DAMAGE MECHANISMS IN THE HANDLING OF FRUITS

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ABSTRACT

Recent findings on the importance of losses due to damage incidence, on causes and on mechanisms of damage in fruits are reviewed and discussed. Incidence of damage in different fruits in some European markets has been proved to be very high. Structure of fruit flesh and skin (hystology) is of foremost importance in the response of fruits to impacts and to compression. Continuous variation of fruit compositional and structural characteristics during maturation has to be taken into consideration when studying damage susceptibility.

1.INTRODUCTION. INCIDENCE OF MECHANICAL DAMAGE

Harvesting, postharvest handling, packing, transportation and distribution of fruits and vegetables involve numerous mechanical operations and many impact-related flesh bruising. Impact has been recognized as the most important damage (bruising) cause in fruits. Also excessive compression causes bruising, as well as repeated impacts.

Apple is one of the most problematic fruits in relation to mechanical damage. It has been extensively studied, and some data have been gathered on the percentage of fruits which become bruised during harvesting and grading: It can be as high as 81% of ("McIntosh") bruised apples during harvesting, 93% after transporting, 91 to 95% caused by bagging (Timm, 1989), when using manual harvesting systems.

In a recent study made in the Danish market (Kampp, 1990), it was established that only a few of the examined fruit samples met the EC quality standards for the products studied: 18 varieties of apples, and different numbers of varieties of strawberries, carrots, peaches and nectarines. In the retail samples, more than 20% of the strawberries had pressure damages; 20% of the examined peaches and nectarines had pressure or impact damages; approx. 95% of the apple samples did not comply with the EC standards for bruises, 55% of the apples had 1 to 6 bruises per fruit... In addition, it was observed that part of the products were being sold unripe, as they had been harvested at a too early stage.

In the Spanish production of fruits and vegetables, quality control is being applied by a leading group of comercializing companies (Valenciano, 1990). Apple and pear samples were examined at retail stores; bruise damage was responsible of a 50% of the total damages observed (which mounted up to 23 to 35%, including diseases, peel, shape, size, peduncle, etc.). In pears, 10 to 25% of the observed total class-rejection damage was due

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to bruises. Other products studied included strawberries, lettuce and green peppers. In the case of strawberries, nearly all damage was caused in the field, and was related to overmaturity of the fruits.

Consumer safety is one of the main concerns in agricultural R&D. From some data gathered during last years in the European fruit markets, we know that some of the retailers base their profit on high quality, high price fresh fruits and vegetables. This is attained by applying a very strong selection for "extra-fancy" quality, that causes a high proportion of rejects. These are then sold in second-class more economic retailer markets. This situation arises the question of safety and value to the consumers of these markets. Efforts to assure good quality of fresh fruits and vegetables are being made worldwide.

2. SOURCES OF MECHANICAL DAMAGE

Bruising appears as a result of impacts and compressions of the fruits on other fruits, parts of the trees, containers, parts of any grading and treatment machinery and on any uncushioned surfaces. Severity of damage in the fruit is primarily related to: 1) height of fall, 2) initial velocity, 3) number of impacts, 4) type of impact surface and 5) physical properties of the fruit, related or not related to maturity.

Fruit that is marketed to be consumed fresh is harvested manually. This means that fruits are picked one by one by hand-pickers and placed into some type of containers, transported to a packinghouse in different types of vehicles (trucks, tractors plus trailers). There, fruits are subjected to a number of operations, which vary greatly between commodities, but which combine similar individual treatments. TABLE 1 shows a list of such operations, and a combination of these is applied to the different species, and also to the different market demands; it is important to state that any combination of treatments may be applied to freshly-picked fruits as well as to cold-stored fruit, some shorter or larger periods of time after harvest; also, the last operations "transportation to wholesale and retail" may add up to various cycles (two, three, and more) as the product proceeds from production site (a different country in export operations) to retail market. This causes important differences in the damage that is caused to the fruits, due to the significant changes which may occur in their physical and physiological properties, related to variations in time lapses and in environmental conditions. Also, transportation/ storage/ grading may have to be combined with a cooling chain; the maintenance of this whole system is of great significance in the changes of the mentioned fruit properties, and therefore in their susceptibility to damage at any stage.

3. MECHANISMS OF FRUIT DAMAGE

Fruits may be classified into different types regarding their most evident physical properties, which are responsible for their susceptibility to bruising. Such a classification is very inaccurate, as many fruits change gradually from one type to another during ripening, or when subjected to different conditions. Nevertheless, two types of fruits may be described:

TABLE 1.
HARVESTING AND HANDLING OPERATIONS USED IN FRUIT MARKETING

Harvest into - buckets
field-boxes, or
pallet boxes
Transportation to packinghouse
Dumping, dry or into water
Washing
Waxing
Sorting
Sizing
Packing
Cooling
Storing
Transportation to - wholesale markets
- chain store distribution centers
- retail markets
Shelf storage

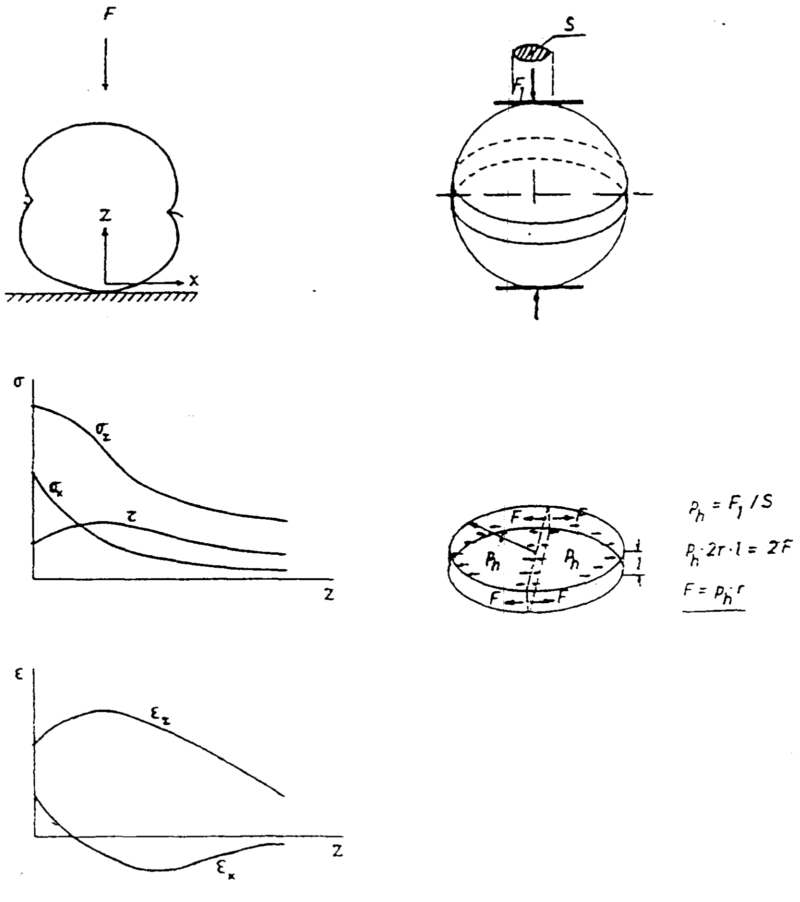


Figure 1. Fruits can be considered as elastic solids (A) or as liquid-filled elastic spheres (B) (Ruiz-Altisent and Gil, 1979); these mechanical models are extreme approximations to real fruits. (p_h = hydrostatic pressure; F = force exerted to the skin due to p_h).

First, one may distinguish between "rigid" ("hard") and "liquid"("plastic" or "soft") fruits.(FIGURE 1).

-Rigid fruits are those whose strength is based on a rigid structure, surrounded by a thin elastic skin: apples, (hard) pears, (hard) peaches, (hard) nectarines, (hard) apricots, avocadoes, mangoes, papaya, kiwi fruits, vegetables like potatoes, etc.In this type of commodities, resistance is based on the structural (i.e. hystological) and physiological characteristics of fruit flesh.

-Liquid fruits are made up by a near-liquid or "soft" mass contained in an elastic skin, being their resistance based on this skin: plums, tomatoes, grapes, cherries, berries, etc.
It is known that many "rigid" fruits gradually become soft when their maturity advances.

Some important facts are:
1) these two types of fruits are extreme models, which have to be studied accordingly, when trying to describe the behaviour of individual fruits, but most fruits change from one extreme to the other during ripening till senescence;
2) in hard fruits, the structure of fruit flesh may show important differences for the different fruits (apples and pears, for example, Ruiz-Altisent et al., 1989); these will have a fundamental influence on their response to damaging inputs (impact, compression) and on their bruising susceptibility;
3) changes may take place: very fast, or at a slow pace or occur suddenly, depending on ambient conditions and fruit species and variety;
4) physiological variables, linked with ripening and its physical characterization, also evolve accordingly;
5) all these variables may affect differently to individual fruits, even when coming from the same tree and when harvested at the same date.

External damage on the fruit skin can be caused by friction and abrasion against bin walls and conveyors. Especially susceptible to this type of damage are oranges (Chen and Squire, 1970; and Juste et al, 1990) and other citrus. Also some pear varieties are very easily damaged by abrasion (Valenciano, 1990). Peeling or "scuffing" of potatoes and other commodities has been studied, and some testing devices are being developed to measure susceptibility of the this type of damage on the skin (Muir et al., 1990).

Cuts and punctures are severe damages, caused by inappropriate equipment or handling; they are not related directly to fruit properties, and they can be avoided by proper care of the equipment and of the handling systems.

4.MEASURING AND MODELLING THE CONTACT PHENOMENA. APPLICATIONS

Various theoretical models have been used to explain and analize the impact problem as applied to fruits. The first one was presented years ago, and consists of considering a fruit as an elastic (generally spherical) body and applying the Hertz contact theory further developed by Shigley (Horsfield et al., 1972; Rumsey and Fridley, 1977). This approach has been shown to be only approximately aplicable, but it has produced much interesting information in many fruits, especially in what we have called hard or rigid fruits. The elastic contact problem in fact describes the internal stresses and strains created in and below the contact area between fruit and impacter of elastic, rigid, isotropic and semiinfinite bodies. It states that bruising can initiate at a certain depth below the skin, where the maximum shear stresses and strains appear. It was first applied to peaches, and pears mainly, but later many applications have been and are being published on apples, and even plums, cherries, potatoes and many more (Chen et al., 1984, Hemmat and Murfitt, 1987; García et al., 1988; Lichtensteiger et al., 1988; Roudot et al., 1989; Blahovec, 1990; Sinn, 1990). Also, different elastic models, adjusted with time-related constants, have been shown to correlate well with bruise size in some fruits (Siyami et al. , 1988).

When studying different kinds of fruits and fruit-probes, in different maturity and turgidity stages, only very few show distinct shear failure surfaces (conical, at 45º slope), and many show rather horizontal failure planes (especially apples, Jarimopas, 1984; Ruiz-Altisent et.al., 1989,) other types of failure patterns, or no failure surfaces at all (Ruiz-Altisent et al. 1989).

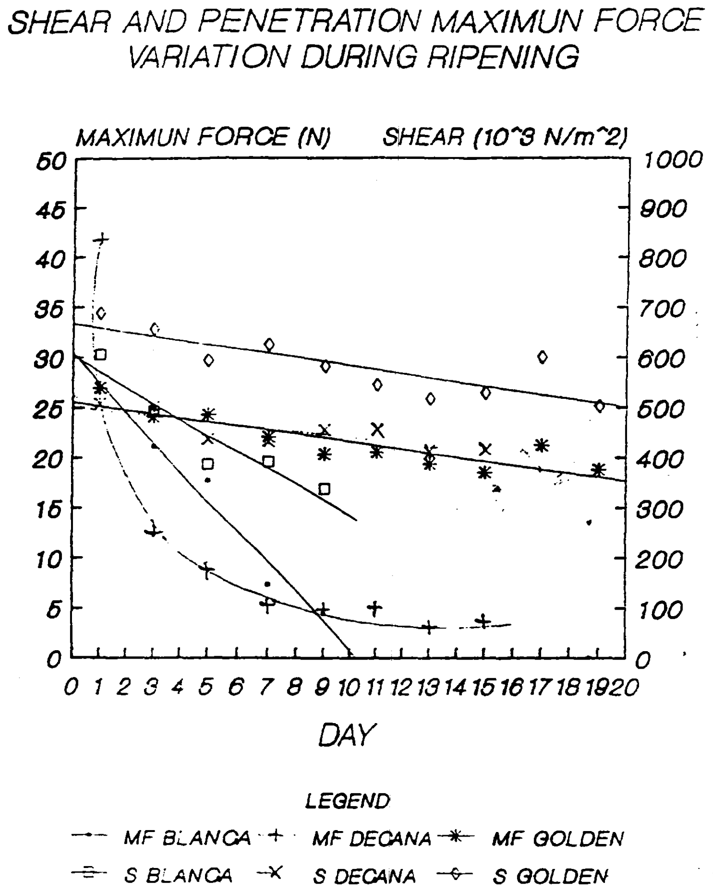
In most cases, size of the observed bruised volume is not correlated to the calculated values of maximum shear or compressive stresses, especially when testing fruits at varying (increasing) maturity. Rodriguez, 1988, Rodriguez et al.,1991, showed that ,in pear "Blanquilla": 1) when a range of impact energies were taken into account, the mechanical variables measuring the impact response were correlated with three main factors: impact energy (IE), impact duration (ID) to fruit firmness (F) ratio (ID/F) and physiological maturity (E/A=sugar content/fruit acidity); in this analysis, bruise size correlated with IE; 2) when data were analyzed for individual impact energies for the whole range of physiological maturities, impact force (IF), maximum deformation (MD), duration of impact (ID) and maturity stage (date of testing) were the variables correlating with impact response, but bruise size was not correlated to any of those variables, it correlated (negativelly and not very highly) with F (Magness-Taylor firmness). Similar observations are derived from the results by Timm et al. (1989), where MD is represented by "Total velocity change", VC. Force/time slope (IF/T), or, similarly, maximum time-rate change of acceleration during impact (DAM) has also been reported as the most important parameter in predicting bruise volume (Chen and Yazdani, 1989), but it also interferes with maturity of the fruits (García et al., 1988).
When working with impact testers, maturity evolution (i.e. firmness) can be determined accuratelly by some variables of the response to impact of the fruits. García et al., 1988, working with three varieties of pears and two varieties of apples, and also Jarén et al. and Correa (1991) showed that time-related parameters like ID (impact duration), and TM (time to maximum force) are very sensitive to maturity changes, in apples and pears, and in avocadoes, respectively. By use of the impact tester, firmness can therefore be determined on the spot and at the same time of the applied impact, and with higher accuracy than by penetrometers. After many tests, it has been observed that bruise size is not uniformly sensitive to maturity (firmness) differences in homogeneous samples of apples and

pears, and of other hard fruits.

FIGURE 2 shows variation of Magness-Taylor (maximum penetration) force, along with calculated values of maximum shear stress during a 20-day period of post-harvest maturation, for two pear varieties ("Blanca" and "Decana") and one apple variety ("Golden"); impacts of 4-cm free-fall of a 50,6 gram spherical mass (0.02 Joules) were applied (avg. values of 12 fruits). Bruise width increases very fast for both pear varieties tested, remaining fairly constant for Golden apples (upper graph). The rest of the lines in the graphs show the variation of different firmness parameters: Final time=impact duration (ID) (Upper), Magness-Taylor penetration force (F, in N) and calculated maximum elastic shear stress, for the same fruits. Bruise width appears well correlated to all firmness parameters, but with specific and different relationships for each sample, and only when firmness decrease is very large and fast.(Jaren et al. unpub.).FIGURE 3 shows evolution of MT along with ID (upper) and with IF/T (lower) for avocadoes (12-day maturation period). Non-destructive impact response (no breuises) measures very accurately maturation process (dotted lines untreated, full lines "green-keeper" treated samples):this process is not constant, showing a sharp change in a specified time, for each commodity.

Roudot et al. (1989), working with two varieties of apples show that firmness is not causally correlated to bruise resistance. When studying bruise size (depth and width) for increasing impact energies, no dependance has been observed of bruise size with the relevant elastic parameters: IF(impact force), and the calculated modulus of elasticity or compressive and shear stresses; maximum and permanent deformation (penetration of indentor) appear most related to bruise size, for any maturity stage and input energies, in a given fruit species. It is observed that in impact testing, in firmer (less mature) fruits of the same variety and sample, the created stresses (higher) relate with smaller deformations of the tissue and the cells; in softer fruits, where stresses are lower strains (deformations) are larger, therefore causing similar bruised volumes. Other authors show that although rupture force decreases during storage, the energy required to cause failure does not change significantly (Van Woensel et al. 1983). One may also observe in some results (Timm et al. 1989) that bruise size decreases for firmer apples, but the percentage of bruised apples is lower for less firm apples of the same variety and sample.

Softening to senescence (over-maturity) as observed in pears, peaches, apricots, etc. converts the fruit into a more plastic mass, with less elasticity, and nearly total absorption of input energy into deformation and bruising; stresses are not transmitted to the surrounding tissue. This complies with the observations made in common practice where softer (less firm) fruits are usually more susceptible to bruising during handling. It has been shown previously (Ruiz-Altisent et al., 1989; Rodriguez et al. 1991) that cells initiate "bruising" reactions when submitted to stresses, even without rupture of their cell-walls. This is the causitive effect of the assumptions made above.
Fruit tissue is made up by cells, forming their walls the rigid structure of the pulp; these cells are bonded together by a connecting substance and the tissue contains varying proportions


SHEAR AND PENETRATION MAXIMUN FORCE VARIATION DURING RIPENING
MAXIMUN FORCE (N)
SHEAR (10^3 N/m^2)
0 5 10 15 20 25 30 35 40 45 50
0 100 200 300 400 500 600 700 800 900 1000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
DAY
LEGEND
MF BLANCA
MF DECANA
MF GOLDEN
S BLANCA
S DECANA
S GOLDEN

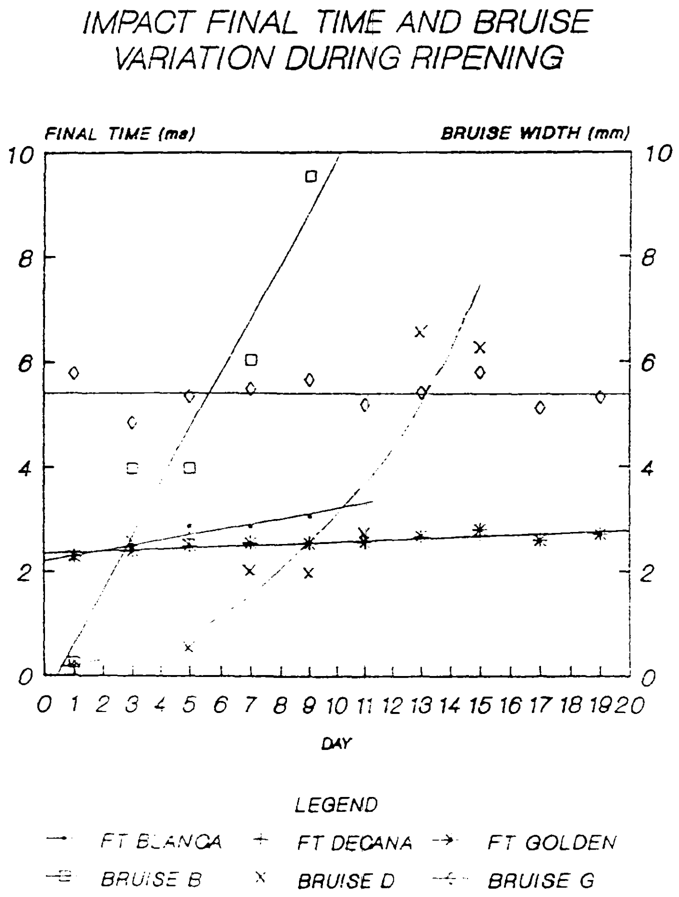

IMPACT FINAL TIME AND BRUISE VARIATION DURING RIPENING
FINAL TIME (ms)
BRUISE WIDTH (mm)
0 2 4 6 8 10
0 2 4 6 8 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
DAY
LEGEND
FT BLANCA
FT DECANA
FT GOLDEN
BRUISE B
BRUISE D
BRUISE G

FIGURE 2.

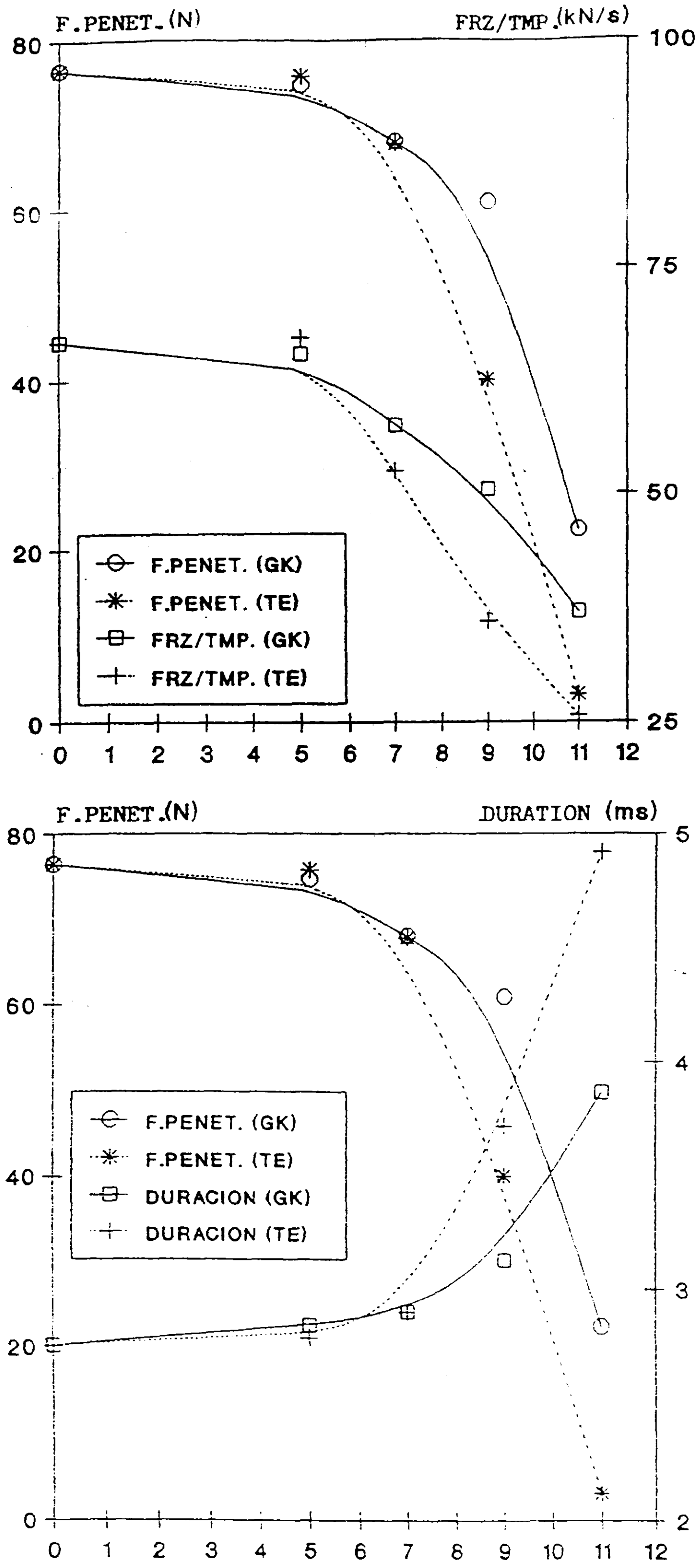


FIGURE 3. Evolution of Magness-Taylor firmness (N) along with impact duration time (ms) (upper) and force/time slope (kN/s) (lower) during ripening of avocadoes. Dotted lines: untreated (TE); full lines: storage with "Green Keeper" (GK). 11 days at 20ºC (Correa et al.1991

of gaseous spaces, free liquids or even oils (Pitt, 1982; Rodriguez et al, 1990; Ruiz-Altisent et al., 1989; García et al., 1988). Both cell walls and bonding material change greatly with ambient conditions and with ripening. Their walls become softer and their bonds looser, so that they deform easier, dissipating stresses. The same effect is created by void spaces and free liquids in the fruit tissue. Also, turgor pressure has been included in a constitutive model of fruit tissue formed by individual cells (Gates et al. 1986).

Lichtensteiger et al. (1988) used a drop testing apparatus where the samples were released from specific heights onto a rigid aluminum plate instrumented with a force transducer. Various types of models (fabricated balls) and also red tomatoes were tested. Changing the properties of the shell in relation to the internal material of the tested balls showed that the shell effect is prevalent when the internal structure is softer than a relativelly thin shell. When the internal material is stiffer than the shell, no shell effect was observed. This result shows that the effect of the skin when testing "soft" fruits is in fact relevant in the response to impacts. Working with soft pears, Rodriguez et al. (1990) and Jarén et al. observed an increase in impact force (IF) for the last stages of senescent fruits due to this skin effect, as it becomes stiffer with overmaturity.

Results obtained so far indicate that higher loading rates and higher firmness (hardness) in the fruits usually show shear failure patterns; slower loading rates and lower firmness show normal stress or strain failure (Chen and Sun, 1984, Ruiz-Altisent et al. 1989). Therefore, discrepancies found in the results of different researchers in relation to fruit tissue failure should be due to these mentioned differences in loading rate and in fruit properties. This refers also to the bruise volume/energy ratio discrepancies, discussed earlier.

Soft fruits have been less studied. They may behave as elastic bodies when impacted, due to their elastic skin properties. Bruising stresses are generally distributed to large parts of the tissue, and therefore bruises appear only for higher energy inputs, and over large volumes. Testing different varieties of peaches and nectarines (Ruiz-Altisent, 1990) a very good resistance to bruising was observed, as compared to apples and pears, even with significant maturity advances.

Sinn (1990) performed free-fall impact testing of cherries and plums. In this and other reported results, a good correlation was observed between impact force (registered on the impacting plate) and fruit damage, for high energy impacts.

As mentioned, bruising is also caused by static and by quasi-static contact loading. Mechanical models which have been applied to describe impact were developed for static contact, with similar results and with the same restrictions for accuracy. Viscoelasticity becomes important in static loading. Chen et al. (1987) compared the bruises produced by compression and by impact, and they observed that bruise pattern could be very different in both loading speeds: for a variety of pears, long spikes extended radially from the impact area into the fruit, showing that loading rate has a great influence when analyzing strength and failure of fruits. Sometimes, soft fruits do not show bruises when impacted, but they show them when applying sustained deformations. This effect has been observed in apricots when studying damage resistance in a selection of apricot varieties (Ruiz-Altisent, unpublished data). They were resistant to impact bruising, but a (axial) deformation of 3 mm applied during 1 minute by means of a spherical indentor of 15 mm radius of curvature produced distinct bruises; when applying a constant compression force of 10 N bruise size increased significantly with advancing maturity.

In electron microscope studies carried out in a variety of apples (see below), it was observed that degradation of cells was different when impacted than when slowly compressed.

5.STRUCTURAL DIFFERENCES

Closer observation of bruises caused by impact shows that different species of fruits (Rodriguez, 1988; Ruiz-Altisent et al. 1989; Rodriguez et al., 1990, studying apple and pear fruits) show different bruise sizes and patterns which appear in the absence of any significant variation in other relevant parameters (like radii of curvature of the fruits or the impacters, or the enrgy of impact). Therefore, they have to be related to structural differences between these fruits, which in fact are very important: size and shape of cells in hypodermis (first cell layers below the skin) and pulp, presence of intercellular spaces, etc.

Rodriguez et al. (1990) made transmission electron-microscope studies in apples (variety "Granny Smith"), showing that after a few hours, cells of the bruised area are altered, with intensive vesiculation, either in the vacuole (inside the cell) or in the middle lamella region between adjacent cells. It was observed that cell wall rupture is not necessary to initiate bruise reactions; if it occurs, it may additionally leak the altered compounds out of the cells to the intercellular spaces. Thus, the browning reaction in fruit under applied loads can take place either outside or inside the cells. Stresses applied to tissue cells which cause no rupture of cell walls, cause also bruising, developed internally in the cells.

Roudot and Duprat (1990) used a graphical model to simulate the effect of these structural differences on failure in apple flesh. The model starts considering that apple flesh is unhomogeneous and that it contains a variable proportion of intercellular voids. Using complex two-dimensional modelling of the cellular tissue it was possible to simulate the collapse of cells as result of varying levels of loading, time of application (1,0.1 or 0.001 seconds), percentage of intercellular voids and cell-covered surface and of a factor describing the shape of the cells. Very different failure patterns could be obtained and compared to real bruises. Interesting observations were: total volume of collapsed tissue increases when void space increases; hetereogeneity in cell size and shape increases tissue collapsing; tissue formed by compacted and small cells is more resistant to collapse.

These results relate to those obtained by Rodriguez, 1988; García et et al., 1989; Rodriguez et al., 1990, in impact bruises in apples and pears. Differences in bruise patterns were apparent: apples show wider and more superficial bruises than pears; their void spaces cause initial cell collapsing and stress dissipation.

6.BIOLOGICAL VARIABLES

One important concern is trying to influence the properties of fruits to increase their bruising resistance. As has been stated above, the properties of fruits change in relation to many biological variables. These influences initiate in the early stages of development of the fruit in the plant, are caused by variations in varietal, agronomic and climatic conditions, and continue throughout the whole growing season. Some attempts have been made to explain the influence of such variables in the susceptibility of fruits to mechanical damage.

Johnson and Dover (1990) studied some factors influencing the bruising susceptibility of a variety of apples (Bramley's Seedling). Fruits from 24 commercial orchards were tested during six seasons. It was observed that bruising susceptibility (measured by means of an instrumented pendulum, applying 0.19 Joules of impact input energy) varies in a greater measure within a season (between orchards) than between seasons. There was no evidence of any agronomic or microlimatic factors which might be responsible for such differences: Neither soil management systems (complete grass covering, strip-herbicide or overall herbicide), nor Nitrogen fertilizer applications or mineral composition of leaves or fruits. Bruise volume was negativelly correlated to fruit firmness (Magness-Taylor puncture test); also, larger fruits were observed to be more susceptible to bruising, within samples of the same orchard : in larger fruits, cells are larger, as well as their intercellular spaces. Bruise volume increased significantly with picking date, as shown in FIGURE 4. Only one effect was important to stress: Water loss appeared to increase bruising resistance to the fruits. Johnson and Dover (1990), citing Hatfield and Knee, 1988, Pitt, 1982, and Pitt and Davis, 1984), and other authors have associated turgor pressure with a reduction in the strength of apple tissue. They also observed that water loss seemed to increase bruising resistance.

Jaren and Recasens (1990) tested the effect of Calcium treatments on the physical properties of apples. Many researchers have stated an increase of tissue firmness when treated with Calcium. This element contributes to keeping the cell membrane and the cell-wall integrity. Samples of "Golden Delicious" apples were treated with different Calcium solutions, different periods of time (weeks) before harvest. Static and impact tests were applied to the fruits, after harvest and after various intervals of cold storage. Significant differences were observed in firmness, as well as a reduction in bruising susceptibility of fruits subjected to some of the Calcium treatments.

7.CONCLUSIONS

In order to improve fruit quality it is necessary to:

A) improve the handling systems
B) reduce damage susceptibility of the fruit itself.

Many attempts have been made during the last years to explain damage in fruit tissues, leading to bruising. We know the importance of:

1) macrostructure of the fruit;
2) microstructure (cells, tissues) and their dependance of its properties on
    a) maturity;
    b) ambient conditions;
    c) turgor pressure;
    d) cell constituents;
    e) content in Calcium and other elements.

There are systems to accurately measure fruit firmness destructively and non-destructively.

There also exist procedures to determine impact and compression response, and for studying damage susceptibility in all types of fruits, and to study them in different conditions. This allows to improve managing systems and equipment.

Knowledge on fruit structure should allow to develop fruits which are less susceptible to mechanical damage.

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