a microphone that records the signal of sound arising from the response vibration. Amplifiers supplied electrical power to the transducer, magnified the signal and give proper output drive signal and permit choosing the proper band-pass filters. The signals of this microphone were collected and processed using a PULSE® program (type 3564, B and K®). Before impact experiments, the mass of apples were measured. The setup was adjusted so that the collision of the apple triggered the measurement. To obtain the signal's frequency spectrum a Fast Fourier Transform (FFT) was performed and consequently, the apples' first resonance frequency was determined. The acoustical stiffness was calculated as:

$$S \cong f^2 m^{2/3} \quad (3)$$

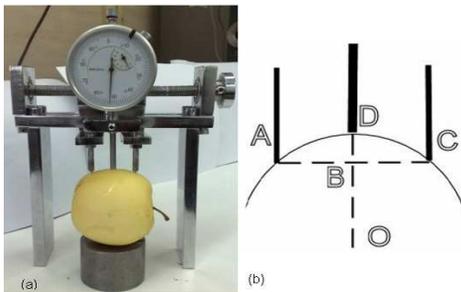


Fig. 2: (a) General view of the radius meter and (b) schematic representation of geometry to calculate the radius of the apple fruit

A total of 120 apples were used for conducting the experiments. These apples were divided into six groups and consequently, 20 apples were tested for each temperature-impact level combination.

Statistical analyses: The dependent variable was the Bruise volume (BD) of apple. The independent variables were impact Energy (E), impact Force (F), curvature Radius at contact location (R), acoustical Stiffness (S) and Temperature of apple (T). A backward multiple regression method was applied to choose the pertinent independent variables influencing the dependent variable. Furthermore, in order to verify the validity of multiple regression models, a chi-square test was carried out using the predicted and experimental data. SAS software was used for data analysis.

RESULTS

Bruise estimation model based on impact force (model 1): Main effects (impact force, temperature, acoustical stiffness and curvature radius) and some interactions were significant at 5% probability level. Table 2 shows the final model having all of the independent variables. For this model, the plot of predicted bruise volume against measured bruise volume is depicted in Fig. 3. A good fit was observed between the measured and predicted bruise volume.

Table 2: Regression equation of bruise volume (mm^3) of the golden Delicious apple in relation to contact Force (F), curvature Radius (R), Temperature (T) and acoustical Stiffness (S) as independent variables

Model 1	R ²
$V = -4.5S - 3.25R + 0.97T + 22.9F - 0.23F \times R - 0.097F \times T$	0.93

Note: Minimum probability threshold $p \leq 0.05$

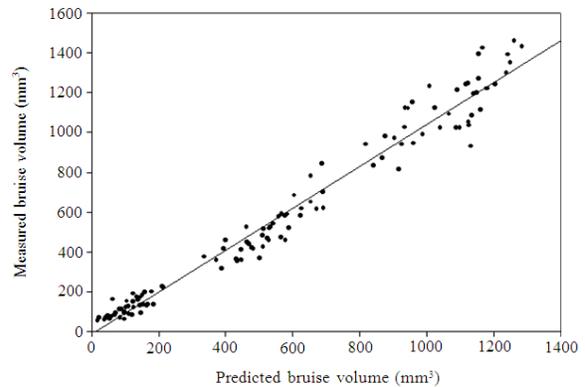


Fig. 3: Measured bruise volume (mm^3) Vs bruise volume predicted by model 1

Effect of fruit curvature radius on bruise damage volume (model 1): Apples with low curvature radius had high bruise volume than those with higher curvature radius (at the contact area). The significant interaction effect at 5% probability level between curvature radius and impact force indicated that the bruise volume at different impact forces differ by the increase in curvature radius. The difference in bruise volume between two extreme values of radius curvature (34 and 46 mm) was not similar at low and high impact forces. Figure 4 shows the combined effect of fruit radius and the impact force on bruise volume. At the low impact force (25.8 N) the bruise volume of an apple fruit with a curvature radius of 34 mm was 54% higher than the one having a curvature radius of 46 mm. At the high impact force (101.5 N) the bruise volume of the apple fruit with a curvature radius of 34 mm was 27% higher than the apple with a curvature radius of 46 mm.

Effect of fruit acoustical stiffness on bruise damage volume (model 1): The data indicated that the bruise volume increased with the increase of acoustical stiffness (Table 2 and Fig. 5) and that no significant interaction was obtained between acoustical stiffness and impact force. However, the relative difference in bruise volume decreased with the increase in the impact force (Fig. 5). The bruise damage volume for the acoustical stiffness of $39 \text{ sec}^{-2} \text{ kg}^{2/3}$ was up to 42% higher than one having $25 \text{ sec}^{-2} \text{ kg}^{2/3}$ at low impacts levels (25.8 N) and up to 21% higher at high impact levels (101.5 N).

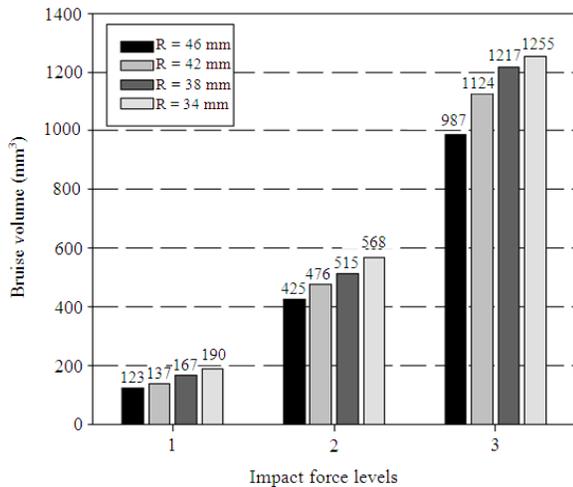


Fig. 4: Effect of curvature radius on bruise volume (mm^3) of apple for each impact force level in relation to model 1

Effect of fruit temperature on bruise damage volume (model 1): Fruit temperature had an inverse effect on the bruise volume (Fig. 6); i.e., in the course of fruit impact, higher temperature led to less bruising. The largest difference between temperatures was observed at lower impact forces (Fig. 6). This difference ranged from about 16% for the low impact (25.8 N) to only 2% for the highest impact (101.5 N).

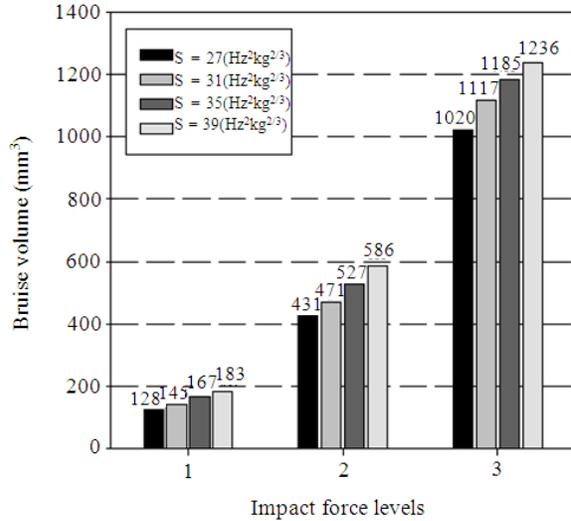


Fig. 5: Effect of acoustical stiffness on the bruise volume (mm^3) of apple for each impact force level in relation to model 1

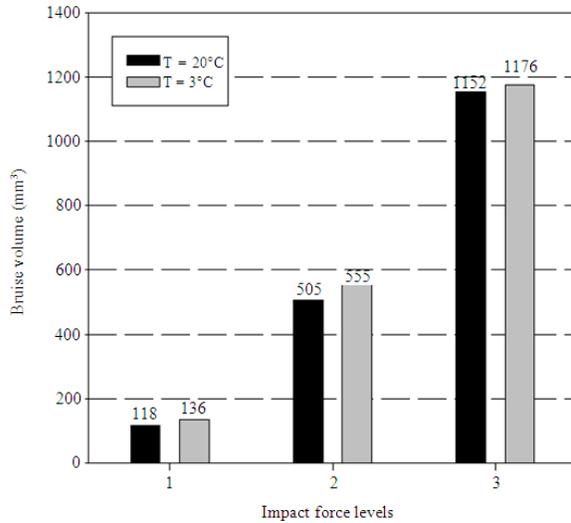


Fig. 6: Effect of temperature on the bruise volume (mm^3) of apple for each impact force level

Table 3: Regression equation of bruise volume (mm^3) of the golden delicious apple in relation to impact Energy (E), curvature Radius (R), Temperature (T) and acoustical Stiffness (S) as independent variables

Model 2	R^2
$V = 1.94S - 6.97R - 1.48T + 7186.95E + 5.97E \times R - 16.09E \times T$	0.97

Note: Minimum probability threshold $p \leq 0.05$

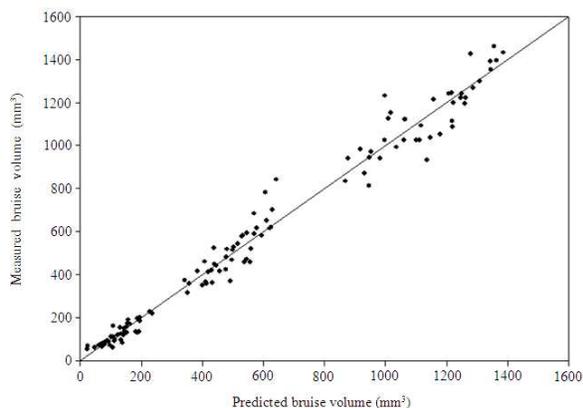


Fig. 7: Measured bruise volume (mm^3) Vs bruise volume predicted by model 2

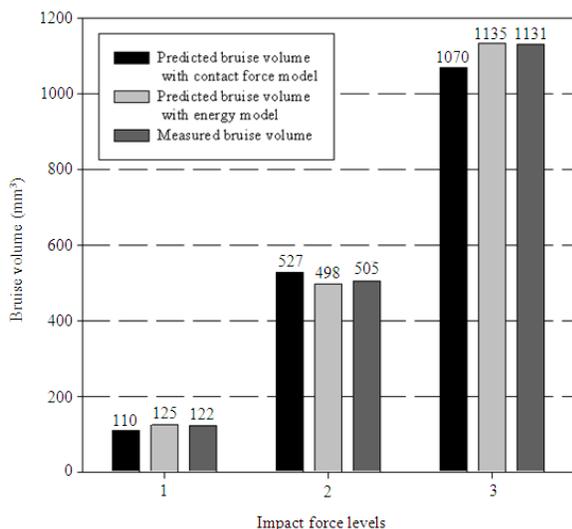


Fig. 8: Measured and predicted values of bruise volume (mm^3) for the apple fruit by model 1 and 2 at different impact levels

Bruise estimation model based on impact energy (model 2):

The results of a multiple linear regression analysis between bruise damage volume and series of independent variables (impact energy, temperature, acoustical stiffness and curvature radius) are presented in Table 3. All main factors in this model (model 2) had significant effect at 5% probability level. For this

model, the plot of predicted bruise volume against measured bruise volume is depicted in Fig. 7. A good fit was obtained between the measured and predicted bruise volumes. No significant differences were observed between the predicted bruise volumes of model 1 and model 2 at all impact levels (Fig. 8).

Effect of fruit curvature radius on bruise damage volume (model 2):

The identical conclusions can be drawn from the model 1 which includes the impact force. However, apples with small curvature radius had more bruise damage volume than those with a larger radius (at the contact area). The interaction between curvature radius and impact energy was also significant at 5% probability level. The effect of curvature radius on bruise damage volume in model 2 (impact energy) was larger than model 1 (impact force). The difference in bruise volume between two extremes of apple curvature radius (34 and 46 mm) was 29% at the low impact force (0.05 J) but only 7% at the high impact (0.19 J).

Effect of apple acoustical stiffness on bruise damage volume (model 2):

Apples with higher acoustically stiffness showed more bruise damage. Significant interaction effect at 5% probability level between apple acoustical stiffness and impact energy was also perceived. Similar difference in the bruise damage volume between low and high acoustical stiffness was observed for model 1 (impact force) and model 2 (impact energy). For the apples of $39 \text{ sec}^{-2} \text{ kg}^{2/3}$ acoustical stiffness, the bruise volume was up to 48% higher than apples with $27 \text{ sec}^{-2} \text{ kg}^{2/3}$ acoustical stiffness at the low impact level (0.05 J) and up to 10% higher at the high impact level (0.19 J).

Effect of fruit temperature on bruise damage volume (model 2):

The effect of apple temperature on bruise volume for impact energy was similar to that of impact force. A higher fruit temperature resulted in less bruising. The interaction between apple temperature and impact energy was significant ($p < 0.05$). Therefore the effect of temperature on the bruise volume was higher at the low impact energy. At low impact energy, the bruise volume of low apple temperature (3°C) was 14% higher than the one with high temperature (20°C), at the high impact level; the bruise volume was 4% higher in identical test conditions.

DISCUSSION

Bruising model was described by combination of impact levels and fruit properties. Impact levels had a

considerable influence on the apple fruit bruise damage susceptibility. The adverse effect of high impact levels was well illustrated. This is in agreement with some other fruits as reported by Van Linden *et al.* (2006) and Van Zeebroeck *et al.* (2007a; 2007b). They observed that the increase in impact levels raises the damage of tomatoes and Jon gold apples.

Effect of apple curvature radius on bruise damage

volume: Apples with low curvature radius led to more bruise damage than Apples with higher curvature radius. Baritelle and Hyde (2001) showed that bruise threshold is a function of fruit tissue failure stress, impact-induced stress, elastic modulus and mass and curvature radius. The researches concerning the influence of the curvature radius on apple bruise damage are scarce (Van Zeebroeck *et al.*, 2007b). Baritelle and Hyde (2001) who studied impact bruising derived the following equation:

$$h = C \cdot \sigma_f \cdot \epsilon_f (1 - \mu^2)^4 \cdot R^3 / (\text{mg}) \quad (4)$$

They concluded that a higher curvature radius resulted in a smaller impact-induced stress and therefore increased a bruise threshold drop height. This is in concurrence with the results of our findings. Van Zeebroeck *et al.* (2007b) stated that at the low impact force, higher curvature radius decreased bruise damage. The current research showed that curvature radius is more sensitive to bruising damage at the low impact level.

Effect of apple acoustical stiffness on bruise damage

volume: Measurement of fruit firmness is a proper manner to observe fruit softening and to estimate bruising injury during harvest and postharvest transportation. According to Roth *et al.* (2005) acoustical stiffness mainly depends on the initial stiffness and correlates with Magness Taylor firmness. While acoustical stiffness gives information about the texture of the whole fruit, Magness Taylor firmness measurement describes only the local texture of the tissue at the penetration area. Stiffness however, is a rather complicated texture characteristic which differs with ripening stages. It is mainly a measure of the mechanical stiffness of the fruit tissue that is related to the cell wall mechanical strength and cell wall turgidity (Hertog *et al.*, 2004). Both diminish during maturity and ripening by moisture loss and by enzymatic changes of the cell wall. The acoustical stiffness is positively associated to the modulus of elasticity (Duprat *et al.*, 1997). According to Baritelle and Hyde

(2001) stiffness of tissue decreases with the decrease of turgor and in apple and potato reduced stiffness results in the increase of failure strain (ϵ_f), as well as increasing tissue strength (σ_f). Therefore tissues that are both stronger and less stiff improve bruise threshold. On the other hand, reducing relative turgor (for example during storage) can decrease tissue modulus of elasticity (stiffness) which in turn makes a specimen more self cushioning, by redistributing an applied force over a larger area of the fruit's surface. Modulus of elasticity, bio-rupture force and rupture stress were all found to decrease as the duration of storage increased (over-maturity) (Vursavus and Ozguven, 2003).

Effect of apple temperature on bruise damage

volume: In this study, high temperature diminished the bruise damage. Other researchers (Pang *et al.*, 1992; Zhang and Hyde, 1992; Thomson *et al.*, 1996) reported reduction bruise damage volume and bruise susceptibility with larger temperature for different apple cultivars. The influence of temperature on apple damage bruise susceptibility can be explained by its influence on apple elasticity and viscosity. Temperature affects stiffness through the activity of enzymes which degrade cell wall. As the cell walls viscosity increases with diminishing temperature, the cell walls might get to be more fragile leading to an increased stiffness but decreasing the cell wall rigidity (Hertog *et al.*, 2004). On the other hand the modulus of elasticity (stiffness) diminishes with rising apple temperature and the modulus of elasticity is positively correlated with the fruit bruising (Van Zeebroeck *et al.*, 2007c). The general effect of temperature will be the consequence of its effects on both tension of tissue and viscosity of cell wall (Bajema *et al.*, 1998). With rising of the fruit temperature, failure stress of tissue decreases and failure strain increases thus reduces elastic modulus substantially with some sacrifice strength of tissue (Baritelle and Hyde, 2001).

According to the kind of fruit and its physiological condition, the comparative contributions of temperature and the mechanical rigidity of the cell wall to stiffness might be changed. However, metabolic activity and thus softening rate increases with the increase in the storage temperature (Chiesa *et al.*, 1998).

CONCLUSION

The main objective of this study was to determine the best reliable statistical model among linear multiple regressions, to estimate the apple (Golden Delicious) fruit bruising susceptibility by bruise damage volume. Bruise estimation models were constructed with

impacts which controlled by an equipped pendulum. Bruise estimation models contained either the impact energy or the impact force as independent variables, together with the fruit properties (fruit curvature radius, temperature and acoustical stiffness). Significant main effects as well as significant interactions between fruit characteristics and the impact properties (impact force or impact energy) were obtained. Apple bruising depended on the curvature radius at the contact point, apple temperature and acoustical stiffness. The estimated bruise models can be apply to organize fruit conditioning and fruit properties for decreasing impact injury during transportation and handling. Effects of the fruit characteristics on the bruise volume are outlined below:

- Higher apple temperature led to decrease bruising
- Bruise volume increased with the increase of acoustical stiffness
- Lower curvature radii led to higher bruising damage
- No significant difference was observed between predicted bruise damage volume of models with impact force and impact energy

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