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DEVELOPMENT OF ENGINEERING DESIGN TOOLS TO HELP REDUCE APPLE BRUISING

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ABSTRACT

A large percentage of apples are wasted each year due to damage such as bruising. The apple journey from orchard to supermarket is very complex and apples are subjected to a variety of static and dynamic loads that could result in this damage occurring.

The main aim of this work was to carry out numerical modelling to develop a design tool that can be used to optimise the design of harvesting and sorting equipment and packaging media to reduce the likelihood of apple bruise formation resulting from impact loads. An experimental study, along with analytical calculations, varying apple drop heights and counterface material properties, were used to provide data to validate the numerical modelling.

Good correlation was seen between the models and experiments and this approach combined with previous work on static modelling should provide a comprehensive design tool for reducing the likelihood of apple bruising occurring.

Keywords: apple bruising, design tools, packaging optimisation

1 INTRODUCTION

The journey of an apple from the orchard to the supermarket is extremely complex and includes a number of processes such as packaging, sorting, storage and transportation. During these processes the apples have to be treated carefully to maintain quality and avoid losses due to damage. The major contributing factor to such losses is bruising (Garcia et al., 1995; O'Loughlin, 1964). This is defined as damage to, and discolouration of apple flesh, usually with no breach of the skin (Labavitch et al., 1998). The discolouration occurs if damage to the apple causes membranes of the individual cells that make up apple flesh to be breached. This allows enzymes from different parts of the cells to mix initiating a reaction that produces the brown colouration, which is associated with bruising. Recent anecdotal evidence from apple distributors has shown that the wastage figure due to bruising could be 50% or higher. This represents a large cost, not only borne by various parties involved in the journey of the apple from orchard to supermarket, but also by the supermarket, as a significant number of apples are damaged while being put out on display.

During its journey to the supermarket an apple may experience a number of different types of loading that may lead to damage and bruising, the two main types being static and dynamic. The dynamic loads may be due to single impacts, which may occur during picking or sorting as the apples are dropped into storage bins, or vibration, which may occur during transportation.

In this work the focus was on dynamic loading due to single impacts as this appeared to be the most prevalent. The situations where this may occur are highlighted in Table 1, along with the drop heights and the materials the apples may impact against.

Extensive studies of apple bruising due to dynamic impacts have been carried out previously using a variety of techniques, such as drop and pendulum tests and with spring loaded devices to propel an apple against a counterface (Pang et al., 1994; Ragni, 2001; Bollen et al., 2002; Holt, 1977). The data coming from this work, however, is relatively limited in nature and most is in a form that would not be useful to apple distributors or sellers. Pang et al. (1994) have produced the most useful contribution. Their work on dynamic impacts against a variety of counterface materials using a pendulum device produced a series of bruising thresholds. These, however, were based on apple accelerations, which would be harder to determine than drop height for example, which limits their application.

The main aim of this work was to develop a numerical design tool for assessing drops typically experienced by apples in harvesting and sorting equipment to reduce the likelihood of apple bruising occurring.

Apple drop testing was also carried out against a number of different materials typical of those used in packing, harvesting and storage media to provide easy to interpret results that can be compared with industry thresholds for apple bruises and to provide data to validate the numerical models. Analytical calculations were also used to provide further comparison.

2 BACKGROUND

2.1 Experimental Studies of Dynamic Apple Loading

A number of different testing methods have been used to study dynamic impacts of apples, as mentioned in the introduction. These include simple drop tests (Pang et al., 1994); pendulum tests, in which it is easier to control the impact point as the apple is held (Ragni, 2001; Bollen et al., 2002); tests where a mass is dropped onto a stationary apple (Garcia et al., 1995) and tests using a spring loaded device to propel an apple against a counterface (Holt, 1977).

The tests were carried out to try and establish bruise thresholds, either in terms of velocity change at impact or impact energy (which are hard to ascertain); to compare the bruise susceptibility of different apple types and establish the effects of parameters such as irrigation, humidity and time of harvest.

Work carried out to study how impact energy affected bruise volume showed that volume was approximately proportional to energy (Holt, 1977). This was for one counterface material and there was no indication of how this may vary with different materials.

In general, while giving large amount of useful data on how particular types of apple react to different types of loading under a variety of environmental conditions, the results from these studies of bruising due to impact are very difficult to interpret and compare, and are more importantly do not help apple distributors or sellers in reducing losses due to bruising. Only a small amount of work has been carried out to study impacts against different materials and there has certainly been no attempt to model the impact behaviour to develop a tool for sorting equipment or packaging design.

2.2 Apple Finite Element Analysis

Numerical Finite Element (FE) techniques have been used previously to investigate modes of vibration in apples (Lu & Abbott, 1996)) and to study transient responses of apples to impulse excitations to determine factors influencing sonic measurements (Lu & Abbott, 1997). Both these analyses were used to ascertain apple firmness, which is a good indication of how ripe an apple is.

In the initial study different properties were assigned to each region of the apple (skin, flesh and core), as shown in Table 2. The magnitude of Young’s modulus and Poisson’s ratio used was found to significantly affect the natural frequencies of vibration. In the second FE study, isotropic elastic properties (of the flesh) were assumed. It was not clear, how the different modelling approaches affected the results as little validation was carried out on either. It could probably be assumed that using different properties for different regions would be a more accurate approach. In both studies a simplified shape was assumed for an apple.

FE has also recently been used with some success to investigate contact areas and stresses in static apple contacts (Lewis et al., 2006). In this work, as well as the present study, an actual apple form was generated using laser scanning. This was thought to be important as area and stress will be extremely sensitive to contact geometry.

3 EXPERIMENTAL DROP TESTING

The aim of the experimental work was to gain an improved understanding of apple bruise formation due to impacts against a variety of counterface materials and to provide the results in a user friendly form. The results were also to be used to validate analytical and numerical calculations detailed in subsequent sections. A drop testing technique was used, as it was thought to be the most realistic simulation of what would actually happen to the apple, although it was difficult to control the impact point.

3.1 Test Apparatus

The drop testing apparatus was relatively simple (see Figure 1). It comprised of a table, the top of which was either the material under examination or the material mounted on a stiffer surface (rubber and cardboard samples were mounted on a steel and perspex counterface respectively to simulate the rubber of a conveyor or a cardboard box on a stiff surface) and a height gauge. In some tests a high speed camera was used to film the contact to determine the impact velocity and rebound distance needed to calculate energy absorbed during the impact. This was set-up to be in line with the impact zone (see Figure 1).

3.2 Specimens

'Golden Delicious' apples were used for the tests. This variety was chosen due to its pale skin, which means any discolouration from bruising is more evident. The apples used were on their way to the supermarket, having been in cold storage. Sugar content and firmness tests were carried out on the apples prior to testing to ensure that apples with consistent properties were used. A spherometer was used to measure the radii of curvature of the apples at the *stem shoulder*, *cheek* and *calyx shoulder* regions (see Figure 2a) to enable relationships between bruising and location of impact on the apples to be determined and to provide input data for Hertz predictions of the contact area and stress to be calculated. The results of the measurements are shown in Figure 2b. As would be expected *cheek* radii were higher than those of the *calyx* and *stem shoulders*.

The properties shown in Table 2 for 'Golden Delicious' apples were used throughout this work. They were taken from tests carried out by Abbott & Lu (1996) and Mohsenin (1970). This work indicated that the elastic properties of the apple flesh varied according to load orientation and position in the apple (data in Table 2 has been averaged). Failure stresses were also determined for the flesh and these also varied with position in the apple. Typical values were around 0.40-0.51MPa, although, as with all properties, these varied with the relative ripeness of the apples. The greatest failure stresses were found for *medium* ripe apples (levels of relative *ripeness* were based on harvest time and appearance).

A number of different materials were used in the drop tests as impact surfaces. These were chosen based on the data collected in Table 2. Their properties are shown in Table 3. The cardboard was Type 150B corrugated board, as shown in Figure 3. Dimensions for the cardboard are shown in Table 4. Data for mechanical properties of such cardboard are quite limited. The values shown in Table 3 were taken from work to determine the elastic constants of corrugated board panels.

3.3 Procedure

Apples were dropped from heights ranging from 0.1 – 1.2m (to cover the range of possible heights identified in Table 1) onto perspex, steel, rubber (on steel), cardboard (on perspex) and wood as well as a half apple to simulate an apple-to-apple contact. Tests were repeated for each height at least three times to ascertain the spread of results.

The aim was to achieve apple impact in the *cheek* region, however, initial testing indicated that it was quite difficult to control the impact position. It was possible, though, using the measurements taken of each apple pre-test, to tie up bruise volumes with radius of the apple at the impact point. A number of tests were therefore carried out to assess how the bruise areas and volumes varied with radius at contact and region of contact (using a perspex counterface).

Apples were left for 24 hours after dropping for the bruises to develop fully. The areas, A, were then determined by measuring the widths ($2a$ and $2b$, as shown in Figure 4) and assuming they were elliptical:

$$A = \pi ab \tag{1}$$

Bruise volumes were calculated using the *elliptical bruise thickness method* (Mohsenin, 1970). This calculation method has been compared with a range of others and found to give the most accurate results (Bollen et al., 1999). Bruise volume, V is given by:

$$V = \frac{\pi(d_b - d_t)}{24}\left(12ab + 4(d_b - d_t)^2\right) \tag{2}$$

The parameters used are defined in Figure 4.

High speed video footage was taken of an apple-to-steel, apple-to-perspex and apple-to-apple contact at heights of 0.1, 0.3 and 0.6m. The filming and analysis process was extremely time consuming so tests were not carried out with all materials.

The captured film was processed and software was used to find the co-ordinates of the apples as they fell by placing circles around them in each frame, as illustrated in Figure 5.

Calculations could then be carried out to determine the impact energy, e_{impact}, which is equal to the difference between the energy the apple has before and after the impact:

$$\text{Energy before, } e_{before} = mgh_{drop} \tag{3}$$

$$\text{Energy after, } e_{after} = mgh_{after} + \frac{1}{2} mv_{after}^{\;2} \tag{4}$$

$$\text{Impact energy, } e_{impact} = e_{before} - e_{after} \tag{5}$$

where m is the apple mass, v is the apple velocity, h_{drop} is the drop height and h_{after} the height after impact.

3.4 Results

Results of tests carried out to see how the location of the impact point on the apple would affect bruise volume are shown in Figure 6. Results have been selected so that the *cheek*, *stem shoulder* and *calix shoulder* radii were similar at each drop height to allow the results to be considered independent of the geometry (the radii for the *cheek*, *stem shoulder* and *calix* shoulder were: ~40mm, ~30mm and ~35mm respectively). As can be seen the largest bruises are seen on the *cheeks*. These typically have larger radii, so there is clearly a relationship between radii and bruise volume. A plot of radius against bruise area against bruise volume is shown in Figure 7. This shows that bruise area and volume clearly increase with increasing radius.

Average apple bruise areas and volumes (calculated using Equations 1 and 2) after impacts against a variety of counterface materials are shown in Figures 8 and 9. Spread in bruise size over the three specimens used at each test condition was a maximum of ±50mm^2. The smallest bruises were seen when using cardboard and wood and the largest with steel and rubber on steel. In the apple-to-apple tests the stationary apples had larger bruises than the dropped apple.

On Figure 8, showing bruise areas, the industry threshold for bruises (100mm^2) is also plotted as well as possible regimes of damage at the various stages of the apple journey. It can be determined at what drop height this is exceeded for each of the counterface materials, which is very useful information when designing equipment for harvesting and sorting or packaging media.

Data in Figure 10 illustrates how bruise volume varies with impact energy. Values determined using the high speed video footage and Equations 3-5. There is an approximately linear relationship between the two, with different gradients for each counterface material. This ties in with observations made by Holt (1977) during tests with 'Jonica' apples, the results of which are also shown in Figure 10.

4 DYNAMIC FINITE ELEMENT MODELLING

4.1 Mesh Construction

In order to use the geometry of an actual apple in the FE modelling, a laser scan was created of a Golden Delicious apple, which was then imported into ANSYS LS-DYNA software to create a mesh. The apple prepared for scanning is shown in Figure 11a. The apple was sprayed white to provide a reflective surface for the laser scanner. The geometry of a real apple is complex and non-symmetrical so the volume was free meshed with tetrahedral elements, as shown in Figure 11b. It was found that a density of 17000 elements was sufficient to accurately represent the apple geometry and also allowed the model to be solved with the resources available.

To simplify the modelling, isotropic properties were assumed, as they have been in most previous FE studies of apples (see Section 2.2).

A Young's modulus of 4MPa was used, as determined for 'Golden Delicious' flesh in the appropriate region of the apple by Abbot & Lu (1996). The data in Table 2 illustrates shows how the Young's Modulus actually varies between the various parts of an apple. Abbott & Lu (1996) have also shown that the properties of apple flesh vary in different parts of the apple and are different if loading is applied from varying directions.

Linear elastic material properties were also assumed, and while this is probably not valid for apple flesh, it is compatible with previous work.

4.2 Modelling Procedure

Dynamic analysis was used to simulate a free fall of the meshed apple for drop heights of 0.2 to 1.2m onto the impact surface, as illustrated in Figure 12. Impact surfaces were given the properties shown in Table 3. Model runs were carried out for impacts on perspex, wood and cardboard. In order to reduce the calculation time, only the short time frame after impact was analysed. Impact velocities were calculated from the drop heights ($v = \sqrt{2gh}$) and are shown in Table 5.

4.3 Results

Figure 13 shows the evolution of the apple during an impact onto perspex from a height of 1.2m. The picture on the left is at initial contact with the counterface. During the impact the contact area and stresses increase. Figure 14 shows a snap shot of the point at which the stresses are at a maximum (at maximum deflection). In order to estimate a *bruise area*, the area of the contact in each case over 0.5MPa (approximate failure stress of ‘Golden Delicious’ apple flesh (Abbott & Lu, 1996)) was calculated. Full results are compared with the experimental and analytical results in the discussion.

5 ANALYTICAL ANALYSIS

Analytical calculations for the impacting apples were based on a scheme using Hertz equations for contacts (Hertz, 1881). This analysis, although both static and elastic in nature has been widely applied to impact situations where permanent deformations are produced, such as the apple contact. The use of the Hertz analysis beyond the limits of its validity has been justified on the basis that it appears to predict accurately most of the impact parameters that can be experimentally verified (Goldsmith, 1960).

Initially the impact force, P_{max}, was calculated using analysis derived for an elastic sphere impacting a rigid plate (Goldsmith, 1960):

$$P_{max} = k_h \delta_{max}^{1.5} \tag{6}$$

where δ_{max}, is the maximum deflection given by:

$$\delta_{max} = \left(\frac{5}{4} m \frac{{v_0}^2}{k_h} \right)^{0.4} \tag{7}$$

where m is the mass of the sphere, v_0 is the sphere velocity at impact (given by $\sqrt{2gh}$, where h is the drop height) and k_h is a constant given by:

$$k_h = \frac{3}{4} R^{0.5} \frac{E}{\left(1-\nu^2\right)} \tag{8}$$

where R is the radius of the sphere (the average value of the *cheek* region of the apple was used) and E and v are Young's modulus and Poisson's Ratio of the sphere material respectively. Results of calculations for a range of drop heights are shown in Table 5 (values of E and v for apple flesh in Table 2 were used and an apple mass of 0.15kg).

Once the force has been calculated it can be used in the following Hertz equations to determine the elliptical contact area half widths a and b and the maximum contact pressure p_0 (equations are outlined in Williams (1994)).

Results of these calculations for an apple impact on perspex are shown in Table 5. Properties for the apple flesh and counterface materials given in Table 5 were used in the calculations. Average values from the measurement of apple specimens in the drop testing were used to determine R_1 (28.8mm) and R_2 (37mm). The contact area does not represent the likely bruise area. To determine area approximations for the bruises the pressure distributions were plotted (as shown in Figure 15 for perspex) using the equation given below:

$$p = p_0\left\{1-\left(\frac{x}{a}\right)^2-\left(\frac{y}{b}\right)^2\right\}^{1/2} \qquad (9)$$

A plot is shown for a perspex impact at a range of drop heights for sections along the x axis. The x and y axis plots were used to determine a and b can be determined from the plots at the point where the stress is over 0.5MPa, the failure stress of 'Golden Delicious' apple flesh. Comparison of the results of the calculations with the FE and experimental results are included in the discussion.

6 DISCUSSION

Data has been generated in this work that can be used by designers of apple harvesting, sorting and packing equipment to reduce the likelihood of apple bruises occurring. Drop heights can be reduced to levels below those that could give a bruise over the industry threshold size (see Figure 8). Although bruise volumes have been calculated throughout the work, it is probably bruise areas that are more important as these are visible and used to define the threshold used. It is also usually how an apple looks that determines whether a consumer will purchase it (Cliff et al., 2002).

The work has shown that the radius at the point of impact heavily influences the bruise volume, with larger radii giving larger bruises. This means that if the point of impact is on the *cheek* of an apple, the bruise will be larger than those on the *stem* or *calix shoulders*, which generally have smaller radii.

It was clear from the results that using counterface materials with a higher energy absorbing capacity led to smaller apple bruises. The rubber, however, because it was backed with steel still gave relatively large bruises. It was also interesting to see that large bruises occurred due to apple-to-apple contacts. This can occur when apples are tipped, for example, into display stands in supermarkets and if this is done from too high a height problems may occur and lead to apple wastage.

It should be noted here that the tests were carried out for a set of apples at one condition. The apples tested had come out of storage and were on their way to a supermarket. At other stages of ripeness they would have had different properties. Previous work has also shown that varying irrigation conditions, humidity and harvest time will affect the mechanical properties of apples and the bruise sizes will vary accordingly (Garcia et al., 1995). Also work has shown that bruise susceptibility changes with apple variety (Pang et al., 1994; Ragni, 2001). In future development of the modelling this will have to be accounted for.

Figure 16 shows how the analytical and numerical *bruise* predictions for perspex, wood and cardboard compare with the experimental results. Good correlation is seen for all, even with the simplifications made in modelling the corrugated board.

The numerical and analytical modelling illustrates the fact that the bruise area is lower than the actual bruise area. When considering just the area at the failure stress of the apple flesh a better prediction of bruise size is achieved. The relationship between contact area and bruise area has been shown experimentally previously in work on apple-to-apple contacts (Pang et al., 1992; Studman et al., 1997) where bruise areas were up to 25% lower than the contact area. The analytical results in the present study illustrated in Figure 16 show a difference of a similar order of magnitude (where unmodified Hertz is the contact area and the modified Hertz is the bruise area).

The numerical model clearly shows great promise, and if developed further to improve the structure of the apple, and combined with the static approach detailed previously (Lewis et al., 2006), could create a comprehensive tool for assessing apple packaging. The results could also be used as part of educational tools for those working in the industries dealing with apples and other produce, to help reduce the likelihood of damage occurring.

7 CONCLUSIONS

Apple bruise areas and volumes resulting from dynamic impacts vary with surface radii of the apple at the point of impact. The larger the radii the larger the area and volume of the bruise formed. Therefore *cheek* impacts will give larger bruises than *stem* or *calix* shoulder impacts as this region tends to have a higher radius.

Experimental data has been generated for bruise area and volumes for impacts against a number of different counterface materials and for a range of drop heights. This has shown that bruise volume is approximately proportional to drop height. Rigid counterfaces gave higher bruise areas than softer more energy absorbing materials. Figure 17 shows the relationship between the Young's Modulus of the counterface materials and the bruise volume at a drop height of 1m (from Figure 9). The trend is clearly for bruise volume to grow with increasing Young's modulus. The only anomaly is rubber, but the value plotted is that for rubber alone and the rubber was actually mounted on a steel base plate which would increase the overall stiffness. The data has been compared with industry thresholds for bruise sizes and indicates maximum drops heights that should be allowed to give bruises below these.

Analytical and numerical tools have been developed to predict bruise sizes for a given drop height against a given counterface material. The numerical model particularly shows reasonable correlation with experimental results and if developed further and combined with previously developed static models will provide a comprehensive design tool for apple harvesting and transportation equipment and packaging media. Average differences ranged between 7% for Perspex to 18% for wood and 26 % for cardboard. It was in modelling the cardboards as a homogeneous material, however, that the largest simplification was made so this error is perhaps not surprising.

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Figure Captions

Figure 1 Drop Test Apparatus and Camera Set-up

Figure 2 (a) Regions where Radii of Curvature were Measured; (b) Values of Radii

Figure 3 Corrugated Card used in Impact Testing

Figure 4 Elliptical *Bruise Thickness* Method for Bruise Determination (Mohsenin, 1970)

Figure 5 Circles Placed around Apples in Film Data Analysis

Figure 6 Bruise Volumes for Apples Dropped onto the *Cheek* (~40mm radius), *Calix Shoulder* (~35mm radius) and *Stem Shoulder* (~30mm radius) from various Heights on to Perspex (radii were similar for each apple impact point for each of the tests)

Figure 7 Bruise Area and Volume against Radius of Apple at Impact Point

Figure 8 Average Bruise Areas for Apple Impacts against Different Materials at Varying Drop Heights

Figure 9 Bruise Volumes for Apple Impacts against Different Materials at varying Drop Heights

Figure 10 Bruise Volume against Impact Energy for Different Impact Surfaces

Figure 11 The Apple (a) Before Laser Scanning and (b) Represented in Ansys

Figure 12 Finite Element Model of Apple and Impact Surface

Figure 13 FE Apple Impact against Perspex from a Drop Height of 1.2m at Point of Maximum Deflection

Figure 14 Stresses in a Node at the Centre of the Contact in Figure 18

Figure 15 Stress Distributions for Drop Heights from 0.2m to 1.2m onto Perspex

Figure 16 Comparison of Experimental, Analytical and Numerical Bruise Areas for Apple Impacts against Perspex, Wood and Cardboard

Figure 17 Bruise Volume at a 1m Drop Height (from Figure 9) against Young's Modulus of the Counterface Material

Table Captions

Table 1 Potential Dynamic Apple Loading Situations and Associated Drop Heights

Table 2 Young's Modulus, Poisson's Ratio and Failure Stress for Different Parts of a Golden Delicious Apple (Abbott & Lu, 1996; Mohsenin, 1970)

Table 3 Impact Surface Material Properties

Table 4 Geometrical Characteristics and Bulk Density of Type 150B Corrugated Board

Table 5 Results of Analytical Apple Impact Calculations

Figure 1

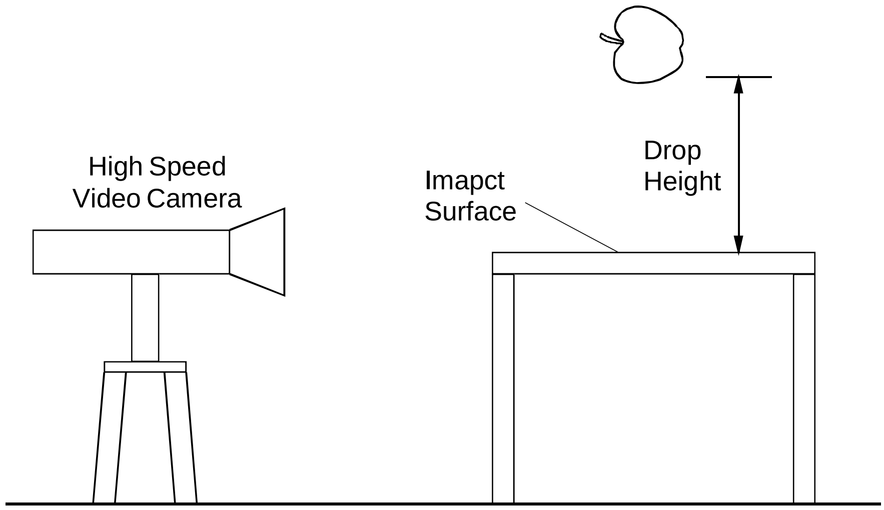


Figure 2

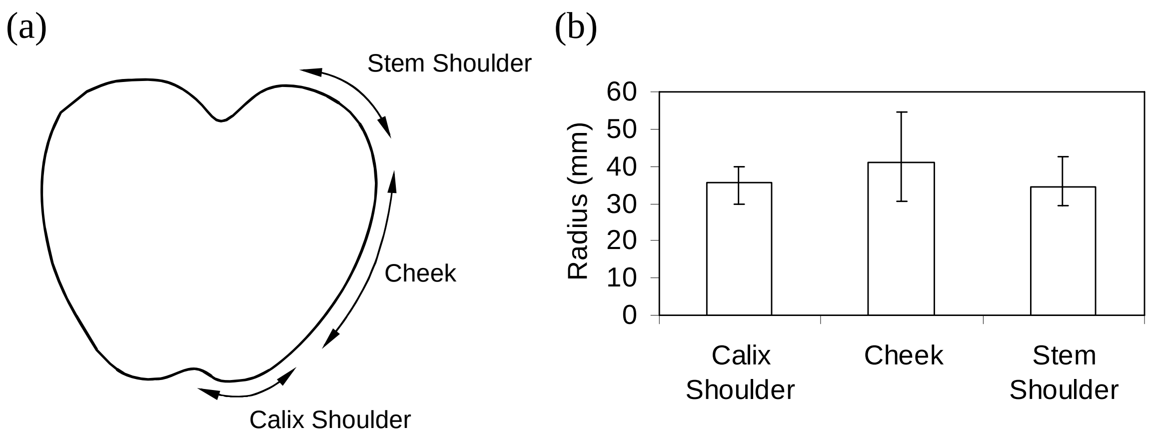


Figure 3

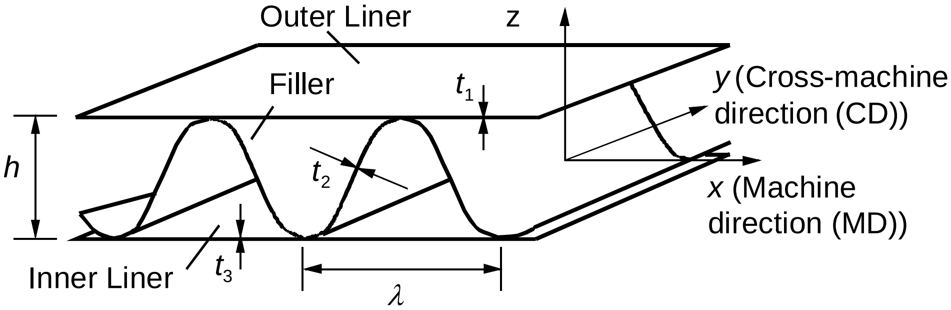


Figure 4

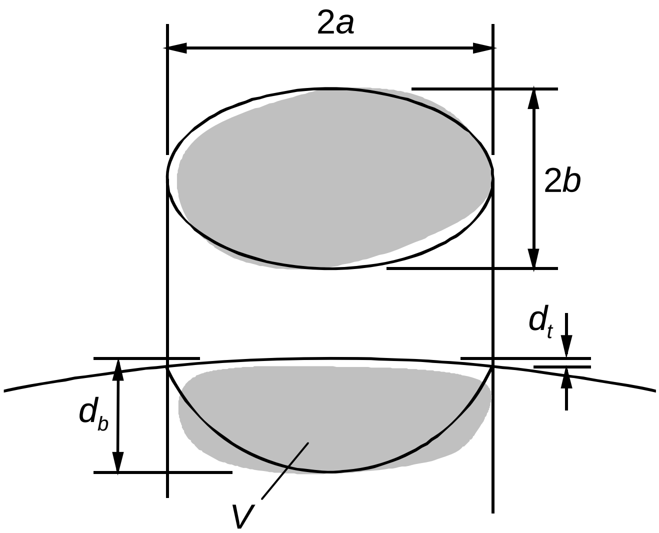


Figure 5

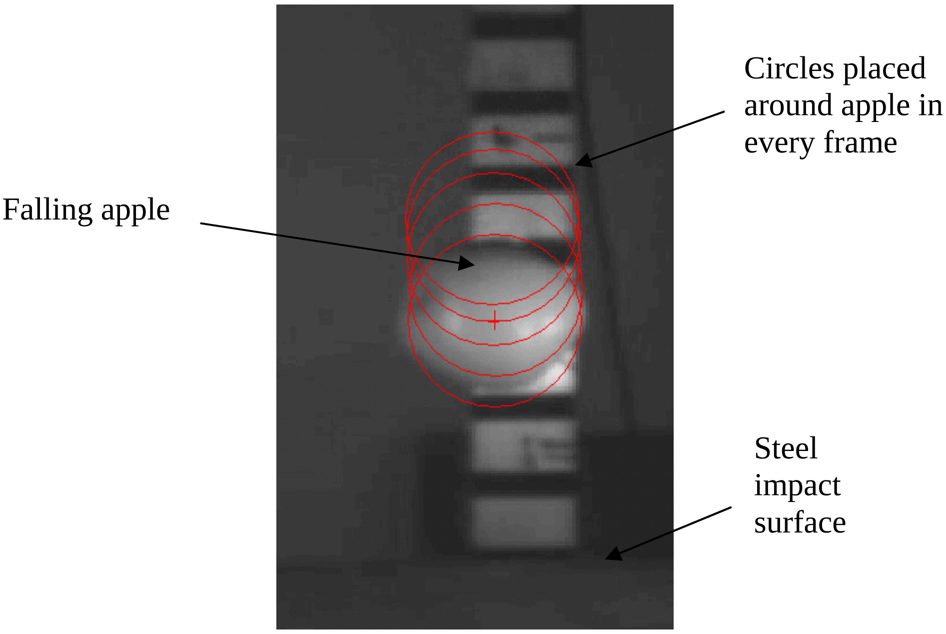


Figure 6

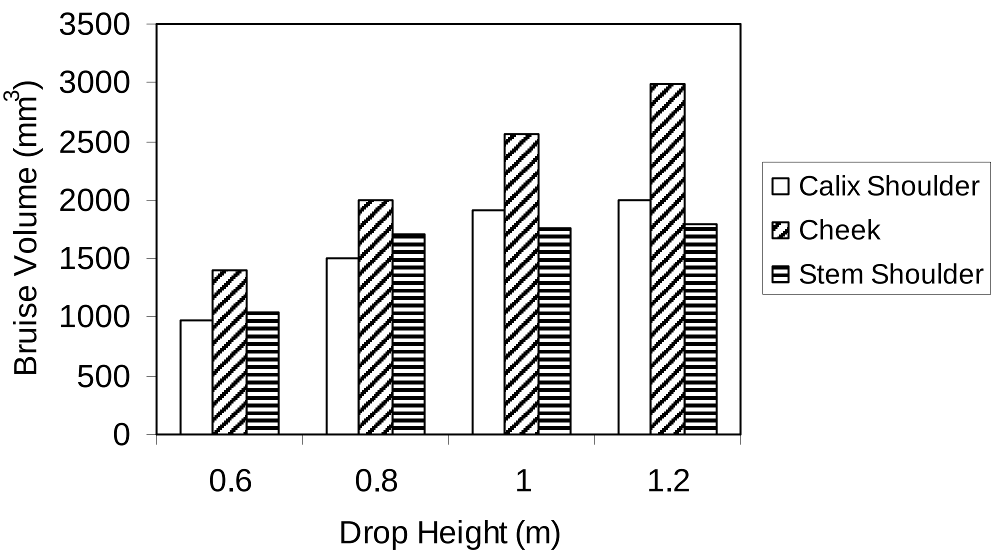


Figure 7

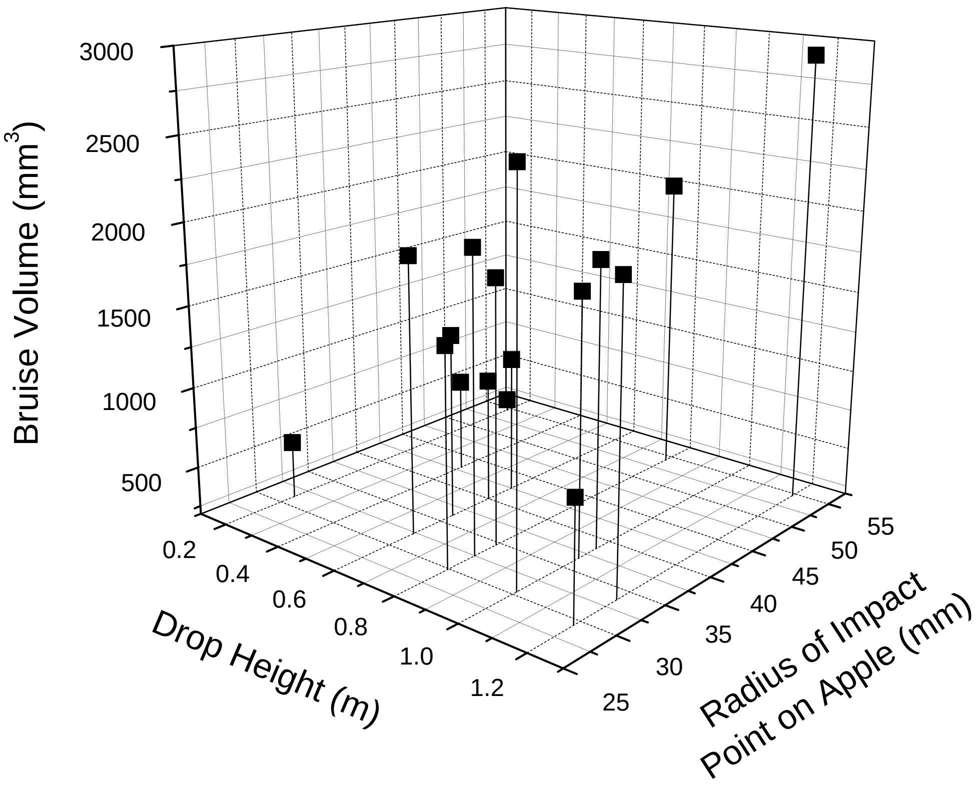

Bruise Volume (mm3)
3000
2500
2000
1500
1000
500
0.2
0.4
0.6
0.8
1.0
1.2
Drop Height (m)
25
30
35
40
45
50
55
Radius of Impact
Point on Apple (mm)

Figure 8

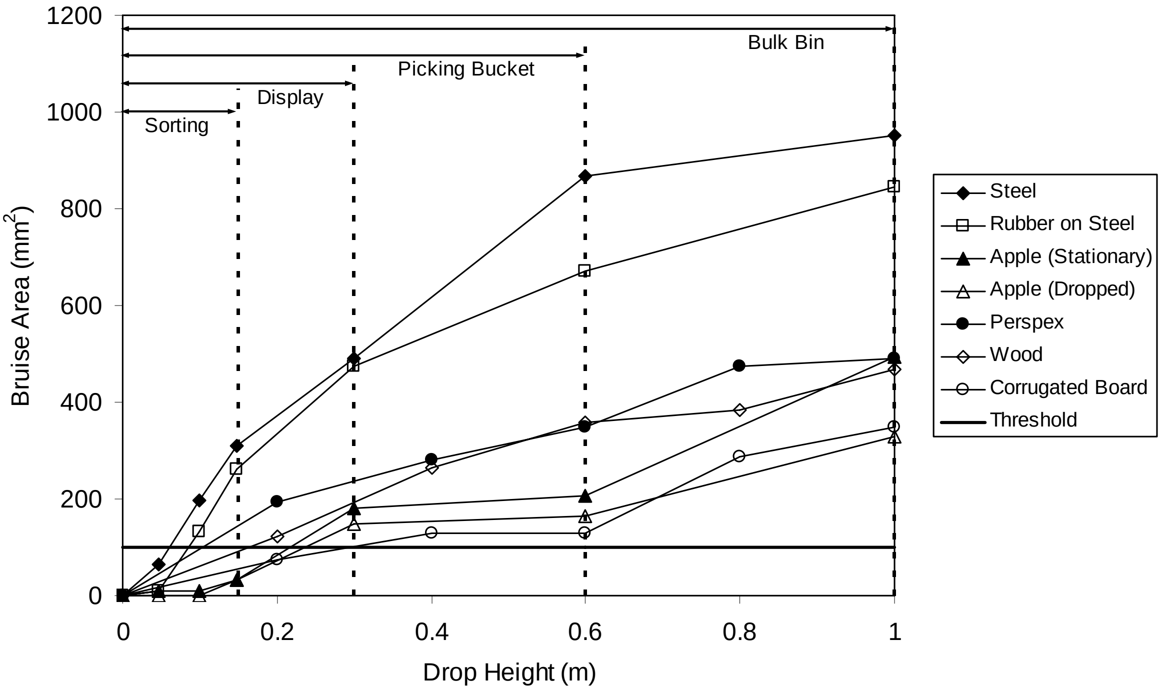

1200
1000
800
600
400
200
0
Bruise Area (mm2)
0
0.2
0.4
0.6
0.8
1
Drop Height (m)
Bulk Bin
Picking Bucket
Display
Sorting
Steel
Rubber on Steel
Apple (Stationary)
Apple (Dropped)
Perspex
Wood
Corrugated Board
Threshold

Figure 9

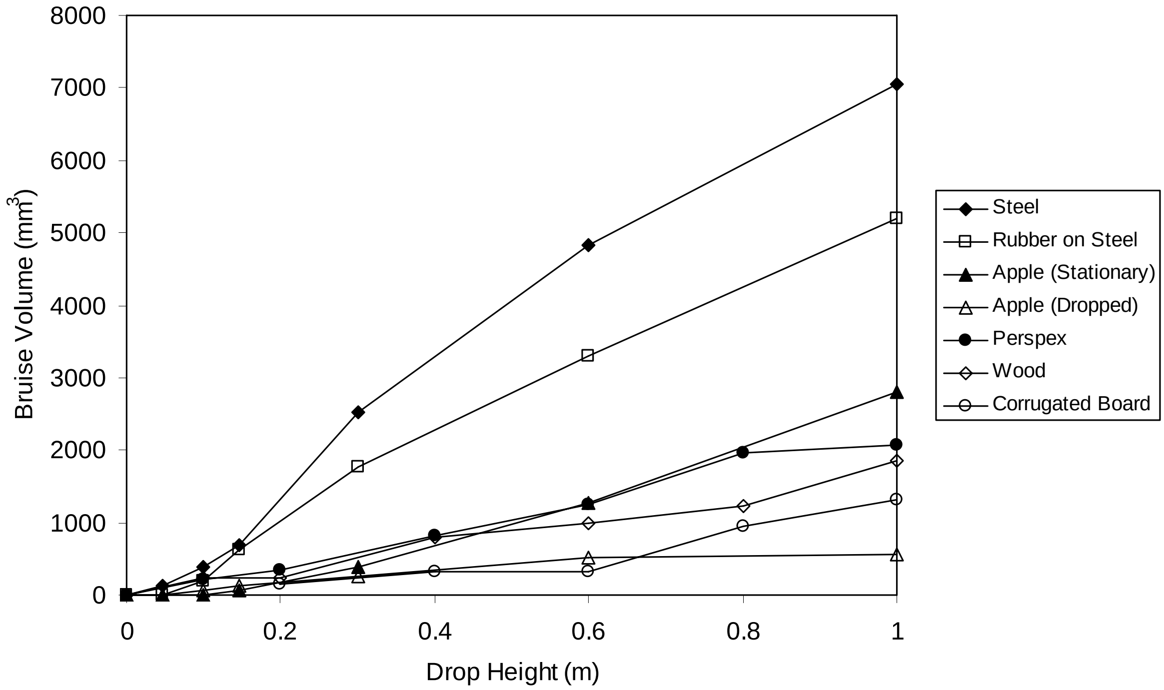

8000
7000
6000
5000
4000
3000
2000
1000
0
Bruise Volume (mm3)
0
0.2
0.4
0.6
0.8
1
Drop Height (m)
Steel
Rubber on Steel
Apple (Stationary)
Apple (Dropped)
Perspex
Wood
Corrugated Board

Figure 10

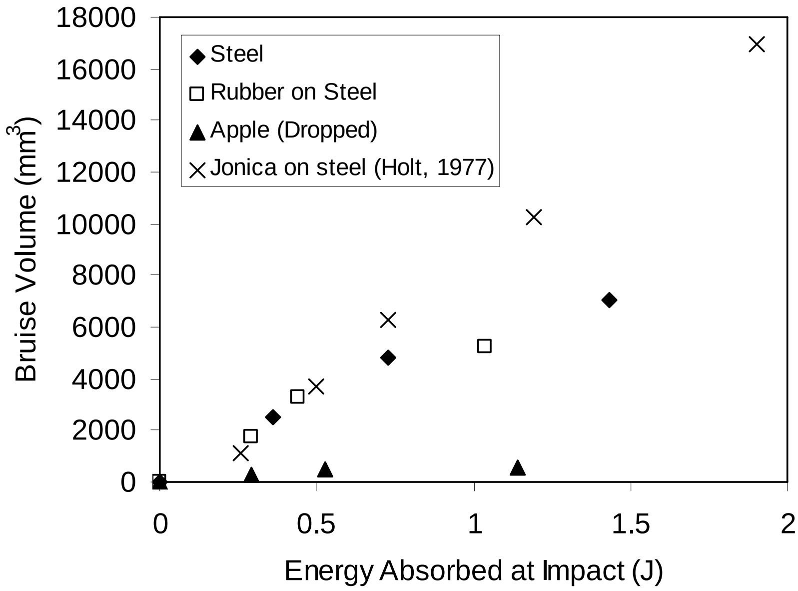


Figure 11

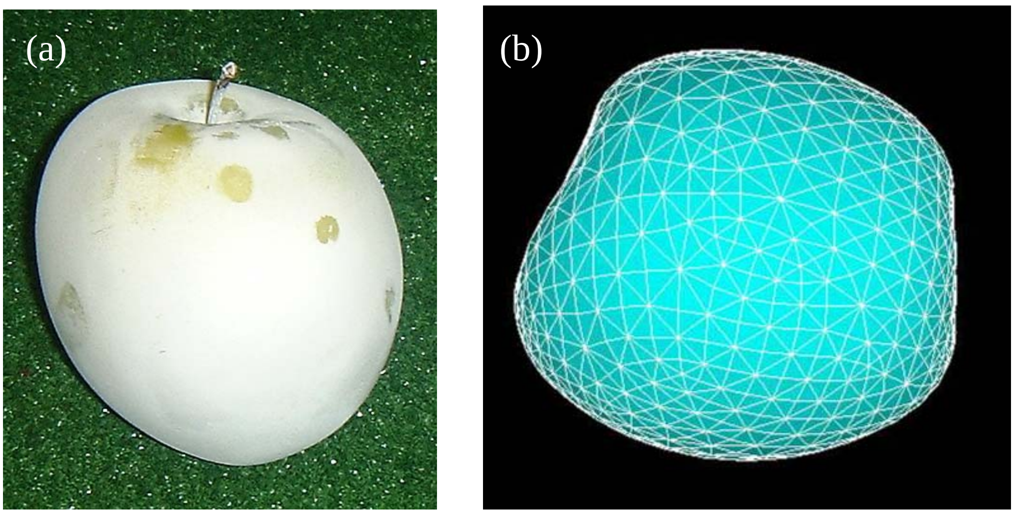


Figure 12

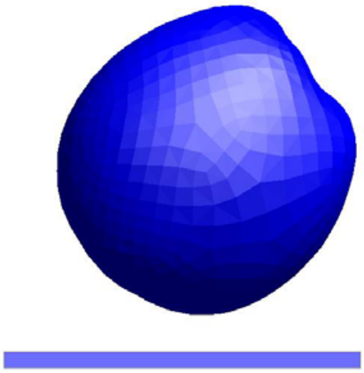


Figure 13

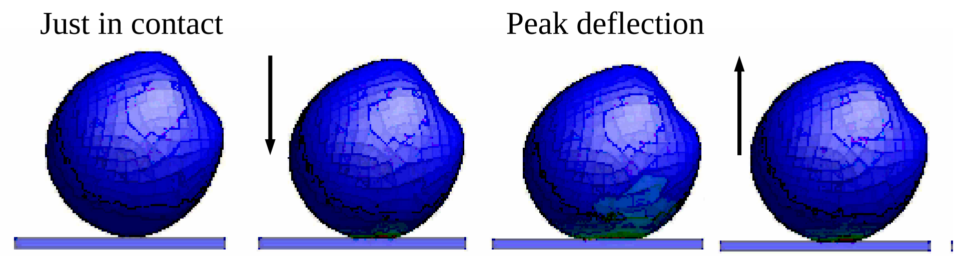


Figure 14

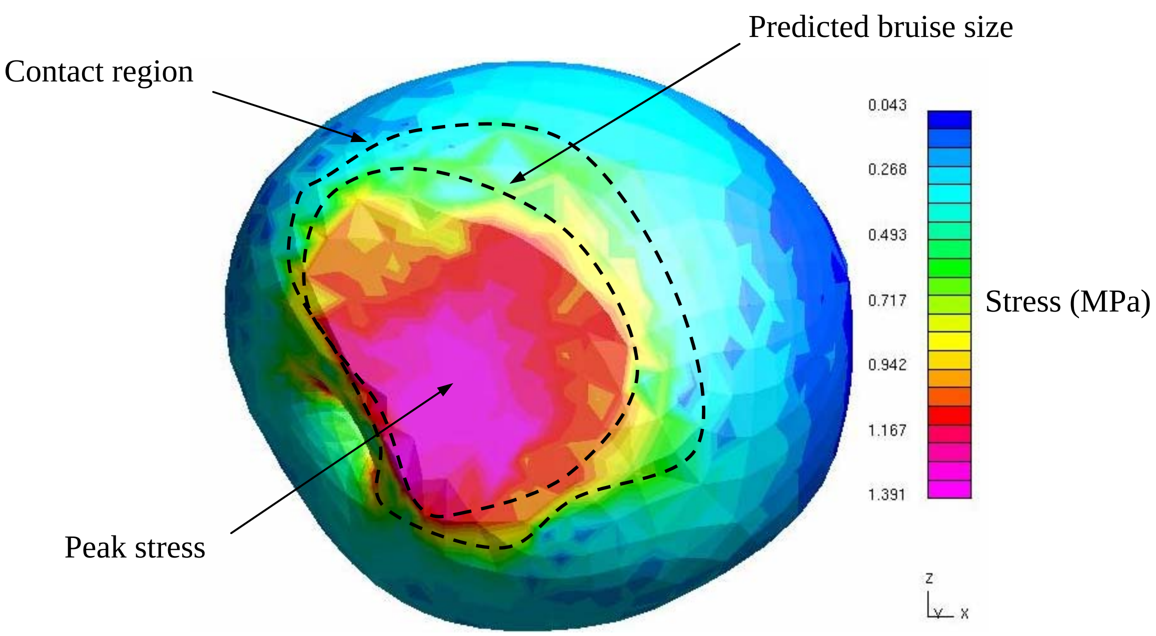


Figure 15

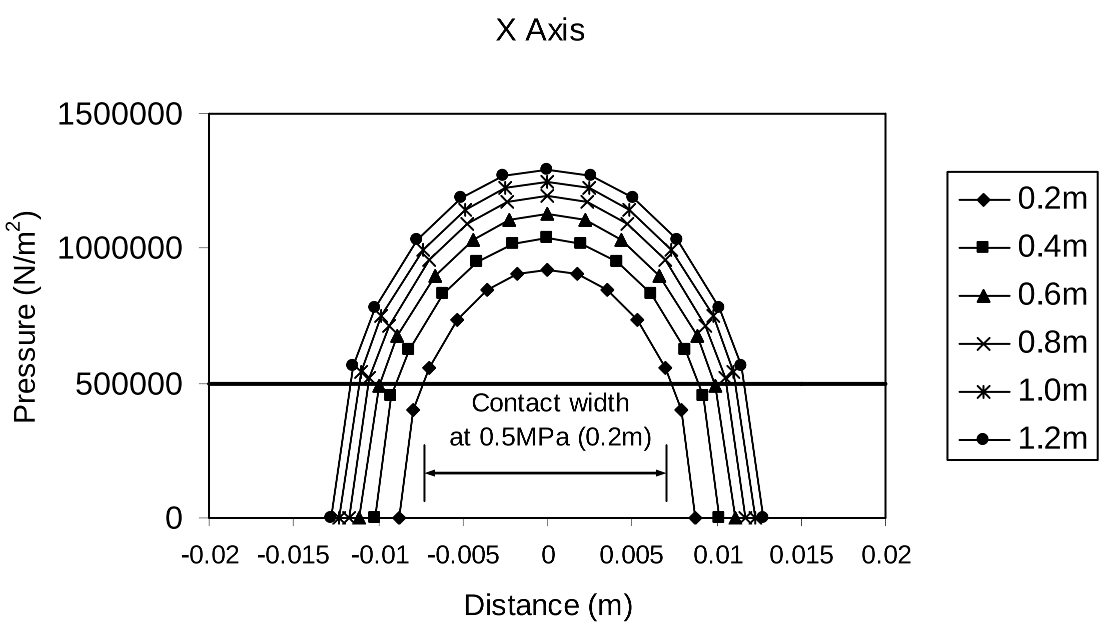
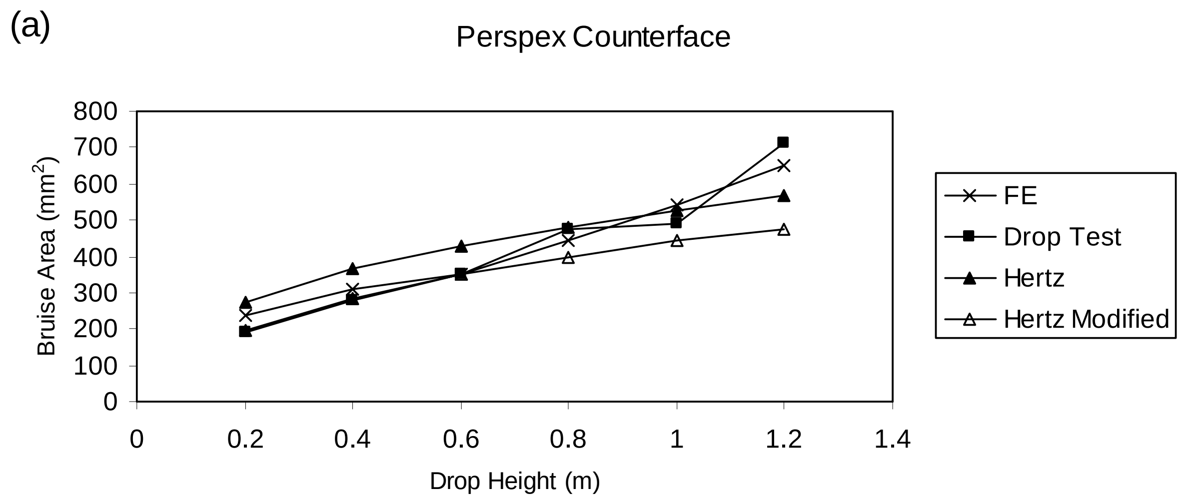
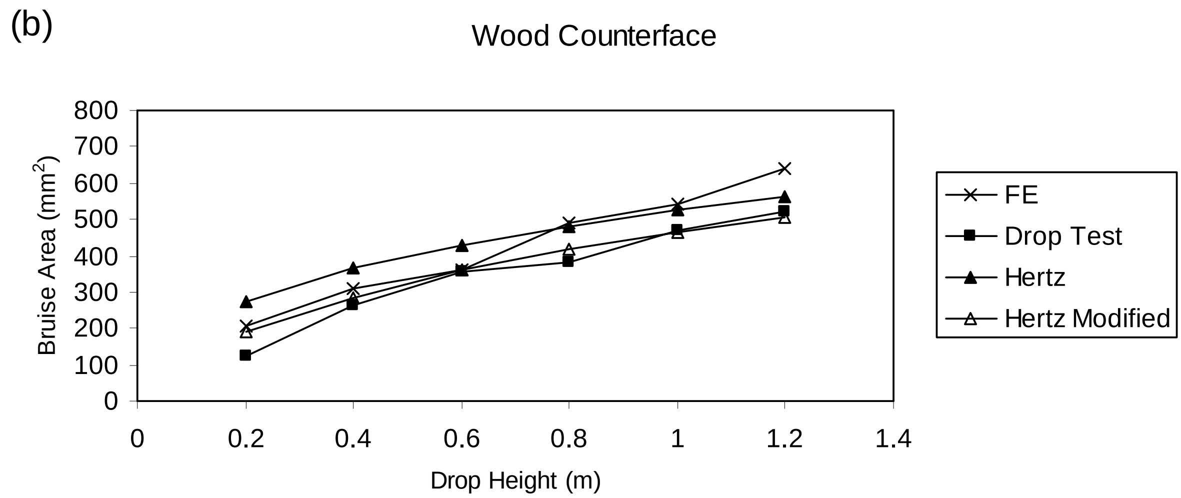


Figure 16


(a)
Perspex Counterface
800
700
600
500
400
300
200
100
0
Bruise Area (mm2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Drop Height (m)
FE
Drop Test
Hertz
Hertz Modified


(b)
Wood Counterface
800
700
600
500
400
300
200
100
0
Bruise Area (mm2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Drop Height (m)
FE
Drop Test
Hertz
Hertz Modified

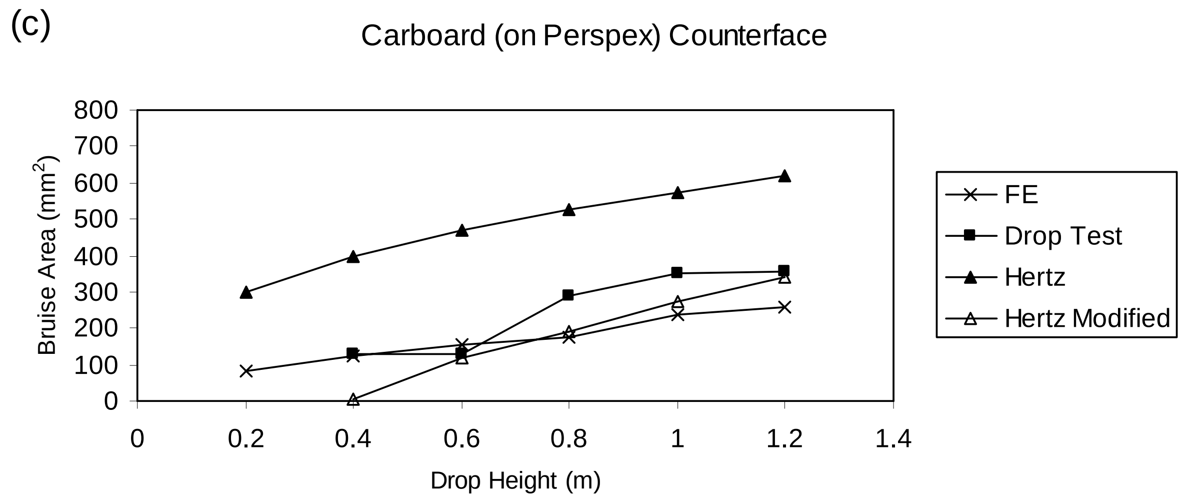
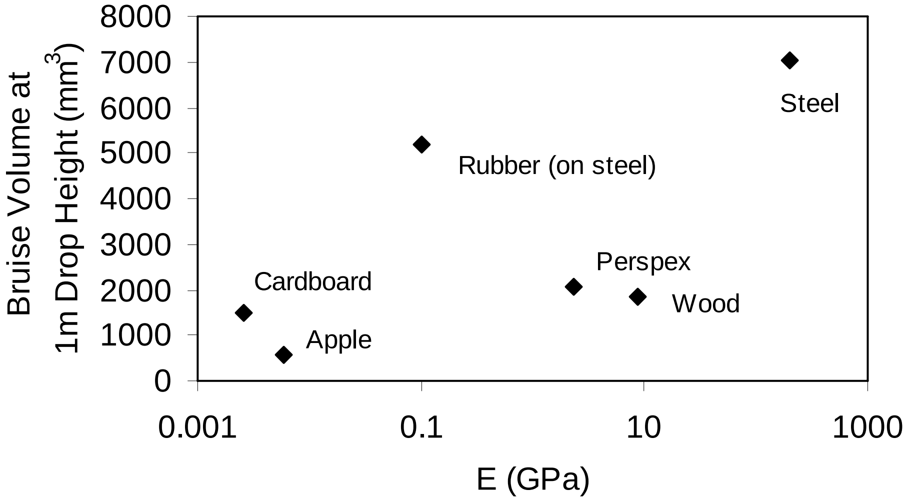

(c)
Carboard (on Perspex) Counterface
800
700
600
500
400
300
200
100
0
Bruise Area (mm2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Drop Height (m)
FE
Drop Test
Hertz
Hertz Modified

Figure 17



Bruise Volume at
1m Drop Height (mm3)
8000
7000
6000
5000
4000
3000
2000
1000
0
0.001
0.1
10
1000
E (GPa)
Steel
Rubber (on steel)
Perspex
Wood
Cardboard
Apple

Table 1

Point in Journey	Process Stage	Potential Drop Height	Impact Material
Orchard	Picking Bucket	0.6m	Perspex Wood Apple
	Bulk Bin	0.6-1m	
Packing House	Repack	0.05-0.15m	Perspex Wood Cardboard Apple
Distributor	Sorting (conveyors etc.)	0.05-0.15m	Steel Rubber on Steel
Retailer	Putting on Display	0.05-0.3m	Cardboard Apple

Table 2

Region of Apple	Skin	Flesh	Core
Young's Modulus (MPa)	20	4	8
Failure Stress (MPa)	-	0.40-0.51	-
Poisson's Ratio	0.3	0.3	0.3

Table 3

Material	Thickness (mm)	Elastic Modulus, E (GPa)	Poisson's Ratio, υ
Perspex	5	2.35	0.38
Steel	5	200	0.3
Rubber	3	0.1	0.5
Wood (Pine)	8	8.89	0.341
Cardboard	3	0.0026 (E_z)	0.01

Table 4

Parameter	Value
h (mm)	2.9
λ (mm)	6.5
t_1	0.25
t_2	0.25
t_3	0.25
Bulk Density (kg/m^3)	194.8

Table 5

Drop Height (m)	Velocity at Impact (m/s)	δmax (m)	P_{max} (N)	*R'* (mm)	*k*	**E**	*E** (N/m^2)	*a* (mm)	*b* (mm)	Area (mm^2)	Mod. Area (mm^2)
0.2	1.98	0.00416	169.9	16.2	0.882	1.46	4.39×10^{-6}	9.80	9.98	276.03	195.51
0.4	2.80	0.00548	257.6	16.2	0.882	1.46	4.39×10^{-6}	10.11	11.47	364.23	284.49
0.6	3.43	0.00645	328.5	16.2	0.882	1.46	4.39×10^{-6}	10.96	12.44	428.36	350.42
0.8	3.96	0.00724	390.4	16.2	0.882	1.46	4.39×10^{-6}	11.61	13.17	480.60	395.98
1	4.43	0.00791	446.3	16.2	0.882	1.46	4.39×10^{-6}	12.14	13.77	525.47	441.37
1.2	4.85	0.00851	497.9	16.2	0.882	1.46	4.39×10^{-6}	12.59	14.28	565.22	476.15