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A STUDY OF BLACKSPOT BRUISING IN POTATOES

BY

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ABSTRACT

A STUDY OF BLACKSPOT BRUISING IN POTATOES

By

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Blackspot bruising is caused by internal tissue failure due to stresses induced by dynamic contact pressure during free fall impact of potatoes. A technique was developed to identify potato bruising rapidly. Dynamic contact pressure was measured by dropping potatoes onto a pressure sensitive film attached to a steel surface. A threshold dynamic contact pressure that causes internal bruising was found for each variety. The dynamic contact pressure was affected by the mechanical properties of potatoes. The study revealed that dynamic contact pressure was highly correlated with yield stress of potatoes. There existed a high correlation between drop height and the polyphenoloxidase activity in a susceptible variety. Therefore, bruise susceptible variety shows higher polyphenol oxidase activity upon impact. Potato samples were characterized as *moderately resistant* to *moderately susceptible* based on the optical density. Varietal differences in measuring bruise susceptibility was found to be significant. The mineral contents was affected by the variety. Stress distributions in a loaded potato model were studied using finite element method. von Mises contour stress band was used to locate failed elements in the loaded potato model. The von Mises stress was found to concentrate at the area of failed elements below the surface at the stem-end of the potato model where most blackspot bruising occurs.

Approved: ______________________
Major Professor

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Department Chairperson

DEDICATION

This dissertation is dedicated to my beloved father late Dr. Luthfor Rahman Chowdhury, LMF, MBBS, and my beloved mother Mrs. Shamsun Nahar Chowdhurani who always encouraged for higher studies and gave strong moral support towards my successful accomplishment.

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1 INTRODUCTION

1.1 Economic Significance and Magnitude of the Problem

The potato is the fourth important crop in the world after rice, wheat and corn providing an important source of vitamin C (Mary et al. 1939). About 356 million cwt of potatoes were produced in 1988 in the USA. Out of this production, 50.3% were processed, 33.5% were consumed as table stock and 8.5% used as seed (USDA, 1990). The estimated value of the 1989-90 US potato crop was over $2.5 billion (MPIC, 1990). The bruising in potatoes causes decrease in shelf life, consumer acceptance, low quality and very high monetary loss. Approximately 8% of the total production is lost during the harvesting and handling operations (USDA, 1990). According to National Potato Council's estimation, the potato industry lost approximately $150 million in 1985, in other words it costs $12,000 to an average grower annually due to bruising. It also costs over $11 millions to the potato processing industries. Washington State alone produced 29 billion kg of potato crop worth $333 millions in 1990, which is 20% of national production. One percentage of the crop loss due to bruise would cost the growers about $3.33 million (Hyde et al. 1992). Therefore, bruising is of great economic significance. The bruise is defined as damage to plant tissues by an external force causing a change in texture, color (blackspot), and/or flavor (Mohsenin, 1980). The blackspot is an important indicator of mechanical bruising. The blackspot bruise is usually identified as a small colored area 2-7 mm under the potato's skin

(Sawyer, 1960; Scuder, 1950; Hughes, 1980; Chase, 1987). Several factors influence the development of the blackspot. Impact during harvesting and handling causes bruising and eventually the blackspot (Bishop, 1990). Soil condition, tuber temperature, variety, chemical contents and the physical properties play a role in the development of blackspots in susceptible potatoes.

According to Hardenburg (1938), 78% of potatoes affected by blackspots were bruised during mechanical harvesting. Nylund (1955) stated that harvesting injury contributed 26% of the observed damage. Soil conditions affect harvester operations. For example, in clay soil, low forward speed of the harvester relative to chain results in increased tuber movement on the chain which causes a higher incidence of tuber bruising. On the other hand, greater harvester forward speed in sandy soil results in direct contact of the tuber with the primary chain during harvester operation which increases the chance of tuber bruising (Timm, 1989).

Davis (1952) reported that 43% of tubers were damaged by the time they were packed. A dry grading line resulted in 12% mechanical injury (Nylund, 1955). Low tuber temperature may enhance impact damage. Seventy seven percent tubers were splitted when dropped from 110 cm height at 4° C tuber temperature. Under the same loading condition, 38% of tubers were bruised at 8° C tuber temperature (McRae, 1976). Nylund (1955) reported that keeping the tubers at 3-5° C storage for 6 months increased damage from 8% to 34%.

Impact during handling increases the incidence of blackspots and also stimulates the bio-chemical synthesis in the tuber. Sowokinos (1987) found that sucrose concentration exceeded 1% (fresh wt basis) in 10 days after mechanical handling. More than 65% of the maximal sugar accumulation occurred within 5 days of handling. It has been generally assumed that impact energy, contact pressure, minerals and polyphenol oxidase activity (ppo) play a substantial role in the blackspot bruising phenomena. To maintain a high quality of raw product it is necessary to know how potato tubers bruise so that its remedy can be prescribed. Although bruising in potatoes is a major problem due to mechanical harvesting and handling, the mechanism of internal bruising is not fully understood.

1.2 Objectives

This dissertation is primarily concerned with the developing an understanding of the mechanism of blackspot bruising. The specific objectives were:

1. to develop a bruise identification technique.
2. to study potato bruising during an impact.
3. to study potato bruising due to quasi-static loading.
4. to develop a measure of bruise susceptibility.
5. to study the relationships between bruise susceptibility and mechanical properties, polyphenol oxidase activities, and mineral contents.
6. to develop a potato model using FEM, study stresses and apply failure criterion.

2 LITERATURE REVIEW

Potatoes are bruised during harvesting and handling operations. The severity of damage depends upon the deformation during impact. The impact velocity, masses, elastic or plastic characteristics determine the amount of deformation during an impact. According to Schippers (1971), an uniform method of bruising is important for 3 reasons: 1) no blackspot will occur without damaging the internal cell of tuber, 2) the intensity of discoloration of bruised tissues is dependent on the location of impact- stem end or bud end, and 3) The severity of the blackspot is dependent on the force of impact. In addition to these, 4) the blackspot is also dependent on contact pressure which many authors have ignored.

2.1 Methods of Inflicting Bruise

2.1.1 Falling Mass

Kunkel et al. 1959; Kunkel et al. 1986 used a metal plug dropped through a cylindrical tube to bruise potatoes. The plug was held by a magnet on the top of the tube and allowed to free fall on to the tuber surface. Slots in the tube reduce air pressure build up as the plug fell. The magnet holder was able to be moved vertically up and down in the tube. The plug rested on a collar clamped to the bottom of the tube. The height of the fall was adjustable to change the momentum of the striking body and the bruising force. The potato tubers were grouped as hydrated and dehydrated. The tubers were dehydrated for 24 hrs and tested at 21° C tuber temperature since blackspot susceptibility was minimum (3%) at this temperature. The tubers were scored on a scale 0-6. The results are discussed later in 2.2.1

To determine the effect of turgidity on blackspot bruises, Sawyer (1960) cut potato discs from the vascular regions. The discs were dipped into mannitol solutions followed by bruising by dropping 20 g mass from 10 cm height through a vertical cylinder. The results are discussed in 2.2.1

Weaver (1966) bruised potatoes at the stem end by dropping a 100 g metal mass 4 times from 61 cm height. He defined bruise susceptibility by counting 3 blackspots out of 4 impact in each tuber. The tubers were evaluated for intensity of black color in a spot as recorded by a densitometer after 48 hrs of bruising. The results are discussed in 2.2.2

Maas (1966) used an apparatus which resembled to Kunkel's (1959) but he modified the instrument. The new apparatus consisted of a 61 cm long and 2.22 cm dia aluminum pipe clamped vertically to a ring stand. The bruising metal plug was 66 g made of a round headed bolt. The drop height was 46 cm. The head of the bolt was 18 mm dia and 13 mm in radius that provided a convex striking surface. Tubers were bruised immediately after removal from 5° C storage. Each potato was held firmly against the bottom of the tube to avoid movement upon impact. Bruises were made in a row along one side of the tuber near the bud, the middle and the stem end (no results were reported).

Schippers (1971) used a procedure similar to Kunkel (1959) and Maas (1966). Copper tubing 16 mm in dia of different lengths were closed at the bottom with a round head bolt (16 mm dia). These tubes were dropped onto the potato tuber through a slotted aluminum tube. Various sizes of lead cylinders were used to adjust the masses from 75 g to 225 g. The masses of the plugs were 75, 125, 175, and 225 g, and dropped from 8, 10, 12, 14, ..30 cm heights. The drop heights were adjusted by a side pin in the plug which protruded through the slot in the guide tube. The bottom of the plug was inked to show the point of impact. One bruise was inflicted about 1-2 cm from the stem end of each tuber. Impacted tubers were left overnight at 15-20° C. The following day the bruised spots were peeled until a maximum discoloration was found. The tuber's temperatures varied from 1.7 to 12.8° C at the time of bruising. The size and the intensity of color was measured on a scale 0-5. The results are discussed in 2.2.2

Howard et al. 1961 also used a device similar to Kunkel et al. 1959. A bolt of 100 g was dropped once through a 60 cm tube onto the stem end. The bolt had a radius of 2.5 cm. Only the larger tubers were bruised after harvest and bruised again after being held for 3 days at 20° C in a ventilated storage. He looked into the effect of plant age and post harvest response to bruise, effect of tuber temperature, humidity and storage with modified atmosphere. He found that all fresh tubers harvested after 92 - 135 days showed blackspots. Holding tubers for 3 days at 10-25° C decreased susceptibility. The potatoes tubers kept under high and low humidity conditions had no difference in blackspot appearance. A concentration of CO_2 between 0.5 and 5% in storage caused tubers to be highly favorable to blackspot bruises.

Fluck (1973) used an impacting device similar to that of Wright (1968). The falling mass was acrylic plastic. Drop heights were 8, 10, 12, 14 and 16 cm. The cylindrical specimen of potatoes were impacted with the falling mass. The falling mass was adjusted from 365 g to 1650 g. The mass was held by a solenoid and dropped by breaking the electric power. All cylindrical specimens failed at 16 cm drop height. A piezoelectric accelerometer was mounted on the falling mass to monitor the deceleration during the impact. He measured peak deceleration during impact. He found peak force increased with height or mass. He stated that peak force, energy of impact, and resulting internal stresses are the critical elements in the incidence of impact bruising. He also recommended to study further to prove if bruise increased with increase in drop height or mass or energy or force that causes bruise in agricultural products.

Massey et al. 1952 stored tubers at 8° C for 3 months and bruised tubers upon removal from the storage. The tubers were returned to storage for 2 days then peeled for blackspot. The bruised tubers were rated on the scale of 0-9. The results show that there was a high correlation between specific gravity and blackspots index. The number of blackspots gradually increased during the 3 months of storage and then declined slightly. He reported that the effect of variety and geographical area significantly affected the blackspot index.

Pavek (1985) used two methods of potato bruising: abrasive and dropping mass. He used 30, 52 and 74 g metal masses to drop one by one from 16 cm heights onto the tuber's surface. Each potato tuber was impacted four times on the stem end resulting in 12 impact points on each potato. The impacted potato tubers were kept at 16-18° C for 24 hr and evaluated by hand peeling and counting the number of blackspot per tuber. Enzymatic color development due to abrasive peeling was correlated with the amount of blackspot due to mass impaction.

McRae (1978) conducted impact tests which showed that damage can occur at 24 cm drop height when potato tubers were dropped onto a steel web rod. Different varieties sustained variable amount of damage.

M.Ito et al. (1994) investigated the effect of drop height on bruising of potatoes. The samples of potatoes were held at a preselected height by a vacuum cleaner. The potatoes were dropped on to 5 different surface types by releasing the valve of the pump. The impacted potatoes were evaluated using a damage index (DI). The damage index was defined as the sum of the damage points from various types of damages inflicted on the potato during impact. Damages were classified as skinning, cracking, and bruising. He found that DI index increased linearly with an increase in drop height beyond 40 cm but the DI was small at below 30 cm drop height.

Various researchers dropped varied amount of masses ranged from 30 g to 1650 g from different heights ranged from 10 cm to 60 cm and used abrasion to inflict bruises to a stationary potato tuber. They incubated the bruised tubers in 5, 10, or 20° C for 1 to 4 days before scoring the blackspots. Tubers were also left in high and low humidity storage with various amount of CO_2 in it. The widely varying methods of determination make it difficult to compare the results of different authors. However, in real field, tubers are dropped on the hard surface during harvesting and handling process. Therefore, bruising a tuber by falling mass onto it is not exactly desirable, instead, bruising a potato by dropping it on to a hard a surface is more relaistic and simulates harvesting and handling.

2.1.2 Pendulum

Parke (1963) used a pendulum constructed with a block of iron attached on one end of a 261 cm long aluminum rod. The 7.6 kg rod was released from different heights to give a range of velocities varying from 35 to 150 cm/s. The potatoes were grouped by mass in 6 groups ranging from 55 g to 170 g. The potatoes being tested were suspended by a pair of threads to the pendulum. Potatoes were struck at the stem and at the bud end. He investigated the effect of the size of the striking bars, potato mass and impact velocity upon energy absorption and tuber damage. He stated that the absorbed impact energy by potatoes was correlated with the volume of bruised tissues. He found a minimum energy value of 1.3×10^6 ergs that produced damage. Potato structure also had influence upon the incidence of potato damage. The potato mass interacted with impact velocity of the striking bar. Bar size influenced the amount of damage at higher velocity above 200 cm/s. He concluded that a definite value of minimum amount of energy absorption required to produce damage could not be identified but bruise could occur at a very low level of energy absorption at 230 cm/s velocity of a bar.

Noble (1985) also used a pendulum of 4 different masses with 4 different drop angle to bruise potatoes. A hemispherical impact head of 12.5 mm radius was used. The pendulum was fitted with a system for measuring the rebound height of the pendulum and the deformation of a tuber upon impact. A piezoelectric accelerometer was fitted to the pendulum head to measure deceleration. He plotted an acceleration-time curve. The results are discussed in 2.2.2.

Skrobacki (1989) used a pendulum that included an electronic readout which displayed the rebound angle. An electromagnet held the 50 cm long impact arm in the raised position until it was released. The mass of the arm varied from 76 g to 257 g and the impact head radius varied from 5 mm to 10 mm. The impact energies varied from 0.08 J to 1.26 J and impact velocities varied from 1.4 m/s to 3.1 m/s. The tubers stored at 5° C were impacted at four points around the circumference of tubers by the pendulum. He left the impacted tubers at 20° C for 7 days to develop blackspots bruise. The results are discussed in 2.2.2.

Hyde et al. (1993) used a pendulum of 4 m radius to bruise the tuber. The potato was suspended with a thin wire so that the pendulum could hit the potato. A piezoelectric force sensor and area sensor were used to measure the impact force and contact area (no detail of how area measured was available). The contact pressure was measured by dividing the force by area. He used constant height multiple impact technique to determine bruise energy and dynamic contact pressure. Bruise energy = Sum of [initial energy- rebound energy-equilibrium energy]. Several varieties were tested. He dropped the tuber from a 17.5 cm 7 times until he found contact pressure that remained almost constant. He found that the pressure decreased with each successive impact. The average of the 5th, 6th and 7th impact was taken as the dynamic yield pressure. The yield dynamic contact pressure ranged from 0.93 MPa to 1.14 MPa. The Russet Burbank was found to be the most resistant variety.

2.1.3 Penetrometer

A hand held penetrometer was used to demonstrate resistance to puncturing of peeled and unpeeled tubers (Killick, 1972). He suggested that puncturing can not be used as a means of selection for high resistant potatoes.

2.1.4 Simulated Handling

Ophuis (1958) ran potatoes once or sometimes twice over a grader and dropped potatoes twice from one box to another. Potatoes were also bruised by dropping through a 40 cm dia cylinder of 3.5 m length fitted with baffles to impact falling potatoes.

Wiant (1951) bruised potatoes in a 56 cm dia spherical drum revolving at 20 hand rpm. Tubers were steam peeled and examined for blackspots. He investigated the effect of temperature on blackspots. He stated that 2 days exposure of potatoes to 18-24° C before or after bruising, caused blackspot disappear significantly. Bruising following an exposure to higher temperature resulted in a smaller blackspot index (% bruise x score). Pavek (1985) peeled potatoes abrasively in a Herbert peeler. Each sample was abraded for 30s with water flowing over the tubers. The tubers were kept at 16-18° C for 24 hr after bruising. Scoring was on 0 (no color) to 5 (darkest color) scale. Readings of discoloration were made with a photovolt model 67 reflectance meter. He found that enzymatic color was correlated to abrasive force.

Skrobacki (1989) used an electric motor to drive an impact head by means of speed reduction pulleys and a cam. The impact head was changeable to allow use of several different radii and the arm lengths were adjustable to attain the desired impact energy and impact velocity. Tubers were placed against a plastic port to receive impact for determination of the shatter and the blackspot bruises. The striking masses were 2.9

kg and 1.7 kg. The height of impact was adjusted from 19.5 cm - 13.0 cm. The impact energy applied were varied from 0.9 J - 0.20 J. The radius of the heads were 5, 7.5, and 10 mm. The findings are discussed in 2.2.2.

James (1945) reported that most of the blackspot found in commercial lots developed soon after the potatoes were graded and sacked and it resulted from the mechanical injuries sustained by pressure bruise during handling. He concluded that temperature was found to have an effect on the development of blackspot. Blackspot developed in greater amount at the lowest and least amount at the highest temperature.

2.1.5 Dropping Packaged Potatoes

Turczyn (1986) dropped packaged fresh and stored potatoes from various heights onto a hard surface to determine the minimum impact shocks that will exhibit shatter bruise. There were 5 replications of dropping in each of the following heights: 12.7, 25.4, 38.1, 50.8, 63.5 and 76.2 cm. The shatter bruise was measured by visual examination. Both fresh and stored potatoes developed shatter bruise at lower deceleration g levels than potato packed in boxes. Potatoes packed in baler bags incurred bruising starting at 20 g while potatoes packed in boxes did not bruised at 30 g. He found that fresh potatoes packed in baler bags and fire board boxes exhibited bruising at 457 cm/s (80 cm) and 605 cm/s (140 cm), respectively, but stored potatoes damaged at 457 cm/s regardless of package type. He concluded that the drop heights and impact acceleration that caused bruising were often found in the normal handling during loading and unloading. He mentioned that temperature of tuber and type of handling affected the severity of shatter bruise. He showed that fresh potatoes had a tendency to shatter more than stored potatoes if tuber temperature was less than 10° C.

2.2 Bruise Identification and Measurement

External damage is readily identified visually. Methods developed by researchers to identify blackspot bruises are as follows:

2.2.1 Visual Examination

Kunkel (1959) assigned bruised tubers a degree of discoloration on a scale of 0 to 6, 24 hrs after peeling:

0 = no black color

6 = intense black color

The results showed that as the force of bruising increased, the severity of black spot increased. By hydrating, the tubers became resistant to blackspot. Rehydration in brine solution over 49 hrs reduced bruise susceptibility. There was no correlation between specific gravity and blackspot susceptibility. Tubers from low humidity were more susceptible to blackspot. He reported that turgid tubers were more resistant to blackspot susceptibility. Degree of discoloration of bruised tissues varied among tubers of the same plant and with position on the tuber. He concluded that blackspot bruise varies with impact force. He also found that susceptibility to blackspot varied significantly among and within the tubers.

The results of Sawyer (1960) showed that a disc of fresh tuber developed deep color upon treating with 0.8M mannitol solution. Long stored tubers when dipped in to the distilled water showed no color after bruising. He concluded that the higher the turgor, less the susceptibility to blackspots.

2.2.2 Temperature and Time Treatment

Schippers (1971) incubated bruised potatoes left overnight at 15-20° C before peeling. Size and intensity of color of the spots were measured on a scale of 0 to 5:

0 = no discoloration

1 = very small spot and faintly colored

2 = gray or brownish color (3-5 mm dia)

3 = intense gray color (5-10 mm dia)

4 = brownish black (10 mm dia)

5 = intensity black color (10 mm dia)

The blackspot rating was measured by averaging a sample of 20 tubers. He found that there was a highly significant interaction between variety and tuber temperature, and between varieties and dates of test. The blackspot rating highly correlated with the potential energy of the metal plug, varieties, and tuber temperatures. Skrobacki (1989) held potato tubers for 7 days at 20° C after impact, then treated with tetrazolium chloride solution, peeled and evaluated as reported by Schippers (1971). He found that the shatter bruise index did not correlate with the tuber's mass, but it correlated with impact energy. The shatter index decreased considerably during storage at all impact levels. The blackspots from lightly impacted tubers also decreased during storage. The blackspot index did not correlate well with impact energy of pendulum or impact velocity. Therefore, these do not appear to be useful parameters for predicting sensitivity to impact damage.

Noble (1985) selected potato tubers of uniform shape and size. Two days after harvest, they were cut in half longitudinally and impacted at 10° C tuber temperature on the rounded side. After the impact, the tubers were exposed to 20° C for 10 days. Width, length and depth of bruising were measured. He found a linear relationship between the kinetic energy of an impact and the energy absorbed by a tuber. Impact duration increased with increasing mass of the pendulum but decreased with increasing drop angle. There was not any damage striking at 50°-60° angle with 445 g pendulum. Some splitting occurred when a pendulum of 577 g hit the tubers at 65° angle. He stated that, for a given amount of energy absorbed, the type of bruise damage will depend on the impact duration and impact velocity, i.e. long duration and low impact velocity produced blackspot and short duration with high velocity produced shattering. He mentioned that a large potato making a low impact will tend to sustain blackspots, whereas small potatoes making fast impact will tend to shatter internally. He concluded that shatter bruising was correlated with energy of absorption. He found a high correlation between impact energy and bruise volume.

Weaver (1966) kept impacted potatoes in an incubator for three hr at 40° C at intervals of 0, 3, 6, 12, 24 hr following bruising. The tubers were evaluated immediately upon removal from the incubator (48 hrs) and after conditioning at 24° C. He assessed the percentage of tubers with blackspots. He stated that a densitometer can be used to measure discoloration of bruised tissues. He found that higher temperature had significant effect on incidence of blackspot bruising. He also determined phenolase activity. He found phenolase activity at the stem end was significant after 1 hr of bruising.

Smittle (1974) dropped 100 g mass from 3, 6, 12 and 24 inch heights on to the stem end of a potato once, twice or fourth to bruise it. He measured the number of blackspot and shatter bruise. He stated that as the blackspot increased shatter bruise decreased in all tuber temperature. Multiple impacts increased incidence and severity of blackspot which affected shatter bruise. He also found that a tuber hydration level which produced little damage when bruised at a tuber temperature ranged from 18-21° C, resulted in shatter bruise when subjected to the same force at 7-10° C. Conversely, a hydration level which resulted in blackspot at 18-21° C resulted in a slight to moderate bruise when subjected to the same impact at 10-13° C of tuber temperature.

2.2.3 Oxygen and Temperature Treatment

Weaver (1966) kept one set of potato tubers in 100% oxygen and another set in 20% oxygen for 8 hr at 24° C. Then the tissue temperature was raised to 40° C. Potatoes were bruised at 0 and 6 hr after reaching tissue temperature of 40° C. Half of each bruised group was kept in 100% oxygen and the other half in 20% oxygen for 12 hrs. All bruised tubers were kept at 24° C for 96 hrs, then peeled and the percentage of tubers with blackspot was determined. The exposure time needed at 38° C or above was between 15 to 24 hrs for blackspot to appear. The tubers subjected to 20% oxygen had more blackspot than those exposed to 100% oxygen. He concluded that the tubers subjected to 100% oxygen for 6 hr had deep blackspot when bruised after being exposed to 40° C. Probably this is true because deep color formation is a result of polyphenolase activity which depends on the amount of oxygen to react with substrate.

2.2.4 Reflectometer

Kunkel (1986) peeled tubers 24 hrs after bruising. The peeled area of a tuber was placed against the orifice of the reflectometer centered on the black spot. The reflectometer measured the intensity of reflected light. The reflectometer could not differentiate between natural color and unusual black color.

2.2.5 Spectrophotometer

Birth (1960) used a spectrophotometer to detect decay, greening, blackspot, hollow heart and other discoloration. More colored area in the affected tuber absorbed more energy than an unaffected potato tuber. It seems that the Spectrophotometer can effectively be used to identify black color and thus optical density of impacted tubers.

2.2.6 Chemical Treatment

Aspinwall (1962) observed for color development after dipping potatoes in solutions of paracresol and/or iodine. Impacted tubers were washed and dipped into iodine solution (250 g iodine + 500 g potassium iodine + 5 gal of water) for 2-3 minutes, and/or into the paracresol solution (500 g paracresol + 100 g sodium hydroxide + 5 gal of water) for 3 minutes and allowed to stand for 10-15 minutes and were examined for black and pinkish color, respectively. The treated potatoes were categorized as undamaged if no bruise was found visually, and skinned, or noticeable damage found by peeling were categorized as severely damaged.

Hudson (1977) immersed the tuber samples into a catechol solution (7.4g pyro catechol/liter) for 10 minutes, and then removed, dried and scored them. The skinned areas were scored against 2.4 cm^2 equivalent areas (less than 2.4 cm^2 was rated as 0).

The depth of colored area due to catechol was measured on the basis of slices that were removed. The depth of cut was measured by a potato peeler; one slice rated as moderate, three as severe, and seven as cull.

Beaver (1985) used a triphenyl tetrazolium chloride solution (4 g in 1 gal of water) at 4.5° C to 27° C to detect the bruised surface of potatoes. The affected potato tuber was peeled and dipped into the solution for 45-60 minutes to develop pink color in the affected tissues.

Sawyer (1960) used mannitol solutions (0.8Mole or 0.9Mole) to identify the internal damage (blackspot) of bruised potatoes. Disks of potato tubers were cut from the vascular region and dipped into the solution for 30 minutes followed by bruising with a 20 g mass dropped from a height of 10 cm. Then potatoes were removed from the solution and were examined immediately for black color formation. A number of other discs were immersed into 0.8M mannitol solution, then in distilled water, and finally in 0.8M mannitol solution. After every dipping, discs were bruised and observed for discoloration. The discs exposed to 0.8M or greater mannitol solutions developed color after bruising.

Smittle (1974) found that in some cases the catechol could identify shatter bruise but failed to detect internal blackspot. Lye peeling and abrasive peeling identified both blackspot and severe shatter bruise. He suggested that this can be used to determine shatter bruise.

Skrobacki (1989) immersed impacted tubers in a 2% catechol solution for 10 minutes. This showed all external damage. The samples were kept for 24 hrs at room temperature, and then peeled to detect internal damage or blackspot appeared by color.

These results revealed that there is a great potential for using chemicals for identification of internal bruise if such a method is developed.

2.3 Bruise Classification

Bruises of potato have been classified as external and internal damage. Bruise occurs when tubers collide with moving or stationary parts of equipment, clods, stones, other tubers and when they are dropped onto a hard surface, such as a floor (Hughes, 1980).

2.3.1 External Damage

Skinning: Some parts of immature tuber's skin fall apart due to handling (Chase, 1987) or due to insufficient skin set at the time of harvesting (Hesen, 1960). It can also be caused by abrasion of tuber against a rough surface or against another tuber (de Haan, 1987; Witz, 1954).

Cuts and Scrapes: When a piece of tuber is totally cut off during harvesting or handling (Hesen, 1960) or when tubers strike or are forced against a sharp cutting object (Chase, 1987), the damage is called a cut. A flesh wound results when a piece of tuber is knocked out during any operation (Hesen, 1960).

Cracks, Shatter or Splits: These occur due to impact. They may occur during harvesting, transportation or handling (de Haan, 1987). Cracks or splits in the tuber surface which penetrate the flesh may occur more often at low temperatures (below 10° C) during harvesting and handling (Chase, 1987).

Pressure Bruise: This is a result of static pressure due to a high stack in storage which is not maintained at a high humidity. Eventually a flattened, softened and indented area develops in the tuber (Chase, 1987; Meijers, 1987).

2.3.2 Internal Damage

Internal damage is caused by impact of a mass onto a tuber. Internal damage may take several forms depending on whether the cell walls (internal crushing and shattering) or the cell contents (chemicals) have been damaged (Hughes, 1980). Thus, internal damage may be evidenced by one or more of the following:

Internal Shattering: Short impact durations and high loading velocities will produce internal shattering, that will look like a ring or star shaped damage (Noble, 1985).

Internal Crushing: Long impact durations and low loading velocities will produce internal crushing. The resulting damage is brownish area with distinct edges with the center of the bruise being dry leaving a hollow cavity. It occurs when a very large mass impacts the potato tuber (Noble, 1985).

Blackspot: Blackspot is often a result of impacts with low loading velocities which cause the disruption of the cell contents (Hughes, 1975). Noble (1985) defined black-spot as a blue gray pigmentation. There are several definitions of blackspot which have been used by various authors, they are as follows:

Hesen (1960): A tuber may be bruised internally without any visible surface damage. The cell walls of the tuber tissues are broken down, the damaged tissues being discolored due to an enzymatic process in the presence of oxygen. The intensity of color increases with time after two to three days. The color is sometimes grey or brownish, but usually intense blue.

Chase (1987): Blackspot is a dark spot in the tuber flesh beneath the skin as a result of a series of biochemical reactions leading to the production of black pigment (melanin) in the impacted tuber. This black spot usually develops 24 to 48 hrs following an impact on a hard surface.

Hughes (1980): A diffused blue-black or brown zone found just under the skin that develops in one to three days after an impact. The blue-black pigment (melanin) is formed by enzymic oxidation of tyrosine by phenolase when cell membranes are damaged.

Gray (1978): Typically a blue-grey (sometimes brown) spherical zone in the region of the vascular tissue found one to three days after impact damage. The skin often does not show any visible sign of damage. The pigments responsible for blackspot are produced by oxidation of phenolic substrates (tyrosine and possibly chlorogenic acid) by phenolase.

Meijers (1987): Blue discoloration found just below the skin of an affected tuber, usually around the vascular bundle. The discoloration of the tissue is caused by oxidation of certain phenols by phenol oxidase (enzyme). Not only tyrosine but chlorogenic acid and caffeic acid are also involved in the discoloration phenomena.

Li (1985): Damage or injuries of tuber flesh under the skin which turns brown or blackish over a period of time. The colored spot in the vascular region is not visible unless the tuber is peeled. This colored spot is called blackspot and within 24 hrs it reaches maximum blue-black color.

Sawyer (1960): A sub-surface discoloration appearing after handling, caused by chemical reactions. It occurs most frequently at the stem end about 6-7 mm below the skin. The skin of the tuber need not be damaged to the extent of a cut or break for blackspot to occur. The color can vary from light grey or bluish grey to an intensive black color. Discoloration is observed in susceptible potatoes 24 hrs after bruising.

Scudder (1950): A sub-epidermal defect of a potato tuber located 1-2 mm under the periderm, which is not discernible until the external tissue has been peeled off. It is induced by bruising forces great enough to rupture cells, and the color develops within 24 hrs following bruising. The shape of the blackspot varies from spherical to an oblate spheroid with the point of maximum diameter occurring below the periderm.

Kunkel (1986): A sub-epidermal blackening of tissue that results when bruising forces, such as impact, rupture the cells of susceptible tubers.

Some authors explained that the gray to black pigment in pre-peeling blackening, blackspot, pressure bruising and black heart of potato tubers result from the enzymatic oxidation of tyrosine by polyphenol oxidase (tyrosinase)- a copper containing enzyme. In the presence of oxygen the enzyme oxidizes tyrosine to 3-4 dihydroxyphenylalanine (Dopa) which is then rapidly oxidized by the enzyme to dopaquinone. The dopaquinone cyclizes to 5-6 hydroxyindole derivatives which are oxidized to the reddish-orange *dopachrome* pigment. This is the pigment seen in the early stages of enzymatic blackening. After formation of dopachrome, a series of non-enzymatic polymerization, oxidations and reactions occurs with proteins to form brown to purple pigmentation, and finally the black pigment called *melanin* is produced (Joslyn, 1951).

The extent of development of black tissue in a potato tuber depends significantly on the force of impact with a colliding object. Thus, tubers with identical susceptibility but when different masses dropped on to a solid object receive different levels of impact and develop different degrees of blackspot (Peterson, 1975). High temperature after damage accelerated the development of the blue coloration. However, not every instance of damage resulted in blackspot (Wiant, 1951).

Several researchers have stated that synthetic melanin can be obtained by the *in vitro* oxidation of benzenoid and phenolic amino acids. This oxidation may be photochemical, chemical, auto-oxidative or even enzymatic (Mason, 1947-49). The intensity of color of melanin is dependent on its chemical constituents and intercellular oxygen content. Dense melanin granules appear black whereas sparse areas appear brown or tan (Jacobson, 1934). Melanin is insoluble in water or organic reagents but moderately soluble in alcohol and pyridine, and completely soluble in acid and alkali. Any black, brown, reddish brown, tan or amber pigment is called *melanin* (Van Middelem, 1953). Definitions of external damage are clear but there are some ambiguities among the definitions of blackspot as described by many authors. However, it is understood that a product of chemical reactions with certain substrates and oxygen influenced by a certain enzyme which eventually forms a product known as *melanin* is so-called the **Blackspot.**

2.4 Mechanical Properties and Measurement

2.4.1 Quasi-Static Loading

Huff (1971) determined the tensile strength, failure strain and failure modulus of two varieties of potatoes. The specimens were collected from three locations of fresh and stored tubers and tested at 21° C and 6° C under varying strain rates. The results showed that tensile strength varied considerably with location of a tuber and with year to year. Increasing strain rate, caused an increase in tensile strength and failure modulus, but failure strain was decreased. The pith in the center was found to be stiffer than the perimedullary zones surrounding it with increased strain rate. However, tensile strength, failure strain and failure modulus (stiffness) were 0.69 MPa, 0.49 and 5.09 MPa, respectively.

Four months of storage caused tensile strength and strain at failure to increase in the center and decrease at the skin. Failure modulus did not change significantly at any location. Lowering tuber temperature to 6° C the specimen became stiffer but tensile strength and strain at failure did not change. Tensile strength of the stored potatoes decreased when stored at room temperature. The tensile strength and strain at failure decreased near the center. There was a significant difference between varieties for any property near the skin. There was an interaction between variety and storage temperature. Mechanical properties of the skin itself were higher than the properties of tissues directly under the skin (Huff, 1971). He concluded that the periderm consisting of thicker cork cell walls was stronger than the tissues under it. The answer to the question as to where and why blackspot bruise occurs under the skin, probably, can be found by measuring contact pressure and by using a theory of failure.

Finney (1964) measured the stress relaxation properties of potatoes. Tubers were removed from 5° C storage about 24 hrs before the testing and were kept at a room temperature of 26° C. The whole tuber was loaded between parallel plates until the load reached 17.5 kg at a loading rate of 2.54 cm/min. Rate of deformation had a greater influence upon the relaxation process during the first few seconds after stopping the loading cycle. He found that stress continued to decrease with time. He calculated the time constant over a 4 hr period which was 10^8s. Finney (1967) postulated that since only a relatively small proportion of the initially induced stress was dissipated during a 1-s interval, this indicated that the potato tubers were highly vulnerable to localized tissue failure upon loading.

Finney (1967) determined Young's modulus (E) of potatoes using uniaxial compression of cylindrical specimens. Tubers stored at 5° C were tested at room temperature. The stress-strain relationship for a cylindrical specimen of potato tissue was linear during loading. The average degree of elasticity (elastic deformation/total deformation) was 46%; i.e only 46% of total deformation was recovered during unloading. Hence, the potato was considered as inelastic. Cyclic loads were also applied to the potato tubers. Elastic hysteresis of the potatoes were found to vary from 72% - 90%, averaging 81.5% of the total energy expended during the loading process. Tissues which had been loaded, unloaded and then reloaded, exhibited an increase in modulus of elasticity (E) during subsequent loadings. During the initial loading, E was 3.50 MPa and due to subsequent loadings of 0.0 - to 0.7 MPa stress, E varied from 0.7-MPa - 7.0 MPa. The E of the tissues taken from the central part of the tubers without previous loading history, was found to vary from 3.2 MPa - 4.6 MPa. He also determined volumetric modulus (K) by applying hydrostatic pressures on to a whole tuber ranged from 5 psi - 50 psi. His study showed that volumetric strain was less than 1%

at all hydrostatic pressure levels. The average bulk modulus was 77.93 MPa (11,300 psi). This showed that the potato tuber became relatively incompressible under high hydrostatic pressure (since 85% of a tuber is water). He showed that an average elastic bulk modulus for the mature potato tubers varied from 68 MPa - 105 MPa. He calculated Poisson's ratio, μ, to be 0.492 by using the following equation:

$$\mu = (3K-E) / 6K$$

where, $E = 3.74 \text{ MPa} \pm 0.30 \text{ MPa}$

$K = 77.93 \text{ MPa} \pm 11.59 \text{ MPa}$

Finney (1964) measured puncture force and surface pressure (force/area of dye) to determine resistance of potato tubers to bruising. He used a metal solid cylindrical dye of 0.05 in^2 size to puncture the tuber. The resistance of potatoes to external forces decreased with time before harvest and increased with time after harvest. It was suggested that soil moisture might have interacted with time to cause a decrease in the resistance of the potato to mechanical pressure during the pre-harvest season. He found a significant difference between certain varieties in their response to applied pressure. He concluded that after attaining maturity, the longer the tuber remains under the soil, the less the resistance to bruise.

Irritani (1974) found that higher shear force was required for potatoes with higher dry matter and higher specific gravity, and increased temperature from 1-7° C. Dal Fabbro et al. (1980) determined failure strain using uni-axial compression tests. He used cylindrical specimens (1.27 cm in length and 1.27 cm in dia). He applied three different stress rates. Dal Fabbro et al. (1980) concluded that the potato had a critical failure strain which was 0.43 but it seems very high for cylindrical specimens.

2.4.2 Impact Loading

Parke (1963) studied the effect of impact force. The amount of energy absorbed by the potato during an impact was dependent on the impact velocity. The amount of energy absorbed by heavy potatoes was 2.7 times higher than light potatoes. The amount of energy absorbed by the potatoes was correlated with the volume of bruised tissue:

$$V = 0.0002928 * J - 381.9 \qquad (r = 0.786)$$

where, V = bruise volume, mm^3

J = energy absorbed by the potato, Joule

r = regression coefficient

He found that bruising can occur at a very low level of impact. An energy of 0.136 J did produce an internal bruise. He stated that one potato was bruised at an energy of 0.09 J while another absorbed 0.6 J without bruising. The lowest recorded energy level to produce a split was 0.2 J for a 143 g potato impacted at 200 cm/s. He concluded that the size and shape of potatoes were very important criteria to be considered for incidence of damage. The possible reason for this anomaly might be due to higher modulus of elasticity of the unbruised potatoes than those of bruised tubers. Besides, the impact energy which developed contact pressure during impact probably did not overcome the threshold pressure because of bigger sizes of tubers (higher contact area). This probably explains as to why some tubers did not bruise at the same impact level.

Ghadge (1988) found that some tubers bruised at 0.4J and some at 0.7J. He concluded that there was no minimum energy level that would surely cause a bruise in a potato. Probably this is not true. Potatoes must have a threshold pressure value. Noble (1985) measured the energy absorbed due to impact. Impact results showed that the type of internal bruising depended upon the impact condition. For a given amount of energy absorbed, the expected type of bruise depended on the impact duration and the loading velocity, e.g., long impact duration with a low loading velocity produced the most blackspot. For the same energy absorption a large potato making a slow impact tended to sustain internal crushing whereas a small potato sustaining a high velocity impact tended to shatter internally.

Hughes (1975) found that blackspot susceptible varieties deformed more for a given kinetic energy. He stated that volume of damaged tissue was inversely related to the amount of potassium fed to the plants.

Johnson (1969) found that an increase of 5° C in soil temperature would tend to increase the impact force necessary to bruise by 2% (by dropping). For potatoes, dropped from 30 cm onto metal rods, the proportion of receiving bruises would be reduced from 11 to 4%. Also, it was indicated that a 5° C increase in soil temperature at harvest reduced the damage by 10%.

Various researchers bruised potatoes by free fall impact of metal mass or pendulum. They measured bruised volume, impact energy and percentage of bruise to draw conclusions. They also tried to find out the minimum energy that bruised tubers, but failed to conclude. None measured contact pressure which can be an important parameter that is responsible for bruising. This dissertation includes a study on contact pressure due to impact or quasi-static loadings and its effect on chemical changes.

2.5 Chemical Reactions and Measurement

2.5.1 Enzymes

Enzymes are organic compounds containing atoms of carbon, hydrogen, oxygen and nitrogen and belong to a class called *Protein*. There are 20 different amino acids with their characteristic side chains. They are strung together like beads on a string to give a long polypeptide molecule, referred to as *protein* or *enzyme*. Precise estimation of number of the different enzymes in each cell is not known yet but it could be around 3,000-50,000 depending on the cell of origin (Nicholas et al. 1989). Each has its own particular pattern of amino acid residues in its molecules. Every molecule of a particular protein has the same characteristic pattern of amino acids. Enzymes are known to have a definite shapes and structure made up of parts of different helixes and chains held together in a complicated arrangement. In proteins with biological activity, the structure of the molecule must be intact if it is to function in a proper way. Proteins may have one shape and behavior when they are in pure crystalline form and they may have different shapes and behaviors when they are dissolved in a solvent. When proteins are roughly handled, they lose their normal or native characteristics by breaking weak bonds that hold molecules in their special shape and become *denatured*. Strong acids and bases also cause protein to denature and so does agitation, eg. beating. Enzymes are especially sensitive proteins and when subjected to denaturation they lose their biological and catalytic activity, and in some cases they may be rendered biologically inactive long before they show signs of protein denaturation. Since protein molecules are complex in structure and have many different chemical groups, they are extremely sensitive to their environment. Protein extraction should be performed in a cold room to prevent denaturation. Enzymes are catalytic agents- they take molecules of one kind and change them into molecules of another kind. Enzymes can speed up chemical reactions 10^{14} folds and catalyze reverse reactions. Enzymes are characteristically very selective. Enzymes clearly influence chemical reactions and remain unaltered by reactions. However, enzymes possess reaction specificity (it catalyzes only one kind of reaction), substrate specificity (particular substrate) and stereo specificity, that is, if substrate can exist as stereoisomer then only one will serve as a substrate for the enzyme (Ferdinand, 1976; David, 1968; Nicholas. 1989). Co-enzymes (non- proteins) can accelerate or hinder enzyme activities. The co-enzyme subsequently restores the atoms or groups to new substrates in new reactions catalyzed by other enzymes. Many proteins require a non-protein (Cofactor-metal ion) component for its activity as an enzyme. For example, Kinase, cytochrome c oxidase need Mg and Cu ions for reaction (Nicholas et al. 1989). Thus, ions apparently alter the shape of the protein molecules in such a way that they are better able to react with molecules of a substrate. Co-enzyme's metal ions are enzyme activators too and they help increase the activity of enzyme (David, 1968; Nicholas, 1989). Factors that lead to enzyme catalyzed reactions rate are proximity and orientation effects, acid-base catalysis, covalent catalysis, distortion and changes in environment.

<u>Proximity and Orientation effects:</u> An enzyme can increase the rate of reaction involving more than one substrate by binding the substrates at the adjacent sites and bringing them

into close proximity with each other. Orientation of reacting molecules with respect to each other can influence the rate of reaction up to 10^8 fold.

Acid-base: Since enzymes contain a number of amino acids side chains they are capable of acting as protein donors or acceptors. The acid-base can influence enzyme catalyzed reaction.

Covalent catalysis: Reaction can be speeded up by the formation of intermediator provided that such intermediators are rapidly formed and rapidly broken down.

Distortion: If a substrate is distorted upon binding to an appropriate enzyme, this would speed up the reaction if distortion lowered the free energy of activation.

Change of environment: The rate of many organic reactions are highly sensitive to the nature of solvents in which they occur. Dipolar solvents are good for enhancing reaction (Nicholas et al. 1989).

Active site: Amino acids make up the active site to create in the enzyme surface a sort of "hole" in to which the substrate must fit. The "hole" in turn must have a certain definite shape which will accommodate substrate and inhibitors but reject other kinds of substrates and prevent them from coming in to active contact with the enzyme - Fisher's lock and key concept. This is called enzyme specificity and is important to enzyme activity. Most enzymes have many residues of the same kind of amino acid but only one of them may be involved in the active site (Nicholas et al. 1989).

Reaction rate: The rate of a particular reaction is dependent on the amount of enzyme and the amount of substrate that are taking part in the reaction. There could be as many as 3000-50,000 enzymes in a cell (Nicholas et al. 1989). Each reaction taking place is cata

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catalyzed by its own particular enzyme in a given cell. The rate of reaction also depends on the concentration (amount/volume) of the enzyme and substrate. In most enzyme reactions the concentrations of enzyme is quite small, compared to the concentration of a substrate. If the concentration is doubled, the reaction will proceed at twice the rate (David, 1968). At a very low substrate concentration, the rate of reaction is proportional to the substrate concentration but further increase in the amount of substrate present per unit volume does not cause the reaction to proceed at a faster rate. The varying effect of substrate concentration on enzyme reaction rates is referred to as *Michaelis-Menten*. The rate,

$$V_o = V_m (S_o) / [K_m + (S_o)],$$

where, V_o = initial reaction rate

V_m = maximum reaction rate

K_m = Michaelis Constant

S_o = substrate concentration.

High concentration of a single substrate does not follow the Michaelis equation; rather, the rate passes through a maximum as the substrate concentration is increased and then falls. The products of some enzyme reactions are able to act as inhibitors of the enzyme that produce them (Stephen, 1991). There are six major types of enzyme catalyzes reactions which are as follows:

1. Oxidation reduction reaction catalyzes by oxidoreductase
2. Group transfer reactions catalyzes by transferase
3. Hydrolytic reactions catalyzes by hydrolase

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4. Elimination reaction (double bond is formed) catalyzes by ligase

5. Isomerization reaction catalyzes by isomerase

6. Reactions in which two molecules are joined at the expense of an energy source (ATP) catalyzed by ligase (Nicholas et al. 1989)

Phenolase refers to a group of enzyme that helps browning of injured vegetables and fruits. This group includes Phenoloxidase, Cresolase, Potato oxidase, Phenolase complex. Phenolase in this dissertation will be called as PPO. Phenolase acts as a catalytic agent in two different reactions: 1) Oxidation of o-dihydroxyphenols to o-quinone or oxidation of catechol to o-benzoquinone; and 2) Hydroxylation of certain monohydroxyphenols to dihydroxyphenols. Phenolase has a copper content of 0.2% (each enzyme molecule contains 4 molecules of copper). The pure form of phenolase is colorless (David, 1968).

Characteristics of Enzyme

1. Enzyme has very strong affinity for a specific substrate and catalyzes only one single reaction.

2. Extreme pH generally inactivates the enzyme because of protein denaturation. Enzyme shows maximum activity between pH value of 4.5-8.0. According to Cash et al. (1976), the optimum activity of crude enzyme in grapes was found at pH between 5.9 to 6.3 at 25° C to 30° C, after which reaction rate declined very rapidly with increase in temperature due to inactivation of enzyme.

3. Enzyme acts slowly at subfreezing temperature and actively as temperature increases up to 45° C, but activity is optimum between 30° C-40° C (Fennema, 1976).

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Oxidation of Polyphenols

Activity of phenolase is based on the change of the copper from the cupric to cuprous state (enzyme is isolated). The changes are as follows:

$4Cu^{2+}$ (enzyme) + 2 Catechol------> 4 Cu^{+} (enzyme) + 2 o-quinone + $4H^{+}$

$4Cu^{+}$ (enzyme) + $4H^{+}$ + O_2-------> 4 Cu^{2+} (enzyme) + $2H_2O$.

The substrate became oxidized by losing 2 electron and 2 protons. By taking two electrons, copper of the enzyme changes to cuprous state. Two electrons are rapidly transferred to O_2. This immediately forms H_20 and 2 protons are liberated. The enzyme returns to cupric state and ready to repeat the catalytic cycle. Indirect oxidation of a reducing agent (hydroquinone) occurs by phenolase with an o-dihydroxyphenol. The changes are as follows.

o-dihydroxyphenol + 1/2 O_2 (Phenolase)----------> o-quinone + H_2O

o-quinone + RH_2-----> o-dihydroxyphenol + R

(RH_2 + 0.5 O_2------> R + H_2O).

RH_2 is the reducing agent (hydroquinone), R is the oxidized form, o-quinone (Frank, 1983). The mechanism of the action of phenolase on o-diphenolic compounds is very complicated.

Oxidation of Monophenols

The hydroxylation of certain monophenols to o-dihydroxyphenols, the second reaction catalyzed by phenolase is brought about in the same enzyme molecules that produces the oxidation of o-dihydroxyphenols. The induction period of this reaction is long and it increases with the amount of purification

of the enzyme. However, phenolase oxidizes the o-dihydroxyphenols at a faster rate than the mono hydroxyphenol (Frank, 1983).

o-quinone

o-quinone are catalytically formed by phenolase and are the precursors of the brown color of certain fruits and vegetables. Colorless o-quinone are most reactive. The formation of unstable hydroquinone results from the main reaction. These hydroquinones easily polymerize and are subject to rapid and nonenzymic oxidation-the result is dark brown slightly soluble polymer. o-quinone forms from o-dihydroxyphenols in the presence of phenolase are reacted rapidly with cystine and glutathione, thus forming a pigment (Frank, 1983).

2.5.2 Enzyme Discoloration of Bruised Tubers

The main ingredients of discoloration are *Enzyme* (phenolase) and *substrate*: tyrosine, etc. The factors that affect substrate (tyrosine, catechol) content are: a) climate, b) mineral, c) cellular damage and d) time and temperature in storage. Discoloration of a substrate is related to the initial rate of reaction. *Climate:* high rainfall caused production of high concentration of tyrosine and high browning potential. *Mineral:* High amount of calcium can depress phenolase and tyrosine levels but it may increase rate of browning (Mapson et al. 1963). *Cell damage:* Enzymic browning normally can not occur unless cells are damaged. The greater the number of damaged cells, the greater the discoloration. *Temperature and storage:* If potato tubers were stored for 100-200 days at 5° C, the rate of browning increased and remained constant at the end of 100 days. This change was related to the change of tyrosine content.

Depending upon variety, temperature tyrosine content may increase or decrease. Variety, climate and cultural conditions influence susceptibility of tubers to enzymic browning. Researchers have found that change of browning was positively correlated with tyrosine content, but not with the phenolase content (Mapson et al. 1963). Phenolase was found in all sub cellular fractions of Russet-burbank approximately in proportion to the protein content of each fraction. Phenolic content is generally highest in tubers of high specific gravity (Craft et al. 1966). Ozeretskovskaya et al. (1965) found an increased amount of phenols in physically damaged potatoes. Phenolic content varies according to variety and maturity. Mature tubers are lower in phenolic content (Walter et al. 1957; Mondy et al. 1960). The potato tubers, having relatively high tyrosine content, are easily injured and tyrosinase can catalyze tyrosine and the o-Dihydric phenols (Rastovski et al. 1981; Learner et al. 1950; Mulder. 1956). *Melanin* (blackspot) formation: Due to the injury to the potato tubers, total phenolic and orthodihydroxyphenolic content show small, but significant increase When cell ruptures, certain phenols of the cell cytoplasm are freed (e.g. tyrosine, catechol) which are then oxidized with the help of specific polyphenol oxidase (ppo) through a series of reactions and the end product is called *Melanin* which is another name for blackspot. The steps of the complex mechanism of melanin or blackspot formation is shown in figure 2.1. The figure 2.2 shows diphenols as a substrate (Fennema, 1976). Bond (1961) found that increased phenolic content caused increased discoloration in the potato tubers. In general, polyphenol oxidase activity increases and then decreases as the tubers mature. The activity is also directly related to the concentration of phenolic substances and oxygen concentration (Walter et al. 1957; Baruah, 1964) in the potato tuber. Therefore, polyphenol oxidase and amount of phenols are believed to be the major contributors of blackspot formation in impacted tubers (Crafts et al. 1966). Mature tubers are lower in phenolic content than immature tubers and the immature tubers may contain a higher amount of phenolic content that leads to increased discoloration of post reacted product (Mondy et al. 1959; Mondy et al. 1960). Phenol concentration decreases as enzyme activity increases. Tubers having high specific gravity showed decreased polyphenol oxidase activity (Mondy et al. 1966). In contrast Rastovski (1981) found that higher the dry matter-greater the susceptibility to blackspot. Phenolase activity differs between variety to variety (Heintz, 1962). Probably due to cell size and dry matter distribution ie, larger the cell more susceptible to blackspot. Action and concentration of tyrosine is higher in the central portions than in the peripheral portion of a susceptible tuber. Concentration of tyrosine is considerably higher in the stem end, than the bud end (Reeve et al. 1969; Metlitsky et al. 1964 and Tsekhomskaya, 1964). Concentration of tyrosinase and rate of enzymatic browning of bruised tubers were found to be closely correlated (Mapson et al. 1963). The initial velocity increases with the increase in substrate concentration up to a certain point, beyond this point it becomes independent of substrate concentration. Thus, at low (<0.1) substrate concentration, the enzyme reaction is approximately first order with respect to substrate concentration and the rate of reaction is proportional to enzyme concentration. Ingraham (1957) found that the Michaelis constant, K_m (mol/lit) for O_2 is dependent on substrate structure and concentration. Increased oxygen can enhance reaction rate for o-diphenol oxidase (polyphenol oxidase, tyrosinase) (Kubowitz, 1938; Ludwig et al. 1939; Ingraham, 1955; Bendall et al. 1963). Manitoba University (1969) observed a linear relationship between O_2 uptake and concentration of crude o-DPO. With potato o-DPO the K_m value for catechol in air and O_2 saturated reaction mixtures at pH 6 was 3mM. They found that the reaction velocity was nearly linear during first minute of reaction and then it sharply decreased due to O_2 depletion and inactivation of enzyme. Maximum reaction velocity was achieved by supplying sufficient oxygen. They found that the rate of browning is linearly related to tyrosine concentration. *Polyphenolase:* Reeve (1969a) studied the chemical components in potatoes. Chlorogenic acid was more concentrated in the outer tissues of the cortex than in the inner tissues and in the perimedullary zone. Tyrosine was found to be distributed more (20-40%) in the stem end than in the bud end. Phenolase also showed a characteristic distribution pattern. Peroxidase affects tissue differentiation and specialization, and has a strong histochemical relationship with cell wall specialization. Phenolase was associated with the distribution of phenolic substrates. Mulder (1949) found that there was a high correlation between tyrosine influenced blackening and potassium deficiency. Tyrosine was also found in the interior tissues while O-dihydric phenols were concentrated in the exterior tissues. Enzyme activity varied appreciably within a tuber for phenolase, peroxidase and catalase. However, enzyme activity may change significantly during storage (Reeve, 1969a; Reeve, 1969b). These results show that polyphenol oxidase and substrate are important contributors in forming blackspot bruise. Therefore, this dissertation also studied the ppo activity in bruised and unbruised potato tubers.

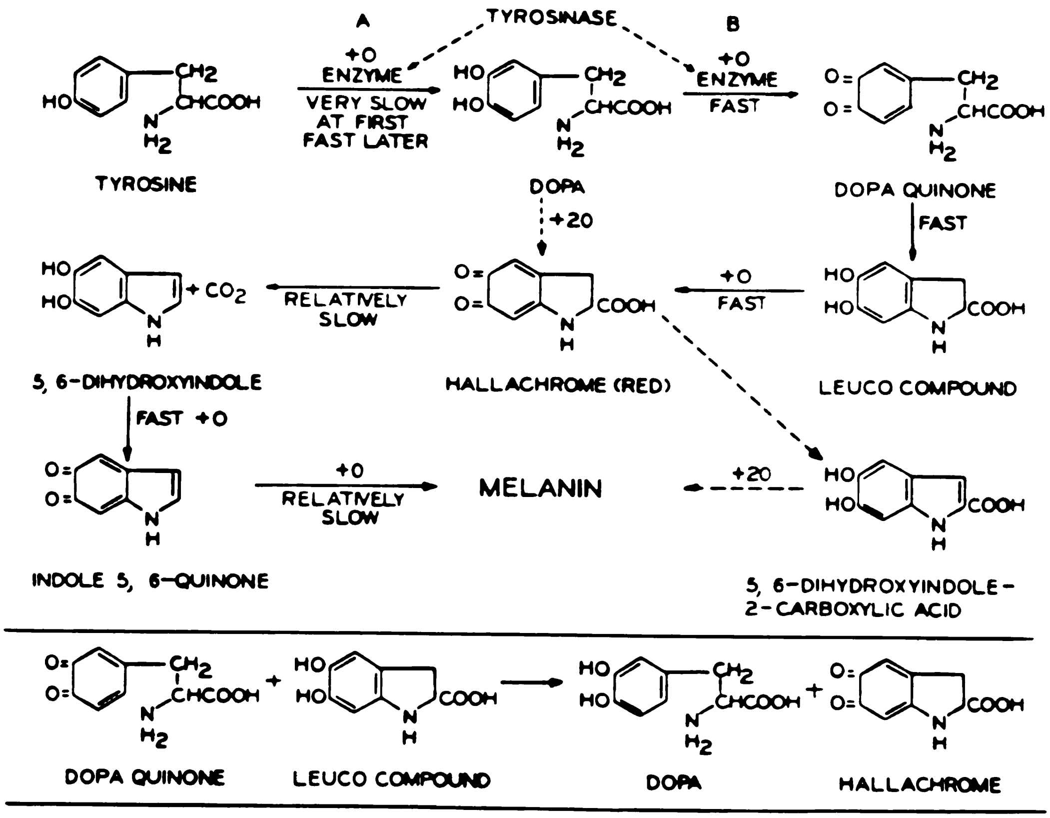

Figure 2.1 The formation of Melanin or blackspot pigments resulting from oxidation of tyrosine by phenolase (Fennema, 1976).

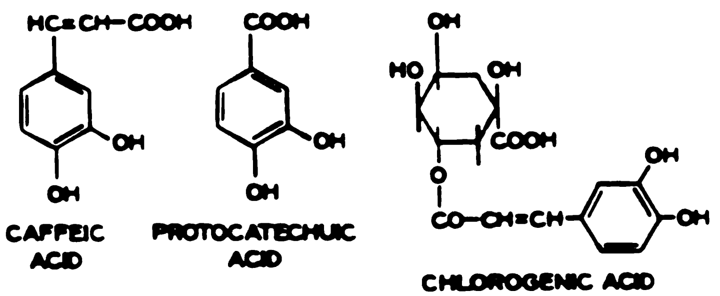

Figure 2.2 O-diphenols that serve as substrates for phenolase (Fennema, 1976).

2.5.3 Minerals

Copper, Calcium and Potassium contribute to phenolase activity, browning, and bruise susceptibility in potato tubers. The mineral content of a potato varies with variety, cultural practices and dates of harvest, as well as variability between potatoes grown under identical conditions (Lampit et al. 1940). Minerals, dates of harvest, and variety are three of many factors that affect processing quality of potato tubers.

Copper (Cu)

Copper deficient tubers were found to have higher tyrosine content but the tyrosinase activity can be much lower than that of tubers supplied with copper. Potato tubers having increased copper content showed more blackening than copper deficient potatoes (Mulder, 1949). Copper also helps improve quality by increasing the starch (1.2%) and the ascorbic acid (Vit C, 2.1 mg/100) contents of a potato tuber (Paseka et al. 1972; Khachatryan, 1972). Copper usually enhances phosphorylase, decreases amylase activity and increases the dry matter and starch content of a tuber (Kostyushina et al. 1974). Other researchers found a varied amount of copper contents in the potato tubers from 1.43 to 6.89 mg/kg because of geographical and climatic effect (Glushek et al. 1972). The copper is also an important part of oxidation of polyphenols, as described earlier.

Calcium (Ca)

Calcium content is important in determining blackspot bruise susceptibility. The potato tubers with low calcium content usually are not firm (Krausz et al. 1971). Calcium level in the tubers can increase during the early stage of growth and decrease before harvest (Bardyshev et al. 1970). Calcium can depress the concentration of copper in tubers (Laughlin et al. 1974). Calcium can also depress phenolase and tyrosine levels (Mapson et al. 1963). Calcium content in a tuber is proportional to pH concentration (Bardyshev et al. 1970). Some researchers found that a high level of calcium can reduce the development of internal browning. A low level of calcium can increase the occurrences of internal browning linearly. Deficiency in calcium nutrition has a detrimental effect on cell wall characteristics that can lead to damage of tuber tissues and develop internal browning (Combrink et al. 1972). Timm (1989) reported that high soil temperature may result in ethylene promotion in root tissue, curtailing root hair growth and lowering Ca^{2+} absorption. An insufficient supply of soluble Ca^{2+} can lead to weakening of the vacuole membrane of the cells in the cortex tissue area of the potato. The weakened vacuole membrane would then be more prone to rupture under bruising impacts during mechanical harvesting.

Potassium (K)

Potassium (K) is an important factor in determining susceptibility to internal bruising (blackspot) in potatoes. It increases the size of the root system, enabling the roots to suck water from the soil (Kunkel, 1965). Potassium (K) level can increase during growth and can rapidly decrease before harvest (Bardyshev et al. 1970). Potassium helps in the water balance of a tuber, influencing the permeability of the cell membrane to water (Hughes, 1975). Potassium is essential in the synthesis of reducing sugars and starch (tuber formation) and in the translocation of carbohydrate (Buchner, 1951; Ward, 1959). Low concentration of reducing sugar signifies physiological maturity and good quality (Welte et al. 1966; Muller, 1964). Potassium (K) deficient tubers are more susceptible to blackspot bruise, but excess potassium does impair quality of the tuber by lowering the starch content (Shumilin et al. 1974). If the amount of potassium increases, the darkness of the potato reduces, increases concentration of amino acid, iron and polyphenol oxidase activity. Potassium tends to keep the reducing sugar level down and some amino acids in tuber (Welte et al. 1966; Muller, 1964. ; Hughes, 1975). Usually, potassium (K) concentration is higher in bud-end than the stem-end, thereby making the stem-end more susceptible to bruising (Reeve et al. 1969b; Johnston et al. 1968). It was found that the potato tubers with less than 2% K in the dry matter are highly susceptible to impact discoloration (Hughes, 1975). The potato tubers with a dry matter potassium content above 2% are less susceptible to blackspot caused by impact (Baukema et al. 1979). Potassium also keeps calcium content steady in the potato tubers (Simson et al. 1973). Phenolic content of a potato tuber is also related to potassium content. Researchers have found that potassium deficient potato tubers contained 3-4 times higher amount of tyrosine and twice as much 0-diphenols as tubers with a normal supply of potassium (Mulder, 1956). Mulder (1949) showed that potassium deficient tubers had a tendency to discolor easily. Mulder (1956) also showed that K-level did not affect the polyphenol oxidase activity. Phenolic content of potatoes and discoloration showed a positive correlation (0.83) as affected by potassium fertilizer (Mondy et al. 1967). Robertson (1931) found that hydrogen ion concentration (pH) increased during growth at the center and bud end but decreased slightly at the stem end. Reeve (1969a, 1969b) reported that pH was lower at the stem end than at the center and bud end (Table 2.1 and 2.2).

Table 2.1 Distribution of chemical components in potatoes by zone (Reeve, 1969a).

Component	Bud End	Middle	Stem End
Chlorogenic acid	+	++	++
Tyrosine	+	++	+++
Phenolase	++	+	+++
Peroxidase	+	+++	++
Catalase	+	+++	++
Iron	+	++	+++
Potassium	+++	++	+

+ = present, ++ = concentrated, +++ = more concentrated

Table 2.2 Concentration of components within the potato tubers (Reeve, 1969b).

	Chlorogenic Acid	Tyrosine	Phenolase	Peroxidase	Iron
Skin	+		++	++	+
Cortex	++	+	++	++	+
Perimedullary zones	++	++	++	++	++
Pith	+	+	+	+	+

+ = present, ++ = greater concentrations (lack of symbols does not indicate absence of chemicals).

Reeves (1969a) noted that storage and environmental changes may alter the distribution pattern of individual constituents while differential distribution may be more pronounced in some varieties than in others. Muneta (1977) reported that different pH levels (7.0, 6.3 and 5.0) resulted in rapid oxidation of tyrosine. Higher pH is associated with greater oxidation. However, the combination of pH and bisulfite resulted in decreasing tyrosine oxidation when decreasing pH from 7.0 to 6.3. At pH of 5.0 and 4.0, bisulfite is an effective enzyme inhibitor, and very low oxidation of tyrosine occurred even after 4 days.

Gestur (1957) suggested that variety, storage temperature and the level of potassium fertilization affect the polyphenol oxidase activities in potatoes. Some varieties possessed higher activity at 5° C storage. The highest activity was shown in tubers grown with the lowest potassium level and stored at 10° C. The bruised tubers held at 24° C accumulated O-dihydricphenols (chlorogenic acid). The rate of accumulation of total phenol was approximately 20 mg/100 g/day. Low temperature affects the rate of respiration. However, it is necessary to provide energy for synthesizing of phenolic substances. Therefore, any condition which causes a decrease in respiration rate will also affect the rate of accumulation of phenolic substances.

It is revealed that polyphenol oxidase activity, amount of phenol and minerals are also the contributors in forming blackspot bruises. However, there is not much information available out there on the effect of impact on instantaneous ppo activity and resulting blackspot bruise in the fresh potato tubers. It was postulated that not only post biochemical activity but mechanical properties also affect the blackspot bruising process.

3 ESSENTIAL THEORETICAL BACKGROUND

3.1 Hertz Contact Stress Theory

Hertz (1881) assumed the followings to solve the contact problem.

1. The material of each body is homogeneous, isotropic and elastic according to Hook's law but the two bodies may be made of different materials
2. The equation for an ellipse can be used to approximate the distance between corresponding points on any two spherical surfaces in contact
3. The boundary line of the area of contact is assumed to be an ellipse
4. Contacting stresses vanish at the opposite end of the body
5. The radius of curvature of contacting solid is very large compared to the radius of the contact area
6. Surface of the contacting bodies are smooth such that no tangential forces exist.

The surfaces of the bodies near the point of contact O (fig. 3.1) have been represented by homogeneous quadratic functions of x and y.

$$z_1 = A_1 x^2 + A_2 xy + A_3 y^2 \tag{3.1}$$

$$z_2 = B_1 x^2 + B_2 xy + B_3 y^2 \tag{3.2}$$

The coordinates are orthogonal cartesian system and xy is the common tangent plane, normal is z axis and A, B are constants. There is a common tangent plane to the

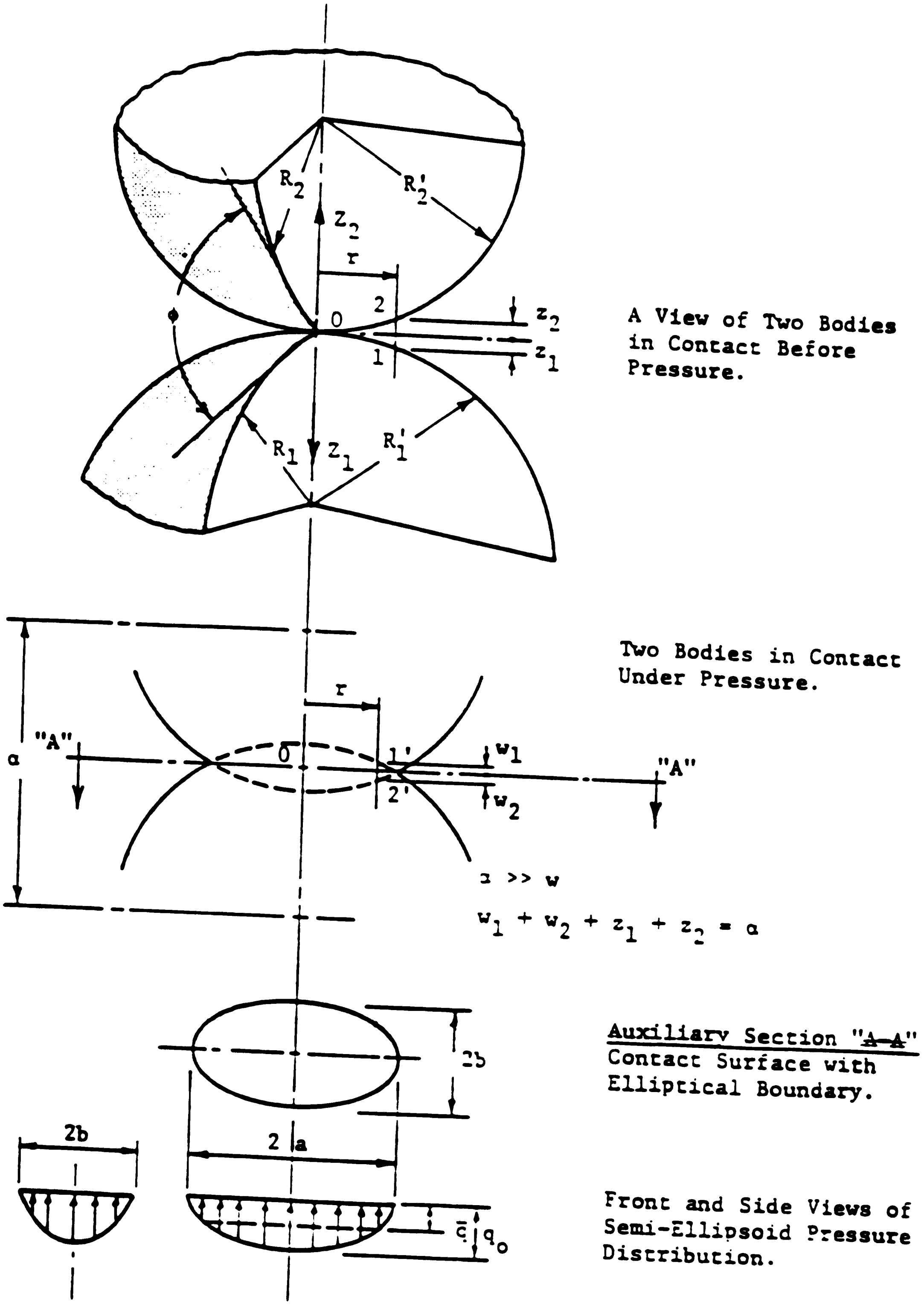

Figure 3.1 Configuration of two bodies in contact and intensity of pressure over the surface of contact (Manor, 1978).

surfaces at the point of contact. An expression for the distances between two corresponding points near the point of contact are needed. The corresponding points are the points that lie on the surface of the contacting bodies and on a line perpendicular to the common tangent plane. In order to determine the deformation of the two bodies near the initial point of contact, the distance between two corresponding points are required. The equation that approximates this distance is as follows,

$$z = AX^2 + By^2 \tag{3.3}$$

the curve representing this equation for a constant value of z is an ellipse. When a load, P, is applied to these bodies, their surfaces deform elastically near the point so that a small contact is formed. It was assumed that the points that come in contact with this area are the points on the two surfaces were that originally at equal distances from the tangent plane. Therefore, these equidistant points lie on an ellipse. Hence, the boundary line of the contact area is assumed to be an ellipse, which is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{3.4}$$

where 'a' and 'b' are the semi-axes of ellipse. The distance between two corresponding points on the surface of contact can be expressed as:

$$z = z_1 + z_2 = Ax^2 + By^2 \tag{3.5}$$

where A, B are the constants and depend on the magnitude of the principal curvature of the surface in contact. A and B can be determined from equations 3.6 and 3.7

$$(A+B)=\frac{1}{2}\left[\frac{1}{R_1}+\frac{1}{R_1'}+\frac{1}{R_2}+\frac{1}{R_2'}\right] \tag{3.6}$$

$$(B-A)=\left[\frac{1}{2}\left(\frac{1}{R_1}+\frac{1}{R_1'}\right)^2+\left(\frac{1}{R_2}-\frac{1}{R_2'}\right)^2+2\left(\frac{1}{R_1}-\frac{1}{R_1'}\right)\left(\frac{1}{R_2}-\frac{1}{R_2'}\right)\cos 2\Phi\right]^{1/2} \tag{3.7}$$

where R_1, R_1' and R_2, R_2' are the principal radii of curvature of lower and upper spheres. ϕ = angle between the normal planes containing the curvature, $1/R_1$ and $1/R_2$

Hertz (1881) assumed that the distribution of contact pressure, q, over the surface of contact is ellipsoid. Therefore, the total applied force, P, is:

$$P=\int\int q\,dA=\frac{2}{3}\pi abq_o \tag{3.8}$$

from equation 3.8 he calculated the maximum pressure, q_o, as:

$$q_o=\frac{3}{2}\left(\frac{P}{\pi ab}\right) \tag{3.9}$$

and it is at the center of the contact surface.

In the general case of two spheres, Timoshenko et al. (1970) showed that when they are pressed together in the direction of normal to the plane tangent at O, a contact surface with an elliptical boundary will be formed. The semi axes 'a' and 'b' of the elliptical boundary of surface of contact can be calculated as,

$$a=m\left[\frac{3}{4}\pi P\left(\frac{k_1+k_2}{A+B}\right)\right]^{1/3} \tag{3.10}$$

$$b = n\left[\frac{3}{4}\pi P\left(\frac{k_1+k_2}{A+B}\right)\right]^{1/3} \qquad (3.11)$$

and (k_1+k_2) is as follows:

$$(k_1+k_2) = \left[\frac{1-\mu_1^2}{\pi E_1} + \frac{1-\mu_2^2}{\pi E_2}\right] \qquad (3.12)$$

where, E and μ are the Young's modulus of elasticity and Poisson's ratio of the homogeneous bodies, respectively. The constants A and B are defined as before and constants m and n depend on $\cos\theta = (B-A)/(A+B)$. The values for m and n for various values of θ can be found in the text authored by Timoshenko et al. (1970). The values for m and n for 90° is 1 when B-A=0. In other words, $R_1 = R_1'$ and $R_2 = R_2'$ represents a particular case of bodies with spherical surfaces.

For a particular case where ordinates of contact radius are equal or a=b, Hertz (1881) assumed that pressure distribution is the ordinates of a hemisphere and the shape of contact area is a circle. The maximum pressure, q_o is at the center of the contact area. This was shown as:

$$P = \frac{2}{3}\frac{q_o}{a}(\pi a^3) \qquad (3.13)$$

From the equation 3.13, q_o can be calculated as follows:

$$q_o = \frac{3}{2}\left(\frac{P}{\pi a^2}\right) \qquad (3.14)$$

where, a is defined by equation 3.15:

$$a=\left[\frac{3}{4}\pi P(k_1+k_2)\left(\frac{R_1R_2}{R_1+R_2}\right)\right]^{1/3} \tag{3.15}$$

If R_1 is ∞ then $k_1=0$. Therefore, contact radius, 'a' and approach 'α', can be calculated from the equations 3.16 and 3.17 as shown below:

$$a=\left(\frac{3}{4}\pi P k_2 R_2\right)^{1/3} \tag{3.16}$$

$$\alpha=\frac{9}{16}\left[\frac{\pi^2P^2k_2^2}{R_2}\right] \tag{3.17}$$

According to Timoshenko et al. (1970), the principal stresses at the center of the elliptical contact surface can be calculated as follows:

$$\sigma_x=-2q_o\mu-(1-2\mu)q_o\left[\frac{b}{a+b}\right] \tag{3.18}$$

$$\sigma_y=-2q_o\mu-(1-2\mu)q_o\left[\frac{a}{a+b}\right] \tag{3.19}$$

$$\sigma_z=-q_o \tag{3.20}$$

where, x and y axes are represented by semi-axes a and b of the elliptical surface of contact and μ is an equivalent of Poisson's ratio for both bodies of the same material. The stresses at the end of the axes of the ellipse are:

$$\sigma_x = \sigma_y \tag{3.21}$$

$$\gamma_{xy} = 0 \tag{3.22}$$

$$\sigma_z = 0 \tag{3.23}$$

It follows that there exist a pure shear, γ_{xy}, but its value is lower than the calculated value obtained at a small distance below the surface at the origin.

3.2 Elastic Impact

Horsfield et al. (1972) derived an equation for maximum compressive pressure, q_o for a fruit that impacts on to a hard flat plane surface. The equation is as follows:

$$q_o = 0.899(Wh)^{1/5} E^{4/5} (1/R)^{3/5} \tag{3.24}$$

Where,

W = mass

h = drop height

R = radius of sphere

E = modulus of elasticity of a falling object

Hertz (1896) extended quasi-static solution to impact. He assumed the following conditions:

1) The time of impact of elastic bodies is very large as compared to the time taken by waves of elastic deformation in the body to transverse the distance x of the order of

magnitude of that part of their contact surface.

2) The time of impact is also large as compared to the time taken by the elastic waves to transverse the impinging bodies from end to end. Based on the above criteria, Timoshenko et al. (1970) defined α as the distance between two centers of mass of spheres approaching one another due to local compression at a point. The velocity of approach, $\dot{\alpha}$ is:

$$\dot{\alpha} = v_1 + v_2 \tag{3.25}$$

where,

v_1 = velocity of impacting sphere1

v_2 = velocity of impacted sphere2

According to the impulse momentum law, the change of momentum is given as

$$\Delta(mv) = I \tag{3.26}$$

where,

$\Delta(mv) = (mv_f)-(mv_i)$

I = impulse

m = mass of the object

v_i = initial velocity at the beginning of impact

v_f = final velocity at the end of impact

$$I = \int_0^t F dt \tag{3.27}$$

the impulse.

where,

F= force acting on the object due to its momentum change

t= time

According to Timoshenko et al. (1970), the above impulse momentum law became:

$$m_1 dv_1 = F dt \tag{3.28}$$

$$m_2 dv_2 = F dt \tag{3.29}$$

where, m_1 and m_2 are masses of the spheres and F is the contacting force acting between the sphere during impact. The acceleration of the impacting bodies can be written as:

$$\ddot{\alpha} = F\left[\frac{m_1 + m_2}{m_1 m_2}\right] \tag{3.30}$$

In quasi-static case Timoshenko et al. (1970) calculated the approach, 'α', as:

$$\alpha = \frac{1}{2}(k_1 + k_2) q_o \pi^2 a \tag{3.31}$$

where, a = radius of contact which can be expressed as:

$$a = \left[\frac{3}{4}\pi P \frac{(k_1 + k_2)(R_1 R_2)}{R_1 + R_2}\right]^{1/3} \tag{3.32}$$

where, k_1 and k_2 are material properties. He defined compression force, F as, by subst

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$$F = n\alpha^{3/2} \tag{3.33}$$

by substituting equation 3.38 in equation 3.33, it gives:

$$F = \frac{4}{3\pi}\sqrt{\left(\frac{R_1 R_2}{R_1 + R_2}\right)}\frac{\alpha^{3/2}}{(k_1 + k_2)} \tag{3.34}$$

and from equation 3.30 the acceleration can be calculated as:

$$\ddot{\alpha} = \left(\frac{m_1 + m_2}{m_1 m_2}\right)\left[\frac{16 R_1 R_2}{9\pi^2 (k_1 + k_2)^2 (R_1 + R_2)}\right]^{1/2} \alpha^{3/2} \tag{3.35}$$

When the velocity of approach, $\alpha = 0$ ($\alpha = v_1 + v_2$), the instant deformation is as:

$$\alpha_{max} = \frac{5}{4}\left(\frac{v^2}{n n_1}\right)^{2/5} \tag{3.36}$$

where, α_{max} = deformation at the instant of maximum compression

v = a velocity of approach of two spheres at the beginning of impact. n_1 and n are

$$n_1 = \left[\frac{m_1 + m_2}{m_1 m_2}\right] \tag{3.37}$$

$$n = \left[\frac{16}{9}\frac{1}{\pi^2}\frac{1}{(k_1 + k_2)^2}\frac{R_1 R_2}{R_1 + R_2}\right]^{1/2} \tag{3.38}$$

by substituting $m_2 = \infty$ in equation 3.37 and $R_2 = \infty$ in equation 3.38 we get:

$n_1 = 1/m_1$

$n = (4E_1 \sqrt{R_1})/3(1-\mu_1^2)$

and $\alpha = F/m_1$

Hoki (1973) calculated F_{max} from equations 3.36, 3.38 and 3.33 as:

$$F_{max} = \frac{4}{3}\left[E_1\left(\frac{\sqrt{R_1}}{1-\mu_1^2}\right)\right]^{2/5} \frac{5}{4}\left(m_1 v^2\right)^{3/5} \quad (3.39)$$

Timoshenko et al. (1970) mentioned that if mass of one of the impacting sphere is regarded as infinite, the time of impact is too small compared to the lowest mode of vibration of that body. Therefore, he calculated 'α'as:

$$\alpha = \frac{a}{2} k_2 q_o \pi^2 \quad (3.40)$$

Where,

q_o = maximum contact pressure at the center of the contact surface

a = radius of the contact surface. From equation 3.40, q_o can be calculated as:

$$q_o = \frac{2\alpha}{\pi^2 a k_2} \quad (3.41)$$

Hertz (1896) solved visco-elastic impact problem by considering:

$$F(t) = -m\frac{d^2\alpha}{dt^2} \quad (3.42)$$

$$\alpha(t) = \left[\frac{9}{16} \frac{(1-\mu^2)^2 F^2(t)}{E^2 R} \right]^{1/3} \tag{3.43}$$

where,

m = mass of a impacting sphere

E = modulus of elasticity of sphere

μ = Poisson's ratio of the impacting sphere

R = radius of the impacting sphere

Jar-Miin et al. (1989) verified the Hertz's assumption of ellipsoidal pressure distribution. He dropped an object from 4 cm drop height and he calculated α_{max} at $t = t_{max}$, $\alpha_{max} = \alpha(t_{max})$

$$\alpha_{max} = \left[\frac{15}{8} \frac{(1-\mu^2) mgh}{E R^{0.5}} \right]^{0.4} \tag{3.44}$$

where,

α_{max} = maximum deformation during impact

g = acceleration due to gravity

h = drop height

$$F(t_{max}) = \left(\frac{250}{9} \right)^{0.2} (mgh)^{0.6} \left[\frac{E R^{0.5}}{1-\mu^2} \right]^{0.4} \tag{3.45}$$

By considering a(t) as follows:

$$a(t) = \left[\frac{3}{4} \frac{(1-\mu^2) R F(t)}{E} \right]^{1/3} \tag{3.46}$$

Jar-miin et al. (1989) calculated the maximum contact pressure, q_o as shown below:

$$q_o = \frac{1}{\pi}\left(\frac{60mgh}{R^3}\right)^{0.2}\left[\frac{E}{1-\mu^2}\right]^{0.8} \tag{3.47}$$

He calculated visco-elastic contact pressure distribution at $t=t_{max}$ as follows:

$$q(x,y,t_{\max}) = q_o(t_{\max})\left[\frac{1-(x^2+y^2)}{a^2 t_{\max}}\right]^{0.5} \tag{3.48}$$

3.3 Viscoelastic Impact

Pao (1955) used Hertz (1881) contact theory for solution of viscoelastic body under impact. The k_1 of impacting body was very high compared to k_2 of the stationary body. The theoretical contact force he obtained was as follows:

$$F(t) = \frac{16}{3}\pi\left[\frac{R_1 R_2}{R_1+R_2}\right]^{1/2} G(t)[\alpha^{3/2} + \int \psi(t-x)\alpha^{3/2} dx] \tag{3.49}$$

where F, R_1, R_2 and α are defined in the previous equations and $\psi(t-x)$ denotes the relaxation function of the material of the impacting sphere. For an elastic material the relaxation time may be considered as infinite then the integral part vanishes. He calculated impact force F, by substituting $G=E/2(1+\mu)$ in equation 3.49,

$$F = \frac{8}{3}\pi\frac{E}{1+\mu}\sqrt{\left[\frac{R_1 R_2}{R_1+R_2}\right]}\alpha^{3/2} \tag{3.50}$$

Pao (1955) also assumed the pressure distribution as ellipsoidal as in elastic case. Pao's solution gave $2\pi(1-\mu)$ times higher contact force than that obtained by Timoshenko et al. (1970).

Yang (1966) developed a formula based on Hertz (1881) pressure distribution but applied to a viscoelastic material. He assumed a pressure distribution given as:

$$q(x,y,t) = C\int_{o}^{t} R_p(t-\tau)\frac{d}{d\tau}g(x,y,\tau)d\tau \tag{3.51}$$

where, C is a constant multiplier, and $R_p(t)$ is:

$$R(t)_p = \frac{1}{k(t)_1 + k(t)_2} \tag{3.52}$$

and $g(x,y,\tau)$ is:

$$g(x,y,\tau) = \left[a^2(t) - x^2 - \frac{1}{\lambda^2}y^2\right]^{1/2} H(t) \tag{3.53}$$

where H(t) is unit step function and $a^2(t)$ is:

$$a^2(t) = \frac{1}{\lambda\psi}\alpha(t) \tag{3.54}$$

where ψ is a coefficient and λ can be defined as follows:

$$\lambda = \frac{b(t)}{a(t)} \tag{3.55}$$

where, a and b are the axes of elliptical indentation and ψ, μ and λ are determined from Yang's (1966) nomograph.

Hamann (1970) expanded Yang's (1966) formulation by using unit step function as an impact force. The total force between two bodies in impact can be written as:

$$F = -m_1 \ddot{\alpha} + w \qquad (3.56)$$

where,

$\ddot{\alpha}$ = acceleration of the center of mass

w = falling body weight

m_1 = mass of a falling body

Researchers used the following methods to inflict bruise in a tuber.

1. Dropping potatoes on to a hard or soft surface
2. Dropping masses on to potatoes
3. Simple pendulum

Eagle (1976) concluded that neither impulse nor each of the parameters measured during the impact by various researchers have been established as a bruise indicator. Therefore, researchers are still looking for the most useful parameter that explains the bruising mechanism.

3.4 Elasto-Plastic Impact

Tabor (1950) assumed that whenever the pressure during an impact reaches the yield pressure, q_o plastic flow occurs and as long as the plastic flow continues the pressure remains constant. The work done, W_3 is the plastic energy which produces the indentation:

$W_3 = q_o V_r$

where, V_r = permanent volume of indentation on the second material

$$V_r = \frac{\mu a^4}{4r_2} \tag{3.57}$$

where,

a= radius of indentation in the second material, r_2 = radius of the indenter after impact and r_1 = radius of indenter before the impact. The r_2 is defined as:

$$\frac{1}{r_2} = \frac{1}{r_1} - \frac{3}{4}\frac{F}{a^3}\left[\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\right] \tag{3.58}$$

W_3 can also defined as:

Tabor (1950) defined W_3 as folows: $W_3 = W_1 - W_2$ where,

W_1= energy of impact

W_2= energy of rebound

W_2= mgh_2 (in case of elastic impact) and can be written as:

$$W_2 = \frac{3}{10}\frac{F^2}{a}\left[\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\right] \tag{3.59}$$

He also defined $W_3 = q_o V_r = q_o(\pi a^4/4r_2) = W_1 - W_2$ and by using equation 3.59

$$W_3 = q_o V_r = q_o \pi \frac{a^4}{4r_1} - \left(\frac{3}{16}\right)\frac{F^2}{a}\left[\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\right] \tag{3.60}$$

This can be written as:

$W_3 = q_o V_a - (5/8)\, W_2$ and he calculated the yielding pressure, q_o as shown below :

$$q_o = mg\left[h_1 - \frac{3}{8}h_2\right]\frac{1}{V_a} \tag{3.61}$$

where, h_1 = impact height and h_2 = rebound height, V_a = volume of apparent indentation.

3.5 Plastic Impact

Siamak et al. (1986) considered fruit as a spherical plastic material. They defined radius of contact, r in equation 3.62:

$$r^2 = R_1^2 - (R_1 - X)^2 = 2R_1X - X^2 \tag{3.62}$$

Where,

R_1 = radius of impacting sphere, X = distance of the center of the sphere depressed. He assumed all the points on the surface are yielded, then, resistive force, F_s and weight of sphere W_s are acting on the sphere. He calculated yielding force, F, as:

$F = \sigma A = \sigma \pi r^2$, where, σ = yielding stress and r = contact radius. By substituting r^2, the yield force became:

$F = \pi\sigma(2R_1X - X^2)$. Summing all the forces Siamak (1986) found that:

$$\sum F = W - \pi\sigma(2RX - X^2) = \frac{WX}{g} \tag{3.63}$$

Siamak et al. (1986) derived an equation for bruise diameter as given below:

$$d = 5.63\left[\frac{HWD}{F}\right]^{1/4} \tag{3.64}$$

where,

H = drop height

W = weight of apple

3.6

accor

whe

α

where,

E = m

μ = P

D= apple diameter

F= magness tailor yield force

From the equation 3.64, once 'd' is calculated, the maximum pressure, q_o can be calculated using Hertz (1881) equation as shown in equation 3.65.

$$q_o = \frac{3}{2}\frac{4F}{\pi d^2} \tag{3.65}$$

3.6 Peleg's Model

Peleg (1984) developed a mathematical model assuming a perfectly elastic sphere according to Timosenko et al. (1970) and Goldsmith (1960) and calculated force, F as:

$$F = \left(\frac{4}{3}\right)\frac{\alpha^{3/2}}{\pi\beta(\delta_1+\delta_2)} \tag{3.66}$$

where,

α = approach of spheres in the contact area

or total deformation of both sphere in the contact area

β = geometry constant of deformation

δ_1, δ_2 = material properties constant which can be defined as:

$$\delta_i = \left[\frac{1-\mu_i^2}{E_i\pi}\right] \tag{3.67}$$

(i= 1,2)

where,

E = modulus of elasticity of sphere

μ = Poisson's ratio

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For the configuration of a sphere and a flat hard solid plane, β is

$$\beta = \frac{1}{\sqrt{R}} \tag{3.68}$$

If the contact area of the deformed sphere is circular (Mohsenin, 1970; Holt et al. 1977) then the diameter of the contact area 'd' for a given compressive force, F can be calculated by:

$$d^3 = 6\pi F \frac{(\delta_1 + \delta_2)}{\beta^2} \tag{3.69}$$

for two spheres in contact. If $R_2 = \infty$, $\delta_1 = \delta$ and $\delta_2 = 0$, then, d, can be calculated from the equation 3.70. R is the radius of the bottom sphere, F, E are defined earlier.

$$d = \left[6FR \frac{(1-\mu^2)}{E} \right]^{1/3} \tag{3.70}$$

The maximum contact pressure, q_o, occurs at the center of the contact circle which can be expressed as:

$$q_o = \frac{6F}{pd^2} \tag{3.71}$$

From equations 3.66 and 3.69, a relation between contact diameter and approach is:

$$\alpha = \frac{\beta^2 d^2}{4} \tag{3.72}$$

Which is a general case of two spheres pressed together.

Peleg (1984) also defined resistive force, F, in non-linear viscoelastic material as a non linear differential equation of the form (3.73):

K

Cx

$F_f(sg$

$K_o =$

$r = s$

inste

vi

$X_o = (n$

$$F = K_o x + r x^3 + C\dot{x} + F_f(sgn\dot{x}) \qquad (3.73)$$

or $F = K_1 X + r_1 X^3$

where,

F = acting force on the test specimen

$K_o x + r x^3$ = cubic elasticity force

$C\dot{x}$ = viscous damping force

$F_f(\text{sgn } \dot{x})$ = internal friction force

K_o = elastic constant that quantifies linear elasticity

r = strain hardening or softening parameter that predicts non-linear behavior of material.

In case of static or dynamic loading, only external load F(t) was considered instead of inertia of mass (M).

Peleg (1984) expressed elastic relaxation modulus, E(t), for a non linear viscoelastic solid as:

$$E(t) = E_o \exp^{(-\frac{t}{T_r})} E_\infty [1 - \exp^{(-\frac{t}{T_r})}] \qquad (3.74)$$

where, $E_o = K_1 + r_1 X_o^2$

$$E_\infty = \frac{1}{K_r}[(K_1 + r_1 X_o^2)(k_1 + 3r_1 + x_p^2) + (\frac{F_f}{X_o})(K_1 + 3r_1 x_o^2)] \qquad (3.75)$$

$K_r = (K_1 + 3r_1 X_o^2) + (K_1 + 3r_1 x_p^2)$.

$$T_r = \frac{C}{K_r} \qquad (3.76)$$

X_o = initial instantaneous deformation of the specimen under test

E_o = instantaneous non linear elasticity modulus at time $t=0$. E_∞ = residual relaxation modulus after a time $t>>T_r$ has been elapsed. Yang (1966) set $r_1=F_f=0$, E(t) in equation 3.74 and he found a relaxation modulus as expressed in equation 3.77:

$$E(t)=K_1\frac{\exp^{\left(-\frac{t}{T_r}\right)+K_1^x}}{2k_1}\left(1-\exp^{-\frac{t}{T_r}}\right) \tag{3.77}$$

E(t) may be viewed as time and deformation dependent spring rate or as a time and strain dependent stress-strain ratio. According to Pao (1955), Goldsmith (1960) and Yang (1966) a good approximation of Hertz contact problem can be obtained for nonlinear viscoelastic bodies by using E(t) from equation 3.74 and by substituting in equation 3.67. This is possible because geometry of the elastic and viscoelastic cases are identical, but the dimension of the indentation in the viscoelastic case is time dependent. This indicates a material property function $\delta(t)$ rather than material property constant δ as in the elastic case. Therefore, the equation 3.67 can be written as:

$$\delta(t)=\frac{1-\mu^2}{\pi E(t)} \tag{3.78}$$

If the loading force F_w, pushing the two contacting bodies together is a constant, then diameter, d(t) of contact circle and the approach $\alpha(t)$ will increase with time while contact pressure, q(t) gradually decreases accordingly. If a viscoelastic body is in contact with a rigid plane then from equation 3.70 and 3.78, Peleg (1984) computed the contact diameter as shown in equation 3.79,

$$d(t)=\left[\frac{6F_w(1-\beta^2)}{E(t)}\right]^{1/3} \tag{3.79}$$

and from equations 3.71 and 3.79 the contact pressure, $q_o(t)$ was calculated as:

$$q_o(t)=\frac{6F_w}{\pi d(t)^2} \tag{3.80}$$

Yang (1966) expressed 1/E(t) for visco-elastic spherical material as:

$$\frac{1}{E(t)}=\frac{1}{E_o}\exp^{-\frac{\xi t}{T_r}}+\frac{1}{E_\infty}[1-\exp^{-\frac{\xi t}{T_r}}]=\frac{1}{E_o}+(\frac{1}{E_o}-\frac{1}{E_\infty})\exp^{-\frac{\xi t}{T_r}} \tag{3.81}$$

where ξ is the ratio of the asymptotic relaxation modulus E_∞ to the instantaneous non linear elasticity modulus, E_o and $\xi = E_\infty/E_o$.

Therefore,

$$\delta(t)=\frac{1-\mu^2}{\pi}\left[\frac{1}{E_\infty}+\left(\frac{1}{E_o}-\frac{1}{E_\infty}\right)\right]\exp^{-\frac{\xi t}{T_r}} \tag{3.82}$$

Since $E_\infty < E_o$ and $1/E_\infty > 1/E_o$, $(1/E_o - 1/E_\infty) < 0$. Therefore, 1/E(t) increases exponentially from $1/E_o$ at t=0 to $1/E_\infty$, when 't' approaches ∞. From the equations 3.79-3.81, contact pressure in the viscoelastic body, $q_o(t)$, at the center of the contact area can be expressed as follows:

$$q_o(t)=\left[\frac{6F_w E(t)^2}{\pi^3 R^2(1-\mu^2)^2}\right]^{1/3} \tag{3.83}$$

The maximum contact pressure, $q_o(t)$ decreases from its initial value at t=0 when $E(t)=E_o$ to its relaxed value as 't' goes to infinity. When $E(t)=E_\infty$, then

$$q_o(t_\infty)=\left[\frac{6F_wE_\infty^2}{\pi^3R^2(1-\mu^2)^2}\right]^{1/3} \tag{3.84}$$

is the contact pressure if viscoelastic sphere is compressed against a plate.

Where,

R = radius of viscoelastic sphere

F_w = loading force due to weight

E(o), E(t), E (α) = relaxation modulii as in equation 3.81

δ(t) = material property function in equation 3.82

δ_o = material property constant in equation 3.67

3.7 Summary

The following equations have been developed to estimate the maximum pressure, q_o, between a sphere and plate.

1. Hertz (1881) contact theory:

$$q_o = \left(\frac{3}{2}\right)\frac{P}{\pi a^2} \tag{3.85}$$

The radius of contact surface is

$$a = \left(\frac{3}{4}\pi F k_1 R_1\right)^{1/3} \tag{3.86}$$

2. In case of sphere on sphere

$$q_o = \frac{3}{2}\left(\frac{P}{\pi a b}\right) \tag{3.87}$$

where 'a' and 'b' can be computed by use of equations 3.10 and 3.11.

3. Elastic Impact (Timosenko et al. 1970):

$$q_o = \frac{2\alpha}{\pi^2 a_{max} k} \tag{3.88}$$

where α is as,

$$\alpha = \frac{5}{4}\left[\frac{V^2}{n n_1}\right]^{2/5} \tag{3.89}$$

According to Jar-miin et al. (1989):

$$q_o = \frac{1}{\pi}\left(\frac{60mgh}{R^3}\right)^{0.2}\left[\frac{E}{1-\mu^2}\right]^{0.8} \tag{3.90}$$

4. Visco elastic impact. Pao (1955) calculated maximum pressure, q_o, as

$$q_o = \frac{3}{2}\left(\frac{F}{\pi ab}\right) \tag{3.91}$$

and he expressed F(t) as,

$$F(t) = \frac{16}{3}\pi\left[\frac{R_1R_2}{R_1+R_2}\right]^{1/2} G(t)[\alpha^{3/2} + \int \psi(t-x)\alpha^{3/2}dx] \tag{3.92}$$

5. Peleg (1984) developed an expression for the maximum static pressure as:

$$q_o = \left[\frac{6F_wE_\infty^2}{\pi^3R^2(1-\mu^2)^2}\right]^{1/3} \tag{3.93}$$

6. Elasto-Plastic impact. Tabor (1950) computed maximum pressure as shown below,

$$q_o = mg\left(h_1 - \frac{3}{8}h_2\right)\frac{1}{V_a} \tag{3.94}$$

7. Plastic impact: Siamak et al. (1986) developed an expression for pressure as follows:

$$q_o = \frac{3}{2}\left[\frac{4F}{\pi d^2}\right] \tag{3.95}$$

The diameter of contact area was computed as follows:

$$d = 5.63\left(\frac{HWD}{F}\right)^{1/4} \tag{3.96}$$

8. Elastic impact (Horsfield et al. 1972).

$$q_o = 0.899(Wh)^{(1/5)}\left(\frac{1}{R}\right)^{(3/5)}E^{0.8} \tag{3.97}$$

(Note: Horsefield et al. 1972 used equation 3.97 for agricultural materials. Therefore, the equation was used for verification of the impact tests results in this dissertation).

4 POTATO BRUISING UNDER IMPACT LOADING

Impact between fruits, vegetables and a hard surface is a major cause of product damage in harvesting and handling system. Such damage is evidenced by bruises, bursts, blackspots depending on the magnitude of impact and product condition. Fruits and vegetables are also subject to damage from static and slow loadings. According to Fluck (1973) most damage that does not occur by static condition can occur by an impact condition. Impact of non biological materials has been studied extensively (Gold smith, 1960). Deformation of fruits during impact has been measured by Fletcher, 1971; Friedley et al, 1966; Mohsenin et al. 1962, but none of them measured contact pressure due to impact which may be an important parameter that causes blackspot.

Blackspot bruise detection has been a long standing problem in potato industry. The methods for identifying bruise has been developed by researchers (O' Leary, 1969; Thronton, 1982; Irritani, 1985; Hammond, 1978). The need for a rapid test to identify bruises is highly desirable (Stills, 1983). Chase (1980) used catechol and Irritani (1985) used paracresol to detect surface bruise of potatoes. Tetrazolium chloride salt has been used for colorometric determination of iodate and bromide (Hashmi et al, 1964). Gary (1985) developed a method using 2-3-5 triphenol tetrazolium chloride to detect surface bruise of fresh potato tubers. Although these methods are effective, they require 6-48 hrs just to detect surface bruises and failed to detect internal bruise (blackspots). The blackspot is related to mechanical and chemical properties. Therefore, the objective is to study mechanical and chemical properties and characterize bruise susceptibility of potato varieties.

4.1 Objectives

The specific objectives of this study were as follows:

1. To develop a method to identify blackspot bruise in a fresh potato tubers.
2. To determine threshold dynamic contact pressure for bruising.
3. To study the effect of mechanical properties on the dynamic contact pressure.
4. To determine polyphenol oxidase activities of bruised and unbruised potato tubers under identical impact loading condition.
5. To characterize potatoes for bruise susceptibility based on the optical density scale as developed by Dean et al. (1993).

4.2 Methodology

Three batches (20/batch) of freshly harvested potatoes (150-350 g) were randomly selected. Each tuber in a batch was held at several preselected heights of 15.24 cm (6 in), 38.10 cm (15 in) or 60.96 cm (24 in) by a vacuum pump (described in 4.2.2). The tuber was dropped freely once at the stem end on to a piece of pressure sensitive film attached to the steel platform. The impacted area of each tuber was circled with a marker pen. All impacted tubers were treated according to the bruise identification technique as described in 4.2.1. Each normally air dried tuber was enclosed in a clear bag and kept temporarily in a styrofoam container filled with ice chips to deter polyphenol oxidase activity (ppo). The potato tubers were peeled, cut slice by slice, and examined one by one for colored spots at the impacted area. The tubers were categorized as unbruised (no color) and bruised (colored) groups after visual examination. Two varieties, *Superior* and *Snowden*, were selected and hand harvested in September and October, 1993 for this study.

4.2.1 Blackspot Bruise Identification Technique

Fifteen tubers (3 tubers /group) were impacted at 10 cm drop height and were held for 24 hrs at room temperature (25° C) to enhance polyphenol oxidase activities (ppo). The chemical (2-3-5 tetrazolium chloride) solutions of five strengths were prepared and assigned each group randomly for the bruise identification as follows:

Strength A: 1 gallon distilled water at 30° C + 1 gr chemical

Strength B: 1 gallon distilled water at 30° C + 2 gr chemical

Strength C: 1 gallon distilled water at 30° C + 3 gr chemical

Strength D: 1 gallon distilled water at 30° C + 3.5 gr chemical

Strength E: 1 gallon distilled water at 30° C + 4 gr chemical

The impacted tubers were dipped in the tetrazolium chloride solution for color development in the impacted area under the skin of each tuber. The samples of the tubers were removed from the solution after 1, 2, 4, 8 and 10 hrs. The skin at the premarked area was removed slice by slice using a sharp knife until a distinct pink colored spot was found. A digital vernier calliper was used to measure the bruise size and depth. The strength with soaking time of 8 hrs developed the distinct pink color in the affected potato and was selected for the entire bruise identification in this research.

4.2.2 Determination of Dynamic Contact Pressure

Pressure sensitive films were used to measure contact pressure. Four types of film have been developed by Fuji Co. These are as follows:

1. Ultra super low. The pressure range is 2-6 kg/cm^2

2. Super low. The pressure range is 5-25 kg/cm^2

3. Low. The pressure range is 25 to 100 kg/cm^2

4. Medium and high. The pressure range is 100 to 500 kg/cm^2

Figure 4.1 illustrates two sheet type pressure sensitive films. The prescale film is composed of an A-film, featuring a layer of microcapsulated color forming material and a C-film layer of color developing material. The Fuji pressure sensitive film consisted of thin and uniformly coated layers.

When a contact pressure is applied over the film against a surface, the micro capsules on the A-film are broken and a color-forming material is released to be absorbed by the color developing materials of the C-film. The C-film generates a red color by reaction. The microcapsules of the color forming materials are adjusted to break at different pressure levels. Therefore, it allows one to obtain a desired color density depending on the magnitude of pressure applied to it.

The pressure sensitive film (type 2) as described above was used to measure dynamic and static contact pressures. A pair of small pieces (5.08 cm X 5.08 cm) of pressure sensitive films (A and C) was tightly attached on the surface of a steel platform using an adhesive paper tape before each drop and replaced by a new pair of films after each drop since they cant be used more than once. A red colored area (fig 4.2) was developed automatically in the C-film depending on the magnitude of the contact pressure. The intensity of red color is proportional to the pressure generated due to

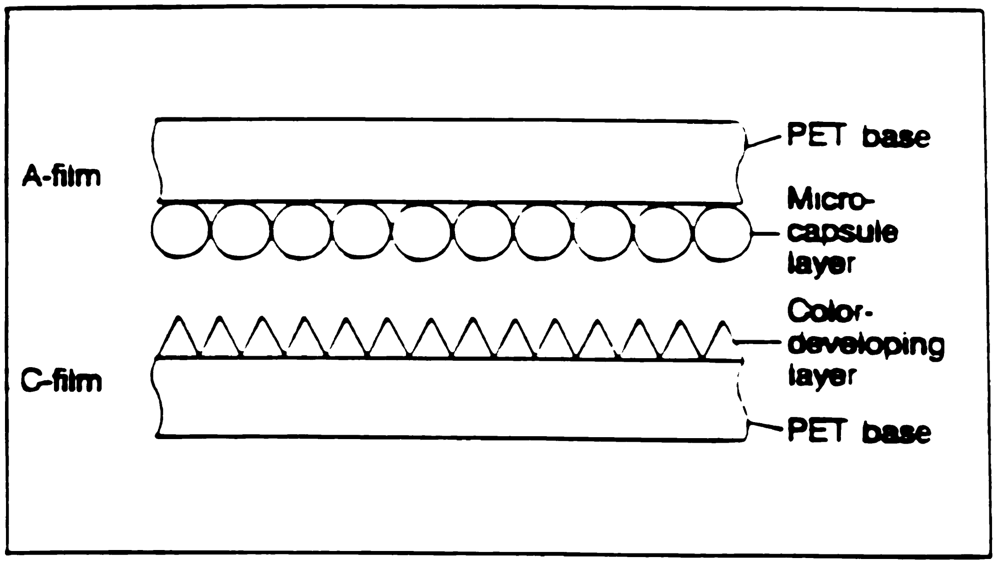

Figure 4.1 Two sheets type contact pressure sensitive films (Fuji Co.).

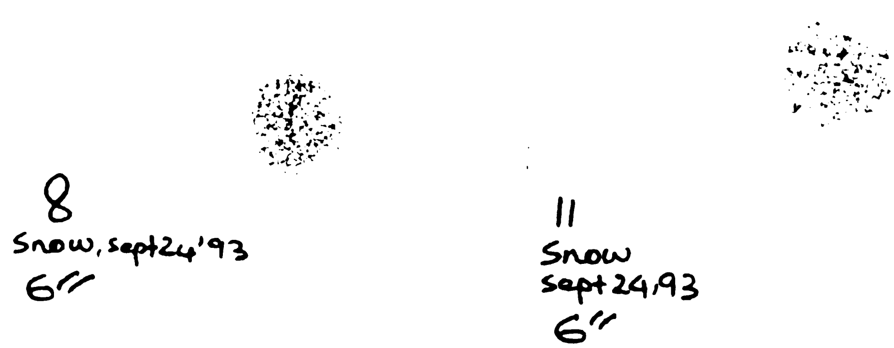

Figure 4.2 A sample of red color formation in the pressure sensitive film after being impacted by a *Snowden* potato from 15.24 mm (6 inch) drop height.

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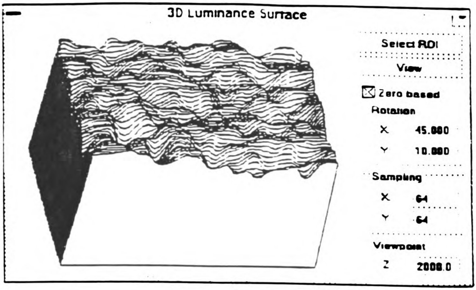

Figure 4.3 A sample of digitized dynamic contact pressure distribution over the contact area of a potato tuber.

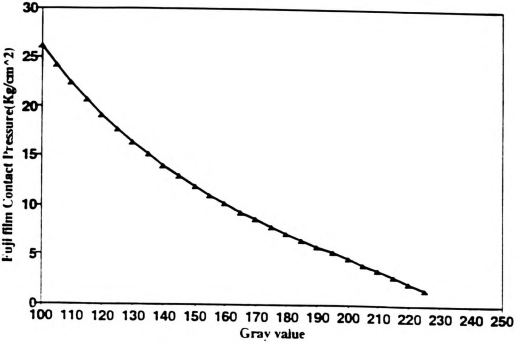

Figure 4.4 A calibration curve for measuring contact pressure on a surface of a potato tuber.

impact. The red color in the film was digitized (fig 4.3) using an image processing software called OPTIMAS and its corresponding gray values were noted. A calibration curve (fig 4.4) was constructed using known contact pressures and their corresponding gray values. A curve fitted to these points. The fitted equation was as follows:

$$Y = 103.77 - 1.24389\,X + 0.0056103\,X^2 + 0.0000093403X^3$$

where, Y = measured contact pressure (kg/cm^2); and X = gray values.

The correlation between gray values and the contact pressures was $R^2 = 0.96$. The calibrated curve was used to determine dynamic contact pressure as exerted by a tuber during free fall impact. The mechanical properties, polyphenol oxidase activity and optical density (as described in 4.2.6) of bruised and unbruised groups of potatoes were determined.

4.2.3 Determination of Mechanical Properties of Core Specimen

Core tests were used to determine pertinent mechanical properties of potatoes. These are yield stress, failure strain, failure strain energy and modulus of elasticity. The relationships between the dynamic contact pressure and the measured mechanical properties were investigated.

One cylindrical core specimen, 25.4 mm long and 15.54 mm diameter, was cut out of each potato tuber using a metallic cylindrical borer. These cores were tested to determine yield stress, yield strain, yield strain energy and modulus of elasticity. All compression tests were performed on an Instron testing machine at 1.27 cm/min (0.5 inch/min) loading rate. The chart speed was 12.70 cm/min (5 in/min). The Instron testing machine was calibrated before starting for force and displacement of the pen on the chart using known loads. A pressure sensitive film (Type 2) was placed each time on each cylindrical core and was compressed along with the core until failure. The film developed color as soon as the crosshead came in contact with the core specimens. The yield stress was calculated as: σ_o= F/A and the corresponding pressure was measured from the digitized gray values in the calibrated curve. The yield stress and the pressure was correlated. Analysis of variances were performed on these variables over the varieties and dates of harvest. The compression loading continued until the core failed which was seen as a point of inflection on the load-deformation curve. The crosshead was immediately stopped and raised to avoid further compression. The yield strain, yield strain energy, yield stress, modulus of elasticity were determined from the force-deformation curve at yield of each potato core (Appendix A.5).

4.2.4 Determination of Dynamic Threshold Pressure

The measured dynamic contact pressures were plotted against the potential energy of bruised and unbruised potatoes of both varieties to determine a threshold value.

4.2.5 Assay Preparation and Determination of Polyphenol Oxidase (ppo) Activity

Polyphenol oxidase activity is the rate of oxygen uptake by a substrate per min. The polyphenol oxidase activity can be used to define bruise susceptibility. Higher the activity higher the bruise susceptibility. To determine the PPO activity, a total amount of 25 g of fresh tissue from each group of bruised tuber's stem end was cut in equal proportion after subjecting the tuber to impact by dropping on to a hard surface. The 25 g tissue sample was mixed with 50 ml cold (3° C) buffer (Trizma 0.1M, M=Mole, pH of 6.5) and blended in a high speed electric blender for 15 seconds. The blended mixture was filtered (Whatman # 4 filter paper). The filtrate was added to 100 ml acetone of -20° C to precipitate and hold ppo activity of the extracted enzyme. The diluted solution was filtered again to collect ppt (enzyme). The collected ppt (enzyme) was added to 25 ml sodium acetate (0.1M, pH 6) and 5 ml cold $CaCl_2$ (0.1M) solution of 3° C. The mixed solution of enzyme was homogenized by centrifugation at 10,000 rpm for 30 min at 5° C to obtain a clear supernatant of fresh enzyme. The cold and clear supernatant (extracted enzyme) was poured into a 25 ml plastic vial and left in a plastic bowl filled with ice chips until the ppo tests were completed in the Spectrophotometer. The ppo activity tests of each bruised and unbruised sub groups of potatoes were performed in the Perkin Elmer Spectrophotometer equilibrated at 30° C. The selected wave length for the light absorption test was 420 ηm. The standard reaction mixture volume of each sample consisted of 0.40 ml catechol substrate (0.3M), 0.2 ml supernatant (extracted enzyme) and 3.40 ml sodium acetate (pH 6). The enzyme kinetics software was used to measure the change in absorbance (oxygen uptake) for 180 seconds and for statistical analysis. The computer output included the enzyme activity, slope, and standard deviation. The rate of change of color (absorbance, mole/lit/min) due to oxidation of substrate was determined from the slope of the reaction curve. The same procedure was followed for the controls and unbruised group of potatoes.

4.2.6 Determination of Optical Density

The optical density (OD) is an absolute value of light absorbance in a liquid. This property can be used to define bruise susceptibility of potato tubers. Higher the optical density, the higher the bruise susceptible. To determine the optical density a total of 100 g tissue from impacted stem end and unimpacted bud end were cut from each group of bruised potatoes in equal proportion. An amount of 100 ml potassium phosphate buffer solution (pH 6.5) was added to stabilize any reaction. The tissues in the buffer solution were blended immediately in a high speed electric blender for 15 seconds followed by filtering using a Whatman #4 filter paper. The filtrate was collected in a glass beaker for open air oxidation at room temperature. The filtrate became black after 24 hrs of oxidation. The oxidized filtrate was centrifuged for 30 min at 10,000 rpm. A quantity of 10 ml homogenized filtrate was diluted to 1:3 ratio. The optical density of the diluted filtrate was measured in a Spectrophotometer at 475 ηm wave length. Five replications of reading were noted for each sample. The same procedure was followed for the samples of unbruised potatoes and the control. The measured optical density of the control, unbruised and bruised groups were compared with the scale developed by Dean et al. (1993) to determine bruise susceptibility of each group of unbruised and bruised potatoes.

4.2.7 Determination of Mineral Contents

A sample of 30 g tissue was collected from each impacted potato tuber and oven dried at 75° C for 72 hrs. A total of 240 samples were prepared, dried and ground to fine powder. The powder was sent to the Soil Testing Laboratory for the determination of amount of calcium, copper and potassium contents in each sample.

4.2.8 Determination of Bruise Susceptibility

Blackspot bruise of potato depends on the tissue injury followed by the biochemical reaction. Several methods have been used to determine blackspot bruise susceptibility (described in 2.1). Homogenizing tuber tissue have been used by Dean et al. (1993). He developed a method on the basis of optical density to determine blackspot susceptibility variation among particular varieties. The method was described in 4.2.6. The optical density was grouped in to 1-5 rating for susceptibility comparison. The table 4.1 as developed by Dean et al. (1993) was used to determine bruise susceptibility of potatoes.

Table 4.1 Bruise susceptibility scale (Dean et al, 1993).

	Resistant	Moderately resistant	Moderately susceptible	Susceptible	Very susceptible
Optical Density	0.0-0.2	0.21-0.40	0.41-0.60	0.61-0.80	>0.80

4.3 Results and Discussion

The impacted potatoes were treated by the tetrazolium chloride solution to identify bruised area in the tubers. Figure 4.5 shows very light pink color in the treated bruised potato dropped at 6 inch height. This means minor bruise has occurred. Figure 4.6 shows no color under the skin due to impact at 15 inch (38.1 cm) drop height. The no color indicates no bruise. Figure 4.7 shows the dense pink color bruised area under the skin than the one found in figure 4.5 which was lightly bruise area. From figure 4.8, a thick circle (about 3 cm dia) of dense pink color on the surface of the tuber was seen. This was a case of severe shatter bruise when tuber dropped at 24 inch height. The figure 4.9 clearly shows the severe blackspot at approximately at 6-7 mm below the surface of the Snowden tuber due to impact from 24 inch drop height. This tuber did not shatter but internally bruised severely. Internal bruise can also occur 6-8 mm below

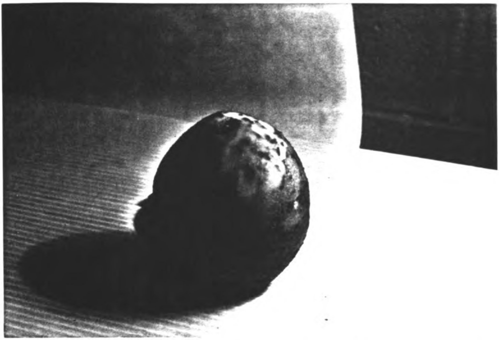

Figure 4.5 Light pink color developed in a bruised fresh *Superior* potato tuber dropped from 15.24 cm (6 inch) drop height.

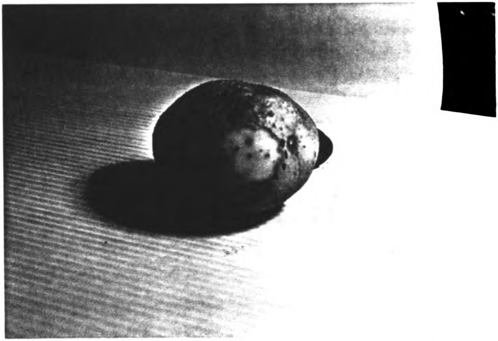

Figure 4.6 No pink color was developed in a fresh *Superior* potato tuber dropped from 38.10 cm (15 inch) drop height.

Figure 4.7 Pink color in the bruised area of a *Superior* potato tuber dropped from 38.10 cm (15 inch height).

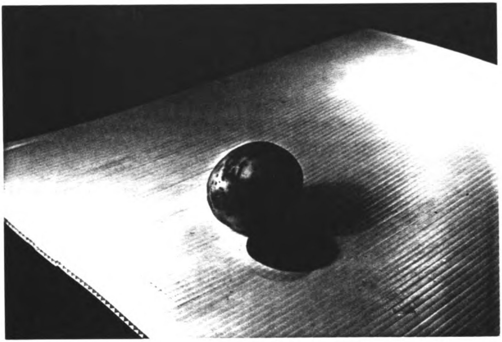

Figure 4.8 A dense red colored circle of shatter bruise shown in a *Superior* potatoe when dropped from 61 cm (24 inch) drop height.

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Figure 4.9 A blackspot occurred in a *Snowden* tuber at 5-6 mm below the skin when dropped from 61 cm (24 inch) drop height.

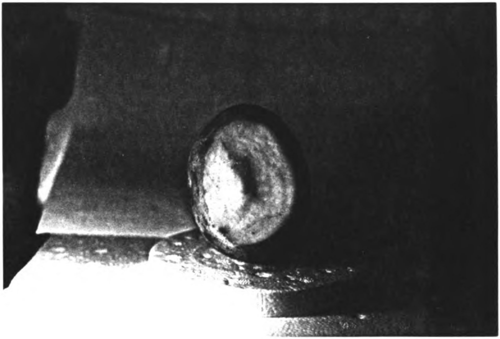

Figure 4.10 Internal crack occurred in a fresh *Snowden* potato when dropped from 38.10 cm (15 inch).

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the skin at a drop height of 15 inch as shown in figure 4.10. This did not produce blackspot. It can be said that tetrazolim chloride solution is capable of locating internal and external bruises of a tuber. Similarly, under different impact loading condition, the pink color developed in a pressure sensitive film was an indication of contact pressure. The examples are shown in figures 4.11 and 4.12, respectively. Two different size and masses of tubers were dropped from 15 inch (38.1 cm) and 24 inch (61 cm) on to a pressure sensitive film. From figure 4.11 the dense pink color at the right sample indicates higher contact pressure than the sample at the left side. This also shows that at the same drop height contact area can be varied. If contact area varies then contact pressure also varies. Figure 4.12 shows pink color formation in the pressure sensitive films due to impact of two different potatoes at 24 inch (61 cm) drop height. The dense pink color at the center of the right sample indicates higher contact pressure than the left one. Therefore, it shows that sometimes at higher drop height contact pressure did not increase at 61 cm (24 inch) drop height rather shatter bruise occurred. A higher percentage of bruising occurred (shatter and blackspot) as they were dropped from increasing heights. M.Ito et al. 1994 reported that damage index (summation of damage points at a height) increased proportionately. It was found that the *Snowden* variety showed 10% higher bruising than the *Superior* variety (table 4.2). Figures 4.13 and 4.14 also show the effect of drop height on percentage of bruise in both varieties. From these figures a general trend can be observed; higher the drop height, the higher the percentage of bruised tubers. The differences in the potential energy that caused bruised and unbruised potatoes of the *Snowden and Superior* variety were found to be significant.

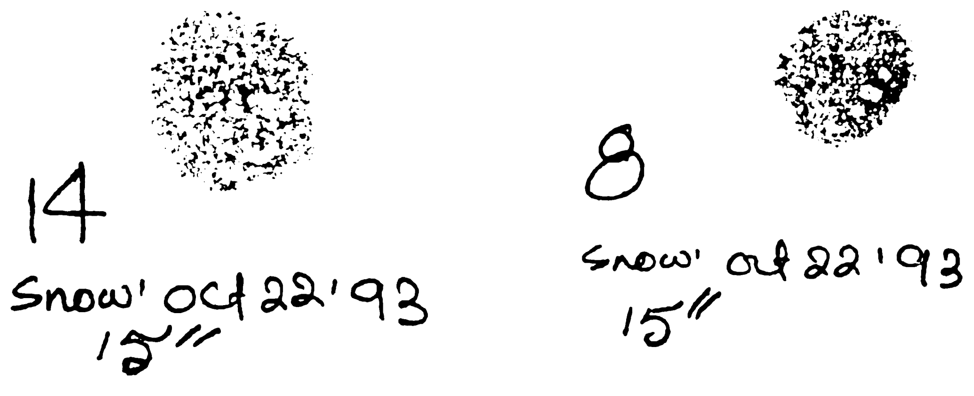

Figure 4.11 Color developed in a pressure sensitive film when a tuber dropped from 38.10 cm (15 inch) height.

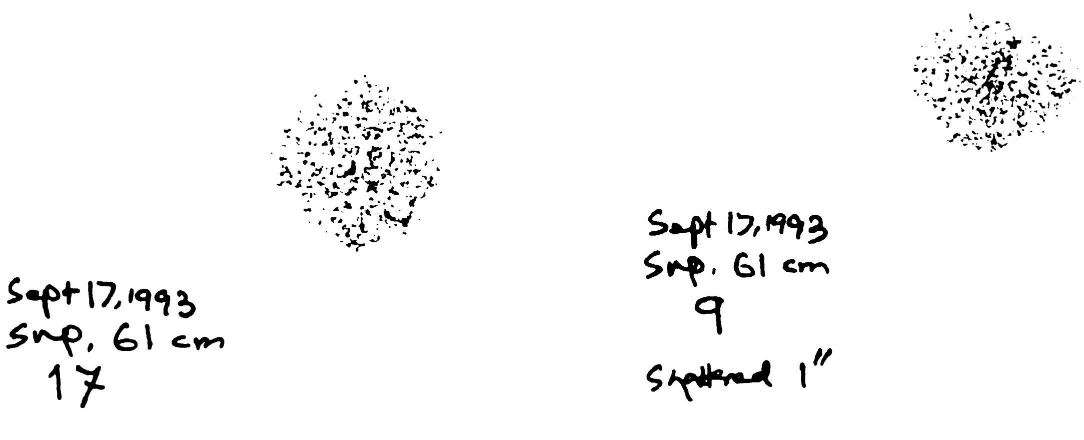

Figure 4.12 Color developed in a pressure sensitive film when a potato tuber was dropped from 61 cm (24 inch) height.

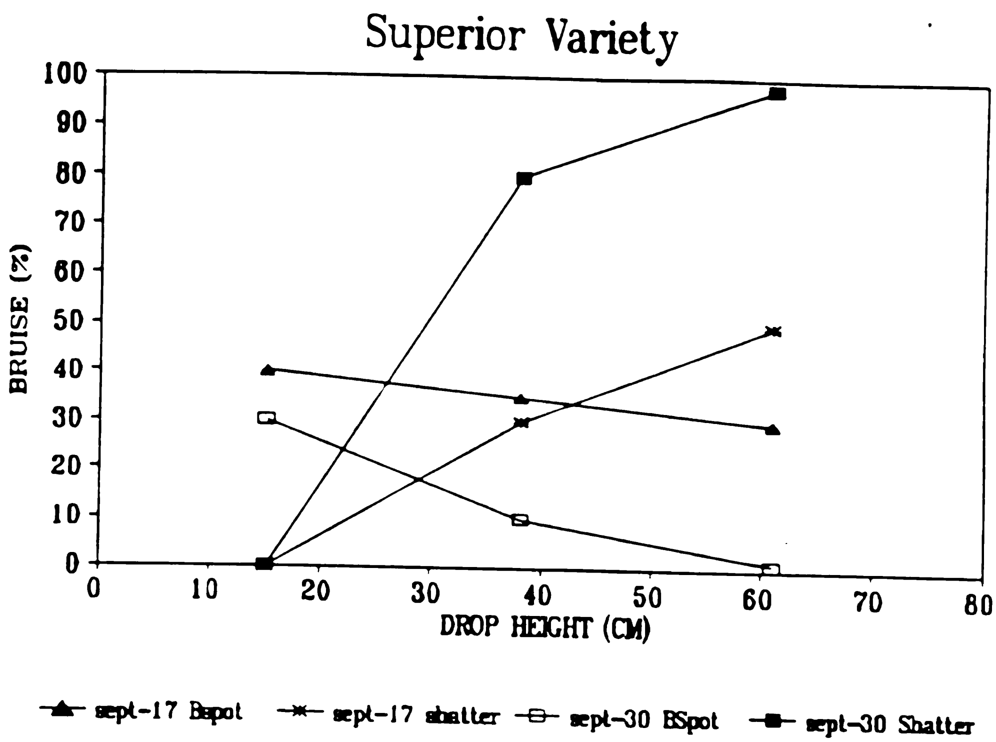

Figure 4.13 The effect of drop height on the percentage of bruised *Superior* potatoes.

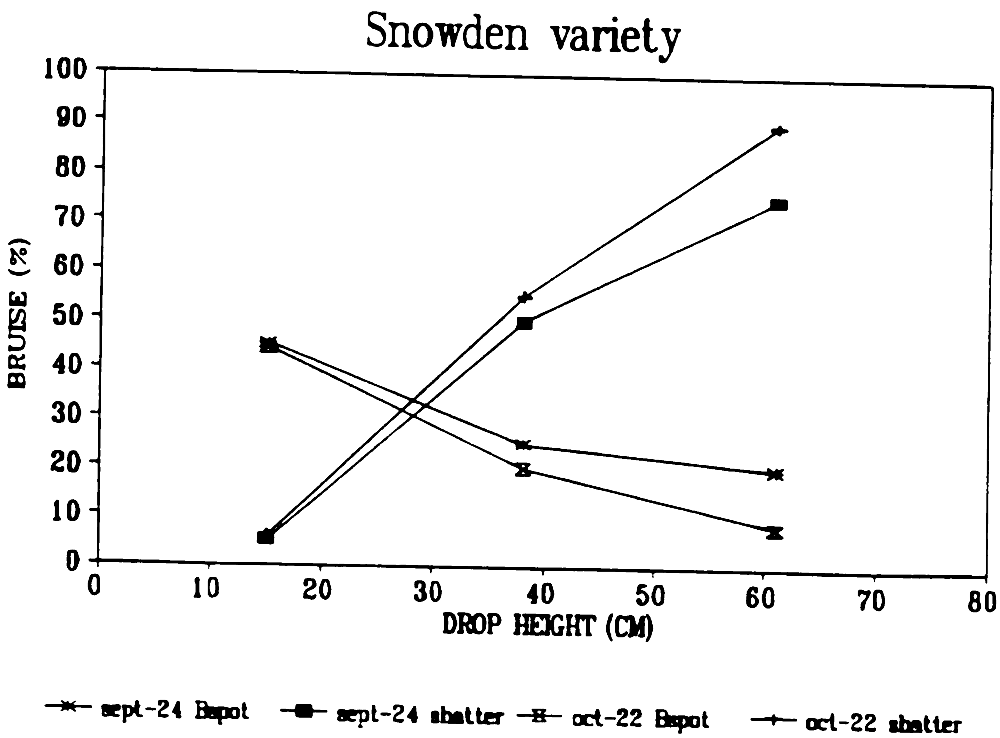

Figure 4.14 The effect of drop height on the percentage of bruised *Snowden* potatoes.

Table 4.2 Drop height and the corresponding percentage of bruised and unbruised tubers.

Variety	Height (cm)	Total bruise (%)	Black spot bruise (%)	Shatter bruise (%)	Unbruised (%)
Superior 9-17-93	15.24	40	40	0	60
	38.10	65	35	30	35
	60.96	80	30	50	20
Superior 9-30-93	15.24	30	30	0	70
	38.10	90	10	80	10
	60.96	100	0	100	0
Snowden 9-24-93	15.24	50	45	5	50
	38.10	75	25	50	25
	60.96	95	20	75	5
Snowden 10-22-93	15.24	50	44	6	50
	38.10	75	20	55	25
	60.96	98	8	90	2

Dynamic Contact Pressure

The pressure sensitive film color was digitized using computer vision and OPTIMAS software. Their gray values were recorded as shown earlier in figure 4.3. The contact pressures were measured from the calibration curve as described earlier. The analysis of variances of contact pressures over variety and the date of harvests are included in tables 4.3-4.4. The event of bruising between the varieties was significant.

The date of harvest and the variety had significant effect on the dynamic bruising contact pressure. Dynamic contact pressure of bruised *Superior* potato tubers was significantly higher than that of the *Snowden* potato tubers. It was seen that as the drop height increased, the contact pressure increased to a certain extent, but after that, increased impact energy resulted in tuber damage and no further increase of contact pressures was noted. This indicated that there was a value of the contact pressure when bruising occurs. It was seen that the potato tubers bruise when the contact pressure reached within 800-1000 kPa depending on the variety. The bruising pressure remained nearly constant with any further increase in the potential energy. From figure 4.15 it is seen that there existed a threshold contact pressure which was 880.94 kPa (127.73 psi) for *Snowden*. From figure 4.16 the threshold contact pressure for *Superior* was found to be 1027.11 kPa (148.86 psi). Hyde et al. (1993) determined dynamic yield pressure for various varieties of potatoes which ranged from 0.93 to 1.14 Mpa. This is in close agreement with the obtained dynamic yield contact pressure.

The contact pressures were measured from the calibrated curve. The contact pressures were also calculated using equation 3.96 as developed by Horsfield (1972). The data are shown in appendix C. The correlation coefficient between the measured and the calculated dynamic contact pressure was 0.94. The relationship was linear. This indicates a very low variability between the measured and the calculated values. Therefore, the error was within acceptable range. The percentage of bruised tubers in *Superior* and *Snowden* potatoes as affected by drop height are shown in figures 4.13 and 4.14, respectively. From the observation it can be stated that as drop height increased

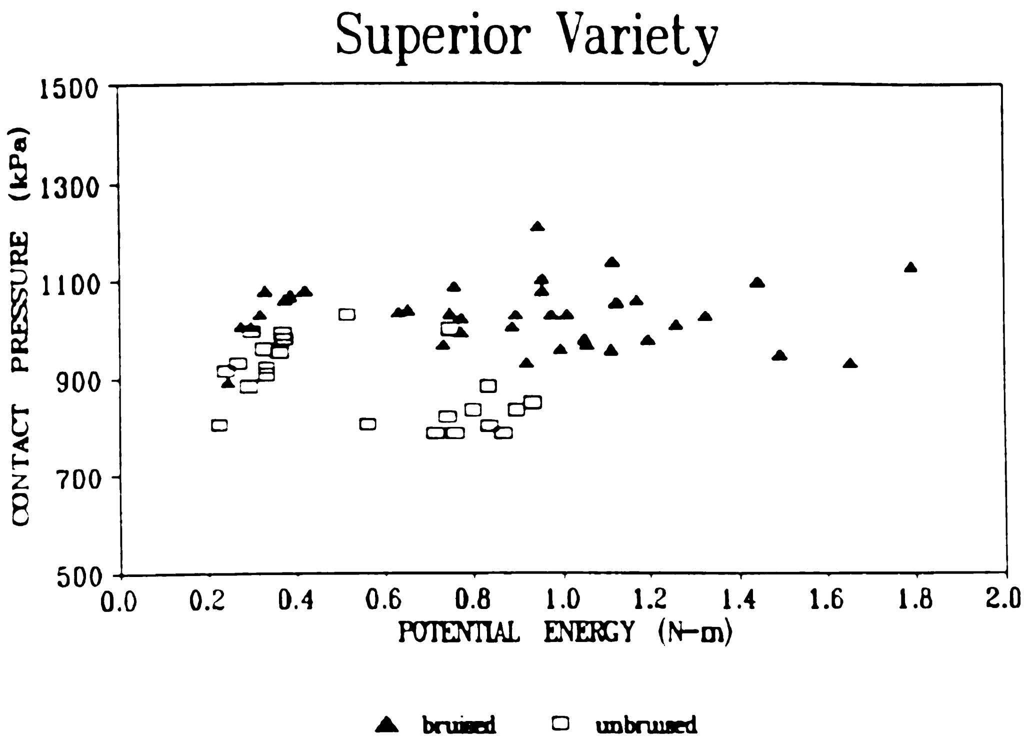

Figure 4.15 The dynamic contact pressure as affected by potential energy of *Superior* potatoes.

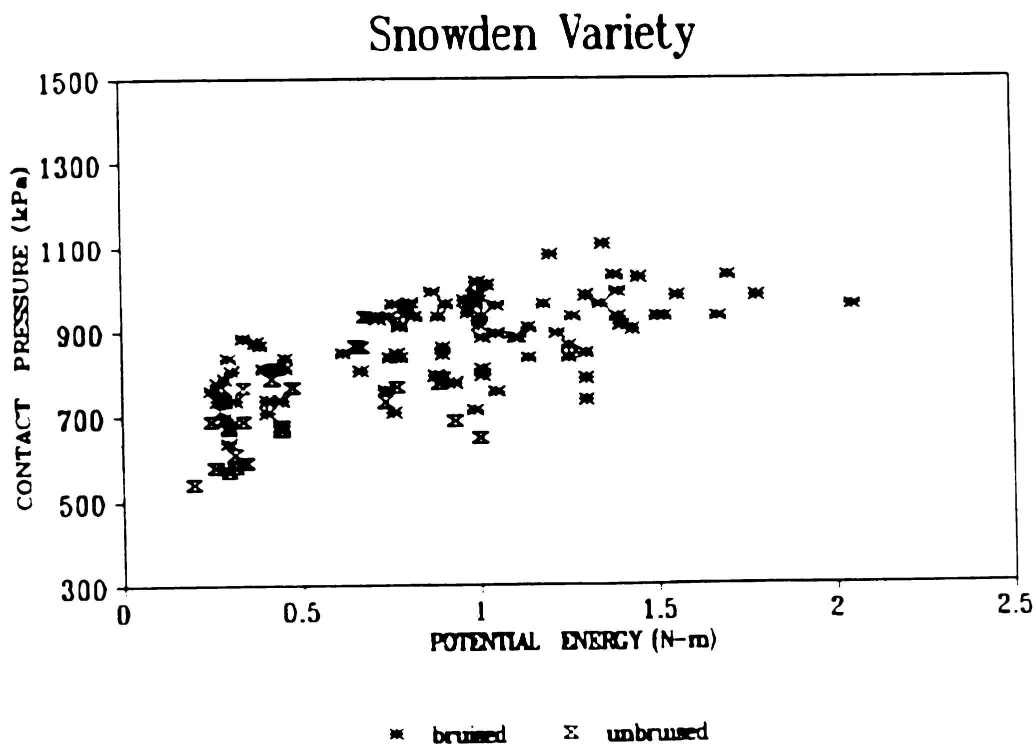

Figure 4.16 The dynamic contact pressure as affected by the potential energy of *Snowden* potatoes.

shatter bruise increased but the blackspot bruise decreased in ***Superior*** potatoes. The similar trend was seen in *Snowden* potatoes as shown in figure 4.14.

Table 4.3 Analysis of variance of dynamic bruising contact pressure over variety

	DF	SS	MSS	F-Value	Prob
Between	1	53.517	53.517	13.886	0.0003
Within	178	685.98	3.85		
Total	179	739.509			

CV= 21.29%

Table 4.4 Analysis of variance of dynamic bruising contact pressure over date of harvests.

	DF	SS	MSS	F-value	Prob
Within	2	194.575	97.288	31.60	0.0000
Between	177	544.93	3.079		
Total	179	739.506			

CV=19.13

Table 4.5 Analysis of variance of event of the bruising over variety.

	DF	SS	MSS	F- Value	Prob
Between	1	139.604	139.604	685.404	0.0000
Within	178	36.866	0.204		
Total	179	176.470			

CV=12%

A step wise regression analysis was performed (table 4.6) on the dynamic bruising contact pressure of bruised *Superior* potatoes to determine which parameters were correlated with it. It can be seen from the table 4.6 that strain energy, elasticity, and yield stress were correlated with the dynamic contact pressure. The adjusted R^2 between potential energy and dynamic contact pressure was low. The reason for poor correlation is that the contact pressure does not increase beyond the threshold value regardless of an increase in potential energy.

Table 4.6 Stepwise regression analysis of variance of dynamic contac pressure for the bruised *Superior* potatoes.

Source	Individual SS	Cumulative DF	Cumulative SS	Cumulative MS	Adjusted R^2
Constant	4055.1				
Mass	1.02800	1	1.0280	1.0280	0.0382
Potential Energy	0.009876	2	10379	0.51895	0.0106
Potato Size	0.32872	3	1.3666	0.45554	0.0033
Yield Strain	0.63013	4	1.9967	0.49919	0.0169
Strain Energy	10.701	5	12.698	2.5396	0.7704
Elasticity	0.038875	6	12.737	2.1228	0.7657
Yield Stress	0.45031	7	13.187	1.8839	0.7929
Residual	2.64050	36	15.828	0.43965	

Cases included	37		
Degrees of freedom	29		
Overall F	20.69	P	Value 0.0000
Adjusted R^2	0.7929		
R squared	0.8332		

Mechanical Properties

The scatter plots of the dynamic contact pressures versus the core modulus of elasticity, strain energy, yield strain, yield stress, of both varieties are shown in figures 4.17-4.24. The figure 4.17 shows that the dynamic contact pressure of the bruised potatoes were higher and linearly related to modulus of elasticity. The dynamic contact pressure of unbruised tubers were lower than that of bruised tubers. Figure 4.18 shows that the dynamic contact pressures were linearly increasing as yield stress were increased. While contact pressure on unbruised potatoes remains below the contact pressure of bruised potatoes. Figure 4.19 indicated that a linear trend of dynamic contact pressure as affected by the failure strain energy of bruised and unbruised potatoes. Figure 4.20 shown the dynamic contact pressure remains nearly constant at all strain levels in bruised and unbruised tubers. This indicates that dynamic bruising contact pressure of bruised tubers was a constant value at any strain. The figure 4.21-4.24 show the similar trend. The measured mechanical properties, such as yield stress, strain, strain energy, modulus of elasticity are also included in appendix A. The yield stress correlated with the dynamic bruising contact pressure in both varieties. Analysis of variance of mechanical properties over the varieties and the dates of harvest were performed. It was found that the varieties and the dates of harvest had a significant effect on the mechanical properties such as, yield stress, yield strain, strain energy and modulus of elasticity (tables 4.7-

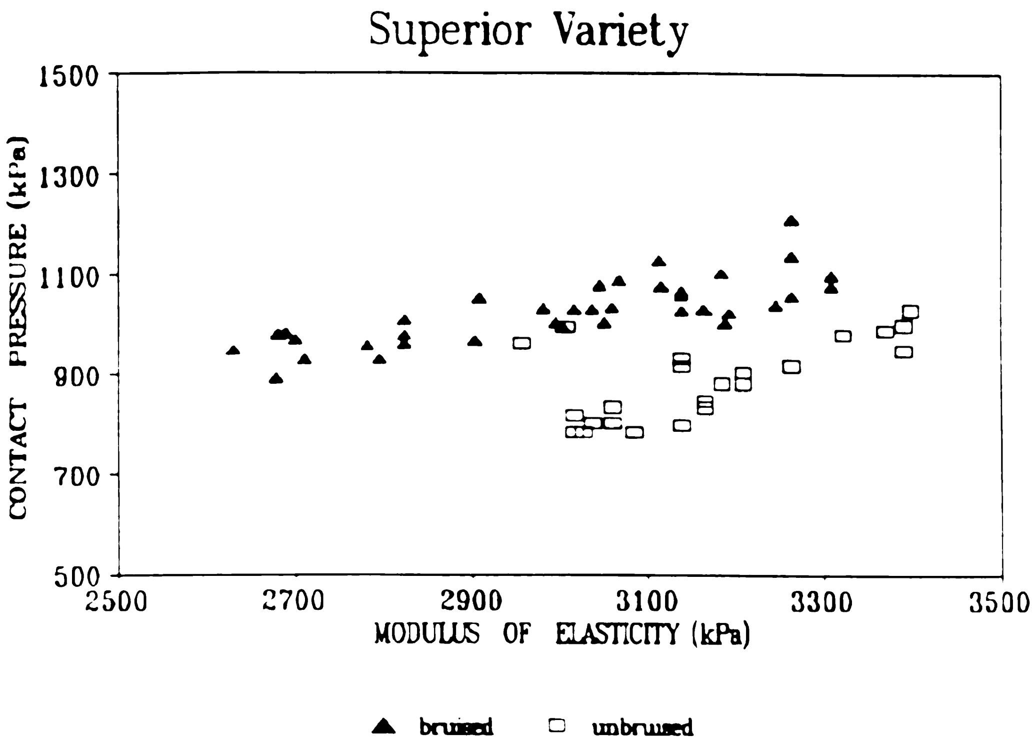

Figure 4.17 The dynamic contact pressure as affected by modulus of elasticity of *Superior* potatoes.

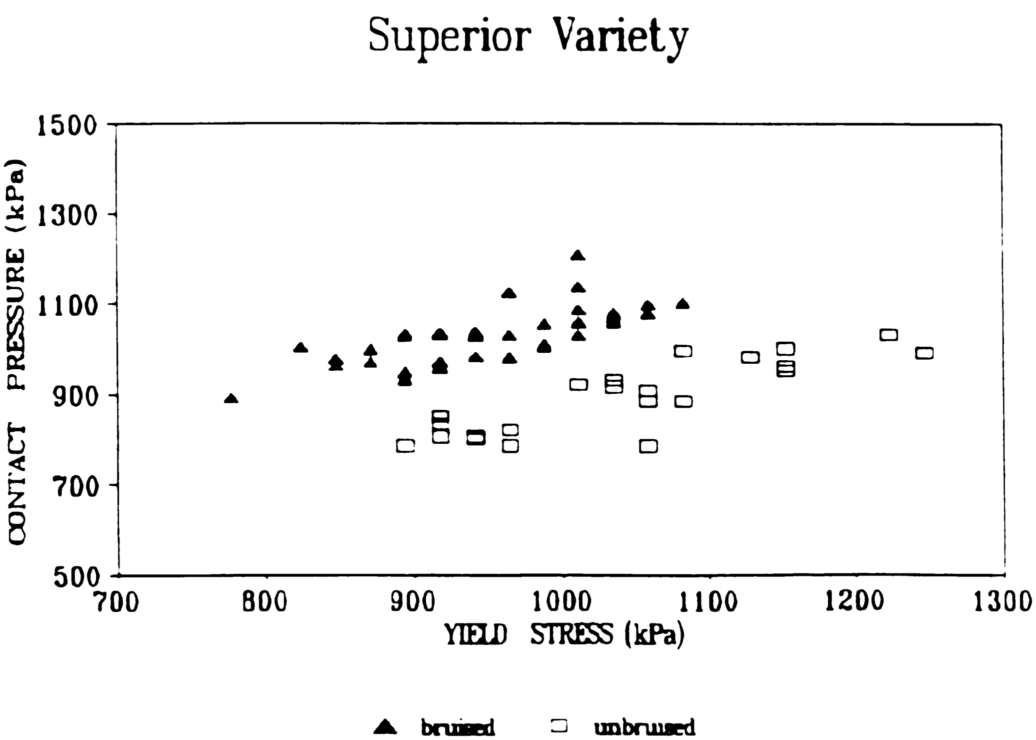

Figure 4.18 The dynamic contact pressure as affected by the yield stress of *Superior* potatoes.

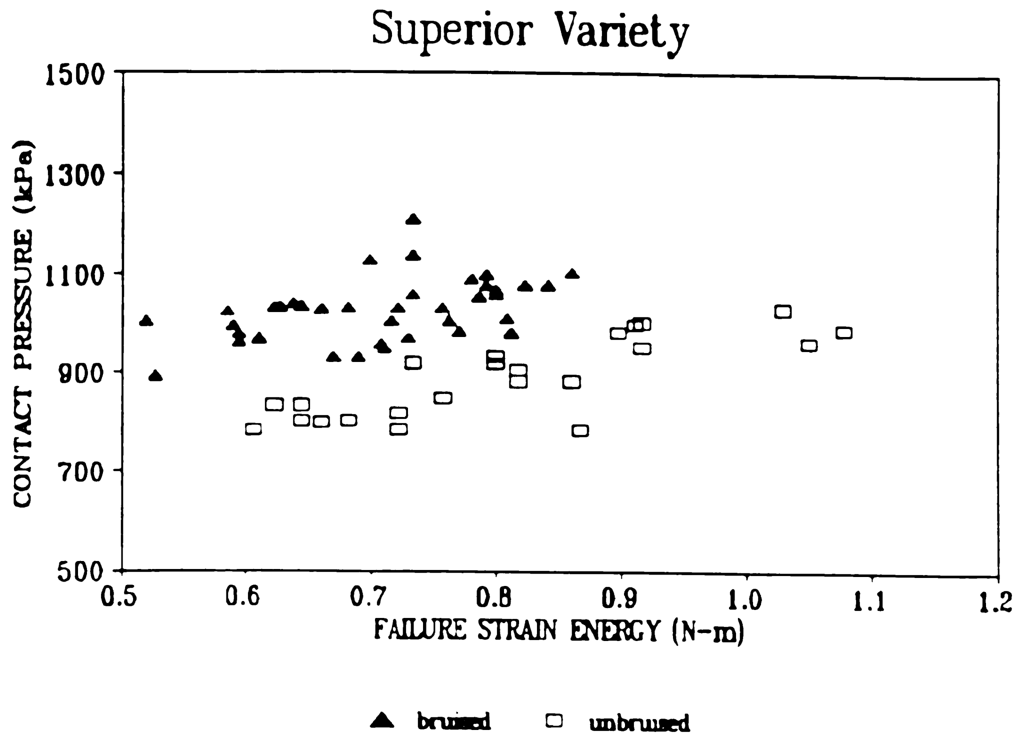

Figure 4.19 The dynamic contact pressure as affected by strain energy of *Superior* potatoes.

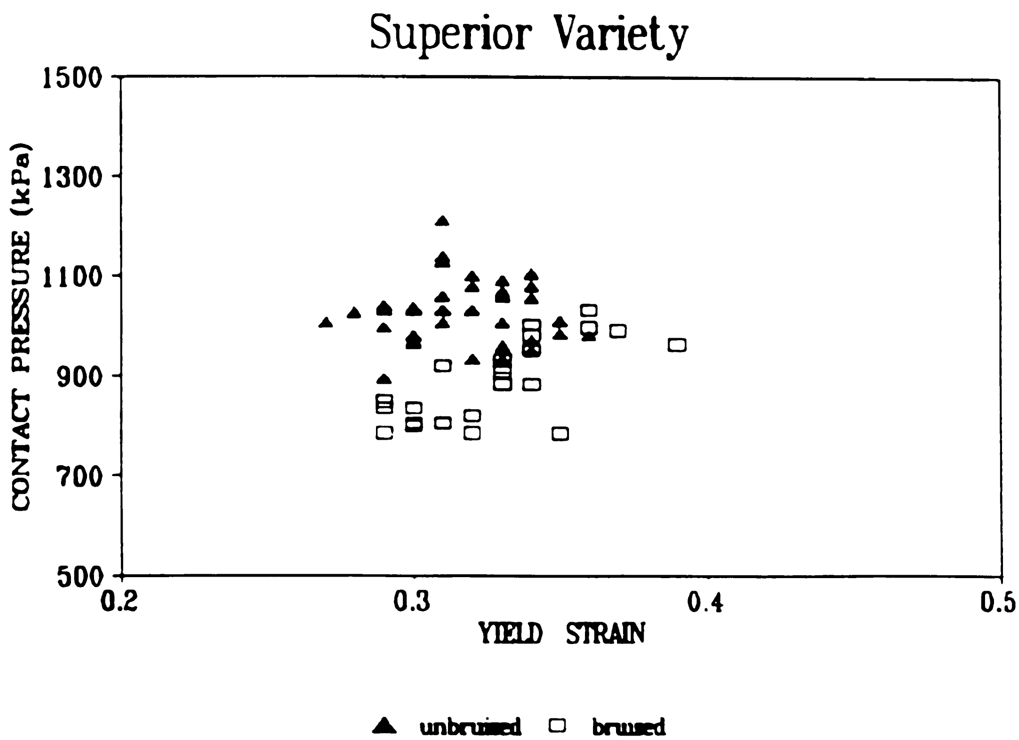

Figure 4.20 Trend of dynamic contact pressure as affected by yield strain of *Superior* potatoes.

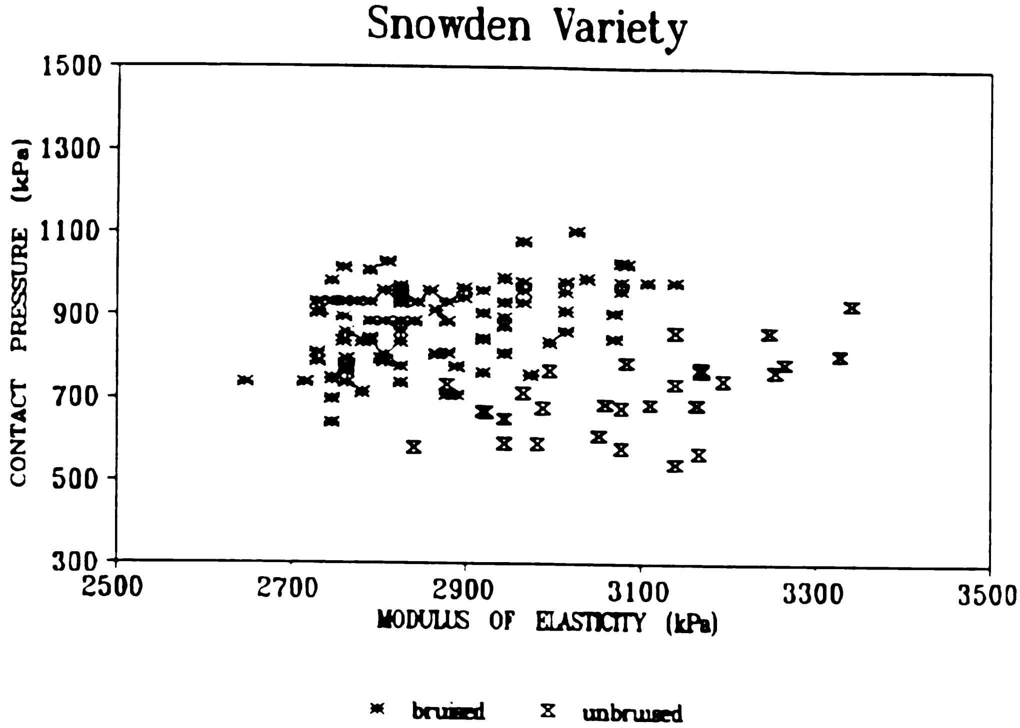

Figure 4.21 The dynamic contact pressure as affected by modulus of elasticity of *Snowden* potatoes.

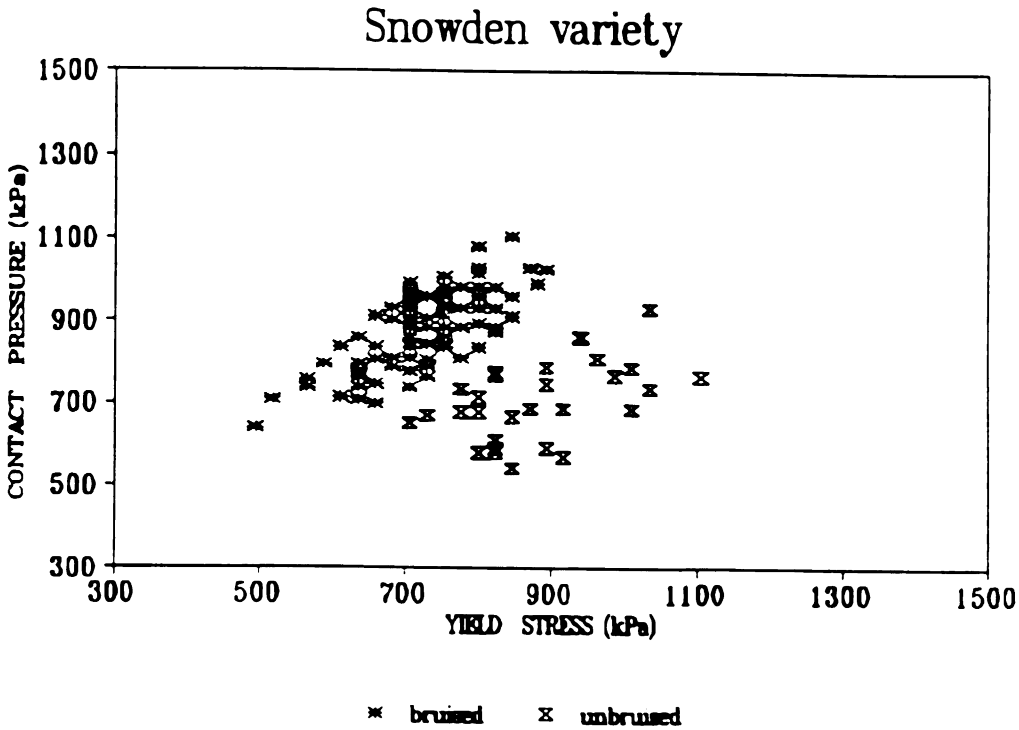

Figure 4.22 The dynamic contact pressure as affected by yield stress of *Snowden* potatoes.

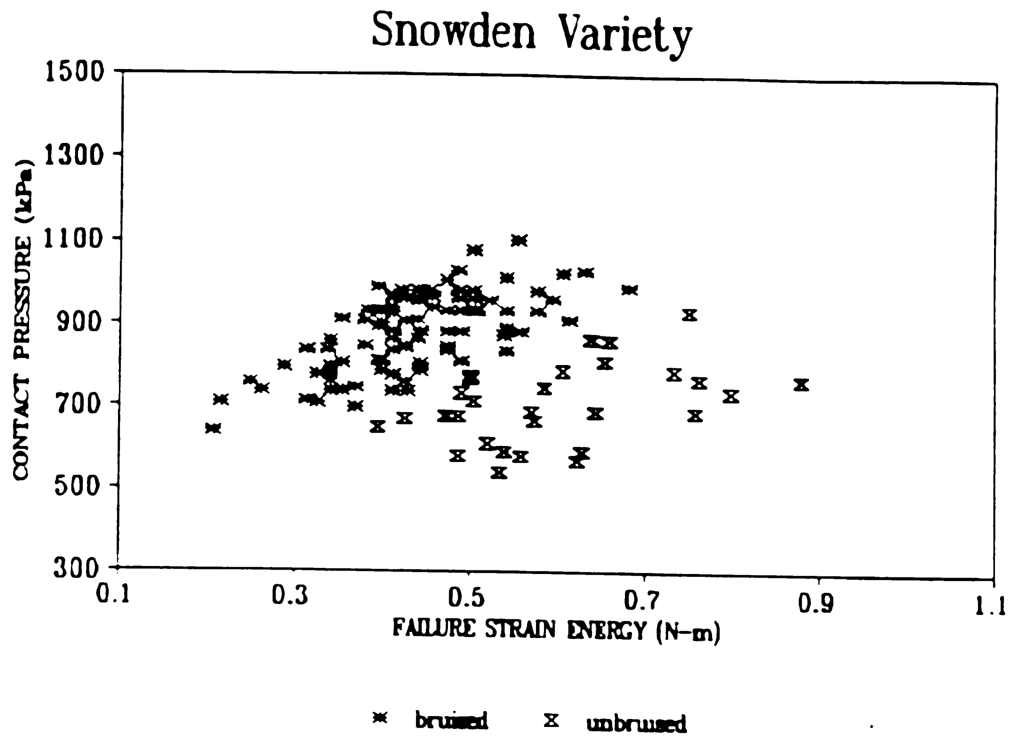

Figure 4.23 The dynamic contact pressure as affected by strain energy of Snowden potatoes.

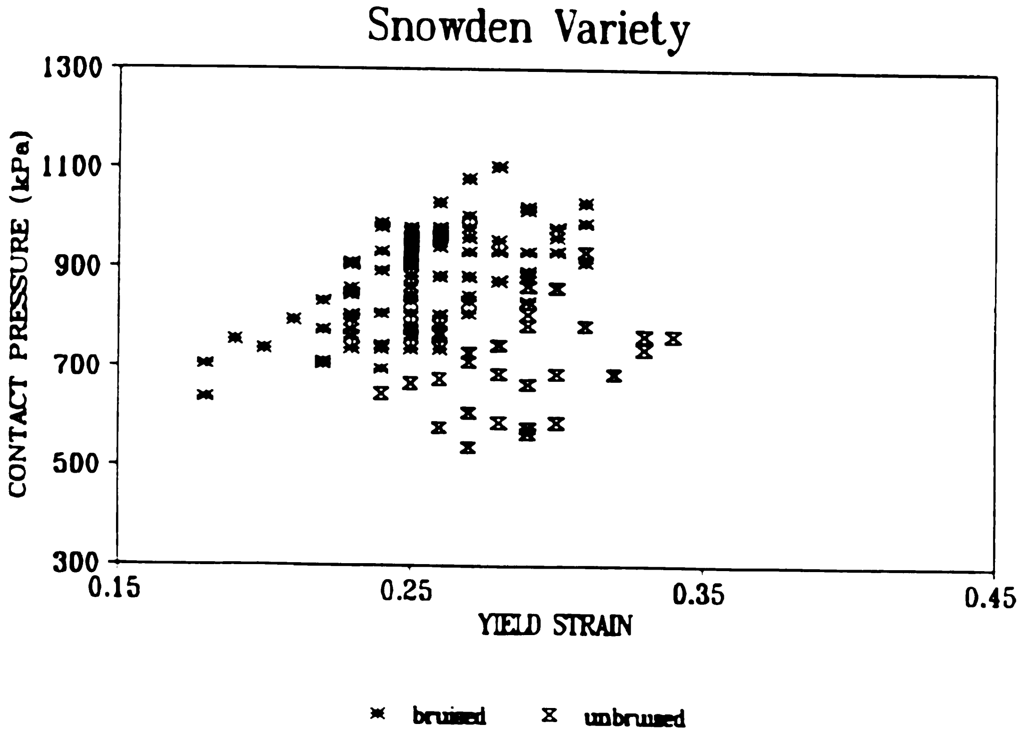

Figure 4.24 The dynamic contact pressure as affected by yield strain of *Snowden* potatoes.

4.13).

The Spearman correlation coefficients of mechanical properties of bruised *Superior* tubers are shown in table 4.14. From table 4.14 it is seen that the correlation between contact pressure and yield stress was high. A similar trend was found in bruised *Snowden* potatoes as shown in table 4.15. The differences in the elasticity, yield strain, yield stress, and strain energy between bruised and unbruised groups in *Superior* and *Snowden* potatoes were significant. The yield stress of bruised and unbruised *Snowden* potatoes was significantly lower than that of the *Superior* variety in general. It was also found that the modulus of elasticity and yield stress of bruised *Snowden* potato tubers were significantly lower than that of the unbruised *Superior* and unbruised *Snowden* potato tubers. The comparison of properties of bruised and unbruised tubers is shown in table 4.16. Table 4.16 indicated that there existed a significant difference of mechanical properties between bruised *Superior* and bruised *Snowden* potatoes. A comparison of mechanical properties of bruised *Superior* and bruised *Snowden* tubers are also shown in table 4.17. The difference in yield force, yield strain, strain energy, yield stress, elasticity, and dynamic contact pressure are significant between the varieties. Therefore, it can be said that the mechanical properties were significantly affected by the potato variety.

Table 4.7 Analysis of variance of yield strain over variety

	DF	SS	MSS	F-Value	Prob
Between	1	0.146	0.146	149.971	0.0000
Within	178	0.173	0.001		
Total	179	0.319			

CV=11.08%

Table 4.8 Analysis of variance of strain energy over variety

	DF	SS	MSS	F- Value	Prob
Between	1	261.167	261.167	214.463	0.0000
Within	178	216.763	1.218		
Total	179	477.930			

CV=21.77%

Table 4.9 Analysis of variance of yield stress over variety.

	DF	SS	MS	F-Value	Prob
Between	1	231.310	231.310	203.73	0.0000
Within	178	202.09	1.135		
Total	179	439.346			

CV=12.54%

Table 4.10 Analysis of variance of elasticity over variety.

	DF	SS	MS	F-Value	Prob
Between	1	119.115	119.115	9.03	0.0030
Within	178	2347.99	13.19		
Total	179	2467.106			

CV = 12.12%

Table 4.11 Analysis of variance of yield strain over dates of harvest

	DF	SS	MSS	F- Value	Prob
Between	2	0.146	0.073	74.171	0.0000
Within	177	0.173	0.001		
Total	179	0.322			

CV=11.10%

Table 4.12. Analysis of variance of yield stress over date of harvest.

	DF	SS	MSS	F-value	Prob
Between	2	236.80	118.401	106.595	0.0000
Within	177	196.60	1.111		
Total	179	433.407			

CV=10.12%

Table 4.13 Analysis of variance of elasticity over date of harvest.

	DF	SS	MSS	F-Value	Prob
Between	2	177.434	88.717	6.858	0.0010
Within	177	2289.671	12.93		
Total	179				

CV=11.99%

Table 4.14 Spearman correlations between mechanical properties of bruised *Superior* potatoes.

	Potential Energy	Yield Strain	Strain Energy	Elasticity	Yield Stress	Contact Pressure
Potential Energy	1.0					
Yield Strain	0.10	1.0				
Strain Energy	0.09	0.85	1.0			
Elasticity	0.15	-0.29	0.08	1.0		
Yield Stress	0.075	0.51	0.88	0.49	1.0	
Contact Pressure	0.25	0.08	0.53	0.55	0.81	1.0

Table 4.15 Spearman correlations between mechanical properties of bruised *Snowden* potatoes.

	Potential Energy	Yield Strain	Strain Energy	Elasticity	Yield Stress	Contact Pressure
Potential Energy	1.0					
Yield Strain	0.11	1.0				
Strain Energy	0.15	0.98	1.0			
Elasticity	0.24	-0.10	0.07	1.0		
Yield Stress	0.19	0.92	0.97	0.19	1.0	
Contact Pressure	0.56	0.55	0.62	0.40	0.70	1.0

Table 4.16 A comparison of mechanical properties of bruised and unbruised potatoes ($\alpha = 5\%$).

Variety	Mechanical Properties	t-value	SD of mean difference	Significance level
Superior	Yield force	-2.90	1.0500	*
Superior	Yield Strain	-1.18	0.0067	*
Superior	Strain energy	-2.71	0.2953	*
Superior	Yield stress	-3.14	0.2461	*
Superior	Elasticity	-2.64	0.9207	*
Superior	Potential Energy	4.07	0.0824	*
Superior	Dynamic Contact pressure	7.18	0.1903	*
Snowden	Yield force	-9.03	0.5772	*
Snowden	Yield strain	-5.00	0.0065	*
Snowden	Strain energy	-7.55	0.1963	*
Snowden	Yield stress	-9.028	0.1823	*
Snowden	Elasticity	-5.79	0.4425	*
Snowden	Potential Energy	7.07	0.0608	*
Snowden	Dynamic Contact pressure	21.90	0.2121	*

* significant

Table 4.17 A comparison of mechanical properties of bruised *Superior* potatoes with bruised *Snowden* potatoes (α = 5%).

Mechanical Properties	t - value	SD of mean difference	Significance
Yield Force	15.56	0.6760	*
Yield strain	11.11	0.0058	*
Strain Energy	15.31	0.1690	*
Yield stress	15.56	0.1596	*
Elasticity	5.47	0.9274	*
Potential Energy	0.39	0.0779	ns
Contact pressure	23.67	0.1723	*

* Significant

Polyphenol Oxidase (ppo) Activities:

A sample of 3 min ppo (oxygen uptake) activity of *Superior* potatoes is shown in figure 4.25. The slope of these curve indicated the uniformity of the sample. The colors of the supernatant after 3 min of reaction in fresh bruised *Superior* and *Snowden* potatoes are shown in figures 4.26 and 4.27, respectively. The faint and the deep color indicated the results of lower and higher ppo activity, respectively, within a 3 min period of reaction. The effect of drop heights on ppo activity of *Superior* and *Snowden* potatoes are plotted in figure 4.28 and 4.29, respectively. There existed a high positive correlation (R^2=0.90) between the drop height and ppo activity in bruised potatoes and unbruised groups of potatoes. The trend of ppo activity of bruised and unbruised *Superior* potatoes of September 17, 1993, plotted against drop height are shown in figure 4.29. The differences in ppo activity between bruised and unbruised groups of

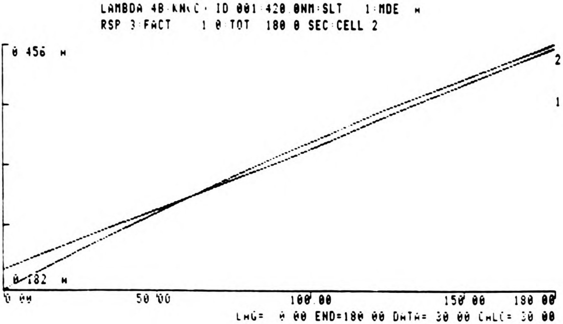

Figure 4.25 Three minutes enzyme activity (Oxygen up take by catechol) of bruised *Superior* potatoes dropped from 38.10 cm (15 inch) height.

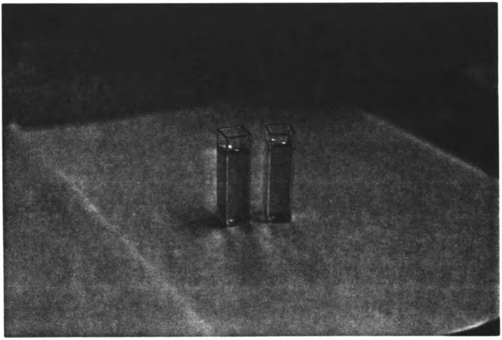

Figure 4.26 The resulting color of a supernatant of *Superior* potatoes after 3 min of reaction.

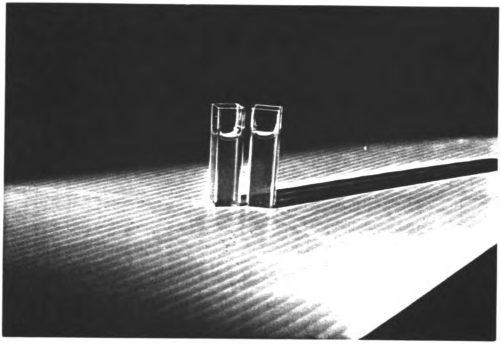

Figure 4.27 The deep yellow color of a supernatant of *Snowden* potatoes after 3 min of reaction.

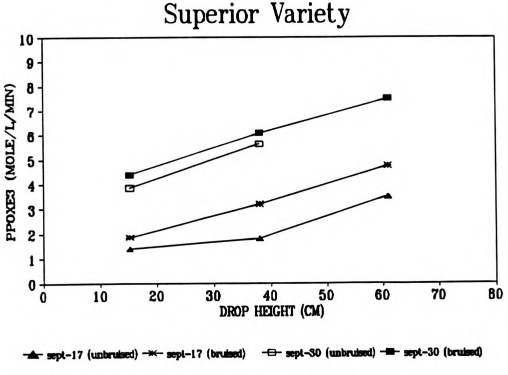

Figure 4.28 The effect of drop heights on polyphenol oxidase activity in *Superior* potatoes.

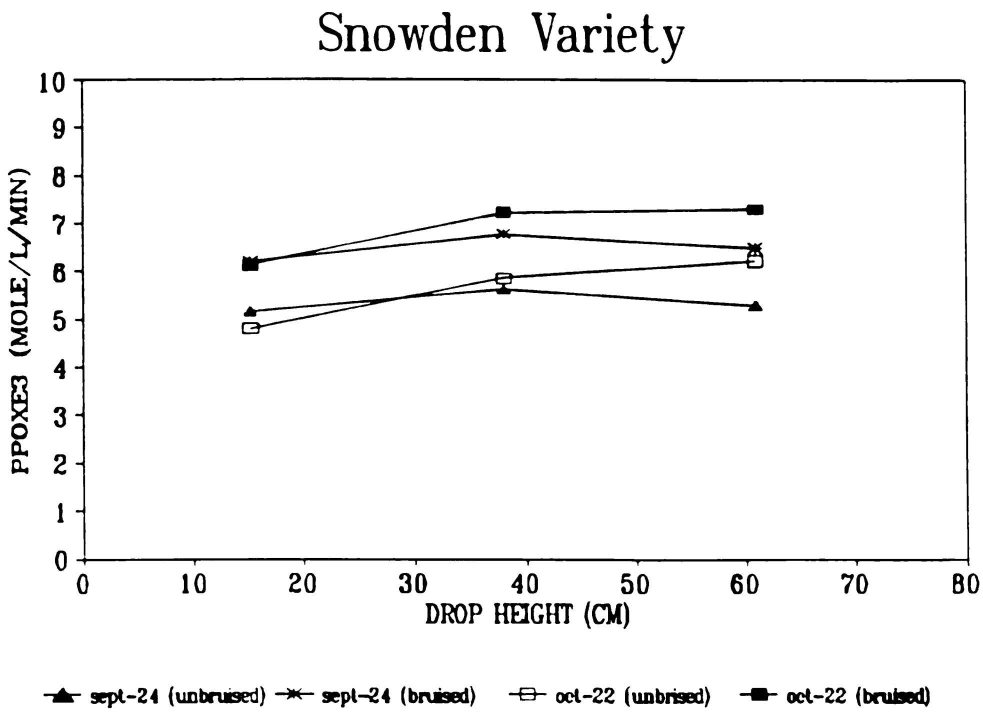

Figure 4.29 The effect of drop height on polyphenol oxidase activity in *Snowden* potatoes.

the *Superior* variety of the two harvests at all drop heights were significant. There existed a high positive correlation ($r^2=0.90$) between the drop height and ppo activities in bruised potatoes and between drop height and polyphenol oxidase activity of unbruised potatoes. This result indicated that if a tuber was impacted at a given height, certainly ppo activities would increase. The difference in polyphenol oxidase activity between the control and impacted potatoes was significant which was expected.

The unbruised group of *Superior* potatoes harvested on September 30, 1993, had significantly higher ppo activity compared to that of the control. This indicated that a greater potential to show blackspot in some unbruised potatoes eventually. The answer to the question as to why the ppo activity was higher in this case inspite of 100% shatter bruise at 61 cm (24 inch) drop height in this particular harvest is not known. The difference in the ppo activity among control of *Snowden* potatoes of September 24, 1993, was insignificant. The trend of ppo activity in bruised and unbruised *Snowden* potato tubers is shown earlier in figure 4.29. It was observed that once a potato tuber was dropped from any height ppo activity began immediately. It is to be noted that the ppo activity at this particular case of 61 cm or 24 inch drop height 24 inch was lesser than 31 inch and 15 inch drop heights. This was expected for two reasons: 1) some of enzymes (polyphenolase) might have been denatured due to shattering; and 2) the substrate in the shattered area had started oxidation due to open air before the sample was collected which resulted in lower ppo activities. The ppo activity of potatoes harvested on September 30'193 was significantly higher than that of the *Superior* potato tubers harvested on September 17, 1993.

The trend of the ppo activity of *Snowden* potato tubers of October 22, 1993, is also shown earlier in figure 4.29. The ppo activity was significantly higher as compared to that of *Superior* potatoes of September 17, 1993 (90% tubers shattered at 61 cm or 24 inch drop height). Similarly, the difference in the ppo activity of the unbruised and bruised *Snowden* potato groups were significant. The results showed that *Snowden* potato had significantly higher ppo activities than the *Superior* potatoes. Therefore, the *Snowden* potatoes can be classified as more susceptible than the *Superior* potatoes.

It should be noted that the severity of the shattering in *Snowden* potatoes was considerable as compared to that of the *Superior* potato tubers. The mechanical properties of *Snowden* tubers showed significantly lower values while its ppo activity was significantly higher than that of the *Superior* potato tubers. These properties strongly suggested that *Snowden* tubers were susceptible to tissue failure causing blackspots compared to the *Superior* potatoes. The *Snowden* potatoes exhibited higher number of blackspots and shatter bruises. The shattered *Superior* potatoes that were impacted at 61 cm (24 inch) drop height showed higher polyphenol oxidase activities as compared to that at lower levels of impact.

In general, polyphenol oxidase activities were significantly higher in bruised *Snowden* potato tubers than that for bruised and unbruised *Superior* and unbruised *Snowden* tubers. These results clearly indicated that the *Snowden* variety was more *susceptible* to bruising than the *Superior* variety. *Therefore, it can be generalized that higher the contact pressure, higher the enzymatic activity and blackspot bruising.*

Optical Density (OD)

Figures 4.30 and 4.31 show before and after 24 hrs of open air oxidation of homogenized extracts of unbruised and bruised *Superior* tubers, respectively. From figures 4.30 and 4.31 it was seen that before oxidation, the color of the extracted juice had faint red color. After 24 hrs of open air oxidation the color became light black (unbruised) or deep black (bruised). Therefore, it supports that blackspot bruise is a result of oxidation process. In order to distinguish the differences of color properly, after complete oxidation, the extracts of bruised adn unbruised potatoes were homogenized after complete oxidation. The homogenized extracts were measured for its optical density by using a Spectrophotometer. The difference in the optical density among and between the controls of *Superior* and *Snowden* potatoes were insignificant. This indicated that the selected controls had low and uniform activity which was expected since no impact was made to these potatoes (fig 4.32). According to susceptibility table 4.1 the controls of *Superior* and *Snowden* potatoes were ranked as *moderately resistant* and *moderately susceptible,* respectively. The effect of the drop height on the optical density of both varieties, as determined in the bruised and the unbruised potato tubers, are shown in figures 4.33 - 4.39. From figures 4.33, 4.34 and 4.35 it was seen that there were differences in OD (*Superior*) between unbruised and bruised extracts at 6 inch, 15 inch and 24 inch drop heights. The OD of unbruised extracts were insignificant but OD of bruised extracts were darker with some variation. From figures 4.36-4.39, in all cases, it was seen that OD of the bruised and unbruised extracts were light to dense regardless of drop heights. This implies that, even a tuber did not show bruise at the

Figure 4.30 The light red color of homogenized extract of *Superior* potatoes before open air oxidation.

Figure 4.31 The dense color of homogenized extract of *Superior* potatoes after 24 hrs of open air oxidation.

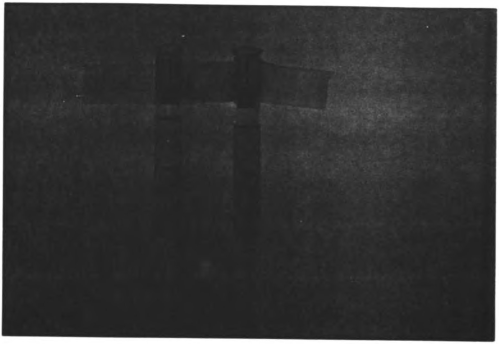

Figure 4.32 A sample of homogenized extract of controls (left-*Snowden*, right-*Superior* for optical density measurement.

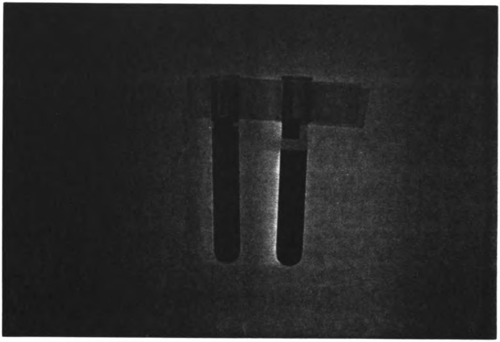

Figure 4.33 Homogenized extract of unbruised and bruised fresh *Superior* potatoes at 15.24 cm (6 inch) drop height for OD measurement.

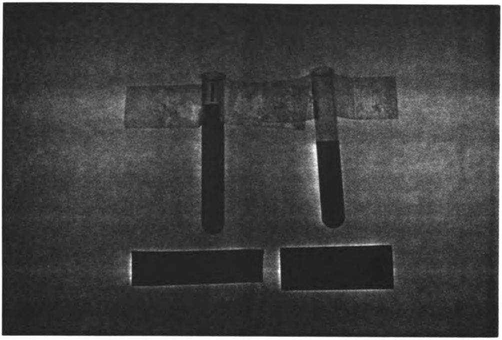

Figure 4.34 Homogenized extract (unbruised and bruised) fresh *Superior* tubers dropped from 38.10 cm (15 inch) drop height for OD measurement.

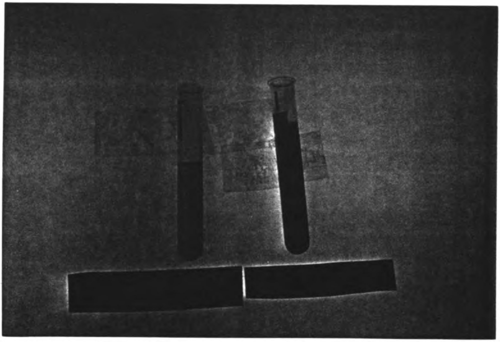

Figure 4.35 Homogenized extract (unbruised and bruised) fresh *Superior* tubers dropped from 61 cm (24 inch) drop height for OD measurement.

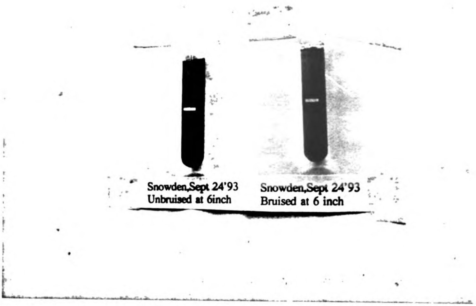

Figure 4.36 Homogenized extract of (unbruised and bruised) *Snowden* tubers dropped from 15.24 cm (6 inch) height for OD measurement.

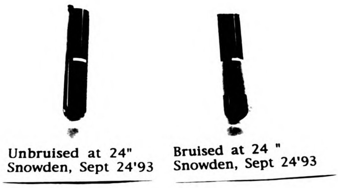

Figure 4.37 Homogenized extract (unbruised and bruised) fresh *Snowden* tubers dropped from 38.10 cm (15 inch) drop height for OD measurement.

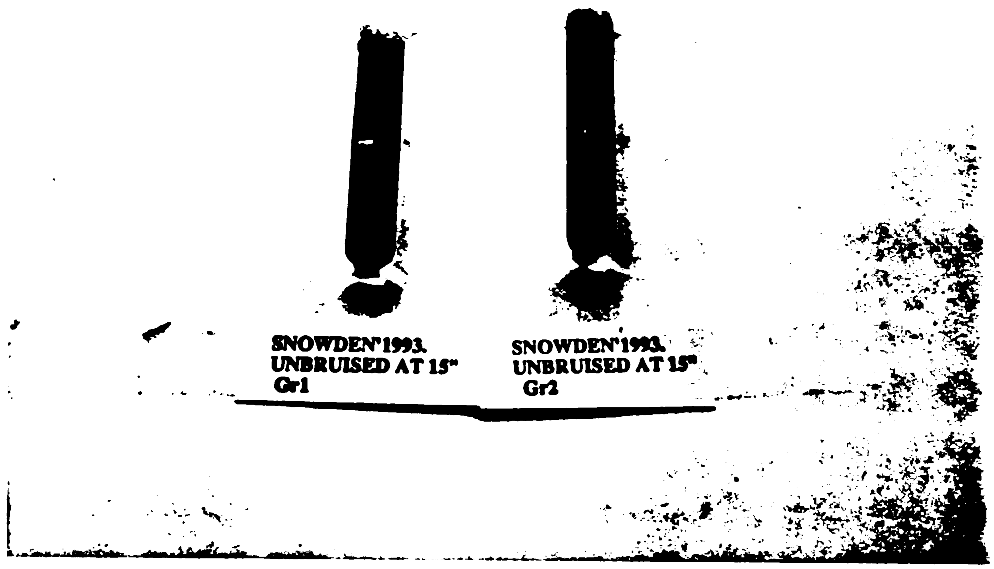

Figure 4.38 Homogenized extract of unbruised fresh *Snowden* tubers dropped from 38.10 cm (15 inch) drop height.

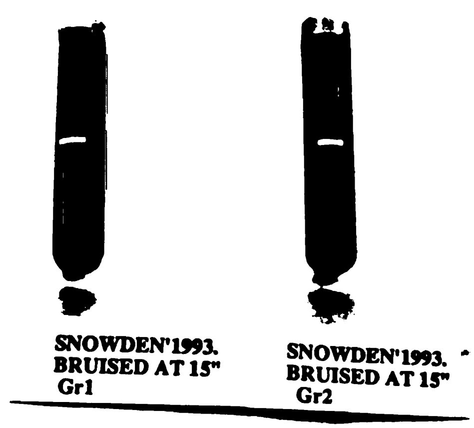

Figure 4.39 Homogenized extract of bruised fresh *Snowden* tubers dropped from 38.10 cm (15 inch) drop height for OD measurement.

same drop height but bio-chemical reaction has started due to impact and eventually unbruised potatoes would show blackspot. The differences of the optical densities between the extracts of bruised and unbruised groups of potatoes at all heights were significant in both varieties. The optical density of the extracts of unbruised *Superior* potatoes remained nearly unchanged, as expected, since the potato tubers did not bruise but unbruised *Snowden* potatoes did show activities. The overall results of the tests demonstrated that the optical density of the *Snowden* potatoes was significantly higher than that of the *Superior* variety. This was expected since ppo activity in bruised *Snowden* potatoes were significantly higher, which resulted in higher optical density for *Snowden* potatoes. According to the defined susceptibility scale developed by Dean et al. (1992), unbruised or bruised groups of potatoes in the *Superior* variety were ranked as *moderately resistant*. The unbruised groups of *Snowden* potatoes were ranked as *moderately susceptible* and bruised as *susceptible*, respectively. The summary of the ppo, optical density is shown in table 4.18.

Hypothesis: A combination of physical and chemical properties can be used to determine the bruise susceptibility of potatoes in a lot. The equation developed was:

$$\mathbf{BS = -0.12 - 2.79^{-06}\,(CP) - 1.28^{-08}\,(E) + 5.03\,(OD) + 1.09^{-01}\,(PPO),\ Adj\ R^2 = 0.91}$$

Where, BS = blackspot susceptibility (table 4.1)

CP = contact pressure (kPa)

E = modulus of elasticity (kPa)

OD = optical density

PPO = polyphenol oxidase activity (mole/lit/min)

Table 4.18. Drop Height, PPO activities, Optical Density of Bruised, Unbruised and Control Potatoes.

Variety Harvested	Superior 9-17-93				Superior 9-30-93				Snowden 9-24-93				Snowden 10-22-93			
Height (cm)	0	15.24	38.1	61	0	15.24	38.10	61	0	15.24	38.10	61	0	15.24	38.10	61
(bruised) ppox10^3	-	1.84	3.18	4.75	-	4.39	6.09	7.5	-	6.21	6.8	6.5	-	6.1	7.2	7.3
SD	-	.013	.019	.045	-	.022	.030	.07	-	8	.17	.13	-	.12	.19	.20
(unbruised) ppox10^3	.80	1.37	1.80	3.50	2.58	3.85	5.65		.90	5.1	5.6	5.3	3.8	4.8	5.8	6.2
SD	.01	.002	.004	.035	.02	0.12	.04		.02	.15	.13	.12	.16	.15	.14	.08
(bruised) OD	-	.35	.402	.527	-	.513	.570	0.6	-	.52	.62	.66	-	.7	.71	.63
SD	-	.017	.005	.018	-	.004	.175	.01	-	.03	.02	.09	-	.01	.09	.06
(unbruised) OD	.26	.27	.30	.33	.349	.473	.520	-	.40	.42	.51	.48	.44	.61	.54	.55
SD	.002	.01	.01	.006	.016	.013	.002	-	.01	.002	.05	.19	.02	.07	.02	.001

PPO-polyphenol oxidase activity (mole/lit/min), OD-optical density (absolute value), SD-Standard deviation.

Determination of Mineral Contents

The Calcium, Copper and Potassium contents in each tuber were determined in the Soil Testing Laboratory (Appendix D). In order to compare the mineral properties of bruised and unbruised potatoes in both varieties, t-tests were performed. The results show that there was a significant difference in the amount of Copper, Calcium and Potassium contents between the *Snowden* and the *Superior* varieties in general. The mineral contents of bruised and unbruised *Snowden* and *Superior* potatoes were not significant. It can be said that the mineral contents probably contribute to the bruising phenomena in fresh potato tubers. It needs to be studied further before one can draw a concrete inference about their roles in blackspot bruising in potatoes.

4.4 Conclusions

The bruised *Snowden* potatoes had significantly higher ppo activity than that of *Superior* potatoes. The optical density of the bruised tubers was significantly higher than that of the unbruised potato tubers in both varieties. This was expected since higher ppo activity caused higher optical density. The control of the *Superior* and the *Snowden* potato tubers were ranked as *moderately resistant* and *moderately susceptible*, respectively. The optical density of the estracts of bruised *Snowden* tubers was significantly higher than that of the extracts of bruised and unbruised *Superior* and unbruised *Snowden* varieties. The bruised potatoes in *Superior* and *Snowden* were ranked as *moderately susceptible and susceptible*, respectively.

The cores of *Superior* and *Snowden* potatoes were tested to determine mechanical properties, such as yield strength, yield force, total deformation at yield,

yield energy and modulus of elasticity (Appendix A). The yield stress of the *Snowden* variety is significantly lower than the *Superior* variety. From the analysis of variance it can be stated that the modulus of elasticity of bruised *Superior* tubers was significantly higher than that of *Snowden* tubers. It was found that the yield stress and the modulus of elasticity of bruised *Snowden* tubers were significantly lower than unbruised *Superior* and *Snowden* tubers. The analysis showed that the varieties and dates of harvest had a significant effect on yield strength, total deformation at yield, yield energy, yield force, yield strain and the modulus of elasticity in both varieties. The differences in elasticity, strain, stress and the strain energy of bruised and unbruised groups were also significant in both varieties. It was found that the properties of unbruised and bruised potatoes were significantly different in both varieties. It was found that the mechanical properties of bruised *Superior* potatoes were highly significant compared to that of the *Snowden* potatoes.

It was found that the correlation between strain energy and yield strain, yield stress and strain energy, dynamic contact pressure and yield stress are positive and very high. There existed high correlation 0.90 to 0.97 between the drop heights and the percentage of bruised potato tubers. The step wise regression shows that the dynamic contact pressure of bruised *Superior* potatoes was highly correlated with strain energy, modulus of elasticity and yield stress. The adjusted R^2 in this analysis was 0.79. These tests clearly revealed that dynamic yielding contact pressure can be an important parameter that explains blackspot bruising phenomena in potato tubers.

There existed a threshold value of the contact pressure at which a particular variety would bruise when subjected to an impact loading. The threshold pressures values were 880.94 kPa (127.73 psi) and 1027.11 kPa (148.86 psi) for the *Snowden* and for the *Superior* potatoes, respectively, indicating that the *Snowden* variety was more susceptible to bruising than the *Superior* potatoes. Therefore, higher percentage of bruised tuber can be expected in *Snowden* potatoes than the *Superior* potatoes. There was a positive correlation between the drop height, ppo activity and the optical density. The ppo activity of bruised *Snowden* tubers was significantly higher than the unbruised Snowden or *Superior* potatoes. The optical density of bruised *Snowden* potatoes was significantly higher than the *Superior* potatoes. The percentage of bruised *Snowden* potatoes was significantly higher than that of the *Superior* potatoes which further supports that the *Snowden* variety was more susceptible than the *Superior* variety.

The threshold values of the dynamic contact pressures may be used to determine the bruise susceptibility of potato tubers. Potato bruising caused a significant change in the polyphenol oxidase activity and the resulting optical density. Bruise susceptible potatoes exhibited higher polyphenol oxidase activity and resulted in higher optical density. There was no strong statistical support to the fact that minerals play a significant role in blackspot bruising phenomena in the fresh potatoes. The mechanical and chemical tests show that the *Snowden* variety is more susceptible than the *Superior* variety. Significant differences existed between the mechanical properties of *Superior* and *Snowden* potatoes. The varieties and the dates of harvests had significant influence over the mechanical properties of the potatoes. The yield stress of *Snowden* potatoes was significantly lower than the *Superior* variety causing the *Snowden* potatoes to be more susceptible to bruising than the *Superior* variety.

Pressure sensitive film is a viable method of measuring dynamic contact pressure. Susceptibility to bruising is an inherent property that can be determined by studying mechanical properties. The yield stress, modulus of elasticity and strain energy of the *Snowden* potatoes were significantly lower than that of the *Superior* potatoes. The varieties and the dates of harvests had significant influence over the mechanical properties of potatoes. Dynamic property, mechanical properties and chemical property revealed that *Snowden* variety is more susceptible than that of *Superior* variety.

5 POTATO BRUISING BY QUASI-STATIC LOADING

Blackspot bruising is caused by internal tissue failure. The internal tissue failure is an indication of resistance to bruise. The method widely used in determining resistance of a material are static indentation, using spherical, pyramid and flat indenter (Tabor, 1950; Davis, 1949). According to Hadfield (1976) a yield point is the measure of resistance to failure of a material. Finney (1963) used spherical indenter to measure strength of a potato when tuber severely failed locally as shown by a hook on the force-deformation curve. He defined this point as rupture point. He stated that there was no yield point found in the load-deformation curve. This section will verify his statement with explanation.

The objective was to determine the potato behavior under quasi-static loading.

5.1 Methodology

5.1.1 Determination of Quasi-static Contact Pressure

A separate group consisting of 60 randomly selected freshly harvested tubers were used to perform compression tests. A steel spherical indenter 22 mm (7/8") dia was fitted on the crosshead of the Instron testing machine. A pair (5.08 cm X 5.08 cm) of Fuji pressure sensitive film (A and C, type 2) were placed together on the top of the whole before the load was applied. A new film was used for each tuber. The indenter compressed the whole tubers with the pressure film at a 1.77 cm/min (0.5 in/min) loading rate. The film started developing color as soon as the indenter touched the pressure sensitive film. The compression was continued until the tuber began to fail which was seen as a hook on the chart. The crosshead was stopped and raised immediately to deter further deformation. The pressure sensitive film developed a red color depending on the magnitude of the contact pressure. The chart recorded the corresponding force and deformation. The color of the pressure films was digitized and the corresponding gray values were recorded. The same calibration curve was used to measure the quasi-static bruising contact pressure.

5.2 Results and Discussion

The figures 5.1 shows instron testing machine fitted with a spherical indenter and potato bruising aarangement and 5.2 shows the hook that indicates bruising of a potato under spherical indenter test. It can be seen that there was no yield point on the curve except a hook at the tip of the curve but yielding must have occurred well before the localized tissue failure. The hook correspond to a rupture force or maximum strength of the tuber. The reason why the yield point was not shown on the curve can be explained as follows: as the indenter starts loading the potato, the contact area increases continuously causing a steady increase in force to deform the tuber. There is no sudden change of area occurs until it fails severely by skin separation. This is the point when hook appears due to sudden change of contact area and skin separation. That is contact pressure exceeds the ultimate strength of the tuber, causing localized major tissue failure. This is the only failure indicated by the hook in the force-deformation curve as shown later in figure 5.2. The resulted intensity of color of the pressure sensitive film is shown in figure 5.3. The dense pink color was digitized as described earlier and maximum pressure for each tuber was measured from the calibration curve. The bruising contact pressure for *Superior* potatoes ranged from 2197.44 kPa (318.69 psi) to

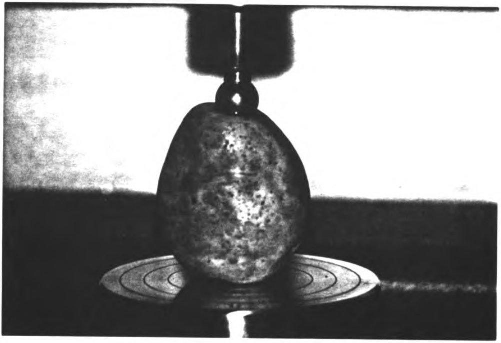

Figure 5.1 Bruising a potato at the stem end using a (7/8 inch dia) spherical indenter on an Instron Testing machine.

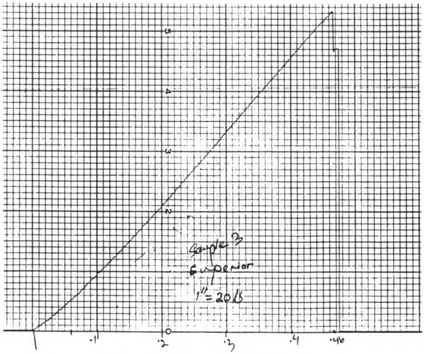

Figure 5.2 The hook which indicates potato bruising during the compression test using a spherical indenter.

Figure 5.3 The deep red color formation in the pressure sensitive film due to high contact created by the spherical indenter.

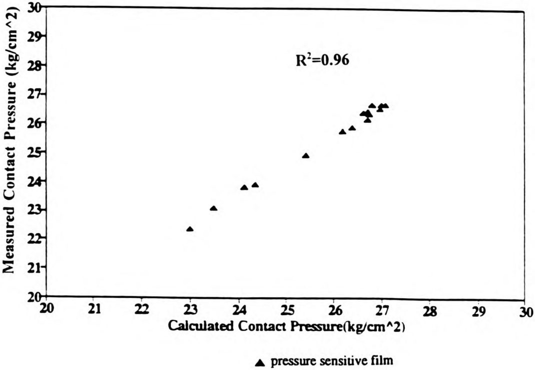

Figure 5.4 Correlation between calculated and measured contact pressure for *Superior* potato tubers.

2618.29 kPa (379.73 psi) having an average of 2498.61 KPa, SD 1.40 (362.37 psi, SD 19.93). Similarly, the bruising contact pressure for the *Snowden* potatoes varied from 2065 kPa to (360.72 psi) 2487.82 kPa (272.50 psi, SD 21.05) having an average value of 2340.67 kPa, SD 1.89 (339.52 psi, SD 26.89). The calculated maximum contact pressure in each case, q_o was calculated using the equation given by Timoshenko et al. 1970 (page 412) as follows:

$$q_o = 1.5\ (F/\pi\ a^2),$$

where, F= yield force

k_1 and k_2 are property constants of the materials.

R_1 and R_2 are the radius of potatoes and sphere, respectively.

'a' the radius of contact can be calculated from the following relation:

$$a^3=\{3\ \pi\ F\ (k_1+k_2)\ R_1\ R_2\}/[4(R_1+R_2)].$$

The data for the *Superior* and *Snowden* potatoes are included in appendix B .

The correlation between the calculated and measured yield pressures was 0.96 for whole *Superior* potatoes as shown in figure 5.4. From the load-deformation curves of *Superior* and *Snowden* potatoes, figures 5.5 and 5.6, respectively, it can be seen that for a deformation of 10.16 mm (0.40 inch) the force was almost 50 kg (110 lb) for *Superior* potatoes whereas it was about 36.39 kg (80 lbs) for *Snowden* potatoes. The average deformation was 10.16 mm (0.40 inch) for *Superior* potatoes and 10.66 mm (0.42 inch) for *Snowden* potatoes. It appeared that *Snowden* tubers can exhibit a wide range of deformation from 7.87 mm (0.31 inch) to 13.97 mm (0.55 inch).

The figure 5.7 shows a non linear trend of contact pressure as deformation

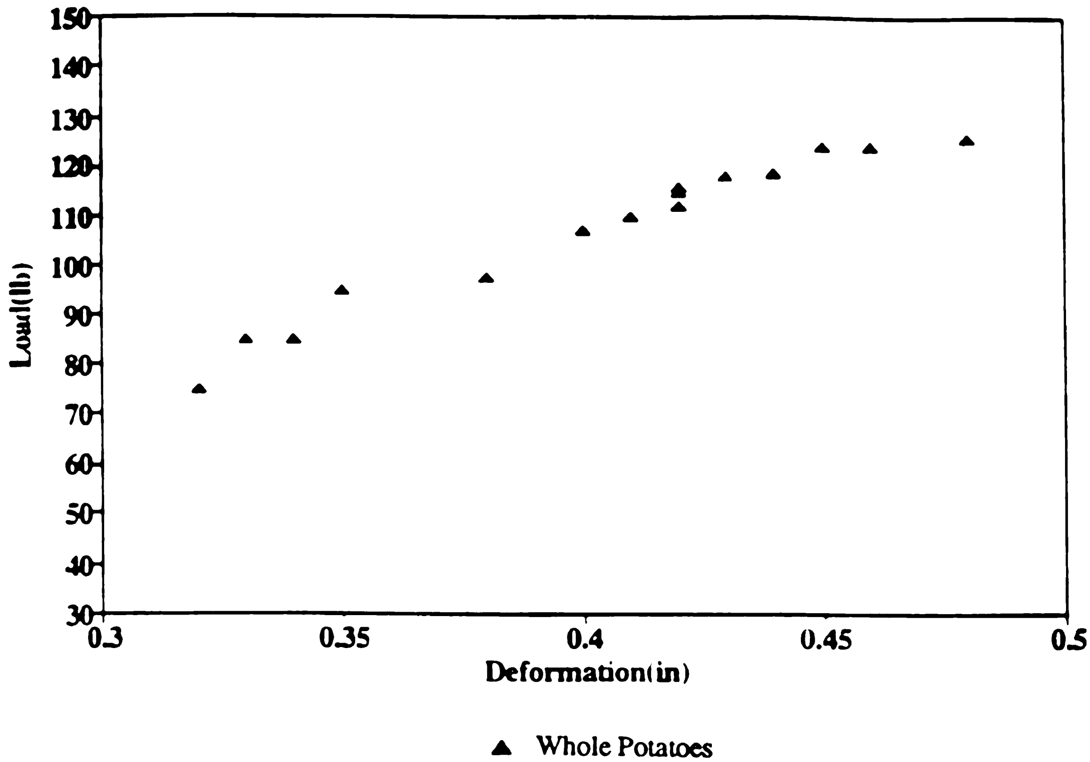

Figure 5.5 Load-deformation as observed in bruised whole *Superior* potatoes under loading by a spherical indenter.

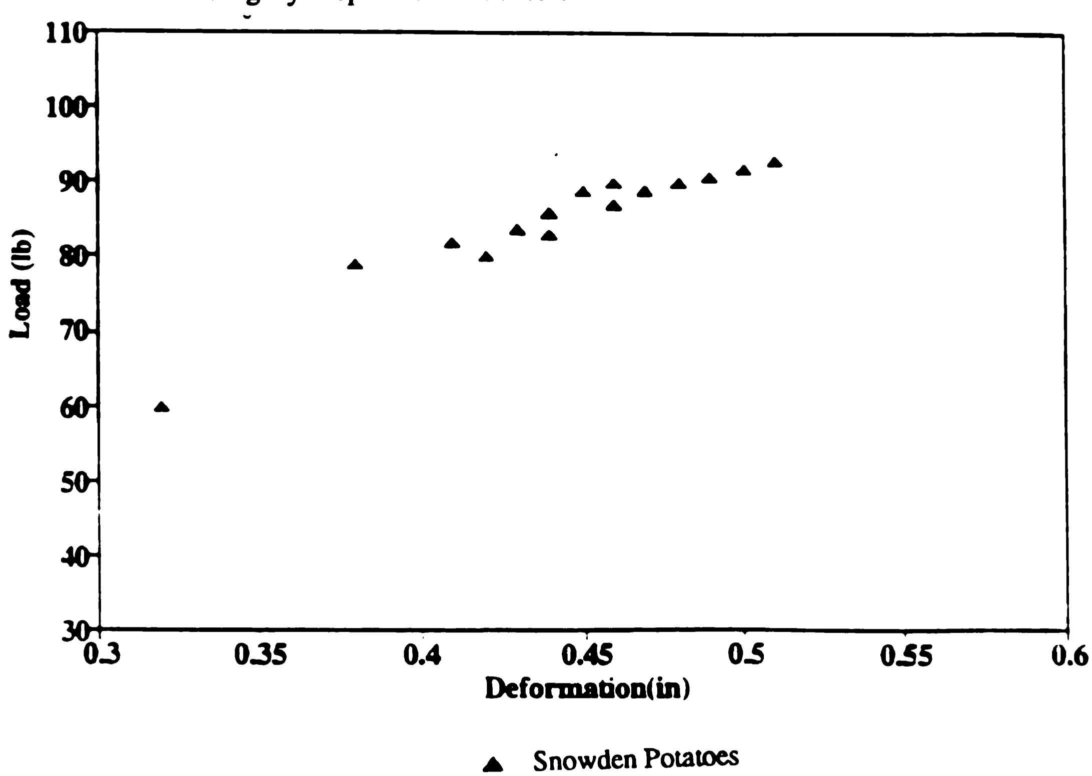

Figure 5.6 Load-deformation as observed in bruised whole *Snowden* potatoes under loading by a spherical indenter.

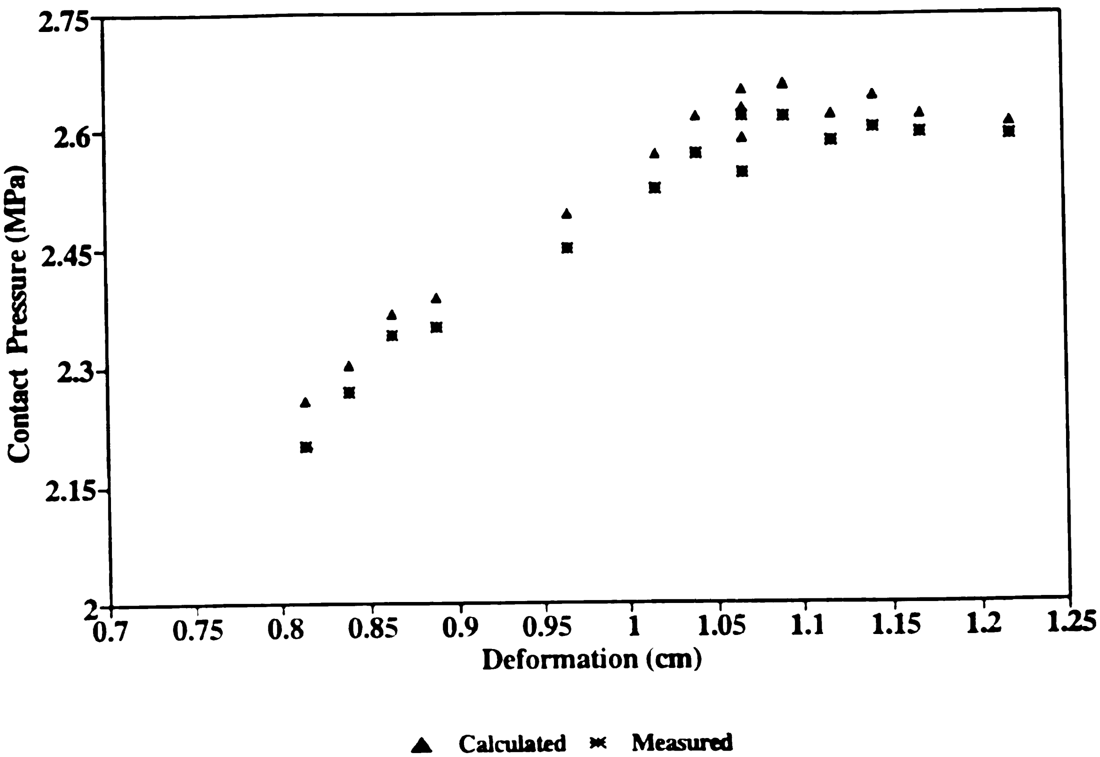

Figure 5.7-A nonlinear trend of measured contact pressure in whole bruised *Superior* potatoes.

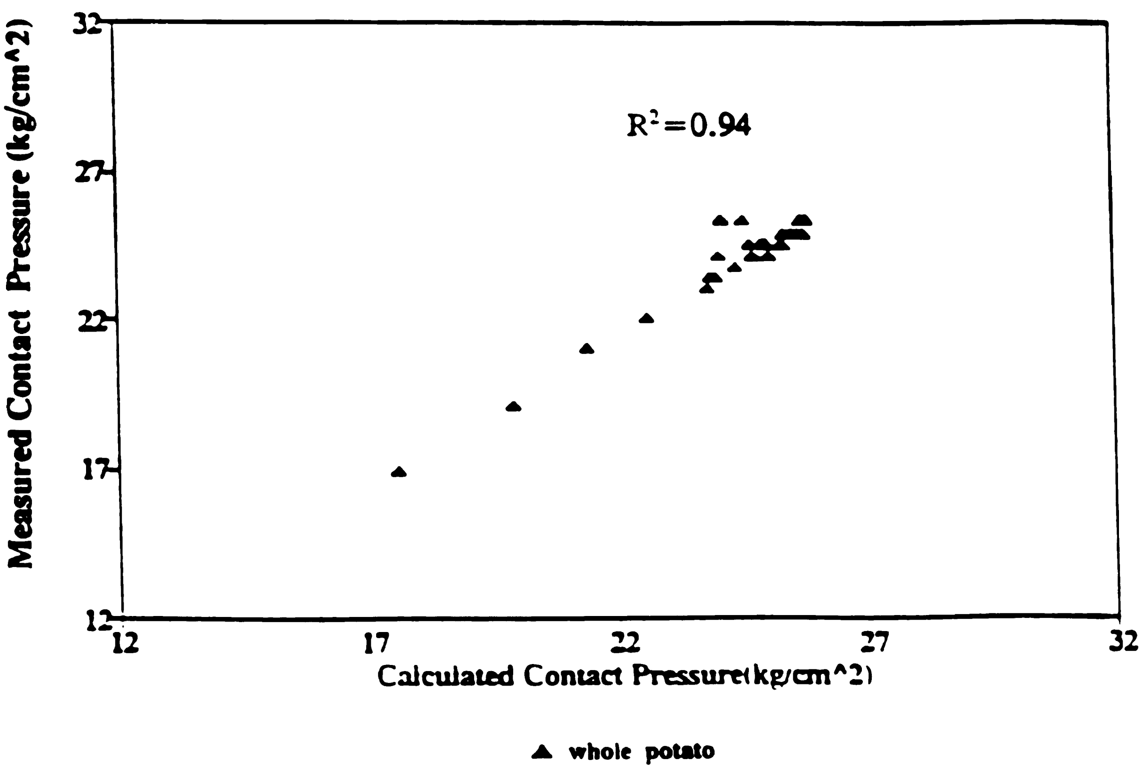

Figure 5.8-Correlation between the measured and calculated contact pressure in whole bruised Snowden potatoes.

continued in *Superior* potatoes. The difference between the measured and the calculated contact pressure was within 5% of accuracy. The contact pressure of the bruised *Superior* potatoes remained nearly constant beyond the deformation of 10.16 mm (0.40 inch). A similar trend of contact pressure and deformation as affected by the bruised *Snowden* potatoes was shown in appendix E.2. It indicates that all tubers have been undergone a permanent deformation above 2503 kPa (363 psi) when major tissue failure occurred. This was because of considering hook as an indicator of failure where as the hook was a major localized failure point not an on set of permanent deformation. The correlation between the measured and calculated quasi-static contact pressures for *Snowden* potatoes was 0.94 shown in figure 5.8. Therefore, the measured contact pressure can be used for analysis with confidence. From the observation it was evident that as the dates of harvests passed by, the contact pressure showed a decreasing trend after certain time. It indicated that potato must have an optimum time for harvesting. The potatoes keeping longer under the soil would not increase resistance of bruising. The difference in quasi-static bruising contact pressures between the *Superior* and *Snowden* potatoes was found to be significant.

It can be stated that potato should not be subjected to pressure equal or more than yield stress. Finney (1963) stated that there was no yield point of potato found on the force-deformation curve, this observation was confirmed with explanation. Therefore, yield point of a potato may not be observed on th force -deformation curve by using spherical indenter. The FEM models were used to verify the induced contact stress distributiom, particularly, maximum stress and its area of location.

5.3 Conclusions

The pressure sensitive film can be used to measure quasi-static bruising contact pressure. Spherical indenter pressure test is not a good method to determine on set of bruising in potatoes. The evidence clearly showed that by the time a hook is seen on the force-deformation curve, actually major localized bruise has already occurred. Therefore, the hook in the force-deformation curve is the indicator of severe localized bruise, not an indicator of onset of bruising. The measured contact pressure was much beyond the yield strength of the potato which resulted in a major localized tissue failure. Therefore, yield point may not be seen on the force-deformation curve as generated by spherical indenter pressure test. Particular potato variety must have an appropriate time for harvest. Keeping potatoes longer under the soil would not increase resistance to bruising.

6 MODELING BASED ON FINITE ELEMENT METHOD

The mechanisms of potato bruising are complicated due to combined stresses and strains. Slow compression causes a bruise to occur internally around the center region of the potato. Bruising also occurs close to the periphery under impact loading (Serif and Segerlind, 1976; Holt and Schoorl, 1983). Blackspots bruises are often found 2-7 mm below the skin of potato (Sawyer et al, 1960). The potato tissue failure is related to the induced stress in the material resulting from an applied load. It is important to know the intensity and the distribution of stresses under a given load in a tuber so that an inference about the tissue failure can be made (Chen et al, 1984).

Although biological materials fail abruptly, the strains develop before failure are larger than those in brittle materials. The deformation properties of potato tubers indicate that they can be considered as elastic, elasto-plastic or viscoelastic depending on the level of load, duration of loadings and the condition of the potatoes. Therefore, any mathematical constitutive relationship for biological material should be sufficient to explain elastic, viscoelastic or elasto-plastic behavior that occurs after a critical amount of strain has developed. Many researchers have mentioned that an analytical solution by idealization does not lead to meaningful results.

Many techniques have been used to study the response of fruits and vegetables to applied loads (Hamann, 1967; Miles et al, 1971; Horsfield, 1972). Instrumented sphere techniques (Siyami et al, 1988), photographic technique (Anazodo et al. 1983), finite element modeling (Sherif and Segarlind, 1976; De Baerdaemaker, 1975; Rumsay et al, 1974; Apaclla, 1973) and electron microscopy (O'Brien et al, 1984) have been used to study bruising of fruit and vegetables. Contact stresses occur during storage, handling and harvesting. Numerous research studies in the past indicated that potato bruising resulted from impact during harvesting and handling, but the exact mechanism of the potato tissue failure yet to be identified (Chen et al, 1984). Mathematical modeling and computer simulation seem capable of providing information on the failure mechanism of biological materials (Sherif and Segerlind, 1976). Researchers concluded that the finite element modeling can provide a better understanding of the bruising mechanism and may effectively be used to solve the contact problems (Fayu et al, 1989).

The objective of this section was to investigate contact pressure due to quasi-static loading that may cause tissue failure in fresh potatoes using finite element method.

6.1 Theoretical Considerations

6.1.1 Stress-Strain Relationship in Elasto-Plastic Domain

When a specimen is subjected to a loading that exceeds the yield point, a permanent plastic deformation occurs. The general strain increment equation can be written as $d\epsilon_{ij}=d\epsilon_{ij}^{e}+d\epsilon_{ij}^{p}$. where the superscripts e and p stand for plastic. The elastic part is related to general Hooke's law $\sigma_{ij}=\lambda\epsilon_{kk}\,\delta_{ij}+2\,\mu\epsilon_{ij}$ while the plastic part of the strain is related to the yield criteria $d\epsilon_{ij}=S_{ij}d\lambda$ or deviatoric stress, which is the difference between the actual normal stresses and hydrostatic pressure, $S_{ij}=\sigma_{ij}\text{-}S\,\delta_{ij}$, where,
S is the hydrostatic stress which equals $1/3\sigma_{ii}$. This is often called mean stress. The corresponding deviatoric strain is $e_{ij}=\epsilon_{ij}\text{-}\epsilon\delta_{ij}$. where $\epsilon=(1/3)\epsilon_{ii}$, $d\epsilon_{ij}^{p}=S_{ij}d\lambda$ and $d\lambda=(3/2)$

$d\bar{\epsilon}/\bar{\sigma}$. When a specimen reaches its yield stress at the inner boundary, a permanent plastic deformation occurs. Then the total deformation is the sum of elastic deformation and plastic deformation. As the load increases, the plastic region spreads outward until the specimen is completely in the plastic range plastic reaching an equilibrium with the outside loads.

The elastic strain increments are given by Hookes's law as follows:

$$d\epsilon_r^e=(1/E)[d\sigma_r-\mu d(\sigma_\theta+\sigma_z)]$$

$$d\epsilon_\theta^e=(1/E)[d\sigma_\theta-\mu d(\sigma_r+\sigma_z)]$$

$$d\epsilon_z^e=(1/E)[d\sigma_z-\mu d(\sigma_r+\sigma_\theta)]$$

The stress-strain relation, known as the Reuss equation is:

$$d\epsilon_r=E^{-1}[d\sigma_r-\mu d(\sigma_\theta+\sigma_z)]+\tfrac{1}{3}d\lambda(2\sigma_r-\sigma_\theta-\sigma_z)$$

$$d\epsilon_\theta=E^{-1}[d\sigma_\theta-\mu d(\sigma_r+\sigma_z)]+\tfrac{1}{3}d\lambda(2\sigma_\theta-\sigma_r-\sigma_z)$$

$$d\epsilon_z=E^{-1}[d\sigma_z-\mu d(\sigma_r+\sigma_\theta)]+\tfrac{1}{3}d\lambda(2\sigma_z-\sigma_r-\sigma_\theta)$$

where, E and μ are the modulus of elasticity and Poisson's ratio, respectively, and

$$d\lambda=d\epsilon_{ij}^p/\sigma_{ij}=\tfrac{1}{2}d\gamma_{ij}^p/\tau_{ij}$$

or $(d\epsilon_r^p-d\epsilon_\theta^p)/(\sigma_r-\sigma_\theta)$

or $(3/2)(d\epsilon^p/\sigma)$ where,

$$d\epsilon^p=\sqrt{(2/3)}\ d\epsilon_{ij}^p\ d\epsilon_{ij}^p$$

Yew (1956) defined strain from the geometry (fig. 6.1) as follows:

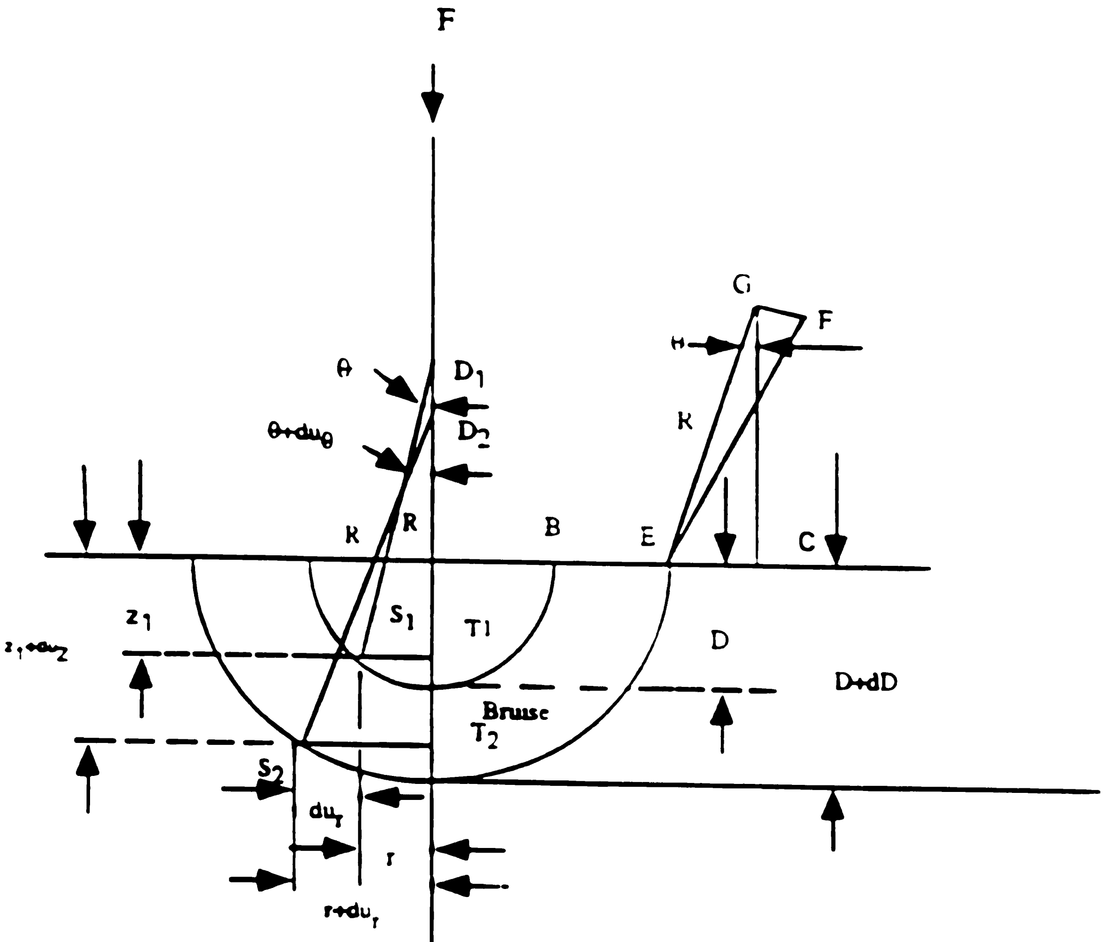

Figure 6.1 A theoretical bruise initiation model for soft material (Yew, 1956).

$$\epsilon_{rr}=\frac{D}{R}\frac{1-2\frac{r^2}{R^2}}{\sqrt{1-\frac{r^2}{R^2}}} \tag{6.1}$$

$$\epsilon_{\theta\theta}=\frac{D}{R}\sqrt{1-\frac{r^2}{R^2}} \tag{6.2}$$

$$\epsilon_{zz}=-\frac{D}{R}\frac{(2-\frac{3r^2}{R^2})}{\sqrt{1-\frac{r^2}{R^2}}} \tag{6.3}$$

D= displacement

R= radius of the potato or a sphere

r= contact radius.

From the deviatoric strain, ε_{zz}' can be written as:

$\epsilon_{zz}'=\epsilon_{zz}-(1/3)\epsilon_{zz}$

or

$\epsilon_{zz}'=(2/3)\epsilon_{zz}$

Due to the change in the bruise geometry in the plastic region, the total strain, e_{zz}^{p} can be written as:

$e_{zz}^{p}=\epsilon_{zz}-2/3\epsilon_{zz}$

$$e_{zz}^{p}=-\frac{1}{3}\frac{D}{R}\frac{2-\frac{3r^2}{R^2}}{\sqrt{1-\frac{r^2}{R^2}}} \tag{6.4}$$

From Levi-von Mises criteria for permanent deformation in plastic region

$$e_{zz}^{p}=\frac{3}{2}\left[\frac{\bar{\epsilon}}{\bar{\sigma}}\right]S_{zz} \tag{6.5}$$

S_{zz} = deviatoric stress

$\bar{\epsilon}$ = effective strain

$\bar{\sigma}$ = effective stress

e_{zz}^{p} = total strain in the plastic region

Combining (6.4) and (6.5), the deviatoric stress component, S_{zz} can be expressed as:

$$S_{zz}=-\frac{1}{3}\frac{D}{R}\frac{2}{3}\frac{\bar{\sigma}}{\bar{\epsilon}}\frac{\left[2-\frac{3r^2}{R^2}\right]}{\sqrt{1-\frac{r^2}{R^2}}} \tag{6.6}$$

From the definition of effective strain Yew, 1956 defined it as follows:

$$\bar{\epsilon}=\frac{2}{3}\sqrt{\left[\frac{1}{2}(\epsilon_{rr}-\epsilon_{zz})^2+(\epsilon_{rr}-\epsilon_{\theta\theta})^2+(\epsilon_{\theta\theta}-\epsilon_{zz})^2+\frac{3}{4}\gamma_{rz}^2\right]}\quad where,\gamma_{rz}^2=\frac{1}{4r^2} \tag{6.7}$$

After derivation of the expressions within the parentheses in equation 6.7, the following equations were obtained:

$$(\epsilon_{rr}-\epsilon_{zz})^2=\frac{1}{R^2}\frac{(25-\frac{90r^2}{R^2}+\frac{81r^4}{R^4})}{9(1-\frac{r^2}{R^2})} \tag{6.8}$$

$$(\epsilon_{rr}-\epsilon_{\theta\theta})^2=\frac{1}{R^2}\frac{r^4}{(1-\frac{r^2}{R^2})} \tag{6.9}$$

$$(\epsilon_{\theta\theta}-\epsilon_{zz})^2=\frac{1}{R^2}\frac{(1-\frac{2r^2}{r^2}+\frac{4r^4}{R^4})}{9(1-\frac{r^2}{R^2})} \tag{6.10}$$

Substituting (6.8), (6.9) and (6.10) in to

$\frac{1}{2}[(\epsilon_{rr}-\epsilon_{zz})^2+(\epsilon_{rr}-\epsilon_{\theta\theta})^2+(\epsilon_{zz}-\epsilon_{\theta\theta})^2]$ and simplifying it became:

$$\frac{25-\frac{90r^2}{R^2}+\frac{81r^4}{R^4}+9r^4+1-\frac{2r^2}{R^2}+\frac{4r^4}{R^4}}{18R^2(1-\frac{r^2}{R^2})} \tag{6.11}$$

By substituting the (6.11) in (6.7) becomes:

$$\bar{\epsilon}=-\frac{2}{3}\frac{1}{4R}\sqrt{\frac{20.11-81.77\frac{r^2}{R^2}+75.55\frac{r^4}{R^4}+8r^4+\frac{3R^2}{r^2}}{(1-\frac{r^2}{R^2})}} \tag{6.12}$$

Substituting (6.12) in to (6.6) yields:

$$S_{zz} = -\frac{4}{3}\bar{\sigma}\frac{(2-\frac{3r^2}{R^2})}{\sqrt{(20.11-81.77\frac{r^2}{R^2}+75.55\frac{r^4}{R^4}+8r^4+3\frac{R^2}{r^2})}} \quad \textbf{(6.13)}$$

and by multiplying and dividing the above (6.13) by r the final results of:

$$S_{zz} = -\frac{4}{3}\bar{\sigma}r\frac{(2-3\frac{r^2}{R^2})}{\sqrt{20.11r^2-81.77\frac{r^4}{R^2}+75.55\frac{r^6}{R^4}+8r^6+3R^2}} \quad \textbf{(6.14)}$$

obtained. The yield criteria for plastic deformation is, $\sigma_{zz}=S_{zz}+S$, where S is hydrostatic stress. If, it is assumed hydrostatic stress has no effect on yielding (according to von Mises), then, (6.14) is the maximum stress that cause yielding.

6.2 Finite Element Formulation

The region under consideration can be divided in to small segments called elements that are connected at the node points along the boundaries. The two unknown displacements u, v are approximated over each area or element by polynomials using parameters. The polynomials are as follows:

$u = \gamma_1+\gamma_2 r+\gamma_3 z+\gamma_4 r^2+\gamma_5 rz+....$

$v = \omega_1+\omega_2 r+\omega_3 z+\omega_4 r^2+\omega_5 rz+....$

where, $\gamma = \pi^2 q\ (a/2)(k_1+k_2)$

$k_1 = (1-\mu^2)/E_1$

$k_2=(1-\mu_2^2)/E_2$

$\omega = (1/2R_1 + 1/2R_2)$ and

q = pressure distribution over the contact area

E = modulus of elasticity

R_1 = radius of a tuber

R_2 = radius of the spherical indenter

u = horizontal displacement

v = vertical displacement

a = contact diameter

Plane strain:

The displacement in each linear element can be expressed in terms of shape function as follows:

$u = [N][U]$

Where,

[N] = shape function relating the element's displacement u and v to the nodal displacement.

$u = N_i u_{2i-1} + N_j u_{2j-1} + N_k u_{2k-1}$

$v = N_i v_{2i} + N_j v_{2j} + N_k v_{2k}$

where, the shape functions are as shown below:

$N_i = (a_i + b_i x + c_i y)/2A_o$

$N_j = (a_j + b_j x + c_j y)/2A_o$

$N_k = (a_k + b_k x + c_k y)/2A_o$

$a_i = X_i Y_k - X_k Y_i$

$b_i = Y_j - Y_k$

$c_i = X_k - X_j$

A_o= Original area of an element.

According to Sherif et al. 1976 hydrostatic pressure can be defined as $H=(3/2)\ \sigma/G(1+\mu)$ where σ, μ and G are normal stress, poisson ratio and shear modulus respectively. The mean hydrostatic pressure can be written in terms of each nodal value (shape function).

$h=[N]\{H\}$ where $H^T=\{H_i\ H_j\ H_k\}^T$ and $[N]=[N_i\ N_j\ N_k]$

Axisymmetric strain can be written as,

$\epsilon_{nm} = (1/2)[(\partial u_n/\partial x_m)+(\partial u_m/\partial x_n)+(\partial u_l/\partial x_n)(\partial u_l/\partial x_m)]$ where n, m, l takes the values 1, 2.. and $\epsilon_{13}=0$ and $\epsilon_{33}=(1/2)(\lambda^2-1)$ and $\lambda= 1+(U/r)$. U = length of deformed circumference and r= original length.

Now,

$$\epsilon_{rr} = (\partial u/\partial r)+(1/2)[(du/dr)^2+(dw/dr)^2]$$

$$\epsilon_{\theta\theta} = (u/r)+1/2(u/r)^2.$$

$$\epsilon_{zz} = (\partial w/\partial z)+[(du/dz)^2+(dw/dz)^2]$$

Shear strain:

$$\gamma_{rz} = (\partial u/\partial z)+(\partial w/\partial r)+(\partial u/\partial r)(\partial u/\partial z)+(\partial w/\partial r)(\partial w/\partial z).$$

Sherif (1976) cited the elastic field equation given by Herman and Toms (1964)

$\tau_{ij}=\lambda\epsilon_{kk}\delta_{ij}+2G\epsilon_{ij}(3\lambda+2G)$

where,

λ, G are the Lame's constant

μ = Poisson's ratio

τ_{ij} = total stress

The mean effective pressure

$\sigma = ⅓\tau_{kk}$

or $\sigma = ⅓(3\lambda + 2G)\epsilon_{kk}$, If $\lambda = 2G\mu/(1\text{-}2\mu)$, then

$\sigma = ⅔G(1+\mu)\epsilon_{kk}/(1\text{-}2\mu)$. By substituting G in the above equation, finally τ_{ij}, becomes:

$\tau_{ij} = (3\ \sigma\mu\ \delta_{ij})/(1+\mu) + 2G\epsilon_{ij}$.

The relation between mean effective pressure and hydrostatic pressure, H

$H = \tau_{kk}/E = 3\sigma/[2G(1+\mu)]$

Total stress, $\tau_{ij} = G[(2\epsilon_{ij}\text{-}\epsilon_{kk}\delta_{ij}) + GH\delta_{ij}]$

or $\tau_{ij} = 2G\epsilon_{ij} + 2\mu GH\delta_{ij}$

For an incompressible material, stress-strain relation is

$\tau_{ij} = 2G\ \epsilon_{ij} + \sigma_{ij}$. This can be written in matrix form as follows:

$[\tau] = [D]\{E\}$.

Strain and elasticity can be written in matrix form as :

$[\epsilon] = [B_o]\{q\} + [B_G]\{q\}$ and

$[E] = [B]\{q\}$. Strain component can be expressed in terms of displacement as

$\epsilon_{xx}{}^2 + \epsilon_{yy}{}^2 + ½\gamma_{xy} = \{q\}^T[I][B]\{q\}$

and $\epsilon_{xx} + \epsilon_{yy} = \{q\}^T[B]^T(J)$

The governing equation for an element is:

$[k]\{\phi\} = \{p\}$ where, $\phi = [q/H]$ and $[p] = \{q/0\}$, $\phi =$ nodal values. q=unknown displacement.

$[K]=$ Global stiffness matrix

$[k_{11}]=2G\int_v[B]^T[I][B]dv$

$[k_{12}]=2\mu G\int_v[B]^T\{J\}[n]dv$

$[k_{22}]=-2\mu G(1-2\mu)\int[N]^T[N]dv$

Force matrix, $Q=\int_v[N]\{F\}dv+\int_s^1[N]^1\{T\}ds_1$

Element stresses are $[\tau]=2G[I]\{\epsilon\}+2\mu Gh\{J\}$, where $h=[N][H]$ and $J^T=[1\ 0\ 0]$

$[\sigma]=2G[I][B]\{q\}+2\mu G[N]\{H\}\{J\}$. For axisymmetric cases, element stresses can be expressed in terms of matrix form as follows:

$$\sigma=E(1+\mu)/(1+\mu)(1-2\lambda)\begin{bmatrix}1 & \mu/(1-\mu) & \mu/(1-\mu) & 0 & \epsilon_z\\ \mu/(1-\mu) & 1 & \mu/(1-\mu) & 0 & \epsilon_r\\ & & 1 & 0 & \epsilon_\theta\\ & & & 1 & -2\mu/2(1+\mu)\epsilon_{rz}\end{bmatrix}$$

Plastic Stress-Strain matrix

In Prandtl-Reuss stress-strain relation, the strain increment, $d\epsilon_{ij}$, is related to the stress-increment, $d\sigma_{ij}$. The relation together with the differential form of the von Mises yield criteria can be represented in matrix form by

$$\{d\epsilon\}=[C^p]\{d\sigma\}$$

where $\{d\epsilon\}$ and $\{d\sigma\}$ are the column matrices of $d\epsilon_{ij}$ and $d\sigma_{ij}$ respectively. Similarly, from the above equation, stress increment can be written as

$$\{d\sigma\}=[D^p]\{d\epsilon\} \text{ where } [D^p]=[C^p]^{-1}.$$

'p' stands for plastic.

Matrix formulation:

For the isotropic, elastic material, stress by Hooks law

$$\{\sigma\} = E[D^e]\{\epsilon\}$$

$$= 2(1+\mu)G[D^e]\{\epsilon\}$$

where $\{\sigma\}$ and $\{\epsilon\}$ are the column matrices of stress, σ_{ij} and strain, ϵ_{ij} respectively, and $[D^e]$ represents the 6X6 symmetric matrix which is:

$$[D^e] = 1/(1+\mu) \begin{bmatrix} 1-\mu/1-2\mu & \mu/1-2\mu & \mu/1-2\mu & 0 & 0 & 0 \\ \mu/1-2\mu & 1-\mu/1-2\mu & \mu/1-2\mu & 0 & 0 & 0 \\ \mu/1-2\mu & \mu/1-2\mu & 1-/1-2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2 \end{bmatrix}$$

E, G and μ are the Young's modulus, torsion modulus and Poisson's ratio respectively.

Plane stress this can be written as:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = E[D^e] \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \tau_{xy} \end{Bmatrix}$$

$$\text{and } [D^e] = (1/1-\mu^2) \begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & (1-\mu)/2 \end{bmatrix}$$

An expression for plastic stress-strain was developed by Yamada(1967) as described below. His assumption was that the plastic deformations are incremental.

The Prandtl-Reuss equations for the deviatoric strain-increment $d\epsilon_{ij}'$ during loading is

$$d\epsilon_{ij}'=\sigma_{ij}'d\lambda+(d\sigma_{ij}'/2G)$$

where, $d\lambda=(3/2)\ d\bar{\epsilon}^p/\bar{\sigma}\ =\ (3/2)(d\bar{\sigma}/\bar{\sigma}\ H')$, $\bar{\sigma}$ and $d\bar{\epsilon}^p$ are the equivalent stress and plastic strain increment, respectively. These can be written as follows

$$\bar{\sigma}=\sqrt{(3/2\ \sigma_{ij}'\sigma_{ij}')}\text{ and }d\bar{\epsilon}^p=\rangle\ (2/3 d\epsilon_{ij}^p d\epsilon_{ij}^p)$$

$H'=d\bar{\sigma}\ /d\bar{\epsilon}^p$ is the slope of the equivalent stress to plastic strain, $(\int d\bar{\epsilon}^p)$

The von Mises yield criterion and its differential form is given below as:

$$\sigma_{ij}'\ \sigma_{ij}'=2/3\bar{\sigma}^2$$

$$\sigma_{ij}\,d\sigma_{ij}'=2/3\ \bar{\sigma}d\bar{\sigma}$$

$$=4/9\ \bar{\sigma}^2\ H'\ d\lambda.$$ By eliminating $d\sigma_{ij}'$ from the above equation it becomes as follows,

$$2G\sigma_{ij}'(d\epsilon_{ij}'-\sigma_{ij}'d\lambda)=4/9\ \bar{\sigma}^2\ H'd\lambda\text{ from which}$$

$$d\lambda=\sigma_{ij}'\ d\epsilon_{ij}'/S$$

$$=\sigma_{ij}'d\epsilon_{ij}/S$$

where, $S=2/3\bar{\sigma}^2\ (1+H'/3G)$.

$\sigma_{ij}'d\epsilon_{ij}'=\sigma_{ij}'=\sigma_{ij}'d\epsilon_{ij}$. Since, $\sigma_{ii}'=\sigma_x'+\sigma_y'+\sigma_z'=$ identically zero and by putting $d\lambda$ and $d\epsilon_{ij}'$, the deviatoric strain increment can be written as

$$d\epsilon_{ij}'=d\epsilon_{ij}-\delta_{ij}d\epsilon_{ii}/3$$

$$d\epsilon_{ii}=d\epsilon_x+d\epsilon_y+d\epsilon_z.$$

and deviatoric stress increment, σ_{ij}' can be written as follows:

$$d\sigma_{ij}'=2G[d\epsilon_{ij}'-\sigma_{ij}'\ (\sigma_{kl}d\epsilon_{kl})/S].$$

$$=2G[d\epsilon_{ij}-(\delta_{ij}d\epsilon_{ii})/3-(\sigma_{ij}'\sigma_{kl}'d\epsilon_{kl})/S].$$

The identity $\sigma_{ij}' d\epsilon_{ij} \equiv \sigma_{kl}' \, d\epsilon_{kl}$. The total stress increment $d\sigma_{ij}$ by definition

$$d\sigma_{ij} = d\sigma_{ij}' + E/\{3(1\text{-}2\mu)\}\delta_{ij} d\epsilon_{ij}.$$

$$d\sigma_{ij} = d\sigma_{ij}' + ⅔(1+\mu)G/(1\text{-}2\mu)\delta_{ij} d\epsilon_{ii}.$$

After manipulation, Yamada (1967) found the folowing equation,

$$d\sigma_{ij} = 2G(d\epsilon_{ij} + \mu/\{1\text{-}2\mu\} \ \delta_{ij} d\epsilon_{ii} \text{-} \sigma_{ij}' \ \sigma_{kl}' d\epsilon_{kl}/S)$$

This equation can be written in matrix form as:

$$\{d\sigma\} = E[D^p]\{d\epsilon\}$$

or $\{d\sigma\} = 2(1+\mu)G[D^p]\{d\epsilon\}$. This is equivalent to the first equation in page 142. Yamada (1967) called this as elasto plastic analysis where D^e was replaced by D^p for yielded elements. The plastic Sress-strain matrix $[D^p]$ is symmetric.

6.3 Model Development

A commercial finite element program called MARC was used to create the model and to determine the contact stresses. The tuber size, shape and composition influence bruise susceptibility of potato tubers (Hugh, 1980). Jasan et al. (1988) stated that the size of bruise is not important to predict tuber quality. Therefore, size of bruise was not considered in the models. The potato properties used in the model were modulus of elasticity, Poisson's ratio, mass density and potato size. The selection of proper number of elements in a model was made by trial and error. Several mesh generations were accomplished. The number of elements used to construct the model were 90, 100, 120 and 136. The models were run to ascertain that the output values of contact stress were within the acceptable error limit (6%) compared to the analytical solution as described by Timoshenko et el. (1970). The preliminary simulation results show that the whole tuber model consisting of 136 elements was found within the acceptable accuracy of output compared to the analytical and experimental values. Two varieties namely, *Superior* and *Snowden* potatoes, were considered for simulation.

The Poisson's ratio was taken as 0.49 (Finney et al, 1967). The Young's modulus and deformations were predetermined by core tests on the Instron testing machine in the laboratory. The modulus of elasticity taken were (426 psi) 2.94 MPa and (410 psi) 2.82 MPa for *Superior* and *Snowden* potatoes, respectively. The mass density of potatoes was taken 1.01 g/cm^3. These data were entered in the core model to test its response. The average displacement of the core specimen of Superior potatoes at yield was 7.6 mm (0.30 inch, SD 0.02) and for Snowden potatoes was 6.3 cm (0.25 inch, SD

0.03), respectively. The average displacement of a whole Superior potato was 10.16 mm (0.40 inch, SD 0.03) and 10.67 mm (0.42 inch, SD 0.05) for *Snowden*, respectively, as obtained by the compression tests. These data were used in the whole models to test its response:

6.3.1 Core Model

To verify finite element model, a finite element model of a cylindrical potato core was formulated. The core model was constructed with 100 quadrilateral elements The fixed boundary conditions were applied. The nodes on the y-axis has no displacement in x-direction and nodes on the x-axis has no displacement on y-direction. The core model was subjected two predetermined deformation of 7.6 mm (0.30 inch)for *Superior)* and 6.35 mm (0.25 inch) for *Snowden*, respectively to verify stress, strain, and force at yielding. The solutions were compared with the calculated and the values obtained from the laboratory experiments.

6.3.2 Whole Tuber Model

The tuber was considered an axisymmetric sphere, therefore, only one quarter of the structure was needed to model and analyze quasi-static contact stresses. The radius of each model was 40.6 mm (1.6 inch) with skin. It was assumed skin had no effect. The model loading was compression by a spherical indentor of 22.22 mm (7/8 inch) diameter. A deformation of 10. 16 mm (0.40 inch, for *Superior*) and 10.67 mm (0.42 inch, for *Snowden*), were imposed to the model for analysis. These deformation values were obtained experimentally and correspond to tissue failure.

A deformation equal to (0.20 inch) 5.08 mm was applied to the model to predict corresponding, stresses, deformation, and von Mises stress in *Superior* potato model. This model represents Snowden whole potatoes.

6.4 Results and Discussion

6.4.1 Core Model

The original shape of core model with mesh and elements is shown in figure 6.2. The corresponding deformation, yield stress, strain and yield force due to imposed deformation of 7.62 mm (0.30 inch, *Superior*) are shown in figures 6.3, 6.4, 6.5 and 6.6, respectively. The predicted FEM stress, strain and yield force were 0.96 MPa (138.80 psi), 7.62 mm (0.30 inch) and 18.73 kg, (41.22 lb), respectively. The calculated stress, strain and yield force due to a displacement of 7.62 mm (0.30 inch) were 0.96 MPa (139.93 psi), 7.87 mm (0.31 inch) and 18.40 kg (40.50 lb), respectively. The error among FEM and calculated and measured values were within 1% (table 6.1). These results verify the model.

Similarly, for an imposed deformation of 0.63 cm (0.25 inch, *Snowden*) which the model predicted stress, strain and force as follows: 0.73 MPa (105.60 psi), 6.3 mm (0.25 inch) and 14.25 kg (31.36 lb), respectively. The calculated stress, strain and yield forces were 0.73 MPa (105.67 psi), 6.3 mm (0.25 inch) and 14.10 kg (31 lbs), respectively. The results are shown in table 6.1. The error is within 1%. Therefore, these findings were verified by the finite element results.

6.4.2 Whole Tuber Model

The whole tuber model of the *Superior* variety with 136 elements and mesh is shown in figure 6.7. The model was tested for a predetermined displacement of 10.16

Force

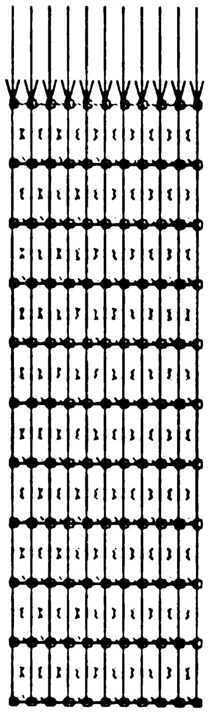

Figure 6.2 A FE model of a cylindrical core of potato with 100 elements mesh and force applied to it.

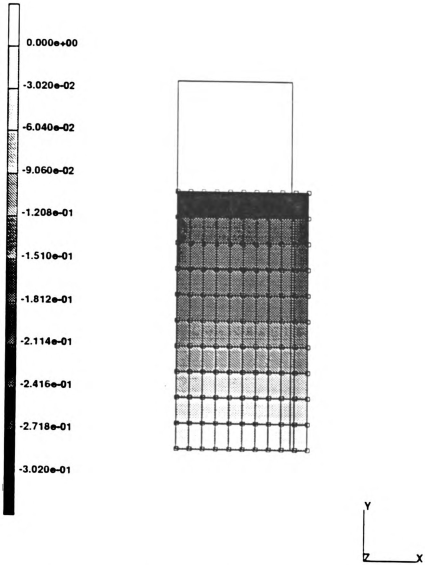

Figure 6.3 The original and deformed *Superior* core model with a deformation of 7.62 mm (0.30 inch). The scale shows on the left deformation in inch.

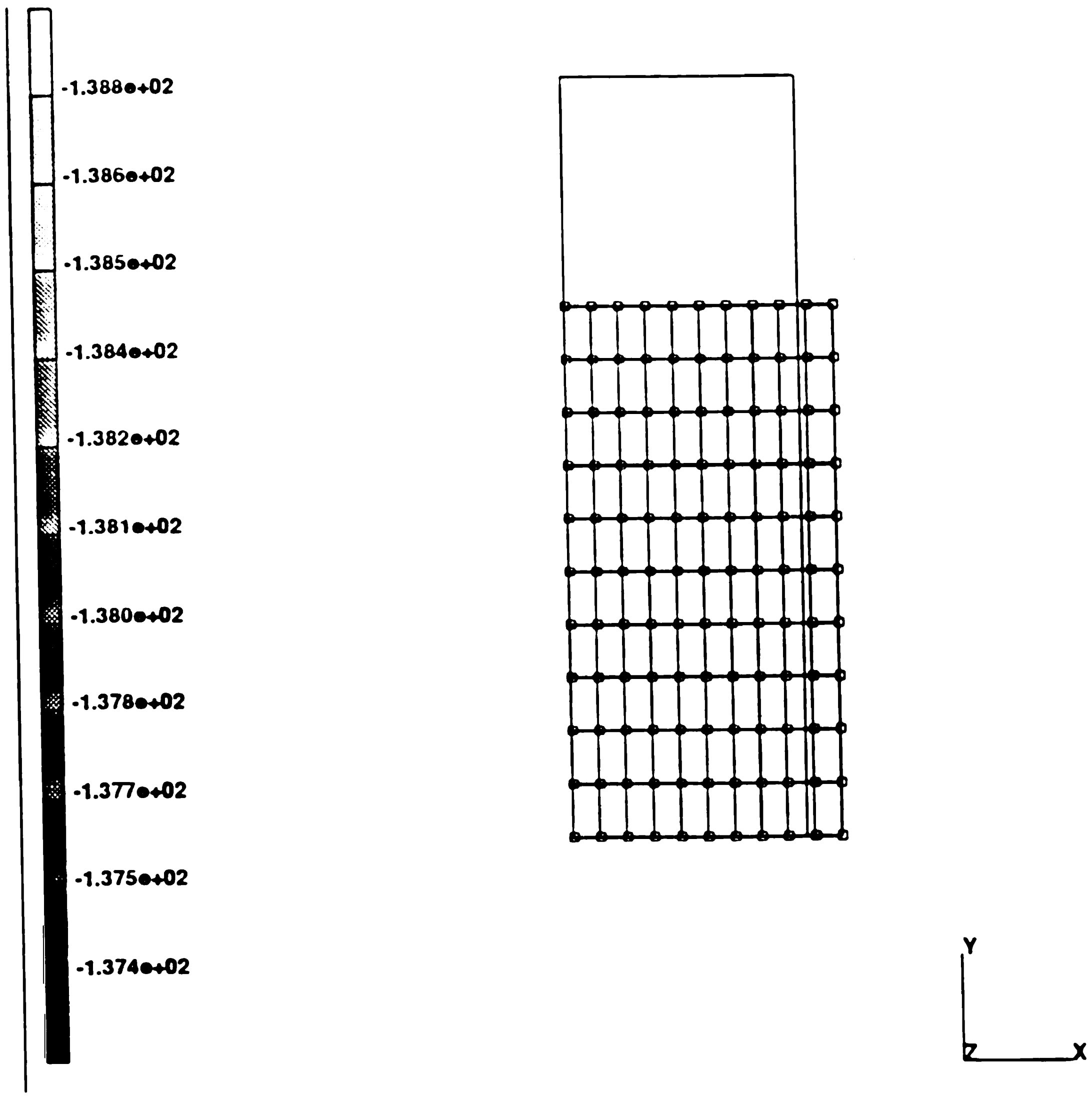

Figure 6.4 The stress(σ_2) in the core model due to an imposed deformation of 7.62 mm (0.30 inch). The scale on the left shows stress in psi.

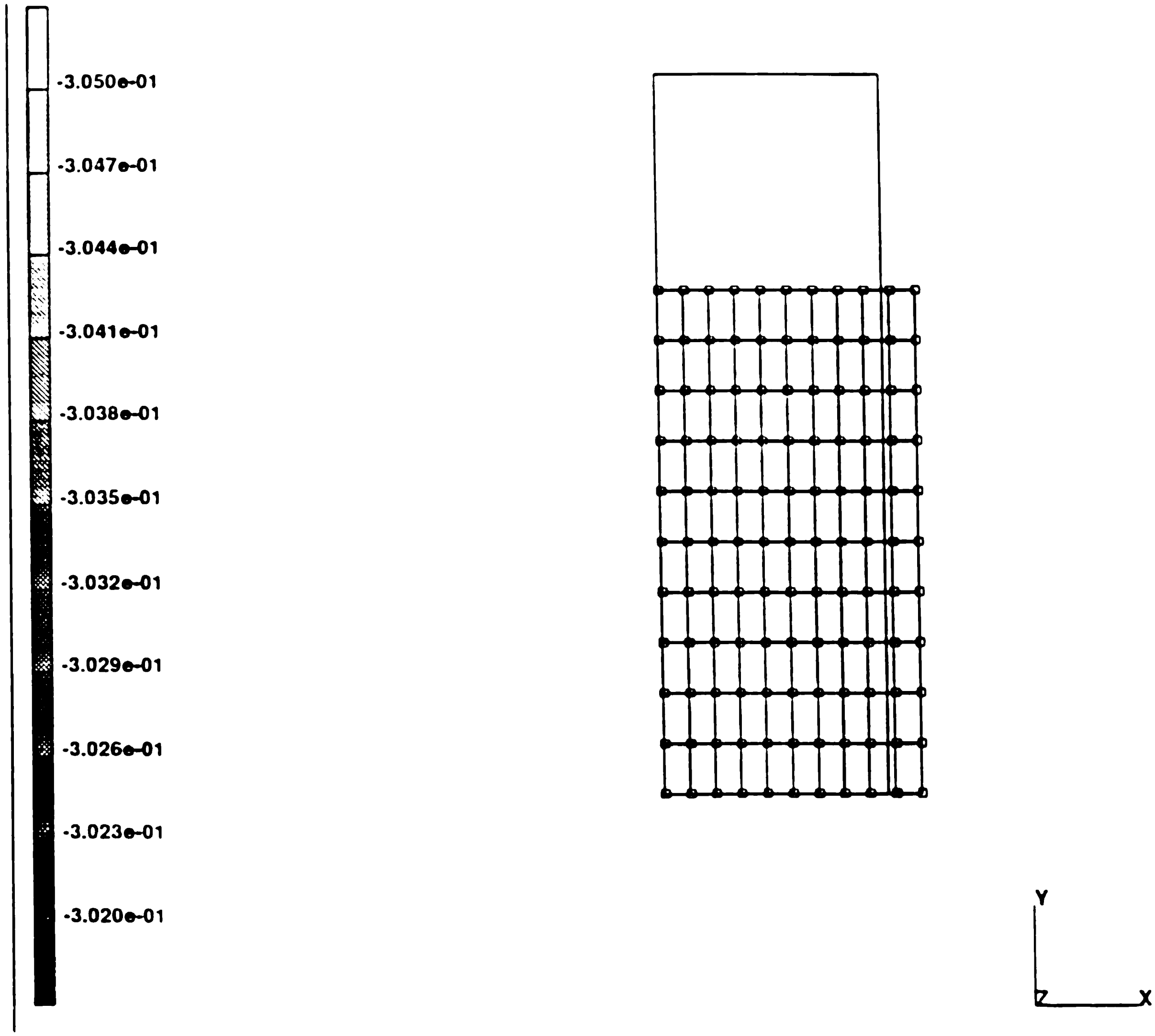

Figure 6.5 The strain in the core model due to an imposed deformation of 7.62mm (0.30 inch). The scale on the left shows in/in.

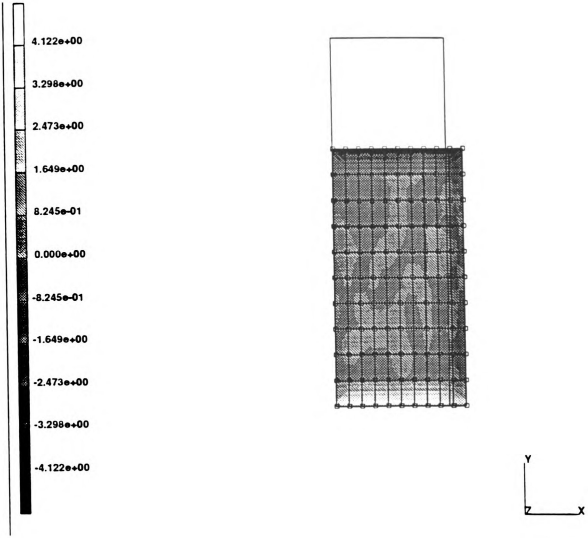

Figure 6.6 The yield force of the core due to an imposed deformation of 7.62 mm (0.30 inch). The scale on the left shows force in lb.

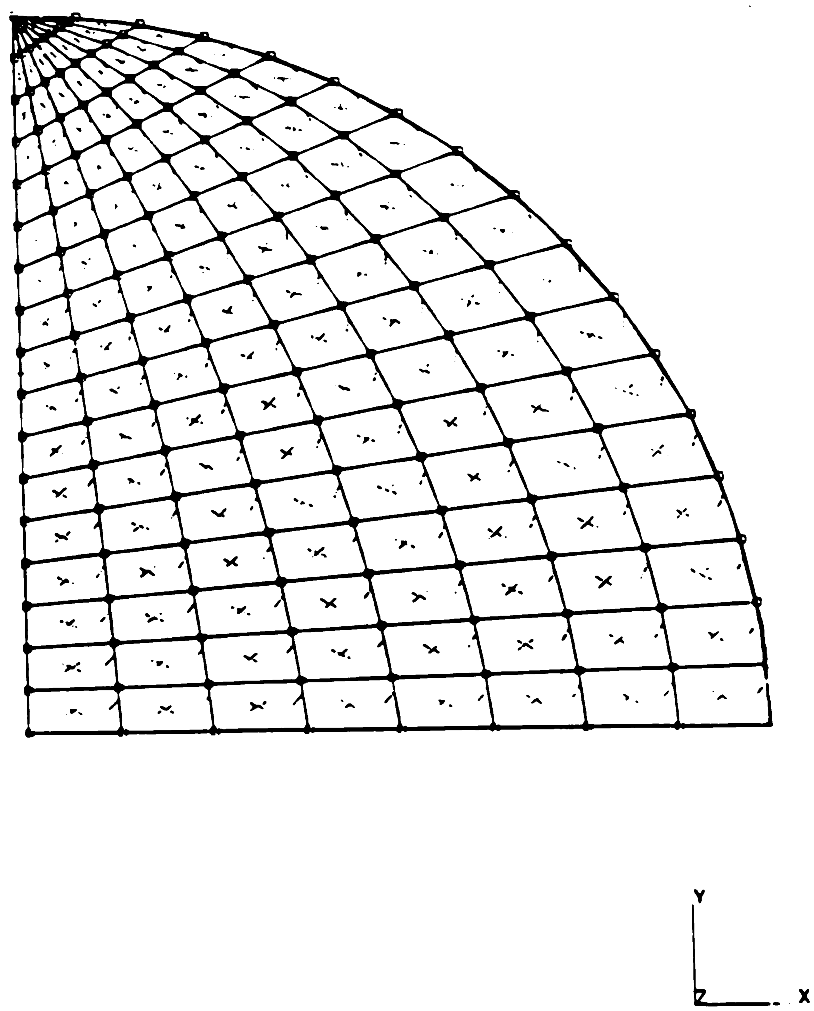

Figure 6.7 The whole (*Superior/Snowden*) tuber model with 136 elelments and mesh.

mm (0.40 inch) (*Superior*, fig 6.8) by the spherical indenter. The resulting contact stress 2.51 Mpa (363.80 psi) and von Mises yield stress 1.80 MPa (261.80 psi) were measured from the figures 6.9 and 6.10, respectively. The yield stress of *Superior* variety was 0.95 MPa (138.22 psi). The predicted von Mises stress was 1.89 times higher than the yield stress. This indicated that the tubers were severely stressed which can easily be visualized from the von Mises stress contour bands shown in figure 6.10. All four elements along the ordinate were above their yield stress indicating that elements yielded. The elements just below the surface and near the top were highly stressed 2.50 MPa (363.80 psi). This situation resembled the actual collapse of the tubers observed during experiments. The calculated, measured, and predicted stresses were 2.53 Mpa (367.64 psi), 2.50 MPa (363.37 psi) and 2.51 MPa (363.80 psi), respectively (table 6.2). The error was within 2% which is in good agreement. The results verify the FEM model (table 6.2).

The model of Snowden variety was subjected to 10.67 mm (0.42 inch) of deformation (shown in appendix F.2). The corresponding bruising contact stress as predicted by the model was 2.37 MPa (344.00 psi), whereas by analytical method, the contact stress was 2.38 MPa (345.27 Psi). The predicted von Mises stress was 1.73 MPa (251 psi) which was 2.37 times higher than the yield stress. The stress condition was similar to the previous models. The errors was within 2%.

When, a deformation equal to 5.08 mm (0.20 inch) (fig. 6.11) was imposed, the model predicted a contact stress of 1.04 MPa (150.90 psi) (fig. 6.12) which was higher than the dynamic bruising contact pressure of the *Superior* variety. The corresponding

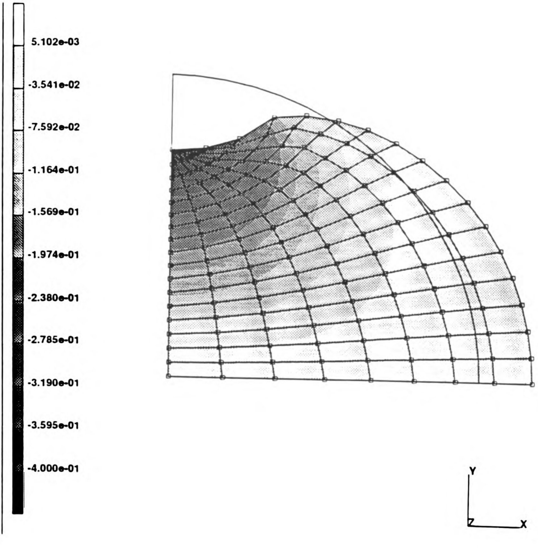

Figure 6.8 The model for Superior variety shows the displacement bands as a result of 10.16 mm (0.40 inch) imposed deformation. The scale shown on the left is in inch.

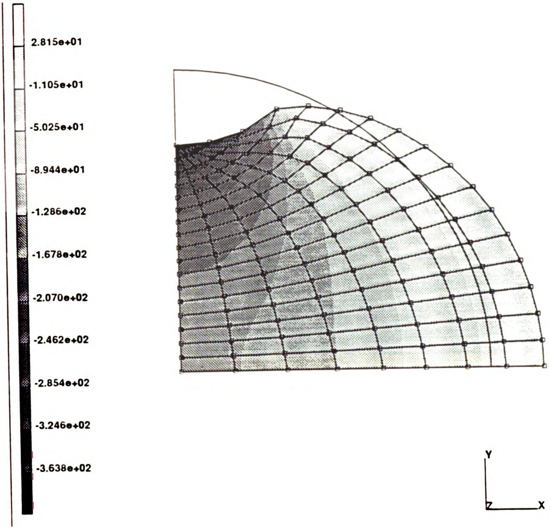

Figure 6.9 The contour stress band (σ_2) due to imposed deformation of 10.16 mm (0.40 inch) in the *Superior* whole potato model. The scale on the left shows stress in psi.

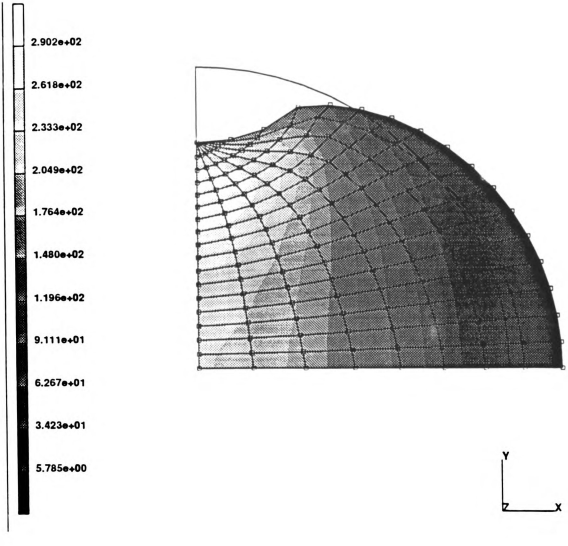

Figure 6.10 The rsulting von Mises stress distribution with contour bands. The scale on the left shows von Mises stress in psi.

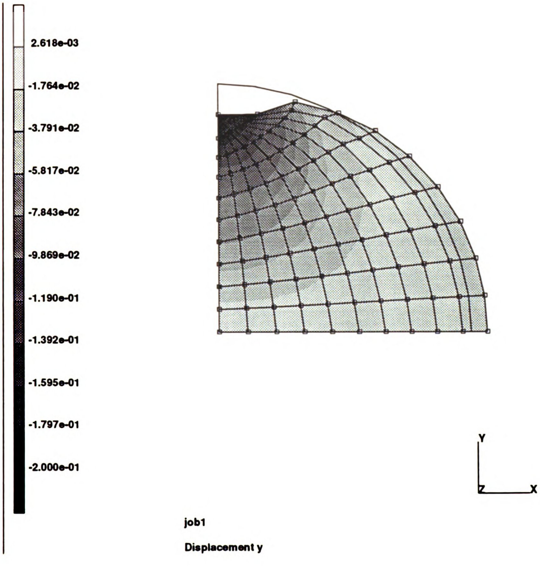

Figure 6.11 The resulting displacement of the *Superior* potato model due to imposed 5.08 mm (0.20 inch) deformation. The scale on the left shows displacement in inch.

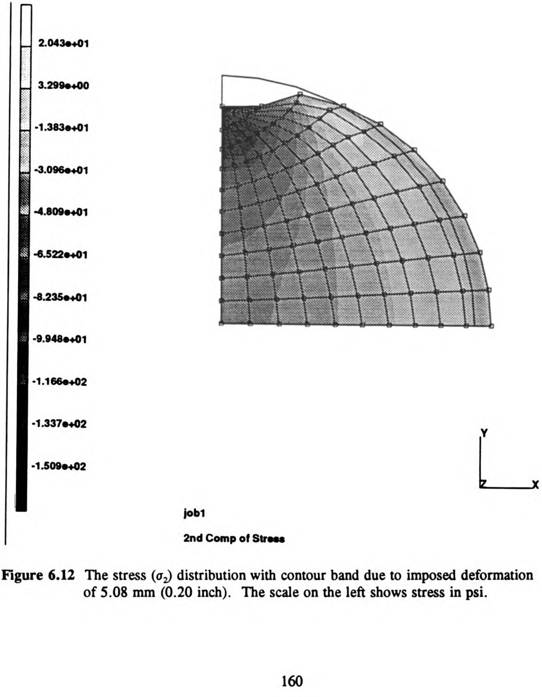

Figure 6.12 The stress (σ_2) distribution with contour band due to imposed deformation of 5.08 mm (0.20 inch). The scale on the left shows stress in psi.

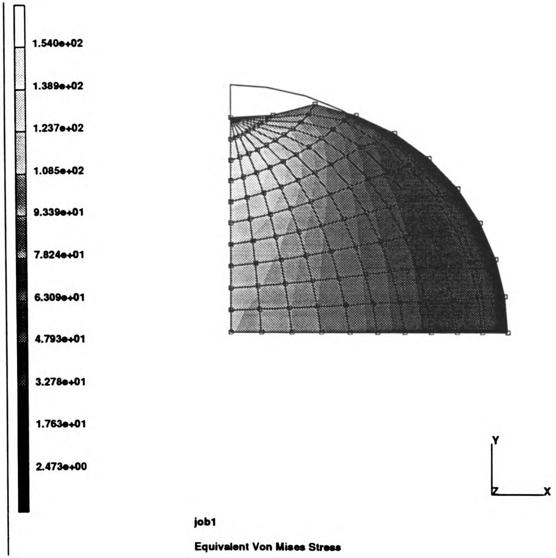

Figure 6.13 The resulting von Mises stress distribution with contour bands due to imposed deformation of 5.08 mm (0.20 imch). The scale on the left shows stress in psi.

contour bands of von Mises stresses are shown in figure 6.13. From figure 6.13, it can be seen that the calculated maximum von Mises stress was 0.96 MPa (138.90 psi) which is equal to the yield stress as found by core testing. This would result in tissue failure and blackspot bruising in region where von Mises stress exceed or equal the yield strength. From the contour band (fig. 6.13) the location of the concentrated von Mises stress can be seen clearly at 5.08 mm below the surface of the model. The experimental data indicate that the blackspot occurred was 2-7 mm below the skin in fresh tubers as shown in figure 6.14. This has been reported by many researchers (Sawyer, 1960; Scuder, 1950; Hughes, 1980; Chase, 1987). These results indicate that, the contact stress that cause blackspot bruising under impact loading is higher than that found under static loading. It can be safely extrapolated that if the contact stresses exceed the yield strength, the blackspot bruise depth would extend from the surface to the point where the von Mises equal the yield strength of potato tissue.

6.5 Conclusions

Finite Element Method can be used to study distribution of stresses in a loaded potato tuber. The capability of FEM to produce pictorial illustration help in understanding stress distribution in a loaded model. The von Mises stress distribution shows the location of the highly stressed element where tissue failure occurs. The Location was found at 5.08 mm below the surface of the potato model. The failure occurs when von Mises stress is equal or higher the yield strength of potato. von Mises stress can be used to investigate the tissue failure and its location in a loaded potato. The static contact stress causing bruising being lower than those for impact condition.

Figure 6.14 A distinct blackspot bruise found approximately at 5-6 mm below the contact surface of an affected potato tuber.

Table 6.1 Simulation of uniaxial compression and force at yield deformation of cores of *Superior* and *Snowden* potatoes.

Superior Potatoes	Stress σ_2 (psi)	Deformation Δ (in)	Strain ϵ_1 (in/in)	Force F (lb)
FEM	138.80	0.30	0.30	41.22
Analytical	139.93	0.31	0.31	40.50
Experimental	138.22 (10.52)	0.31 (0.02)	0.31	40.50 (3.08)
Snowden potatoes	-	-	-	-
FEM	105.60	0.25	0.25	31.36
Analytical	105.67	0.25	0.25	31.00
Experimental	105.65 (11.44)	0.25 (0.03)	0.25	30.96 (3.35)

Note: Numbers in the parenthesis are standard deviation

Table 6.2 Verification of measured quasi-static contact pressure on a whole potato with the pressure predicted by FEM.

Superior potatoes	FEM	Analytical	Experimental
Maximum contact pressure	(363.80 psi) 2.51 MPa	(367.64 psi) 2.53 MPa	(362.37 psi) 2.49 MPa
Snowden potatoes	-	-	-
Maximum contact pressure	(344.00 psi) 2.37 MPa	(345.27 psi) 2.38 MPa	(339.52 psi) 2.34 MPa

7 SUMMARY AND CONCLUSIONS

7.1 Summary

Potato bruising is a complex process involving tissue failure due to induced stress followed by bio-chemical reactions that form blackspot. The study described in this dissertation discusses many aspects of potato bruising.

It is difficult to identify internal bruise in a potato tuber. Therefore, it was essential to develop a technique to identify bruise before any further study could begin. Five strengths of tetrazolium chloride solutions were prepared. Five groups consisting of 3 tubers in each group were impacted at 10 cm drop height. Each group of tuber was dipped into the assigned solution for 1, 2, 4, 8, or 10 hrs. The tubers were removed after the assigned period and peeled to find pink coloras an indicator of internal bruise. Eight hours of submerging showed distinct pink color at the internal bruised area. The strength of this solution was 1 gallon of distilled water at 30° C mixed with 3.5 g of tetrazolium chloride. This method was used to identify internal bruises for the entire study.

Dynamic contact pressure developed between the potato and impacting surface was measured by dropping the tuber once onto a pressure sensitive film attached to a steel platform. The pink color density of the pressure sensitive film indicated the contact pressure. The film color was digitized using a computer vision system and the corresponding contact pressure was determined from the calibration curve. The impacted tubers were categorized as bruised and unbruised groups. It was found that as the potential energy increased the contact pressure also increased to certain extent. Further inrease in potential energy caused bruising but no further increase of contact pressure was observed. The bruised tubers had higher contact pressure than that of the unbruised tubers. It was found that there existed a threshold contact pressure when tubers started to bruise internally. These were 148.86 psi (1027.60 kPa) for *Superior* and 127.73 psi (880.89 kPa) for the *Snowden* potatoes.

In order to determine the relationship between contact pressure and mechanical properties, the tubers used for free fall impact were also used for mechanical properties tests. The modulus of elasticity, yield stress, yield strain, and strain energy were determined by performing a compression test on a core sample. A 2.54 cm (1 inch) long and 1.54 cm (0.61 inch) diameter core was cut out of each impacted tuber using a metallic cylindrical borer. The core was compressed on an Instron testing machine until it failed at a loading rate of (5 in/min) 12.70 cm/min. The differences of modulus of elasticity, yield stress and strain, and strain energy of the bruised groups of *Superior* variety were significantly higher than that of the *Snowden* variety.

To determine the correlation between drop height and ppo activity, the ppo activity of all impacted tubers (bruised and unbruised) was measured and compared. A small piece of impacted tissue from the stem end was taken after 24 hrs of incubation. The tissues were mixed with buffer (pH 6) to stabilize enzymes and blended in an electric blender for 15 seconds and filtered. Acetone of-20° C was added to precipitate enzyme.

The enzyme was diluted with sodium acetate and calcium chloride solution respectively to precipitate any pectin. The mixture was centrifuged at 10,000 rpm to separate impurities from the enzyme. The substrate catechol was added to the samples of the extracted enzymes for activities test. The ppo activity of enzymes for 3 min tests was performed in a Spectrophotometer. The activity was measured by the rate of change of color formation in the solution. The activities (oxygen uptake) was determined from the slope of the reaction curve. It was found that the ppo activities of bruised potatoes was significantly higher than that of unbruised potatoes in both variety. There existed a high correlation between the drop height and ppo activity of bruised potatoes. The ppo activity of bruised *Snowden* potatoes was significantly higher than that of the *Superior* potatoes. Increasing drop heights caused more bruising of the susceptible variety releasing more substrate that resulted in higher ppo activities.

The color of the extracts of bruised or unbruised potatoes were the direct results of the ppo activities. The measure of the color density is the optical density an absolute value. According to Mapson (1963) concentration of PPO (tyrosinase) and enzymatic browning of bruised potatoes were closely related. Dean's et al. (1993) method was used to determine bruise susceptibility of potatoes using optical density. First, extracts of each bruised group of potatoes was tested for color formation as measured by optical density to determine bruise susceptibility. Tissues from bud-end and impacted stem-end in equal amount was taken and mixed with potassium phosphate buffer to stabilize enzyme during extraction. The tissues were blended immediately in a high speed electric blender. The mixture was filtered and left 24 hrs for open air oxidation in a room temperature. The oxidized filtrate became dense black (bruised groups). This filtrate was centrifuged at 10,000 rpm for 30 min. A quantity of 10 ml homogenized filtrate was diluted 1:3 ratio and measured for optical density (unbruised and bruised) in a Spectrophotometer. It was found that the differences of optical density of bruised and unbruised groups of tubers at all drop heights were significant in both varieties. The results show that bruised *Snowden* variety had significantly higher optical density than that of the *Superior* variety. This was expected since ppo activity of *Snowden* variety was significantly higher than that of the *Superior* variety which resulted in higher optical density. This indicated that the bruised *Snowden* variety had higher amount of substrate (phenol) than of the *Superior* variety. Optical density and ppo activity were highly correlated. Therefore, optical density may be used to determine bruise susceptibility of a variety. The optical density method is simple and easy unlike measuring ppo activity. According to Dean's et al. (1993) bruise susceptibility scale the *Superior* variety was ranked as "Moderately resistant" and *Snowden* variety as "Susceptible".

In order to understand the role of minerals in bruising, the mineral contents of each potato was determined in the laboratory. A small quantity (30 g) of tissues from each impacted tuber was collected and oven dried at 75° C for 72 hrs. The dried samples were ground and Calcium, Copper and Potassium contents were determined by the Soil Testing Laboratory at MSU. The differences of the amount of Potassium, Calcium and Copper between the varieties was found to be significant. The difference of Ca, K and Cu contents between the bruised and unbruised potatoes were insignificant in both varieties. Therefore, the contribution of minerals on bruising was unclear.

The onset of bruising or Internal bruising can not be detected by pressing a spherical indenter into a potato. The hook in the force-deformation curve indicates only a major localized tissue failure and there was no indication of onset of internal tissue failure found on the force deformation curve. The reason for this is, as the indenter starts to load the potato, the contact area increases continuously and monotonotally causing a steady increase in force to deform the tuber. When the stress exceeds the ultimate strength of the tuber, localized major tissue failure occurs. This is the failure shown by the hook on the force-deformation curve. Finney (1963) defined this point as rupture point and he stated that potatoes did not exhibit yield point during a spherical indenter test because of above reason.

In order to gain an insight into the internal bruising it is essential to understand internal stress distribution within the tuber. The finite elelment method was used to study internal stress of a statically loaded potato. A commercial numerical program called MARC was used to create the potato models. The potato tuber was assumed to be a homogeneous body. The modulus of elasticity, Poisson ratio, density and yield strength were used to define the models. The boundary nodes on the ordinates were allowed displacement only in the direction of the load application and the nodes on the abscissa were allowed to move only in the x- direction.

The top node was subjected to deformations of 10.16 mm (0.40 inch)and 10.66 mm (0.42 inch) to simulate *Superior* and *Snowden* potatoes, respectively. These deformations were determined experimentally by loading potato statically by a spherical indenter. The pressure sensitive film was used to measure the contact stress between the

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spherical indenter and the tubers. The simulated distribution of the contact stress, von Mises stress and deformation were illustrated by contour bands. The pictorial illustrations show a high stress concentration directly under the applied load. The concentrated stress was about 3 times higher than the yield stress. Therefore, from the deformed model it can be assumed that tuber was bruised severely which extended far below the surface at the stem end. This was confirmed by experimental observation. The error of contact stress and deformation were within 2% of the experimentally measured values.

The simulated contact stress corresponding to 5.08 mm (0.20 inch) was 1040.73 kPa (150.90 psi) which was higher than the dynamic bruising contact pressure of the *Superior* variety. The corresponding von Mises stress was 957.96 kPa (138.90 psi) which was equal to the yield stress as found by core testing. This would result in internal tissue failure and consequently would cause blackspot bruising in the region where von Mises stress equals the yield strength. The location of such von Mises stress was at 5.08 mm below the surface-the location of commonly occurring blackspot.

7.2 Conclusions

External and internal bruise can be detected by using appropriate strength of tetrazolium chloride solution. Using of pressure sensitive film is a viable method of measuring contact pressure directly. There appeared to be a threshold value of contact pressure when bruising occured. These were 880.89 kPa for Snowden and 1027.11 kPa for *Superior* variety, respectively. The threshold bruising pressure was affected by the variety, making some varieties more bruise susceptible due to a lower threshold value, and the mechanical properties of potato tubers. If the contact stress during impact does not exceed the threshold value, bruising may not occur.

The hook in the force-deformation curve generated by a spherical indenter actually indicates a major localized tissue failure. The internal tissue failure occurs well before the major failure since it exceeds the ultimate strength. The internal tissue failure can not be traced in the force-deformation curve.

Bruise susceptible tuber exhibited higher ppo activity than that of less susceptible variety. Optical density (OD) was a direct result of ppo activity. Therefore, OD could be used to determine bruise susceptibility of a given lot of potatoes. There were differences between the variety but more study is needed to understand the role of minerals (Ca, Cu and K) in blackspot bruising.

Finite Element Method could be used to investigate internal stress distribution within a loaded tuber. The capability of FEM to produce pictorial illustration helped in understanding the stress distribution in a loaded potato model. The von Mises stress distribution showed the location of the highly stressed element where internal tissue failure occured. The element failure occurs when von Mises stress in that element is equal or higher than the yield strength of a potato. The location of bruised tissue may not necessarily be on the surface of contact. Under a given loading condition it occured below the surface of the tuber where von Mises stress equal the yield stress of potatoes.

The varietal differences may be detected using the techniques described in this dissertation. The *Snowden* variety was found to be more blackspot bruise susceptible than the *Superior* variety.

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Appendix A.1: Mechanical Properties of Bruised *Superior* Potatoes.

Br M(kg)	Br Mgh(Nm)	Br D(mm)	Br YldF(lb)	Br Def(in)	Br S.enrgy	Br YldS(psi)	Br E(Psi)	Br E(kg/cm^	Br Yld(kg/c	Measur DyP(kg/cm
0.164	0.24519	65.03	33.00	0.29	4.785	112.628	388.372	27.304	7.91817	9.10
0.201	0.3005	68.4	35.00	0.27	4.725	119.454	442.422	31.1039	8.39805	10.25
0.281	0.42011	76.88	45.00	0.34	7.650	153.584	451.717	31.7573	10.7975	10.99
0.259	0.38722	73.47	44.00	0.33	7.260	150.171	455.063	31.9926	10.5576	10.89
0.215	0.32143	69.59	43.00	0.32	6.880	146.758	458.618	32.2425	10.3176	10.50
0.222	0.3319	71.16	45.00	0.32	7.200	153.584	479.949	33.7422	10.7975	10.99
0.251	0.37526	76.57	44.00	0.33	7.260	150.171	455.063	31.9926	10.5576	10.79
0.185	0.27658	67.49	42.00	0.33	6.930	143.345	434.378	30.5384	10.0777	10.25
0.262	0.97925	74.33	40.00	0.31	6.200	136.519	440.383	30.9606	9.59778	10.50
0.203	0.75873	67.93	43.00	0.33	7.095	146.758	444.720	31.2655	10.3176	11.10
0.200	0.74752	68.00	38.00	0.30	5.700	129.693	432.309	30.393	9.11789	10.53
0.169	0.63166	65.18	39.00	0.30	5.850	133.106	443.686	31.1928	9.35783	10.55
0.256	0.95683	74.57	46.00	0.34	7.820	156.997	461.755	32.4631	11.0374	11.25
0.238	0.88955	74.27	42.00	0.31	6.510	143.345	462.402	32.5086	10.0777	10.25
0.207	0.77369	68.94	37.00	0.29	5.365	126.280	435.448	30.6136	8.87794	10.16
0.282	1.05401	79.33	36.00	0.30	5.400	122.867	409.556	28.7933	8.638	9.98
0.196	0.73257	68.56	37.00	0.30	5.550	126.280	420.933	29.5931	8.87794	9.88
0.271	1.01289	75.41	41.00	0.32	6.560	139.932	437.287	30.7429	9.83772	10.50
0.299	1.11755	80.32	43.00	0.31	6.665	146.758	473.412	33.2826	10.3176	11.60
0.207	0.77369	68.77	38.00	0.28	5.320	129.693	463.189	32.5639	9.11789	10.45
0.175	0.65408	65.18	40.00	0.29	5.800	136.519	470.754	33.0958	9.59778	10.59
0.25	1.49504	77.3	38.00	0.34	6.460	129.693	381.450	26.8173	9.11789	9.67
0.2	1.19604	68.74	41.00	0.36	7.380	139.932	388.699	27.327	9.83772	10.00
0.176	1.05251	65.36	40.00	0.35	7.000	136.519	390.054	27.4222	9.59778	10.02
0.16	0.95683	62.83	44.00	0.34	7.480	150.171	441.678	31.0516	10.5576	11.00
0.15	0.89703	71.14	39.00	0.29	5.655	133.106	458.986	32.2684	9.35783	10.50
0.3	1.79405	78.72	41.00	0.31	6.355	139.932	451.393	31.7346	9.83772	11.49
0.177	1.05849	65.69	39.00	0.34	6.630	133.106	391.488	27.523	9.35783	9.89
0.277	1.65851	76.29	38.00	0.33	6.270	129.693	393.009	27.63	9.11789	9.50
0.196	1.17211	69.17	43.00	0.31	6.665	146.758	473.412	33.2826	10.3176	10.80
0.186	1.11231	69.54	39.00	0.33	6.435	133.106	403.351	28.3571	9.35783	9.76
0.188	1.12427	65.83	42.00	0.34	7.140	143.345	421.602	29.6402	10.0777	10.76
0.167	0.99869	64.78	36.00	0.30	5.400	122.867	409.556	28.7933	8.638	9.80
0.211	1.26182	68.94	42.00	0.35	7.350	143.345	409.556	28.7933	10.0777	10.30
0.159	0.95085	64.17	43.00	0.31	6.665	146.758	473.412	33.2826	10.3176	12.34
0.154	0.92095	63.17	38.00	0.32	6.080	129.693	405.290	28.4934	9.11789	9.50
0.242	1.4472	71.72	45.00	0.32	7.200	153.584	479.949	33.7422	10.7975	11.20
0.222	1.3276	72.00	40.00	0.30	6.000	136.519	455.063	31.9926	9.59778	10.49

Appendix A.2 Mechanical Properties of Unbruised *Superior* Potatoes.

NbR M(kg)	Nbr mgh(nm) 0	Nbr D(mm)	NoBr F(lb)	NoBr Def(in)	NoBr St.energy	NoBr YldS(psi)	NoBr E(Psi)	Mea: NoBrP kg/cm^2	NoBr Ylds(kg/c
0.247	0.36928	66.9	53.00	0.37	9.805	180.887	488.885	10.10	12.7171
0.161	0.2407	63.02	44.00	0.33	7.260	150.171	455.063	9.35	10.5576
0.244	0.36479	72.77	49.00	0.34	8.330	167.235	491.869	9.70	11.7573
0.223	0.33339	63.9	43.00	0.31	6.665	146.758	473.412	9.38	10.3176
0.219	0.32741	71.72	49.00	0.39	9.555	167.235	428.809	9.80	11.7573
0.181	0.2706	67.89	44.00	0.33	7.260	150.171	455.063	9.50	10.5576
0.15	0.22426	75.42	40.00	0.31	6.200	136.519	440.383	8.20	9.59778
0.2	0.29901	68.07	46.00	0.36	8.280	156.997	436.102	10.15	11.0374
0.25	0.37376	65.45	48.00	0.34	8.160	163.823	481.831	10.00	11.5173
0.345	0.51579	67.9	52.00	0.36	9.360	177.474	492.984	10.50	12.4771
0.195	0.29153	68.17	45.00	0.33	7.425	153.584	465.405	9.00	10.7975
0.223	0.33339	71.41	45.00	0.33	7.425	153.584	465.405	9.25	10.7975
0.223	0.83349	69.79	46.00	0.34	7.820	156.997	461.755	9.00	11.0374
0.203	0.75873	69.64	41.00	0.32	6.560	139.932	437.287	8.00	9.83772
0.214	0.79985	71.85	39.00	0.30	5.850	133.106	443.686	8.50	9.35783
0.191	0.71388	76.9	38.00	0.29	5.510	129.693	447.217	8.00	9.11789
0.25	0.9344	69.87	39.00	0.29	6.890	133.106	458.986	8.65	9.35783
0.198	0.74005	77.9	41.00	0.32	6.560	139.932	437.287	8.35	9.83772
0.15	0.56064	75.89	39.00	0.30	5.850	133.106	443.686	8.20	9.35783
0.2	0.74752	64.17	49.00	0.34	8.330	167.235	491.869	10.20	11.7573
0.145	0.86713	78.48	45.00	0.35	7.875	153.584	438.810	8.00	10.7975
0.15	0.89703	78.27	39.00	0.29	5.655	133.106	458.986	8.50	9.35783
0.14	0.83722	69.22	40.00	0.30	6.000	136.519	455.063	8.15	9.59778

Appendix A.3 Mechanical Properties of Bruised *Snowden* Potatoes.

Br M(g)	Br D(mm)	Br YldF(lb)	Br Def(in)	Senrgy (in-lb)	Yldstrss Psi	Elast Psi	PE (Nm)	MeasP kg/cm^2	Ylds Kg/cm^2	Elast kg/cm^2
239	78	35	0.28	4.900	119.454	426.621	0.38	8.90	8.39805	29.9931
277	79	27	0.22	2.970	92.150	418.864	0.41	7.20	6.4785	29.4477
275	78	30	0.25	3.750	102.389	409.556	0.41	7.50	7.19833	28.7933
229	72	31	0.26	4.030	105.802	406.931	0.34	9.00	7.43828	28.6088
229	76	33	0.27	4.455	112.628	417.141	0.40	8.25	7.91817	29.3265
205	75	35	0.29	5.075	119.454	411.910	0.34	9.00	8.39805	28.9588
207	73	31	0.26	4.030	105.802	406.931	0.31	8.20	7.43828	28.6088
221	72	32	0.25	4.000	109.215	436.860	0.39	8.80	7.67822	30.7129
204	73	34	0.29	4.930	116.041	400.141	0.30	8.50	8.15811	28.1314
245	77	33	0.27	4.455	112.628	417.141	1.10	9.00	7.91817	29.3265
244	77	34	0.27	4.590	116.041	429.781	0.91	9.80	8.15811	30.2152
242	78	27	0.23	3.105	92.150	400.653	0.90	8.75	6.4785	28.1674
220	80	34	0.27	4.590	116.041	429.781	0.82	9.50	8.15811	30.2152
215	77	30	0.25	3.750	102.389	409.556	0.80	9.60	7.19833	28.7933
237	79	36	0.28	5.040	122.867	438.810	1.35	11.25	8.638	30.85
214	65	34	0.28	4.760	116.041	414.432	0.80	9.75	8.15811	29.1361
166	70	31	0.25	3.875	105.802	423.208	0.62	8.60	7.43828	29.7531
218	75	32	0.26	4.160	109.215	420.058	0.81	9.84	7.67822	29.5316
189	72	34	0.29	4.930	116.041	400.141	0.71	9.50	8.15811	28.1314
189	69	35	0.30	5.250	119.454	398.180	0.71	9.50	8.39805	27.9935
257	82	30	0.25	3.750	102.389	409.556	0.96	9.90	7.19833	28.7933
204	78	36	0.30	5.400	122.867	409.556	0.76	9.80	8.638	28.7933
234	69	40	0.31	6.200	136.519	440.383	0.87	10.10	9	30.9606
203	72	22	0.18	1.980	75.085	417.141	0.76	7.20	5.27878	29.3265
199	67	27	0.23	3.105	92.150	400.653	0.74	7.75	6.4785	28.1674
197	76	31	0.25	3.875	105.802	423.208	1.18	9.80	7.43828	29.7531
207	76	34	0.29	4.930	116.041	400.141	1.05	9.10	8.15811	28.1314
233	73	32	0.27	4.320	109.215	404.500	1.39	9.50	7.67822	28.4379
210	72	32	0.27	4.320	109.215	404.500	1.01	9.00	7.67822	28.4379
208	79	27	0.23	3.105	92.150	400.653	0.88	8.10	6.4785	28.1674
230	74	32	0.27	4.320	109.215	404.500	1.30	8.60	7.67822	28.4379
279	85	33	0.28	4.620	112.628	402.243	1.67	9.50	7.91817	28.2792
255	83	35	0.30	5.250	119.454	398.180	1.52	9.50	8.39805	27.9935
239	75	29	0.25	3.625	98.976	395.904	1.43	9.20	6.95839	27.8336

Appendix A.3 (cont'd)

Appendix A.3 (cont'd)

198	74	35	0.30	5.250	119.454	398.180	0.99	10.00	8.39805	27.9935
361	80	36	0.31	5.580	122.867	396.345	1.00	9.30	8.638	27.8645
186	70	34	0.26	4.420	116.041	446.311	0.99	9.80	8.15811	31.3773
209	70	30	0.25	3.750	102.389	409.556	1.25	8.80	7.19833	28.7933
192	72	32	0.27	4.320	109.215	404.500	0.78	8.50	7.67822	28.4379
184	72	33	0.27	4.455	112.628	417.141	0.89	9.50	7.91817	29.3265
186	70	33	0.25	4.125	112.628	450.512	0.99	10.00	7.91817	31.6727
186	70	34	0.27	4.590	116.041	429.781	1.20	11.00	8.15811	30.2152
190	70	29	0.24	3.480	98.976	412.400	1.01	9.50	6.95839	28.9933
192	75	32	0.27	4.320	109.215	404.500	1.02	10.25	7.67822	28.4379
198	80	34	0.29	4.930	116.041	400.141	1.00	10.35	8.15811	28.1314
182	85	30	0.26	3.900	102.389	393.804	0.27	7.50	7.19833	27.6859
201	82	21	0.18	1.890	71.672	398.180	0.30	6.50	5.03883	27.9935
308	87	34	0.29	4.930	116.041	400.141	0.46	8.50	8.15811	28.1314
308	87	30	0.24	3.600	102.389	426.621	0.46	8.25	7.19833	29.9931
195	71	32	0.25	4.000	109.215	436.860	1.00	10.00	7.67822	30.7129
179	74	30	0.25	3.750	102.389	409.556	0.27	7.90	7.19833	28.7933
192	70	28	0.24	3.360	95.563	398.180	0.29	7.10	6.71844	27.9935
214	69	27	0.23	3.105	92.150	400.653	0.32	7.50	6.4785	28.1674
191	87	31	0.26	4.030	105.802	406.931	0.29	8.00	7.43828	28.6088
189	74	28	0.24	3.360	95.563	398.180	0.28	7.60	6.71844	27.9935
179	72	27	0.22	2.970	92.150	418.864	0.27	7.90	6.4785	29.4477
169	70	31	0.25	3.875	105.802	423.208	0.25	7.75	7.43828	29.7531
201	70	30	0.25	3.750	102.389	409.556	0.75	8.50	7.19833	28.7933
179	70	28	0.23	3.220	95.563	415.492	0.67	8.20	6.71844	29.2106
200	85	29	0.25	3.625	98.976	395.904	0.75	9.50	6.95839	27.8336
192	84	30	0.25	3.750	102.389	409.556	0.72	9.45	7.19833	28.7933
341	74	32	0.24	3.840	109.215	455.063	1.30	10.00	7.67822	31.9926
210	72	30	0.23	3.450	102.389	445.170	0.78	9.24	7.19833	31.2971
199	77	34	0.26	4.420	116.041	446.311	1.70	10.50	8.15811	31.3773
177	79	30	0.24	3.600	102.389	426.621	1.39	10.10	7.19833	29.9931
341	74	38	0.29	5.510	129.693	447.217	1.45	10.45	9.11789	31.441
210	73	28	0.23	3.220	95.563	415.492	0.78	9.30	6.71844	29.2106
199	77	34	0.26	4.420	116.041	446.311	1.56	10.00	8.15811	31.3773
194	77	30	0.24	3.600	102.389	426.621	1.50	9.50	7.19833	29.9931
328	86	30	0.25	3.750	102.389	409.556	1.34	9.80	7.19833	28.7933

Appendix A.3 (end)

194	66	37	0.31	5.735	126.280	407.354	1.38	10.50	8 87794	28 6385
312	80	25	0.21	2.625	85.324	406 306	1.01	8 10	5 99861	28 5648
210	90	27	0 24	3 240	92 150	383 959	0 45	7.50	6 4785	26 9937
202	73	31	0.25	3 875	105.802	423.208	0.90	8.59	7 43828	29 7531
206	78	26	0.22	2 860	88.737	403.351	0.99	7.25	6.23855	28.3571
177	72	30	0.23	3 450	102.389	445.170	0 77	8.60	7.19833	31.2971
194	77	29	0.25	3.625	98.976	395.904	1.01	8.25	6.95839	27.8336
211	74	30	0.24	3 600	102.389	426.621	1.26	9.50	7.19833	29.9931
190	70	28	0.22	3.080	95.563	434.378	1.14	8.50	6 71844	30.5384
162	73	32	0.26	4 160	109.215	420.058	0.97	9.60	7.67822	29.5316
156	70	27	0.23	3 105	92.150	400.653	0.93	7.90	6 4785	28.1674
176	65	31	0.26	4.030	105 802	406.931	1.05	9.75	7.43828	28 6088
148	70	32	0.25	4 000	109 215	436 860	2.05	9 75	7 67822	30 7129
190	70	31	0.25	3 875	105.802	423.208	1 14	9.24	7.43828	29.7531
176	70	24	0 19	2.280	81.911	431.112	1.05	7.70	5 75857	30.3088
148	69	24	0.20	2 400	81.911	409.556	1.30	7.50	5.75867	28.7933
141	67	26	0.22	2.860	88.737	403.351	1.25	8.50	6.23855	28.3571
290	85	34	0.27	4.590	116 041	429.781	1.78	10.00	8 15811	30.2152
340	78	32	0.25	4 000	109.215	436.860	1.40	9.30	7.67822	30 7129
185	70	29	0.25	3.625	98.976	395.904	1.30	8.00	6.95839	27.8336
168	69	30	0 24	3 600	102.389	426.621	1.22	9.10	7.19833	29.9931
204	70	30	0.25	3.750	102.389	409.556	1 11	9.00	7 19833	28.7933
168	80	32	0.27	4.320	109.215	404.500	1.00	9.56	7.67822	28.4379

Appendix A.4 Mechanical Properties of Unbruised *Snowden* Potatoes.

NBr M(g)	Nbr D(mm)	Nbr YldF Lb	Nbr Def(in)	Nbr Snrgy (in-lb)	Nbr Ystrss Psi	Nbr Elasti Psi	Nbr PE (Nm)	NBr YldS Kg/cm^2	NBr Elast kg/cm^2	NBrP Press kg/cm^2
176	73	44	0.33	7.26	150.171	455.063	0.29	10.5576	31.9926	7.50
214	75	36	0.29	5.22	122.867	423.679	0.45	8.638	29.7862	6.78
226	74	35	0.28	4.90	119.454	426.621	0.34	8.39805	29.9931	6.00
284	83	43	0.31	6.67	146.758	473.412	0.42	10.3176	33.2826	8.00
225	70	47	0.34	7.99	160.410	471.793	0.34	11.2774	33.1688	7.80
298	79	34	0.26	4.42	116.041	446.311	0.45	8.15811	31.3773	6.90
234	70	38	0.30	5.70	129.693	432.309	0.35	9.11789	30.393	6.00
215	72	35	0.29	5.08	119.454	411.910	0.32	8.39805	28.9588	5.90
217	77	35	0.27	4.73	119.454	442.422	0.32	8.39805	31.1039	6.20
228	74	43	0.32	6.86	146.758	458.618	0.34	10.3176	32.2425	7.00
198	75	33	0.27	4.46	112.628	417.141	0.74	7.91817	29.3265	7.45
248	74	39	0.30	5.85	133.106	443.686	0.93	9.35783	31.1928	7.00
206	70	42	0.33	6.93	143.345	434.378	0.77	10.0777	30.5384	7.80
239	72	35	0.26	4.55	119.454	459.438	0.89	8.39805	32.3002	7.87
170	80	36	0.27	4.86	122.867	455.063	0.20	8.638	31.9926	5.50
184	78	37	0.28	5.18	126.280	451.000	0.25	8.87794	31.7069	7.00
198	80	38	0.29	5.51	129.693	447.217	0.90	9.11789	31.441	8.00
286	84	41	0.29	5.95	139.932	482.523	0.43	9.83772	33.9232	8.24
173	71	34	0.26	4.42	116.041	446.311	0.26	8.15811	31.3773	5.90
180	75	39	0.29	5.66	133.106	458.986	0.30	9.35783	32.2684	5.78
198	75	33	0.26	4.29	112.628	433.185	0.30	7.91817	30.4545	6.90
186	70	38	0.28	5.32	129.693	463.189	0.28	9.11789	32.5639	7.60
324	87	35	0.26	4.55	119.454	459.438	0.48	8.39805	32.3002	7.80
203	71	31	0.25	3.88	105.802	423.208	0.30	7.43828	29.7531	6.80
188	68	34	0.27	4.59	116.041	429.781	0.28	8.15811	30.2152	7.25
180	70	40	0.30	6.00	136.519	455.063	0.67	9.59778	31.9926	8.78
177	77	40	0.29	5.80	136.519	470.754	0.66	9.59778	33.0958	8.80
183	71	44	0.31	6.82	150.171	484.421	0.68	10.5576	34.0566	9.50
168	72	30	0.24	3.60	102.389	426.621	1.00	7.19833	29.9931	6.60
200	72	35	0.27	4.73	119.454	442.422	0.87	8.39805	31.1039	7.89

Appendix A.5

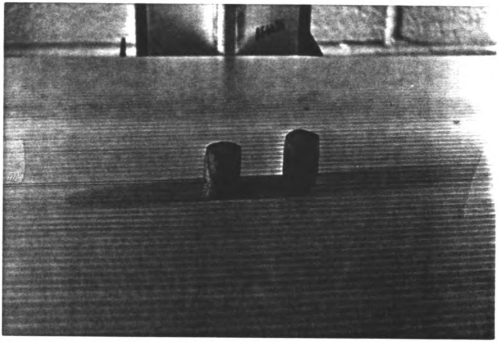

Figure A.5 Yielded cores of fresh *Superior* potato tubers.

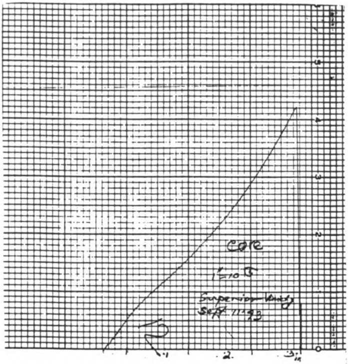

Figure A.6 Load-deformation curve at yield of a *Superior* potato core.

Appendix B.1 Calculated and Measured Quasi-Static Contact Pressure for *Superior* potatoes.

a= radius of contact

Max Pr=1.5P/3.14 a Timu eq.231 page 413 where a^3= [3*3.14*P(k1+k2)(R1*R2)/{4(R1+R2)}

k2 of sphere is zero

R2=sphere

R1=potatoe

							page 413 Calulated by Timushenko			FilmPr	FilmPr	
F(LB)	mue1^2	K1	R1	R2	a^3	a	Pmax(psi	kg/cm^2	Gray	Psi	kg/cm^2	Def(in)
124	0.2401	0.0006	1.56789	0.44	0.06066	0.39293	383.673	26.9718	99	377.758	26.5578	0.45
119	0.2401	0.0006	1.51234	0.44	0.05778	0.38659	380.362	26.739	99.45	375.157	26.3749	0.44
107	0.2401	0.00059	1.5748	0.44	0.05084	0.37047	372.427	26.1812	101	366.323	25.7539	0.4
126	0.2401	0.00063	1.4679	0.44	0.0633	0.39854	378.952	26.6399	99.26	376.253	26.452	0.48
118	0.2401	0.00059	1.47638	0.44	0.05593	0.38243	385.421	27.0946	98.66	379.733	26.6967	0.43
116	0.2401	0.00058	1.55512	0.44	0.05474	0.3797	384.368	27.0206	98.67	379.675	26.6926	0.42
115	0.2401	0.00059	1.5748	0.44	0.05471	0.37962	381.212	26.7987	98.68	379.617	26.6885	0.42
85	0.2401	0.00058	1.6789	0.44	0.04067	0.34389	343.356	24.1375	106	339.106	23.8404	0.34
95	0.2401	0.00062	1.5748	0.44	0.04746	0.36205	346.221	24.3389	105.67	340.844	23.9626	0.35
110	0.2401	0.00059	1.45901	0.44	0.05142	0.37187	379.995	26.7132	99.91	372.515	26.1892	0.41
112	0.2401	0.0006	1.49568	0.44	0.05377	0.37745	375.55	26.4007	100.52	369.038	25.9447	0.42
124	0.2401	0.00062	1.50346	0.44	0.06151	0.39474	380.159	26.7247	99.15	376.889	26.4967	0.46
98	0.2401	0.00059	1.52346	0.44	0.04656	0.35977	361.693	25.4265	103	355.205	24.9722	0.38
85	0.2401	0.0006	1.79346	0.44	0.04238	0.34865	334.041	23.4827	108	328.751	23.1124	0.33
75	0.2401	0.00061	1.45669	0.44	0.03622	0.33086	327.288	23.008	110	318.69	22.4051	0.32
					Avg	0.37197	367.648	25.8452	101.798	362.37	25.476	0.40333
					Std	0.01899	19.2578	1.3538	3.66801	19.9321	1.4013	0.04756

Appendix B.1 (end)

Pot(R1)	Poisson	1/R1	4/d	R1(potat	1/R1'	Sqrt		1-mu^2
1.58903	0.49	0.62931	4.57143	1.58903	0.62931	2.41455	165.772	0.76
1.48977	0.49	0.67125	4.57143	1.48977	0.67125	2.43186	164.542	0.76
1.5748	0.49	0.635	4.57143	1.5748	0.635	2.4169	170.688	0.76
1.47896	0.49	0.67615	4.57143	1.47896	0.67615	2.43387	157.809	0.76
1.47638	0.49	0.67733	4.57143	1.47638	0.67733	2.43436	167.452	0.76
1.55512	0.49	0.64304	4.57143	1.55512	0.64304	2.42023	171.17	0.76
1.5748	0.49	0.635	4.57143	1.5748	0.635	2.4169	170.503	0.76
1.6789	0.49	0.59563	4.57143	1.6789	0.59563	2.40056	173.025	0.76
1.89658	0.49	0.52727	4.57143	1.89658	0.52727	2.37191	165.448	0.76
1.45901	0.49	0.6854	4.57143	1.45901	0.6854	2.43767	169.093	0.76
1.49568	0.49	0.66859	4.57143	1.49568	0.66859	2.43076	166.055	0.76
1.45368	0.49	0.68791	4.57143	1.45368	0.68791	2.4387	160.396	0.76
1.52346	0.49	0.6564	4.57143	1.52346	0.6564	2.42574	168.834	0.76
1.89765	0.49	0.52697	4.57143	1.89765	0.52697	2.37178	170.305	0.76
1.78654	0.49	0.55974	4.57143	1.78654	0.55974	2.38556	167.203	0.76
1.59536	0.49	0.63167	4.57143	1.59536	0.63167	2.41542	167.22	0.76
0.14624	1.7E-10	0.05301	ERR	0.14624	0.05301	0.02204	3.97229	2.4E-10

Cal-Filmpr

Regression Output:		
Constant		-0.4822
Std Err of Y Est		0.30751
R Squared		0.95977
No. of Observations		15
Degrees of Freedom		13
X Coefficient(s)	1.00707	
Std Err of Coef	0.05718	

Appendix B.2 Calculated and Measured Quasi-static Contact Pressure for *Snowden* Potatoes.

Max Pr=1.5P/3.14 a   Timu eq.231 page 413   where a^3= [3*3.14*P(k1+k2)(R1*R2)/(4(R1+R2))
k2 of sphere is zero

F(lb)	mue1^2	K1	R1	R2	a^3	a	Calulated by Timushenko Pmax(psi	kg/cm^2	Gray	FilmPr Psi	FilmPr kg/cm^2	Def(in)
80	0.2401	0.00056	1.40552	0.44	0.03507	0.32734	356.655	25.0724	105	344.396	24.2123	0.42
90	0.2401	0.0006	1.45322	0.44	0.04325	0.35101	348.948	24.5306	102	360.725	25.3603	0.46
89	0.2401	0.0006	1.1755	0.44	0.04042	0.3432	360.957	25.3748	104	349.762	24.5896	0.45
93	0.2401	0.00066	1.18907	0.44	0.04655	0.35972	343.327	24.1354	102	360.725	25.3603	0.51
87	0.2401	0.00058	1.16977	0.44	0.03821	0.33682	366.339	25.7532	103	355.205	24.9722	0.46
89	0.2401	0.00059	1.25929	0.44	0.04001	0.34203	363.428	25.5485	103	355.205	24.9722	0.47
79	0.2401	0.00057	1.29417	0.44	0.0347	0.32618	354.71	24.9357	104	349.762	24.5896	0.38
83	0.2401	0.0006	1.21805	0.44	0.03792	0.33597	351.265	24.6935	104	349.762	24.5896	0.44
90	0.2401	0.0006	1.25984	0.44	0.04115	0.34524	360.716	25.3579	103	355.205	24.9722	0.48
84	0.2401	0.00055	1.3263	0.44	0.03615	0.33066	367.012	25.8005	102	360.725	25.3603	0.43
91	0.2401	0.00064	1.35202	0.44	0.04542	0.35679	341.491	24.0064	107	333.892	23.4738	0.49
92	0.2401	0.00063	1.29267	0.44	0.04516	0.35612	346.544	24.3616	106	339.106	23.8404	0.5
60	0.2401	0.00077	1.89764	0.44	0.03867	0.33816	250.656	17.6208	128	240.32	16.8954	0.32
86	0.2401	0.00057	1.45964	0.44	0.03934	0.3401	355.177	24.9685	104	349.762	24.5896	0.44
82	0.2401	0.00058	1.27442	0.44	0.03648	0.33167	358.095	25.033	104	349.762	24.5896	0.41
75	0.2401	0.00054	1.89766	0.44	0.03433	0.32502	339.154	23.8421	108	328.751	23.1124	0.39
85	0.2401	0.00058	1.26873	0.44	0.0379	0.3359	359.879	25.299	104	349.762	24.5896	0.45
61	0.2401	0.00053	1.29	0.44	0.0249	0.29202	341.712	24.0219	105	344.396	24.2123	0.35
90	0.2401	0.0006	1.36394	0.44	0.04266	0.34941	352.151	24.7557	105	344.396	24.2123	0.47
70	0.2401	0.00057	1.89077	0.44	0.03348	0.3223	321.923	22.6308	111	313.768	22.059	0.35
90	0.2401	0.00057	1.34193	0.44	0.04035	0.34298	365.473	25.6923	102	360.725	25.3603	0.45
70	0.2401	0.00053	1.89564	0.44	0.03092	0.31385	339.471	23.8644	107	333.892	23.4738	0.36
85	0.2401	0.00058	1.51483	0.44	0.0393	0.33999	351.273	24.6941	104	349.762	24.5896	0.43
65	0.2401	0.00067	1.89765	0.44	0.03641	0.33146	282.631	19.8686	120	272.572	19.1628	0.33
79	0.2401	0.00054	1.32085	0.44	0.03321	0.32145	365.23	25.6752	103	355.205	24.9722	0.41
83	0.2401	0.00055	1.31072	0.44	0.03556	0.32886	366.631	25.7737	103	355.205	24.9722	0.43
89	0.2401	0.00058	1.38925	0.44	0.04041	0.34315	361.057	25.3819	103	355.205	24.9722	0.45
90	0.2401	0.00064	1.34812	0.44	0.04522	0.35626	338.742	23.8132	108	328.751	23.1124	0.49
60	0.2401	0.00061	1.36851	0.44	0.02892	0.30695	304.211	21.3857	114	299.424	21.0506	0.34
81.6207	0.2401	0.00059	1.41813	0.44	0.038	0.33554	345.27	24.2721	106.138	339.522	23.8696	0.42821
9.97726	ERR	4.9E-05	0.2318	1.7E-10	0.00495	0.01509	25.7813	1.8124	5.65517	26.8902	1.89048	0.05282

Pot(R1)	Poisson	1/R1	4/d	R1(potat	1/R1'	Sqrt		1-mu^2
1.40552	0.49	0.71148	4.57143	1.40552	0.71148	2.44834	177.916	0.76
1.45322	0.49	0.68813	4.57143	1.45322	0.68813	2.43879	164.276	0.76
1.1755	0.49	0.8507	4.57143	1.1755	0.8507	2.50456	160.424	0.76
1.18907	0.49	0.84099	4.57143	1.18907	0.84099	2.50068	148.26	0.76
1.16977	0.49	0.85487	4.57143	1.16977	0.85487	2.50622	165.57	0.76
1.25929	0.49	0.7941	4.57143	1.25929	0.7941	2.48186	166.576	0.76
1.29417	0.49	0.7727	4.57143	1.29417	0.7727	2.47322	172.279	0.76
1.21805	0.49	0.82098	4.57143	1.21805	0.82098	2.49267	161.776	0.76
1.25984	0.49	0.79375	4.57143	1.25984	0.79375	2.48172	163.825	0.76
1.3263	0.49	0.75398	4.57143	1.3263	0.75398	2.46564	177.471	0.76
1.35202	0.49	0.73963	4.57143	1.35202	0.73963	2.45982	154.129	0.76
1.29267	0.49	0.77359	4.57143	1.29267	0.77359	2.47358	154.094	0.76
1.98675	0.49	0.50333	4.57143	1.98675	0.50333	2.3618	133.763	0.76
1.45964	0.49	0.6851	4.57143	1.45964	0.6851	2.43755	172.838	0.76
1.27442	0.49	0.78467	4.57143	1.27442	0.78467	2.47806	169.093	0.76
1.56789	0.49	0.6378	4.57143	1.56789	0.6378	2.41806	183.822	0.76
1.26873	0.49	0.78819	4.57143	1.26873	0.78819	2.47948	168.446	0.76
1.29	0.49	0.77519	4.57143	1.29	0.77519	2.47423	185.153	0.76
1.36394	0.49	0.73317	4.57143	1.36394	0.73317	2.45719	162.819	0.76
1.89077	0.49	0.52889	4.57143	1.89077	0.52889	2.37259	179.306	0.76
1.34193	0.49	0.74519	4.57143	1.34193	0.74519	2.46208	171.119	0.76
1.89564	0.49	0.52753	4.57143	1.89564	0.52753	2.37202	194.307	0.76
1.51483	0.49	0.66014	4.57143	1.51483	0.66014	2.42729	173.177	0.76
1.45322	0.49	0.68813	4.57143	1.45322	0.68813	2.43879	149.017	0.76
1.32085	0.49	0.75709	4.57143	1.32085	0.75709	2.4669	181.39	0.76
1.31072	0.49	0.76294	4.57143	1.31072	0.76294	2.46927	177.471	0.76
1.38925	0.49	0.71981	4.57143	1.38925	0.71981	2.45175	171.119	0.76
1.34812	0.49	0.74177	4.57143	1.34812	0.74177	2.46069	152.953	0.76
1.56897	0.49	0.63736	4.57143	1.56897	0.63736	2.41788	162.847	0.76
1.40142	0.49	0.72659	4.57143	1.40142	0.72659	2.45423	167.356	0.76
0.20575	2.4E-10	0.0899	ERR	0.20575	0.0899	0.03691	12.7416	0

Appendix C.1 Calculated and Measured Dynamic Contact Pressure for *Superior* Potatoes.

Horsfield(1972)

P max= 0.899(Wh)^(1/5) (1/R)^(3/5)(E^0.8)

(1/R)	(1/R)^.6	Elas(E) Psi	(E^0.80)	Wh	(wh)^.2	P(max) Psi	calculated P(max) Kg/cm^2	Elas(E) Kg/cm^2
0.68455	0.7966	488.45	141.598	3.2604	1.26664	128.586	9.04009	34.3398
0.80605	0.87866	439.00	130.008	2.1252	1.16273	119.54	8.40409	30.8633
0.698	0.80596	479.92	139.616	3.2208	1.26355	127.962	8.99624	33.7402
0.70497	0.81078	454.66	133.706	2.9436	1.24101	121.079	8.51233	31.9643
0.70826	0.81304	464.14	135.931	2.8908	1.23653	122.993	8.64685	32.6308
0.74823	0.84027	473.00	138.003	2.3892	1.19028	124.223	8.73335	33.2537
0.67355	0.7889	450.00	132.608	3.696	1.29881	122.287	8.59726	31.6367
0.74626	0.83895	454.67	133.707	2.4288	1.1942	120.562	8.47595	31.9648
0.75164	0.84257	497.68	143.733	2.1384	1.16417	126.889	8.92075	34.9885
0.70916	0.81367	435.72	129.231	2.9304	1.2399	117.339	8.24936	30.6327
0.74523	0.83825	481.41	139.963	2.574	1.20815	127.57	8.96867	33.8449
0.71133	0.81516	454.67	133.707	2.9436	1.24101	121.735	8.55844	31.9648
0.78117	0.86228	331.82	103.924	2.1648	1.16703	94.1223	6.61714	23.3279
0.74264	0.8365	480.34	139.715	2.6532	1.2155	127.852	8.98845	33.77
0.66075	0.77987	451.72	133.013	3.7092	1.29974	121.344	8.53091	31.7576
0.69142	0.80139	455.06	133.8	3.4188	1.27872	123.401	8.67553	31.9924
0.72992	0.82787	458.62	134.636	2.838	1.23198	123.587	8.6886	32.2427
0.71385	0.81689	511.94	147.02	2.9304	1.2399	134.019	9.42202	35.9913
0.66342	0.78176	455.06	133.8	3.3132	1.27072	119.625	8.4101	31.9926
0.75263	0.84324	434.38	128.912	2.442	1.1955	116.959	8.22267	30.5384
0.7793	0.86104	436.90	129.511	5.577	1.4102	141.53	9.95011	30.7157
0.68122	0.79428	440.00	130.245	8.448	1.53232	142.668	10.0301	30.9336
0.68391	0.79616	443.30	131.026	7.854	1.51014	141.781	9.96776	31.1656
0.64036	0.76534	479.53	139.525	9.306	1.56226	150.142	10.5555	33.7127
0.63243	0.75964	540.89	153.634	9.867	1.58065	166.025	11.6722	38.0266
0.72782	0.82644	474.96	138.46	7.359	1.49061	153.513	10.7925	33.3915

0.72941	0.82753	500.84	144.464	6.699	1.46286	157.394	11.0654	35.2109	11.0654
0.70695	0.81214	443.30	131.026	7.062	1.47838	141.586	9.95399	31.1656	9.95399
0.74778	0.83997	423.31	126.278	6.303	1.44514	137.957	9.69888	29.7603	9.69888
0.72697	0.82587	466.03	136.374	7.326	1.48927	150.959	10.613	32.7636	10.613
0.77723	0.85967	511.50	146.919	6.534	1.45558	165.457	11.6322	35.9603	11.6322
0.68271	0.79532	477.40	139.029	9.108	1.55555	154.801	10.8831	33.563	10.8831
0.68339	0.7958	435.06	129.074	8.646	1.53944	142.314	10.0052	30.5863	10.0052
0.74778	0.83997	470.34	137.382	6.699	1.46286	151.928	10.6811	33.0666	10.6811
0.79159	0.86916	431.93	128.331	5.214	1.39134	139.672	9.81944	30.3665	9.81944
0.73681	0.83256	436.90	129.511	6.831	1.46858	142.515	10.0193	30.7157	10.0193
0.74094	0.83535	473.00	138.003	6.468	1.45263	150.715	10.5958	33.2537	10.5958
0.67359	0.78893	462.78	135.612	8.943	1.54987	149.236	10.4919	32.5352	10.4919
0.73866	0.83381	470.34	137.382	6.831	1.46858	151.403	10.6442	33.0666	10.6442
0.77935	0.86107	431.26	128.171	5.775	1.42007	141.054	9.91659	30.3192	9.91659
0.714	0.817	436.90	129.511	13.4112	1.68071	160.052	11.2523	30.7157	11.2523
0.64727	0.77029	477.40	139.029	17.2128	1.76673	170.283	11.9715	33.563	11.9715
0.64905	0.77155	506.89	145.858	15.3648	1.72705	174.922	12.51	35.6362	12.2977
0.77328	0.85704	487.14	141.294	9.3456	1.56358	170.409	11.9804	34.248	11.9804
0.6658	0.78344	436.48	129.411	14.6256	1.7101	156.043	11.50	30.6862	10.9704
0.67659	0.79103	539.00	153.204	13.1472	1.67404	182.589	12.8367	37.8937	12.8367
0.78419	0.86428	501.47	144.609	8.8176	1.5455	173.845	12.2219	35.2553	12.2219
0.79154	0.86913	461.35	135.278	8.3952	1.5304	161.942	11.3851	32.4348	11.3851
0.73383	0.83053	400.00	120.684	11.0352	1.61643	145.815	10.2513	28.1215	10.2513
0.65716	0.77733	473.00	138.003	15.3648	1.72705	166.74	11.7224	33.2537	11.7224
0.73909	0.8341	418.94	125.234	10.5600	1.60226	150.632	10.59	29.453	10.59
0.77722	0.85966	465.00	136.133	9.2928	1.56181	164.499	11.5649	32.6912	11.5649
0.8084	0.88019	457.91	134.47	8.448	1.53232	163.228	11.4755	32.1928	11.4755
0.64526	0.76885	495.00	143.115	16.2624	1.74677	172.984	12.1614	34.8003	12.1614
0.73438	0.83091	511.50	146.919	10.3488	1.5958	175.327	12.3261	35.9603	12.3261
0.73049	0.82826	477.40	139.029	9.8208	1.57917	163.661	11.7012	33.563	11.506
0.77167	0.85597	459.00	134.726	10.5	1.60043	166.108	11.678	32.2694	11.678
0.73691	0.83262	404.94	121.874	11.1408	1.61951	147.905	10.3983	28.4686	10.3983
0.80422	0.87745	479.53	139.525	8.1312	1.52066	167.552	11.7795	33.7128	11.7795
0.70823	0.81303	454.67	133.707	12.7776	1.66452	162.852	11.4491	31.9648	11.4491
						avg	10.2234		10.2078
						Std	1.38602		1.3706

Appendix D.1

Table D.1 Mineral Contents of *Superior* and *Snowden* Potatoes.

Variety: **Superior**
Date of harvest: September 17, 1993.

Bruised at 6 inch drop height

Cu(ppm)	Ca(%)	K(%)
9.70	0.05	2.04
10.40	0.08	2.43
9.65	0.07	2.14
8.70	0.06	1.78
8.60	0.05	1.74
9.50	0.08	2.24
12.05	0.04	1.81
8.90	0.06	1.84

Unbruised at 6 inch drop height

7.70	0.05	1.97
7.65	0.06	2.35
9.70	0.06	2.03
6.95	0.05	2.54
6.60	0.05	1.89
6.90	0.05	1.93
6.15	0.06	1.93
6.45	0.07	1.83
9.15	0.04	1.81
8.95	0.06	1.91
8.70	0.06	1.86
7.35	0.04	1.77

Bruised at 15 in drop height

9.50	0.05	2.03
11.75	0.06	2.32
8.75	0.06	2.16
13.10	0.07	2.37
9.15	0.07	2.39
10.15	0.06	2.12
9.55	0.05	2.17
7.40	0.05	2.13

6.25	0.05	1.95
7.65	0.04	2.02
9.10	0.04	1.89
7.35	0.04	1.83
10.55	0.05	2.22

Unbruised at 15 inch drop height

7.50	0.05	2.05
13.00	0.06	1.89
10.15	0.04	2.20
8.10	0.05	2.06
7.70	0.06	2.12
9.90	0.06	2.25
5.50	0.05	2.10

Bruised at 24 inch drop height

9.40	0.05	2.25
7.35	0.06	2.19
7.75	0.06	2.29
8.90	0.04	2.16
7.75	0.05	1.57
8.90	0.05	2.10
9.55	0.07	2.13
8.15	0.06	2.27
8.90	0.06	2.15
9.35	0.05	2.31
6.25	0.06	2.12
12.05	0.06	2.20
8.45	0.06	2.13
9.80	0.07	2.09
7.10	0.05	2.53
7.50	0.05	2.32

Unbruised at 24 inch drop height

6.10	0.06	2.23
6.75	0.06	2.13
8.20	0.06	2.09
8.55	0.06	2.11

Variety: **Superior**

Date of harvest: September 30'1993.

Bruised at 6 inch drop height

Cu(ppm)	Ca(%)	K(%)
10.95	0.05	2.26
9.55	0.06	2.18
10.25	0.05	2.33
11.00	0.05	2.47

Unbruised at 6 inch drop height

9.85	0.06	2.04
8.10	0.04	2.21
10.65	0.06	2.34
7.15	0.06	2.36
12.10	0.06	2.52
10.40	0.06	2.19

Bruised (all) at 15 inch drop height

11.20	0.05	2.20
10.10	0.04	2.46
7.40	0.04	2.22
7.55	0.04	2.34
9.40	0.05	2.34
12.15	0.05	2.30
9.20	0.04	2.21
6.70	0.05	2.13
8.20	0.06	2.30
11.15	0.06	2.45

Bruised at 24 inch drop height

7.65	0.09	2.46
10.95	0.07	2.39
9.40	0.06	2.16
10.20	0.06	2.22
11.15	0.07	2.62

9.85	0.07	2.18
9.10	0.08	2.67
11.55	0.06	2.2
12.75	0.07	2.72
8.75	0.06	2.42

Variety: **Snowden**
Date of harvest: September 24, 1993.

Bruised at 6 inch drop height

5.10	0.03	1.55
6.15	0.03	2.06
6.10	0.04	1.96
6.55	0.04	1.74
5.45	0.03	1.83
7.45	0.04	1.86
4.10	0.03	1.87
5.05	0.02	1.82
4.75	0.02	1.75
5.85	0.03	1.77

Unbruised at 6 inch drop height

4.85	0.04	1.79
5.00	0.03	1.68
6.50	0.05	1.98
5.40	0.04	1.73
4.20	0.03	1.84
5.40	0.03	1.72
6.05	0.03	1.72
6.05	0.04	1.92
7.20	0.05	1.84
6.95	0.04	1.82

Bruised at 15 inch drop height

6.95	0.04	1.61
8.45	0.04	1.65
8.55	0.05	1.82
10.55	0.04	1.54
8.70	0.05	1.67
7.70	0.04	1.85

7.50	0.04	1.69
8.10	0.04	1.74
8.60	0.07	1.81
9.05	0.04	1.98
8.50	0.05	1.81
10.20	0.05	2.07
8.50	0.05	1.62
8.80	0.05	1.64
7.45	0.04	1.93

Unbruised at 15 inch drop height

7.30	0.03	1.59
5.35	0.03	1.56
7.00	0.04	1.82
7.70	0.04	1.66
6.70	0.03	1.53

Bruised at 24 inch drop height

9.35	0.05	1.68
6.80	0.04	1.57
8.40	0.04	1.44
12.40	0.03	1.65
8.60	0.04	1.44
6.45	0.04	1.45
7.70	0.04	1.60
10.30	0.05	1.78
5.70	0.04	1.55
5.45	0.04	1.92
9.40	0.06	1.45
11.05	0.04	1.84
9.45	0.04	1.87
8.35	0.04	1.75
9.45	0.05	1.97
10.00	0.05	1.67

Unbruised at 24 in drop height

9.25	0.05	1.51
9.40	0.04	1.69
8.70	0.05	1.36
7.75	0.05	1.73

Variety: **Snowden**
Date of harvest: October 22, 1993.

Bruised at 6 inch drop height

Cu(ppm)	Ca(%)	K(%)
3.30	0.01	1.51
3.15	0.02	1.57
3.15	0.02	1.67
2.40	0.02	1.77
4.55	0.02	1.96
4.25	0.03	1.91
2.60	0.02	1.69
2.95	0.01	2.09
3.30	0.03	1.75
2.70	0.03	1.81

unbruised at 6 in drop height

2.50	0.02	1.64
1.80	0.02	1.92
2.75	0.02	1.68
2.65	0.01	1.75
2.60	0.01	1.64
2.70	0.01	1.65
2.50	0.02	1.66
3.05	0.01	2.09
2.90	0.02	1.38
4.00	0.02	1.62

Bruised at 15 inch drop height

4.20	0.02	1.67
3.25	0.02	1.80
3.80	0.02	1.66
3.50	0.02	1.66
3.30	0.01	1.73
3.35	0.02	1.80
3.60	0.01	1.59
4.45	0.02	1.88
6.75	0.02	1.93
3.75	0.01	1.92
4.35	0.02	1.60

3.75	0.01	1.90
4.05	0.02	1.60
2.85	0.01	2.05
4.25	0.01	1.70

Unbruised at 15 inch drop height

4.05	0.01	1.68
2.95	0.02	1.89
3.70	0.02	1.81
6.65	0.01	1.74

Bruised at 24 inch drop height

9.35	0.03	1.65
3.55	0.02	1.86
4.60	0.02	1.94
5.25	0.04	2.27
3.20	0.02	1.86
5.56	0.01	2.03
5.55	0.01	1.61
4.75	0.03	2.0
3.80	0.02	2.14
6.50	0.04	1.96
3.65	0.02	2.19
9.65	0.04	2.02
7.05	0.04	1.83
4.50	0.02	1.70
5.80	0.03	1.93
4.10	0.02	1.67
5.90	0.03	1.88

Unbruised at 24 inch drop height

5.50	0.04	2.15
4.95	0.03	1.84

Appendix D.2

Table D.2 t-test for the differences of mineral contents of *Superior* and *Snowden* varieties ($\alpha=0.05$).

Mineral	Significance	t-values	Probability
Calcium	*	4.83	0.00
Copper	*	11.42	0.0
Calcium	*	14.27	0.0

Appendix D.3

Table D.3 t- test for the differences of the bruised and unbruised tubers impacted at various drop heights ($\alpha=0.05$).

Date in 1993	Minerals	6 inch	15 inch	24 inch	Variety
Sept 17	Calcium	ns(1.5)	ns(0.72)	ns(0.62)	*Superior*
Sept30	Calcium	ns(0.53)	*(5.7)	all bruised	*Superior*
Sept 24	Calcium	ns(1.40)	ns(1.58)	ns(0.64)	*Snowden*
Oct 22	Calcium	ns(1.05)	ns(1.02)	ns(-1.31)	*Snowden*
Sept 17	Potassium	ns(-0.08)	ns(0.37)	ns(0.35)	*Superior*
Sept30	Potassium	ns(0.34)	ns(-1.84)	all bruised	*Superior*
Sept 24	Potassium	ns(0.32)	ns(1.74)	ns(0.93)	*Snowden*
Oct 22	Potassium	ns(0.85)	ns(0.31)	ns(0.50)	*Snowden*
Sept 17	Copper	*(3.79)	ns(0.42)	ns(1.6)	*Superior*
Sept30	Copper	ns(0.76)	ns(-1.09)	all bruised	*Superior*
Sept 24	Copper	ns(.18)	*(3.15)	ns(0.09)	*Snowden*
Oct 22	Copper	ns(1.75)	ns(0.49)	ns(0.04)	*Snowden*

Note: Value in the parentheses is t- value and * is test for significance.

Appendix E.1

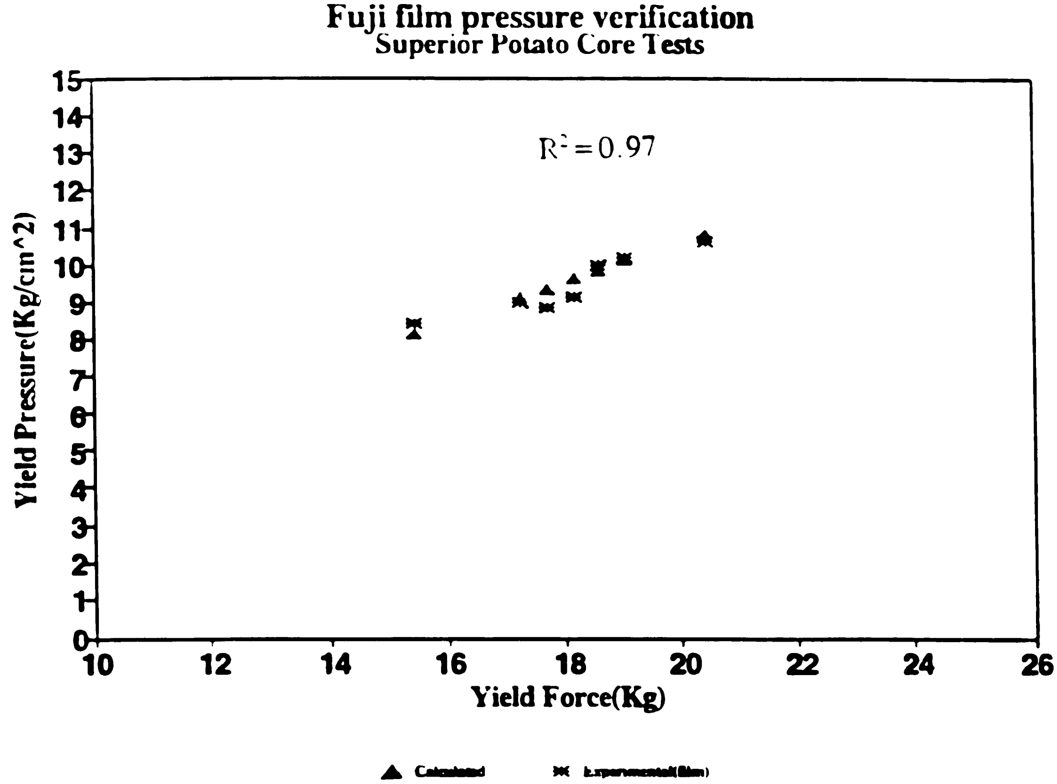

Figure E.1 Compressive Pressure Verification for *Superior* Potato Core Specimen Using Pressure Sensitive Films During Uniaxial Tests.

Appendix E.2

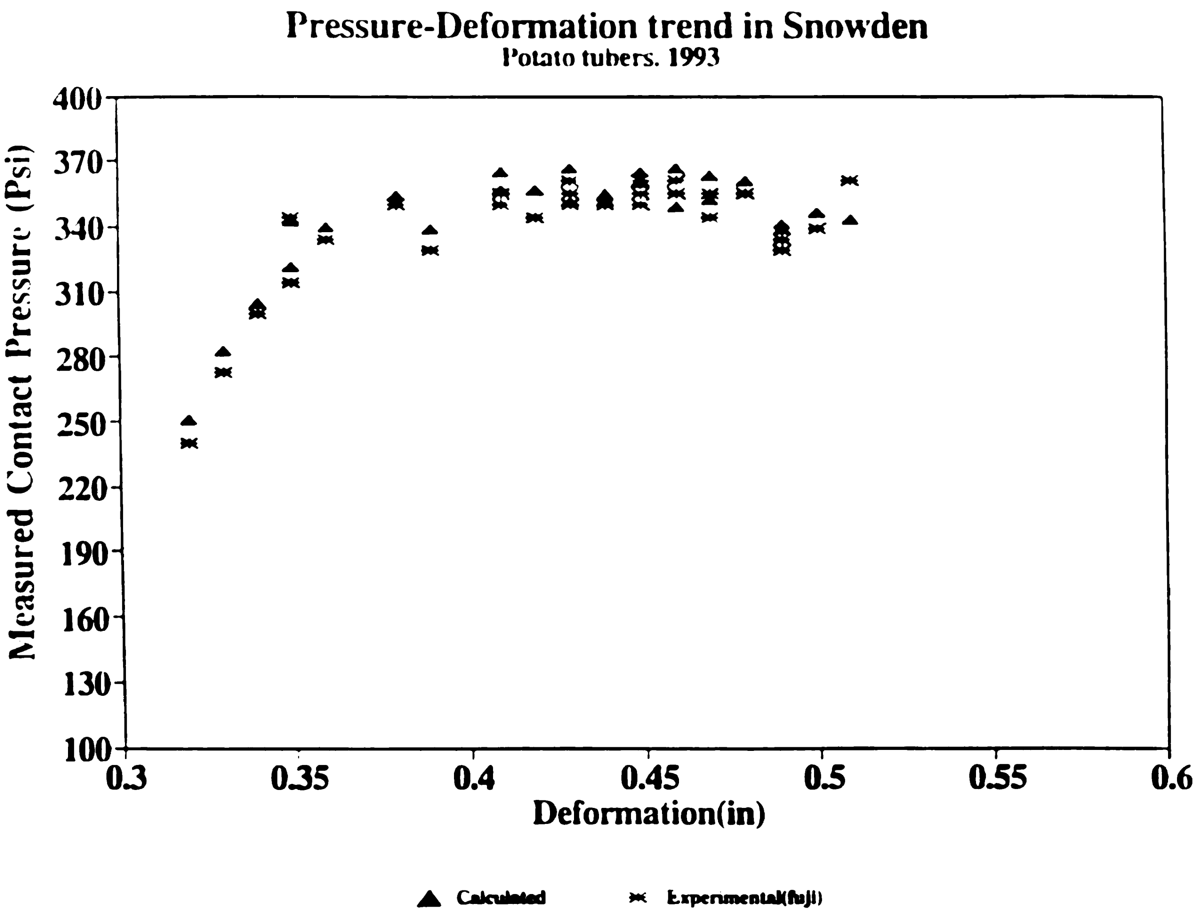

Figure E.2 Pressure-Deformation Trend on Whole *Snowden* Potato Tubers (sperical indenter).

Appendix F.1

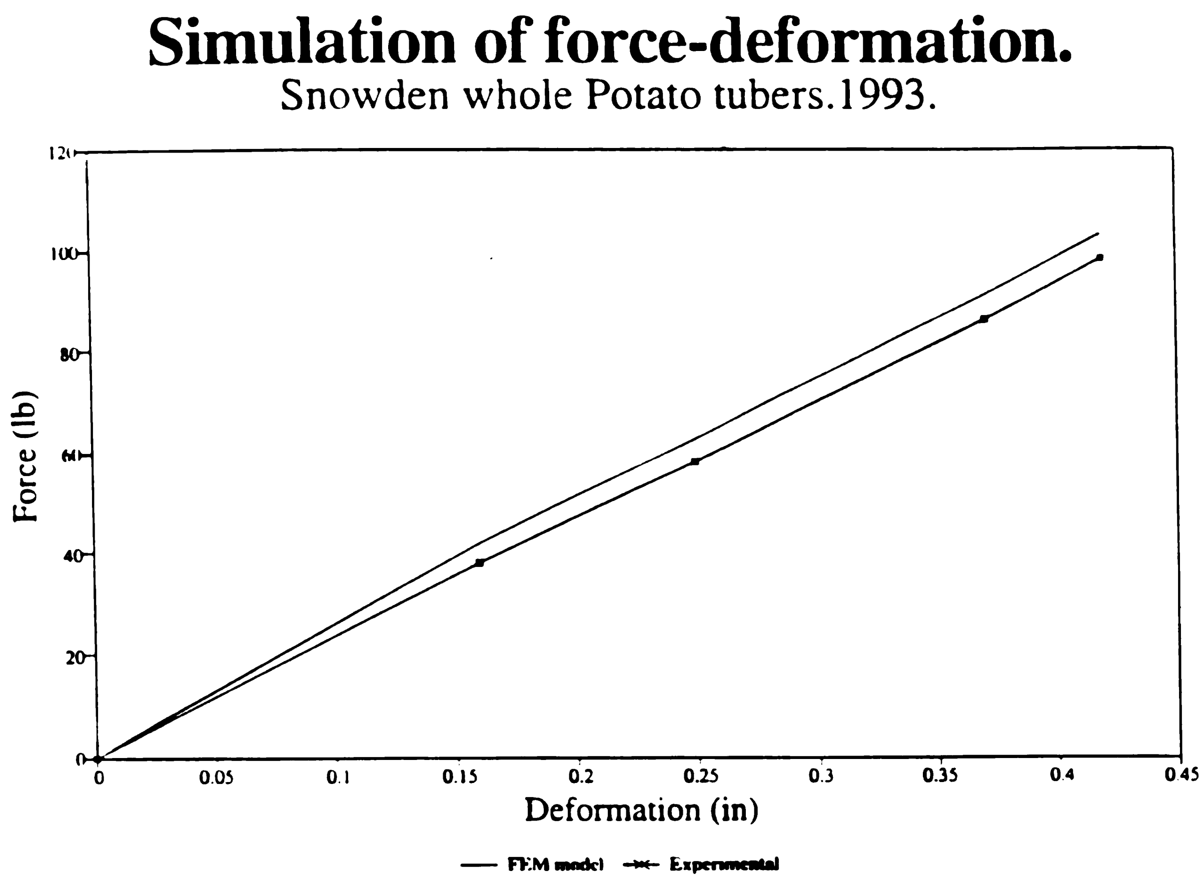

Figure F.1 Simulation of Force-Deformation for *Snowden* Whole Potato Tubers.

Appendix F.2

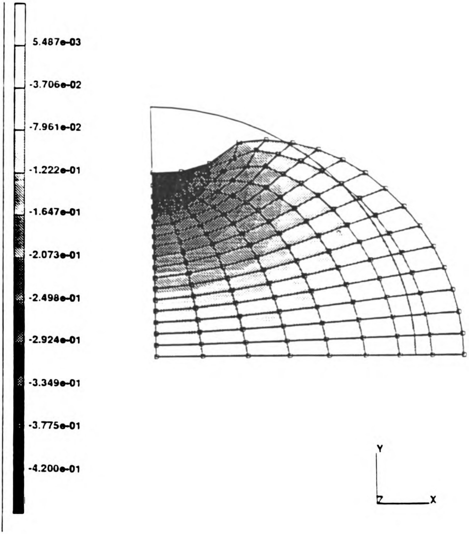

Figure F.2 The deformed model and its deformation contour lines due to 0.42 inch imposed displacement (*Snowden*). The scale shown on the left is in inch.

Appendix F.3

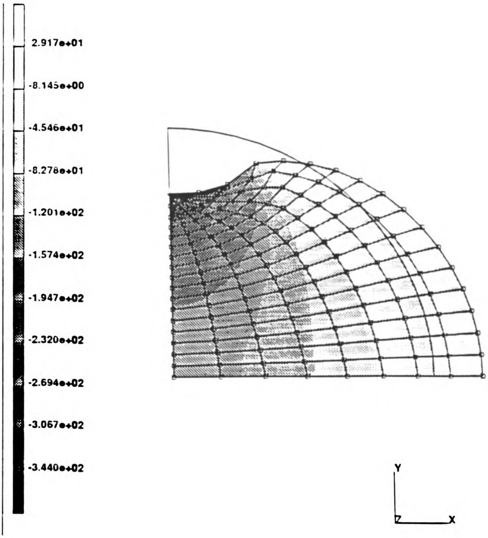

Figure F.3 The resulted contour stress distribution within the model due to 0.42 inch of imposed displacement (*Snowden*). The scale on the left shows stress in psi.

Appendix F.4

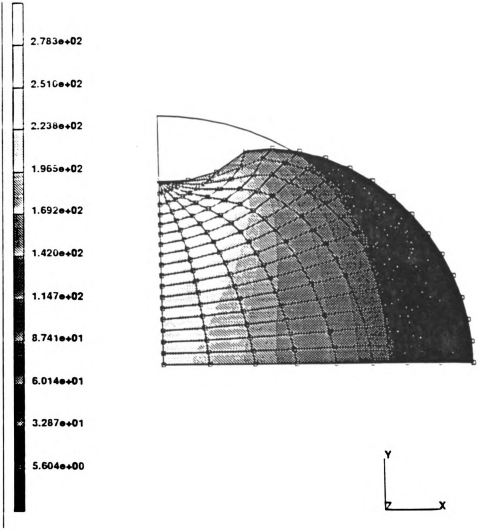

Figure F.4 The corresponding von Mises contour stress distribution in the model due to 0.42 inch of imposed displacement (*Snowden*). The scale on the left shows stress in psi.

Appendix F.5

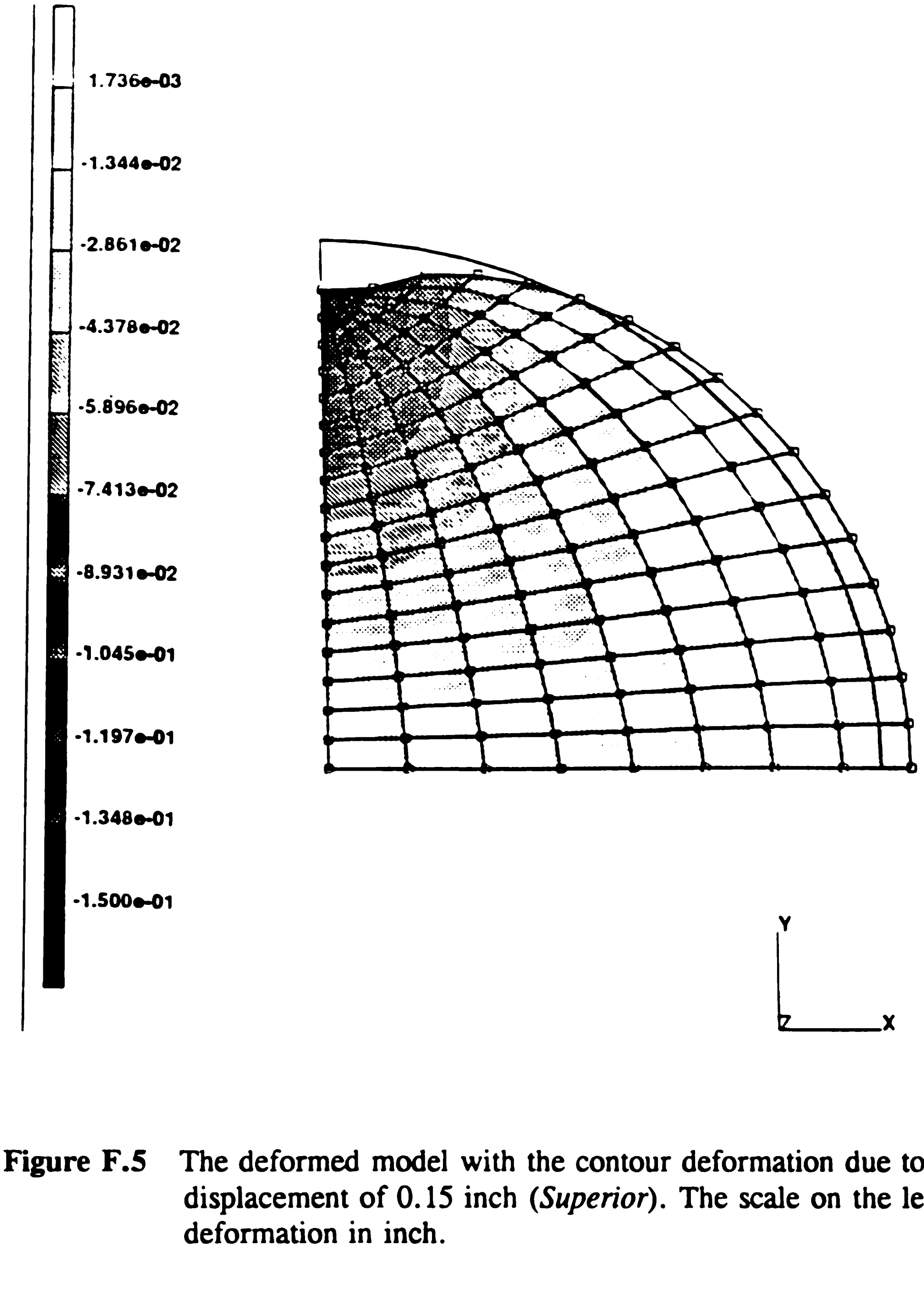

Figure F.5 The deformed model with the contour deformation due to imposed displacement of 0.15 inch (*Superior*). The scale on the left shows deformation in inch.

Appendix F.6

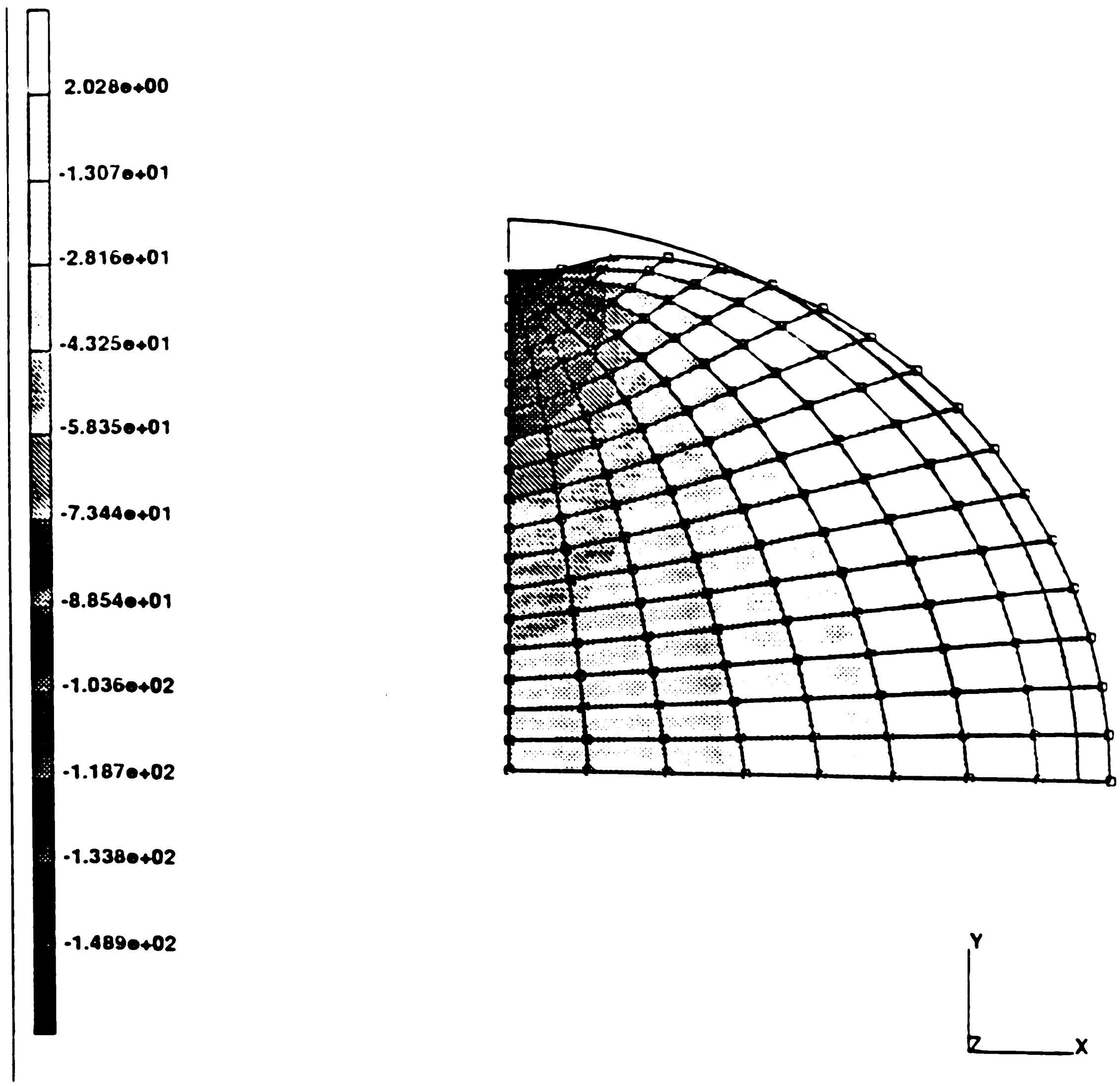

Figure F.6 The resulting contour stress distribution in the model due to the imposed displacement of 0.15 inch (*Superior*). The scale on the left shows stress in psi.

Appendix F.7

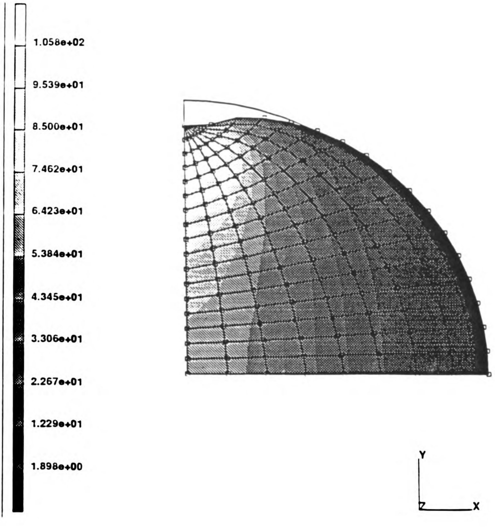

Figure F.7 The corresponding von Mises contour stresses with bands within the model due to 0.15 inch of imposed displacement. The scale on the left shows stress in psi.

Appendix G.1 Stepwise Analysis of Variance of BS (Bruise susceptibility)

STEPWISE ANALYSIS OF VARIANCE OF BS

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED	MALLOW'S CP	P
CONSTANT	1093.9						
CP	8.6376E-01	1	8.6376E-01	8.6376E-01	-0.0006	1320.6	2
E	3.5812	2	4.4450	2.2225	0.0215	1279.8	3
OD	105.94	3	110.38	36.795	0.9021	15.6	4
PPO	1.0508	4	111.44	27.859	0.9102	5.0	5
RESIDUAL	10.625	131	122.06	9.3176E-01			

CASES INCLUDED	132	MISSING CASES	0
DEGREES OF FREEDOM	127		
OVERALL F	333.0	P VALUE	0.0000
ADJUSTED R SQUARED	0.9102		
R SQUARED	0.9129		
RESID. MEAN SQUARE	8.366E-02		

Appendix G.2 Unwighted least square linear regression of BS (Bruise susceptibility)

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BS

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-1.2228E-01	9.8934E-02	-1.24	0.2188
CP	-2.7922E-06	3.0978E-06	-0.90	0.3691
E	-1.2776E-08	9.7676E-09	-1.31	0.1933
OD	5.0348	4.0024E-01	12.58	0.0000
PPO	1.0951E-01	3.0901E-02	3.54	0.0006

CASES INCLUDED	132	MISSING CASES	0
DEGREES OF FREEDOM	127		
OVERALL F	333.0	P VALUE	0.0000
ADJUSTED R SQUARED	0.9102		
R SQUARED	0.9129		
RESID. MEAN SQUARE	8.366E-02		