International Journal of Horticultural Science 2005, 11 (4): 59–64
Agroinform Publishing House, Budapest, Printed in Hungary
ISSN 1585-0404

Mechanical behavior of catching surfaces used for fruit harvesting

Horváth, E.

Corvinus University, Faculty of Horticulture, Technical Department, H-1118 Budapest, Villányi út 29-35.

Summary: Various fruit gathering devices are important part of tree shakers used in fruit harvesting. The catching surface is generally used in the form of a stretched thin sheet interacting with the falling fruit. This interaction depends on many factors such as the shape and mass of the fruit, the falling height and the mechanical properties of the catching material.

In recent investigation different canvas, composite and silk materials were selected and their mechanical behavior was experimentally determined. Using the energy conservation principle, the main impact characteristics of the falling fruit was derived and used. Static and dynamic loading tests were carried out using spherical intenders and artificial fruits. Investigations have shown that, using the appropriate material characteristics, the catching surface can serve as a cushioning material and it can considerably reduce the impact stresses in the falling fruits.

Key words: gathering device, fruit impact, cushioning, fruit-membrane interaction.

Introduction

Catching surface is an essential part of any tree shaker used for fruit harvesting. The catching surface is generally treated as a fruit gathering device and other possible functions are not examined yet. At the same time, the catching surface, as a stretched thin membrane, may serve as a cushioning material and it can considerably reduce the impact stresses in the falling fruits.

The survey of literature, however, has shown that the dynamic behavior of catching surfaces and their cushioning effect are very poorly examined. The knowledge of material properties, including the viscoelastic properties, is indispensable, therefore, the most important material properties must experimentally be measured. Using the energy conservation principle and taking elastic bodies, the deformation of the surface, the maximum force and other parameters of the impact can be derived. The viscoelastic properties, if they are present, should also be taken into account.

The materials generally used for fruit harvesting are different canvas materials with fibre reinforcement which may cause some anisotropy in the material behavior. The anisotropy can be treated in several ways. In order to obtain a closed form solution a more simple characterization of the anisotropy was chosen.

Material and method

The main purpose of these investigations to characterize the materials used for catching surfaces and to establish general relationships determining force, displacement, velocity and deceleration of the falling body during the impact process, and the maximum stress in a given fruit falling onto the surface. If the allowable stress for the falling fruit is known then, using an appropriate catching surface material, fruit damages can be avoided.

In recent investigations different canvas, composite and silk materials were selected and their mechanical behavior experimentally determined. The specific weight of the materials varied between 300 and 900 g/m^2. In order to determine the strength and viscoelastic properties a universal testing machine was used. Specimens were cut parallel to the reinforcement in both directions, perpendicular to each other. Three specimens were used from each material and an average value was determined for a given characteristics.

A 2 m x 2 m model catching frame was constructed allowing to set different stretching forces and to change the catching surface materials. Static and dynamic loading tests were carried out in the middle of the surface and the deformation was determined as a function of load using spherical intenders and artificial fruits respectively. A special pendulum hammer test was also used determining the deceleration of the falling body during impact as a function of drop height. In the case of dynamic loading tests the displacement of the catching surface was determined using a video camera which was previously certified for known displacements.

Mechanics of catching surface

Catching surface is an essential part of any tree shaker used for fruit harvesting. The catching surface is generally treated as a fruit gathering device and other possible functions are not examined yet. At the same time, the catching surface, as a stretched thin membrane, may serve as a cushioning material and it can considerably reduce the impact stresses in the falling fruits.

The main purpose of these investigations to characterize the materials used for catching surfaces and to establish general relationships determining force, displacement, velocity and deceleration of the falling body during the impact process, and the maximum stress in given fruit falling onto the surface. If the allowable stress for the falling fruit is known then, using an appropriate catching surface material, fruit damages can be avoided.

The most important characteristics of the catching surface materials are given in *Table 1*.

Table 1. Properties of catching surface materials

		Canvas			Synthetic leather	Syn. Silk textile
		1	2	3		
thickness,	mm	0.32	0.54	0.76	0.3	–
spec.weight,	g/m^2	350	650	900	300	120
k$_{av}$,	N/cm	985	1610	2520	320	440
E,	N/cm^2	(30 – 32) . 10^3			10600	–

The materials tested suffer high tensile strain and breaking occurred at 15 – 30% strain. The force-deformation curve is generally not linear and it shows some hardening properties. This means that the exponent of the deformation is slightly higher than one (*Fig. 1*).

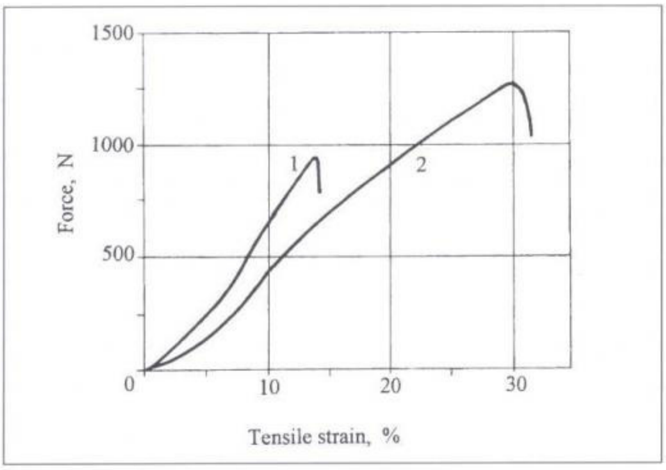

Fig. 1. Force – deformation relationships.
1 – synthetic leather, width 2.5 cm
2 – synthetic silk textile, width 10 cm

To obtain a more simple material characterization, linear approximation was used in the following form:

$$F = k_{av} \cdot \varepsilon \qquad \text{N/cm} \qquad (1)$$

or

$$\sigma = E_{av} \cdot \varepsilon \qquad \text{N/cm}^2 \qquad (2)$$

where F is the force related to the unit width, k_{av} is the average virtual spring constant, and σ is the tensile strain.

It should be noted that most of the materials shows a definite anisotropy, i. e. the force- deformation curves in directions perpendicular to each other are different. The averaged material constants combine also this latter effect.

Concerning an elastic catching material, the deformation, force, velocity and deceleration during the impact can also be calculated.

Keeping in mind Eq. (12), the maximum deformation of the catching surface under a falling body is given by the energy equation (*Sitke*i, 2005):

$$mgh = \int_0^x F dx \qquad \text{and} \qquad x_{\max} = \left(\frac{mgh(n+1)}{B} \right)^{\frac{1}{n+1}} \qquad (3)$$

Falling a body onto a surface, the force is given by the deceleration and, therefore, the following equation is valid

$$F = m \,.\, a = B \,.\, x^n$$

and

$$a = \frac{B \cdot x^n}{m} \qquad (4)$$

After contacting the surface, the velocity of the falling body decreases. At the beginning of the impact the approaching velocity has the value of, $v_o = \sqrt{2gh}$, where h is the falling height. As the deformation reached its maximum value, the velocity tends to zero.

The change in velocity can be calculated as

$$v_x dv = -a \cdot dx = -\frac{B}{m} x^n dx$$

after integration we have

$$\frac{v_x^{\,2}}{2} = -\frac{B \cdot x^{n+1}}{m(n+1)} + C \qquad \text{and} \qquad C = \frac{v_0^{\,2}}{2}$$

and further

$$v_x = \left(v_0^{\,2} - \frac{2 \cdot B \cdot x^{n+1}}{m(n+1)} \right)^{\frac{1}{2}}$$

Generally $n = 2$ may be used and, therefore, the final equation has the form

$$v_x = \left(v_0^{\,2} - \frac{2 \cdot B}{3 \cdot m} x^3 \right)^{\frac{1}{2}} \qquad (5)$$

If the deformation x approaches its maximum value x_{max}, then the velocity of the body tends to zero.

Making use of Eq. (5) and keeping in mind that $v = dx/dt$, the impact duration can be determined as

$$t^* = \int_0^{x_{\max}} \frac{dx}{\left(v_0^{\,2} - \frac{2 \cdot B}{3 \cdot m} x^3 \right)^{\frac{1}{2}}} \qquad (6)$$

Fig. 2 shows the displacement, velocity and deceleration of a falling body during the impact process. Due to the quadratic force – displacement function, the impact duration is relatively high compared to linear elastic bodies.

Using Eqs. (12) and (3), the maximum impact force can be obtained.

$$F_{\max} = B^{\frac{1}{3}} \cdot (3mgh)^{\frac{2}{3}} \qquad (7)$$

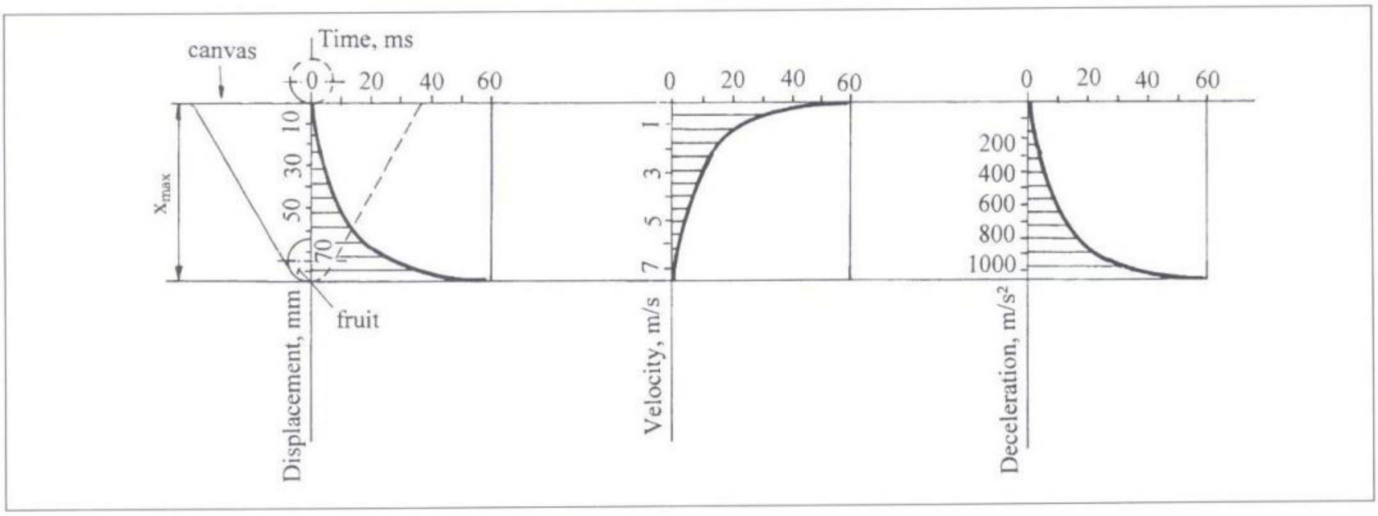

Fig. 2. Displacement, velocity and deceleration during an impact.

In order to determine the average and maximum stress produced in a spherical body, the contact surface is also needed. The contact surface is a function of the diameter and deformation of the catching surface. The following simple approximation was found

$$A_x = 0.25 . d^{1.5} (.x_{max})^{0.5} \qquad \text{cm}^2 \qquad (8)$$

where the diameter d and the deformation x_{max} must be substituted in cm.

Combining Eqs. (7) and (8), the average and maximum stress in the falling spherical body can be approximated as

$$\sigma_{av} = F_{max} / A_x \qquad \text{and} \qquad \sigma_{max} \cong 1.5 \cdot \sigma_{av}$$

or in a more detailed form

$$\sigma_{av} = \frac{B^{0.5} (3mgh)^{0.5}}{0.25 \cdot d^{1.5}} \qquad \text{N/cm}^2 \qquad (9)$$

Example. Concerning a falling apple of 7 cm diameter from a height of 3 m. Its mass is 143.7 g, and using a catching surface with B=15300 gives x_{max}=9.4 cm. The maximum force is 135 N, the contact surface is 14.2 cm2, the average stress is 9.5 N/cm^2 and the expected maximum stress is 14.3 N/cm^2. This value is much less than the allowable stress, which is at least 30–40 N/cm^2.

In the above discussion the mass of the catching surface has been neglected. In real cases a given reduced mass of the catching surface should also be accelerated resulting less displacement and greater force. It is obvious that the mass ratio composed of the falling and reduced mass of the catching surface has the main influence on the impact process. Harvesting sweet and sour cherries, the falling fruit has a mass of 10–12 g while the reduced mass of the catching surface may be several time greater. In this case the calculation method given above should slightly be modified.

The reduced mass of the catching surface can approximately be calculated in the following way (see *Fig. 3*).

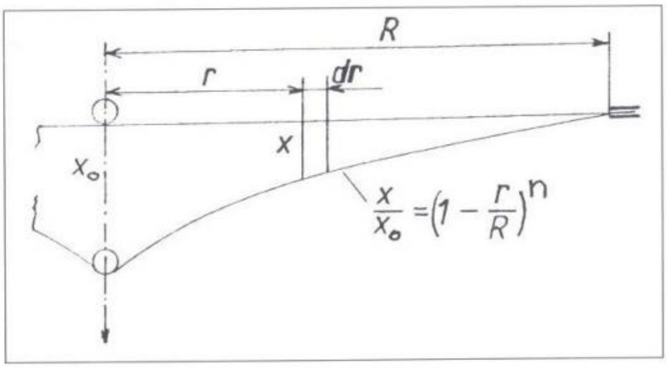

Fig. 3. To the calculation of reduced mass of catching surfaces.

The maximum displacement of the catching surface occurs in the mid (on the place of impact) and the displacement is diminishing towards the clamping edge. Using the general rule for reducing masses [2]:

$$m_r = \sum m_i (l_i / l)^2$$

we can write

$$dm_r = m_F \, 2 \cdot r \cdot \pi dr \left(1 - \frac{r}{R}\right)^{2n}$$

or

$$m_r = 2 \cdot \pi \cdot m_F \int_0^R r \left(1 - \frac{r}{R}\right)^{2n} dr$$

where mF means the specific mass of the catching material, kg/m^2.

For n=2 the reduced mass has a value of m_r=M/15, and for n=3 a value of m_r=M/28 is valid. Here M is the mass of the entire (round) catching surface.

The total force on the contacting body contains now an inertia force component which is calculated as

$$F = B \cdot x^n + m_r \frac{B \cdot x^n}{m_{fr}} = B \cdot x^n \left(1 + \frac{m_r}{m_{fr}}\right) \qquad (10)$$

where m_r is the reduced mass of the catching surface,

m_{fr} is the mass of the falling fruit.

If the m_r/m_{fr} mass ratio is greater than 0.5, the effect of inertia forces should be taken into account. For this in all equations instead of B the greater value of $B(1 + m_r/m_{fr})$ should be substituted.

There are experimental evidences [3] which demonstrate that the common catching surface can cause mechanical damage in small fruits (sour cherry), especially in overripe conditions. The use of a light material can help to avoid an excess damage.

Results and Discussion

The tensile properties of the tested materials have already shown in Fig. 1 and they were characterized by the average spring constant and average modulus of elasticity as defined in Eqs. (1) and (2) and given in Table 1.

Force relaxation tests were also conducted on the materials to determine the main viscoelastic properties (*Fig. 4.*).

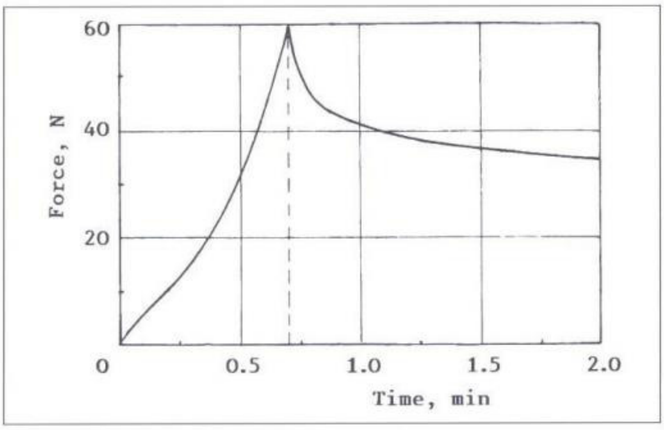

Fig. 4. Force relaxation as a function of time. Synthetic leather.

The spectrum of relaxation time, using double logarithmic scale, gave always a straight line, that means that the relationship can be described by a power function (exponents between 0.7 and 0.8 are typical). It is important, however, that the relaxation time at beginning of relaxation always has a finite value taken uniformly as the value belonging to the elapsed time of 1 s. (*Fig. 5.*).

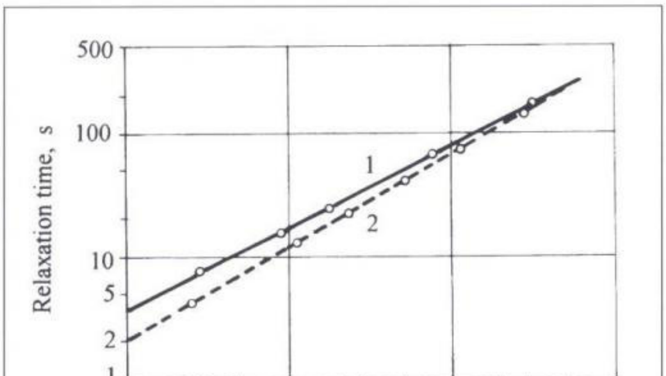

Fig. 5. Relaxation time as a function of elapsed time.
1 – synthetic leather, 2 – synthetic silk textile

Another important viscoelastic property of the materials is the asymptotic value of the loading force after a longer period of relaxation. This asymptotic value F_a may be related to the nominal force F_0 acting at the beginning of relaxation

$$F_a = a \,.\, F_0$$

and the decrease of force during the relaxation process is given as

$$F_t = a \,.\, F_0 + b.\, F_0 \,.\, e^{-t/T} \tag{11}$$

$$a + b = 1$$

where t is the elapsed time, and T is the relaxation time taken from Fig. 3. or from similar curves.

Materials having a–values around 0.7 showed almost no velocity effect in the force – deformation relationships. On the contrary, materials with a = 0.4 or so had a clear difference in the static and dynamic loading curves.

The catching surface is a stretched membrane fixed to a rigid frame. A model catching frame was constructed allowing to set different stretching forces and to change the catching surface materials. The model catching frame measured 2 x 2 m. In order to clear the size effect, a model frame of 1 x 1 m size is also constructed.

The different catching surface materials were subjected to static load using spherical intender. In all cases, the force – deformation relationship showed a highly non–linear character (*Fig. 6.*). The curve may be described in the following general form:

$$F = B \,.\, x^n \tag{12}$$

where x is the deformation of the catching surface and the exponent n is very close to 2.

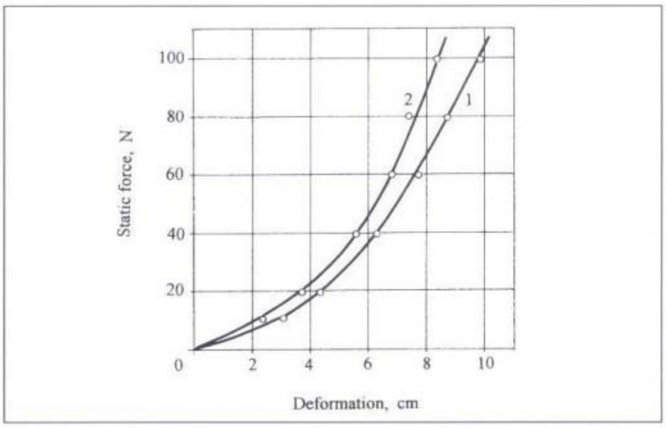

Fig. 6. Static force – deformation relationship for catching surfaces.
1 – synthetic leather, 2 – synthetic silk textile

The dynamic behavior of the catching surface was tested using artificial fruits with different masses and sizes.

The above discussion and equation are valid for elastic materials. Viscoelestic materials can produce somewhat less

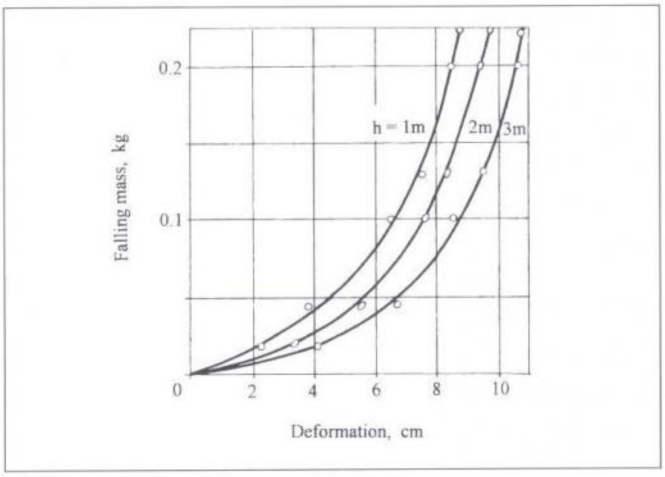

Fig. 7. Deformation of the catching surface under falling fruits for different drop heights. (synthetic silk textile)

deformation depending on the impact velocity. *Fig. 7.* shows the result of dynamic test on catching surface made of synthetic silk textile. The evaluation of results, using Eq. (7), has shown that the curves fully correspond to an elastic behavior. At the same time, other materials, such as synthetic leather, show a definite viscoelastic effect, i.e. deformations due to dynamic load are 8–12% less compared to the static load (*Fig. 8.*). The less deformation of the catching surface always means a higher deceleration of the falling body, a higher inertia force and also a higher stress in the contacting surfaces. However, it can also be seen that the viscoelastic effect depends rather on the actual deformation velocity of the catching surface than simple on the impact velocity. Therefore, differences occur only at higher deformations.

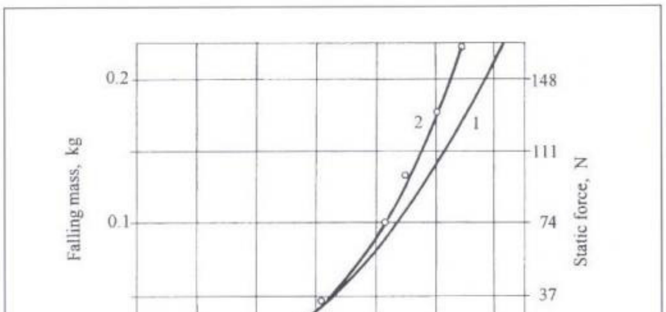

Fig. 7. Deformation of the catching surface under falling fruits for different drop heights. (synthetic silk textile)

The effect of inertia forces due to catching materials can be determined in a simple way. Keeping in mind Eq. (10), the relative variation of displacement, contact area, force and average stress (see Eqs. (3), (7), (8) and (9)) are only the function of the single variable $C=(1 + m_r/m_{fr})$ and they can by expressed by the following equations

$$\frac{x}{x_0}=\left(\frac{1}{C}\right)^{\frac{1}{3}} \quad \frac{F}{F_0}=C^{\frac{1}{3}} \quad \frac{A}{A_0}=\left(\frac{1}{C}\right)^{\frac{1}{6}} \quad \frac{\sigma}{\sigma_0}=C^{\frac{1}{2}} \quad (13)$$

where the subscript *o* refers to the case without mass effect.

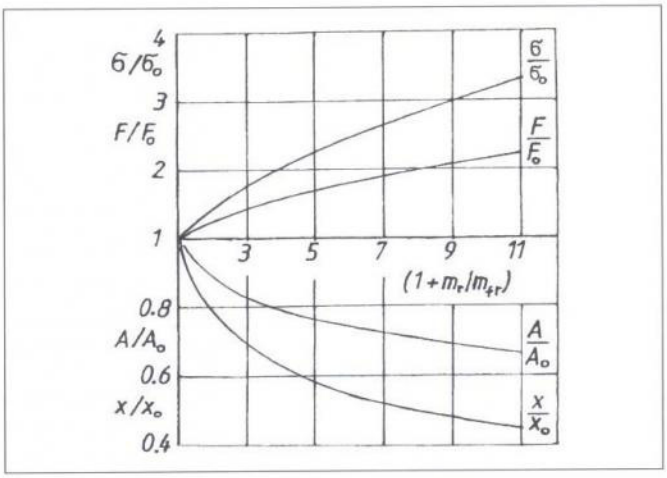

Fig. 9. Effect of inertia forces due to catching materials on various parameters of the impact process.

The above functions are depicted in *Fig. 9*. The specific weight of the catching materials *mF* is already given in *Table 1*. Knowing the fruit mass m_{fr}, the m_r/m_{fr} mass ratio can approximately be given as

$$\frac{m_r}{m_{fr}}=\frac{m_F}{10\cdot m_{fr}}$$

Harvesting cherries and using a light silk textile as catching material, the mass ratio $m_r/m_{fr}=1$. At the same time, a heavy camvas gives values about $m_r/m_{fr}=7.5$. Using Fig. 9, the effect of the additional inertia forces can easly be evaluated.

In an earlier experiment [3] it was surprisingly observed that, harvesting sour cherries, the damage was higher for fruits falling onto the canvas than for those falling onto an other fruit. The explanation in now clear, the heavy canvas due to its inertia effect can cause higher stress in the contacting fruit.

In recent investigations different canvas materials (fiber reinforced synthetic materials), synthetic leather and synthetic silk textile were selected and their mechanical properties experimentally determined. Strength and viscoelastic properties were measured using a universal testing machine (Instron). The static and dynamic behavior of these materials as a catching surface was determined on a model catching frame allowing to set different stretching forces and to change the catching surface materials.

The measurement results have shown that these materials generally have a given anisotropy and are always viscoelastic. The viscoelastic effect, however, appears in cases, if the force relaxation is large compared to the initial force. Furthermore, the viscoelastic effect may be expected, first of all, for large deformations.

The derived equations for the elastic case agreed well with the experimental results. An important finding that, harvesting small fruits, the reduced mass of the catching material can have a significant effect on the impact process. Therefore, it is recommended to use possibly light catching materials such as silk textile while harvesting small and sensitive fruits.

Summarizing the results, it can be concluded that the catching surface material can also serve as a cushioning material absorbing the kinetic energy of the falling fruit considerably and so decreasing the mechanical stresses in the internal tissue of the falling fruit.

Referneces

Sitkei, G. (ed.). (2005): Technical Aspects of the Horticultural Production. MGI Books, Gödöllő.

Horvath, E., Sitkei, G. (2001): Energy Consumption of Selected Tree Shakers under Different Operational Conditions. J. Agric. Engng. Res. 80(2): 191–199.

Horvath, E. (2003): Analysis of Primary Fruit Damage using Mechanical Harvesting. Lippay János-Ormos Imre-Vas Károly Scientific Symposium, Abstracts Section of Fruit Science. November 6–7. Budapest. 324–325.