

# SUGAR BEET ROOT PROPERTIES IN RELATION TO HARVESTING

## DAMAGE

by

T.A.Gemtos, Assoc. Professor,  
Laboratory of Farm Mechanisation,  
University of Thessaly,  
Pedio Areos, 38334 Volos, Greece.

## ABSTRACT

Sugar beet main roots (MR) break during lifting causing a considerable loss of saleable product in the field. These losses are caused by stresses developed into the MR during lifting. In this work an analysis of the strength of beet secondary roots and rootlets as well as the tensile, compressive, shear and bending strength of MR parts is presented. The main root is composed, from the strength point of view, of two materials: (1) The parenchyma which is more abundant in the inner parts. It is relatively weak in tension (mean strength 2.1 MPa, range 0.65-4.29 MPa) but stronger in compression (mean strength 3.05 MPa range 2.50-4.00 MPa ) and (2) The vascular tissue, which forms several rings within the parenchyma. The rings are denser in the outer parts of the root especially near the epidermis. The vascular tissue is stronger in tension than the parenchyma (mean strength in tension of outer parts of root 2.8 MPa range 1.4 -4.46 MPa). It was found that secondary roots and rootlets required an average force of 39.6 N to break sections of 15 mm in diameter. The main mean root shear strength was 0.60 MPa when the shearing load was applied at the plane normal to the plane including the root grooves and 0.68 MPa at the plane including the root grooves. When the main root was subject to bending the maximum strength in tension or compression of the outer layers depends on the dimensions of the breaking section. Two exponential relationships and one inverse were fitted to the data, which can be used in modelling sugar beet lifting. The exponential formulae gave a better and more realistic approximation of the root strength.

**Keywords:** Sugar beet, root strength, root lifting, harvesting losses, root breakages, root-metal friction

## INTRODUCTION

Sugar beet is, in most European countries, harvested by lifting the root from the soil after removing the tops and the leaves. During this process main roots (MR) may break leaving a part in the soil. These losses are called «dug losses» and they cause a 5% loss of saleable roots in Britain (Davies 1976) or a range from 5.4 to 13.8% in Greece (Gemtos et al. 1998). Work by von Hulst (1957), Gemtos (1980) and Miller (1984) suggested that bending stresses developed during lifting could cause root fracture. According to the model proposed by Gemtos (1980), for pronged lifting shares, the MR is squeezed between the prongs and pushed to move through the soil. The soil reacts to the MR movement by a force whose limit is the soil strength. Due to a wedge action developed between prongs and the MR, and the beet sliding on the inclined pronged shares, an upward force is developed tending to uproot the beet. The MR is resisting uprooting by the force required to break the tap and secondary roots and the adhesion force between root and soil. The forces on the MR cause the development of stresses, which under certain conditions can cause root breakages and dug losses. A study of the physical properties of the beet root, namely its strength properties as well as the properties of the interface between root and the metal parts of the lifting mechanism is needed to understand the functioning of the lifting mechanism, and to assess the risk of breaking under a given force combination.

Reported work on sugar beet strength is limited. Von Hulst et al (1957) tested sections from different parts of the MR of  $1 \text{ cm}^2$  cross-section area in tension. They concluded that the sugar beet MR is composed of different materials from the periphery to the centre with strength varying from 4 MPa at the outer parts of the root to 1.6 MPa at the middle. Maslikov and Bleednov (1971) have measured the compressive strength of the MR at different water contents and at two directions along and across the groove. Yield

strength was 1.96-2.45 MPa with small effect from water content. Strain was more affected by the water content of the root. Ostrovski et al. (1970) have studied the cutting process of sugar beet in the factory. They inferred from the literature that the modulus of elasticity of fresh beet was 6.5-14 MPa and for highly wilted beet 1.8 MPa. They stated also that the modulus of elasticity varied little when subject to tension, compaction and bending. Alizadeh and Segerlind (1997) have measured the modulus of elasticity (mean 11.6 MPa), the Poisson ratio (0.35) and the normal stress at failure (2.54 MPa). They found an increase of the modulus of elasticity during the harvesting season.

From the analysis of the forces acting on the beet MR during lifting presented in Gemtos (1980), the friction coefficients of root skin and polished mild steel are needed for the assessment of the forces developed. From that analysis two additive actions take place in order to form the lifting force which will overcome the anchoring force as well as the weight of the root and result in the proper lifting of the sugar beet:

- (1) The action due to the pitch of the prongs results in a simple sliding of the root on metal surfaces. In this case the coefficient of friction (coefficient of sliding friction  $FR_{sl}$ ) between the two surfaces can be found experimentally by sliding pieces of root 'skin' on metal surface. The coefficient of friction will then be calculated by dividing the maximum pulling force by the normal load. The maximum pulling force is used because in the present work the action takes place before the actual movement of the root, until the anchoring force is overcome. The value of the static coefficient of sliding friction must therefore be known.
- (2) In the wedge-like action of the prongs on the MR, due to the squeezing of the MR, pushed by the soil reaction, between the prongs, the friction coefficient is different (friction coefficient due to wedge action  $FR_w$ ). It is highly possible that some local curvature on the MR surface will be formed such that the friction will not be simply a

resistance in sliding but also will include the force needed to overcome the unevenness of the root and deformation of its surface.

Klapp (1964) has suggested that in actual conditions the MR slides on the prongs, producing a certain line of contact, and therefore only one coefficient of friction should be used. That is true when, after uprooting, the MR slides backwards relative to the prongs and upwards relative to the soil surface. But before the anchoring force is overcome, the two actions take place at the same time and it seems most likely that two types of friction take effect. Measurements of friction between beet root and different materials have been carried out in USSR and reported by Burmistrova et al (1956). They measured the static coefficient of friction for roots without cleaning the soil, as they came out after lifting. The normal loads used were: the root own weight, 29.4 N, 58.9 N, 117.7 N. The values found are shown in Table 1.

As it can be seen from the table, the static coefficient of friction decreased with increasing loads. Klapp (1964) reported that in a previous work in Germany (he did not give the reference) the coefficient of friction between roots and a metal surface was measured and found equal to 0.7. But as Klapp pointed out, a coefficient of friction as high as that would make the lifting of beet roots difficult if not impossible. Klapp has estimated by indirect calculation that the friction coefficient should be of the order of 0.2. Other information about beet-metal coefficients of friction was not found in the literature. Several workers have made measurements of coefficients of friction between different agricultural products and metal surfaces for specific purposes. Mohsenin (1970) gave a summary of different values of static coefficient of friction. Bickert and Buelow (1966) found that the coefficient of friction for barley and corn sliding on metal increased with increasing moisture content. In the same work it was found that the coefficient of friction of corn on metal increased as the experiment progressed as a result of wax and other materials which were

deposited on the metal surface. Richter (1954) found that the coefficient of friction between metal and chopped hay, straw and silage decreased as the experiments progressed up to a constant value due to polishing of the metal. He gave the following values for the static coefficient of friction, for chopped hay and straw 0.35 with a range of 0.17-0.42; for silage 0.80 range 0.52-0.82. Mohsenin (1965) measured the coefficient of friction between the skin of potatoes to cause skinning. He found that the coefficient of friction varied with the period with range 0.42 - 0.82. From the references on the work on coefficients of friction between agricultural products and metal a big variation is apparent. The data on sugar beet MR metal coefficients are inadequate.

A series of experiments were designed and performed to find the strength of the root in tension, compression, shear and bending and to define its structure from strength point of view and are reported here. Additionally the strength of the secondary roots and tails in tension was measured to give an estimation of the root anchoring force and the root-metal friction properties are presented. The results of the experiments are presented in this paper.

## **MATERIALS AND METHODS**

The beet roots used in the present work were taken from a plot of the crop especially established for two consecutive years. All crop husbandry (tillage, sowing time, fertilization, and plant protection) followed the local farmers' practices. Sugar beet samples were taken from September till November (the harvesting period) of each year and tested within three days from uprooting such that no considerable dehydration could affect any of the studied properties. This was important for the investigation of the causes of MR breakages during lifting compared to the problem of MR processing in the sugar factory. The characteristics of the roots were measured as soon as the roots were taken in the laboratory, after removing the leaves, cleaned by running water and dried. The following parameters were measured:

1. MR maximum diameter and the diameter at soil level In two directions: that in the row of beet and normal to the row.
2. The MR root overall length
3. The MR weight
4. The MR volume
5. The inclination of the MR sides

The MR specific weight was estimated. The characteristics of the MR used are shown in Table 2.

For the application of the stresses a Housfield Tensometer, type w, was used. For the tensile tests a clamping device was constructed and strips of emery paper were used, to increase friction and so decrease the normal load needed for gripping the specimen both in the measurements of the strength of secondary roots and tails and in the parts of beet MR.

In order to test the hypothesis that the vascular tissue has different strength properties compared to the parenchyma, it was attempted to separate and test specimens from each plant part in tension. That proved impossible with the existing facilities, as, although the vascular tissue seemed to be cylindrical and formed a continuous tube, there were changes in direction and discontinuities which made the separation difficult. On the other hand, it was difficult to avoid producing cracks during the separation and which were difficult to detect and would decrease the strength, producing inconsistent results. Instead segments taken from the outer parts and others from the central parts of the MR were prepared and tested. The former had more than two rings of vascular tissue in sections of about 7 mm thickness while in the latter there was no more than one in sections of 10 mm thickness. In this way the strength of the segments of the outer parts of the root would be nearer to the strength of the vascular tissue and those of the inner parts nearer to the parenchymatic one.

The specimens of the outer material had to be cut parallel to the vascular tissue within the limitations of the MR morphology which resulted in high variation of the dimensions. The skin of the root was then pulled off and the inside material (parenchyma) was scratched off till the first bundle. The specimens were as thick as the dense vascular rings in the direction normal to the surface. In the other direction they were as wide as the curvature of the material permitted which resulted in specimens of relatively small cross-sectional area. Due to the curvature of the rings the material had a difficult shape to estimate the area of its cross-section. The middle part of the specimen was therefore cut as rectangularly as possible. That reduced the cross-section area of the middle of the specimen relatively to the sides and so it was weaker (Figure 1). In that way failure at the sides, where a concentration of stress occurred due to gripping, was avoided. This process had a high propensity to cause cracks on the specimen surface. That happened some times and the specimens were broken at very low stress. These values were rejected.

For the specimens of the inner parts of the MR a thick initial piece was cut having three annual rings with thick parenchymatic tissue between them. Then in the middle of the length, the two side-rings were scratched off carefully leaving the parenchymatic material with the middle ring. That was not always achieved due to the curvature, the discontinuities and dislocations of the rings. The parenchymatic tissue was much more easily cracked than the outer where a crack could be stopped by a vascular ring. The attempt to leave as much parenchymatic material with the ring for testing explains the larger cross-sectional area of the inner specimens.

Due to the changing dimensions of the specimens the cross section could not be measured before fracture. Instead the dimensions of the pieces were measured after fracture, near the broken section in such a way that the damaged tissue was avoided and the average

was used. Although some error was introduced in the estimation of the cross-section dimensions it should be rather small.

For the compression experiment, the Hounsfield tensometer was used with the plates for compression. Specimens were cut from inner and outer parts of the root. The difficulty of isolating different specimens was present again. The testing of the outer layers presented much more difficulties since the specimen should be parallel to the surface of the root, which usually was not parallel to the inner rings. Sometimes that made the specimen to consist of half rings, which weaken it. The thickness of the dense rings section was usually 10 mm-15 mm while the specimens cut were 27.5 mm in diameter. Specimens of smaller diameter could not be used because their length would have to be very small in order to avoid failure by bending. Additionally with very short specimens it would be difficult to observe the failure pattern. The specimens were cut by a cylinder for rubber cutting and were 27.5 mm in diameter and 32 mm in length.

In order to assess the strength of the sugar beet MR in shear loading a device was constructed which permitted two plates 50 mm x 20 mm to move towards each other using the mechanism of the Hounsfield tensometer and leaving a space of 10 mm between them. The maximum load at failure was recorded. Tests were limited to sections up to 50 mm in diameter at the middle of the MR which is the probable area of breakages from shear. Fifty-seven measurements were made 28 in the plane normal to that including the grooves and 29 in the plane including the grooves.

The combination of the forces during lifting suggests that the breakages occur due to bending of the root (Gemtos 1980). In order to find out the strength of the MR in bending, experiments were carried out. After several trials, in order to avoid the difficulty of clamping, the MR were built in plaster of Paris that was secured by a simple clamp on a bench. Instead of applying a single force at the end of the root, which produced an

increasing moment along the MR length, a couple was applied. So the moment of bending was constant throughout the length of the MR between the point of couple application and the clamped section. During bending a stress concentration could develop only at the plaster of Paris surface or in its body and so the roots were expected to break at the plaster surface or further in. That would possibly reveal any relationship between bending moment and cross-section area at breaking. On the other hand, any breaking which occurred well outside the plaster would indicate a weaker part of the MR. If that were the rule, it would mean that the MR breakage is a random phenomenon depending on random discontinuities in the MR body. In this case the only useful result would be the finding of limits of moment application under which the possibility of root breakage is at a minimum.

Two parallel prongs welded normally on a plate applied the couple (Figure 2). On the other side of the plate a copper tube was connected which on the other side had a handle parallel to the plate. The tube was secured on a base bearing so that only rotation of the tube was possible and no lateral movement. The base, could be moved horizontally or vertically before the securing such that the tube was parallel to the ground and normal to the axis of the MR. The torque was produced manually. The copper tube was strain-gauged in order to measure torque by using a couple of wire strain gauges forming an angle of  $90^\circ$  between them and  $45^\circ$  to the axis of the tube (Doebelin 1983 p 385). The signals, after amplification, were recorded in a Ultra Violet (U V) recorder. The system was calibrated by applying different loads on the prongs after securing the tube from any movement or bending. The moment was calculated from the known load and arm. The system was linear and the scale of the U V recorder was regulated to measure torque up to 50 Nm.

For the estimation of the friction coefficients the following laws of friction were assumed to hold:

1. The magnitude of frictional force is proportional to the normal load between the two surfaces.
2. It depends on the roughness of the surfaces and the material they are made of.
3. It is independent of the area of contact and of sliding speed.

Those laws hold only within certain limits as proved by different recent works but in the present study the effect of factors like speed, temperature, normal load were not studied.

Two pieces of root skin were pressed against the two sides of a polished mild steel strip. A normal load was provided and measured by a tensometer (Hounsfield Type W). Two cylindrical sections of beet (15 mm in diameter and 30 mm long) were cut without damaging the skin of the root. The pieces were located in two small tubes that were fixed to the two plates of the tensometer. The steel strip was placed between the beet sections, to which the normal load was applied. The force required to move the steel strip was measured by a strain gauged plate and recorded by the U V recorder. The coefficient of friction was calculated by:

$$FR_{sl} = f/2N \quad [1]$$

where:  $f$  is the pulling force and  $N$  is the normal load that applied to the two sides of the strip.

The normal load was around 736-891 N with maximum 1472 N. Higher loads caused fracture of the root pieces usually in the surface layer which could not be perfectly flat. Care was taken for the roots to be fresh (maximum three days from uprooting), well cleaned and dry. Several polished mild steel pieces were used. After each measurement they were cleaned with hot water and left to dry before the next use. The repeated use of the same piece of metal without cleaning would result in the build-up of a layer of root juice and other material from the root skin which could alter the frictional force. On the other hand the

movement of prongs between consequent beet roots through the soil should clean them from any material taken from the root and polish them due to the abrasive action of the soil.

In order to measure the friction coefficient due to wedge action of the pronged shares, two rods of 3 cm in diameter were pushed at the two sides of a beet root. The weight of the root and the value of the two forces were measured at the time the root started moving upwards. The root perimeter was drawn before the squeezing and the slope of the root at the points of contact was measured. The coefficient of friction was estimated by the equation (see appendix I):

$$FR_w = (2*Q*\tan(\alpha/2) - P/\cos^2(\alpha/2))/2*Q \quad [2]$$

where:  $FR_w$  is the coefficient of static friction due to wedge action,  $Q$  is the squeezing normal load,  $\alpha$  is the angle the sides of the root formed at the point of contact, and  $P$  is the root weight.

The two rods were secured on the two plates of the mechanism for compression tests of the Hounsfield tensometer. The same mechanism was used for the application and measurement of the squeezing forces.

## RESULTS AND DISCUSSION

### Strength of Tails and Small Secondary Roots in Tension

Altogether 49 measurements were made. The average force was 39.6 N (standard deviation=46.9) with broken section area of 15.0 mm<sup>2</sup> (standard deviation =20.11 ). The maximum force was 236 N for area of 99.0 mm<sup>2</sup> (14 x 9). The relationship between force and cross-section area at breaking is shown in Table 3. The relationship is linear with high correlation coefficient. When the stress is related to the broken section area the linear

relationship is very poor ( $R^2=0.22$ ), shown in Table 3. In Figure 3 the scatter diagram of stress with broken section area shows that the relationship was not linear. The fitting of an exponential and one  $1/\text{Area}$  function are given in Table 3. The exponential curve had the best fitting ( $R^2= 0.52$ ). This relationship indicates that the smaller the cross-sectional area the higher the tensile strength of the root. An explanation of the results was that sugar beet main root is composed of 8 to 9 rings of vascular tissue and in between parenchymatic tissue (Gill and Vear 1968). The rings are equally and widely spaced at the centre of the root and are denser at the sides. The number of rings remains about the same at different cross-sectional areas of root. So, the smaller the cross-section of the root the greater part of it, is occupied by vascular material and the thinner parts of the root are mainly composed of vascular tissue. In the light of the results of the present experiment the vascular tissue should be stronger in tension than the parenchymatic tissue.

### **Strength of Parts of the Root in Tension**

Fifty-three measurements were made 25 for the outer parts and 28 for the inner parts of the MR. The means, the standard deviations and the range of the maximum stress before fracture are given in Table 4. The length of the specimen and the cross section area at breaking were different each time. A comparison of the maximum stress for failure shows that the tensile strength of the specimen of the outer layers of the MR was higher than the inner ones (significant difference at  $P=0.05$ ) (Table 4). Although the above values do not represent the exact strength of the materials, they show that vascular tissue is stronger than parenchymatic tissue. They can also be used in the case of the consideration of the root as a composite beam. Von Hulst et al. 1956 found that the main root strength was varying from 4 to 1.6 MPa from the outer to the inner parts which is in agreement with the present findings.

From the linear part of the stress-strain diagrams of the above mentioned experiments the modulus of elasticity was around 7.5 MPa. In a work referred by Ostrovskii et al. (1970)

the modulus of elasticity for freshly cut sugar beet root was found to vary between 6.5 and 14 MPa while Alezadeh and Segerlind (1997) found a range 7.4-15.3 MPa, which include the found value.

### **Strength of MR in Compression**

The mean, the standard deviation and the range of the stress for failure for the two parts of the root are shown in Table 4. The comparison of the two values through a t - test shows that there was no statistically significant difference between them. Differences were rather unlikely to be revealed by the experiments because as mentioned previously, the specimens from the outer parts of the root consisted of half by inner material. Although the difference is not significant the strength of the inner material in compression was higher than the outer. From the stress-strain diagram it was found that the slope of the inner part of the curve (presenting the modulus of elasticity) corresponds to a value about 10 MPa .

The curves for the inner part are linear while the ones for the outer parts have a curved part at the end. It was also observed that the specimens of the inner parts of the root failed in a diagonal plane (about 45<sup>0</sup>, Figure 4) like a brittle material while the specimens of the outer parts failed by buckling of the vascular fibres (Figure 5). For specimens of mixed material (most of the outer part specimens), the part of parenchymatic tissue failed by forming a diagonal plane which stopped at the area of dense rings where a buckling of the fibres was observed .

A comparison of the values of the compressive and tensile strength from Table 4 shows that the inner material is stronger in compression than in tension while for the outer tissues there is no significant difference between compressive and tensile strength.

### **Strength of Root in Shear**

The means and standard deviations of the shear strength for the force applied at two directions, at a plane normal to that including the grooves and at a plane including the grooves

are shown in Table 5 as well as the relationships of the stress and the area of section. From the results in the Table 5 it was shown that the breaking cross-sectional area could explain a very small part of the variation of the MR strength in shear. An explanation is that the beet MR has in the outer part dense vascular tissue which caused the initial resistance to shearing. Once this layer was cut, the shearing plane moved through the beet with lower resistance and the total section had a low influence to the strength. The comparison of the average stress in relation to the mean area at breaking for the application of forces normal and to the plain including the grooves, while the stress is about equal (non significant difference at  $p= 0.05$  ) the area in the case of the plane of the grooves is larger than in the plane normal to grooves.

### **Strength of Root in Bending**

Twenty-three measurements were made with the moment applied in the plane including the grooves and 21 in the plane normal to that including grooves. In 21 cases in the first group and 20 in the second, the roots were broken in a diagonal plane of which at least half were inside the body of the plaster (Figure 6). Fracture on the tension side (downward) was well inside the plaster while on the compression side was usually at the surface of the plaster. In two cases in the first group and one in the second the breaking sections were outside the plaster body and in a plane rather normal to the axis of the root (Figure 7). The torque recorded in these cases was very small relatively to the broken section. When the three measurements were excluded the following relationships were found between torque ( $T$ ) and the area of the broken section ( $A$ ):

a) bending couple applied at the plane of the grooves.

$$T=7.3 + 0.01A \quad R^2 = 0.44 \quad T_{mean} = 21.7 \text{ Nm}, \quad S.D.=7.6, \quad A_{mean}=1434 \text{ mm}^2$$

b) Bending couple application at the plane normal to grooves.

$$T= 5.2 + 0.01A \quad R^2 = 0.58 \quad T_{mean}=20.4 \text{ Nm}, \quad S.D. = 8.8, \quad A_{mean}= 1459 \text{ mm}^2$$

The strength of the MR in bending is the same at the two directions (non significant difference at  $p= 0.05$ ). A further analysis of the data, assuming that the theory of a simple beam can be applied, gave the relationships between the stress at the outer layers of the MR at breaking and the dimensions of the breaking sections shown in Tables 6 and 7. In Figures 8 and 9 the scatter diagrams of stress developed at the outer parts of the broken sections vs the area of broken section are shown. The average stress was 2.71 MPa and 3.60 MPa for the two cases studied. Those values are of the same order as those in the experiment on tensile strength of the MR. For the present study, due to the assumption that the cross-sections of the MR are circles for the approximation of the shape, the most appropriate relationships for further use in the modelling of lifting are those with the area of the broken section. The relationship which gave a good agreement with the experimental data was an exponential relationship. In order to test if the function gave the most reasonable results for practical use, the values of maximum stress at the outer layer of roots were calculated for areas of cross sections with diameters between 20 mm and 50 mm using the found formulae. The results show that the exponential formula gave reasonable approximation of the root strength.

### **Friction coefficient**

From 32 measurements made, the mean static coefficient of sliding friction ( $FR_{sl}$ ) found was 0.110 (standard deviation = 0.033) with range 0.057 and 0.170. This coefficient of friction is rather small compared to the U S S R measurements. But considering the much higher normal loads it appears to be of the correct order of magnitude.

From 33 measurements in which the root moved upwards, the mean coefficient of friction due to the wedge action ( $FR_w$ ) found was 0.28 (standard deviation = 0.097) with a range 0.16 to 0.62. In 4 cases, the MR did not move upwards but crushed at normal loads of 1717, 1864, 2011 and 2256 N. In two of those cases the MR were doubles with the sides of

the root nearly parallel and in the fourth a local cavity prevented the sliding of the root. In most cases the coefficient of friction depended upon the local slope of the MR sides at the point of contact which was different from the average slope of the MR between soil level and 10 cm depth. That meant that the use of the average slope of the MR sides in the estimation of the upward force due to wedge action of the MR was not absolutely correct. But, in field conditions, due to the inclination of the tines to the horizontal and some movement of the root due to the sliding of the root on the prongs, the average slope should have a greater effect. It is also possible that small cavities on the MR surface are filled by soil. Nevertheless, the local slope of the root sides is completely random and cannot be estimated. So that the average slope is the only measurable slope which can be used in modelling root lifting.

## CONCLUSIONS

From the experimental results presented, it can be concluded that:

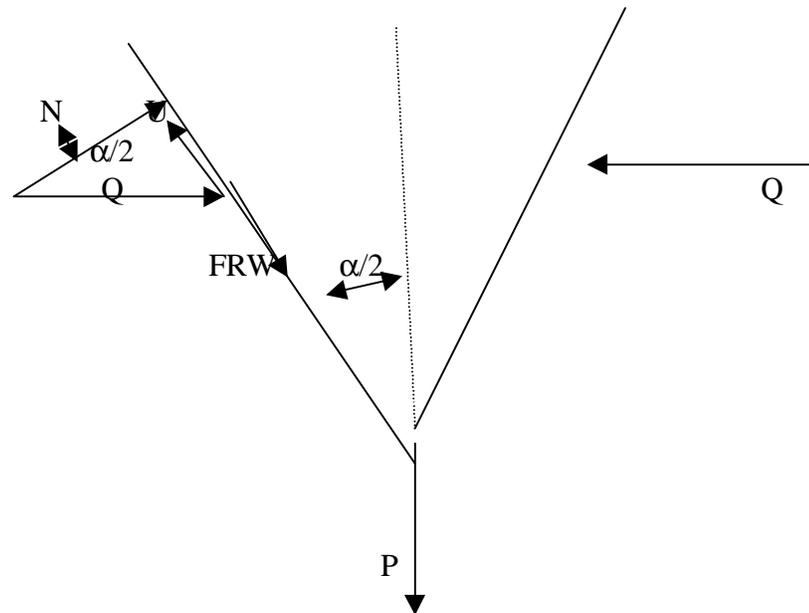
1. Root tails and secondary root breaking force depends on the broken area section.
2. Sugar beet MR is composed, from strength point of view, of two materials:
  - a) The parenchyma which is more abundant in the inner parts and it is relatively weak in tension (mean strength 2.1 MPa, range 0.65-4.29 MPa) but stronger in compression (mean 3.05 MPa range 2.50-4.00 MPa ).
  - b) The vascular tissue which forms several rings within the parenchyma. The rings are denser in the outer parts of the MR especially near the epidermis. The vascular tissue is stronger in tension than the parenchyma (mean strength in tension of outer parts of root 2.8 MPa range 1.4 -4.46 MPa).
3. When the MR is subject to bending the maximum strength in tension or compression of the outer layers depends on the dimensions of the breaking section. From the curve fitting models,

the exponential models show a better agreement with the data of the real conditions and it is anticipated that they can be used for modelling sugar beet lifting.

4. In some cases random weakness of the beet MR can cause fracture at very low stress.
5. During the lifting of sugar beet two types of friction are involved. The first is due to MR simply sliding on the metal surface of prongs. This coefficient of friction has a mean value of 0.110 with range 0.057 to 0.170. The second is due to the shape of the MR which results in a wedge-like action when the root is squeezed between the prongs. The later coefficient of friction was found to have a mean 0.280 with range 0.160 to 0.620.
6. Due to random unevenness of the MR surface, the upward movement of the root can be prevented. That happened in 4 out of 37 cases in these experiments..

## **Appendix I**

## Analysis of the development of the friction coefficient due to wedge action of the root during lifting.



Appendix, Figure 1. Forces acting on the beet root during the wedge action of the shares

The prongs squeeze the root by the two opposite forces  $Q$ . The force  $Q$  is analyzed in two components the  $N$  normal to the root surface and  $U$  the upward force to causing the uprooting force. Additionally, a friction force  $FRW$  is developed resisting the upward movement of the root. This friction force is due to the wedge action taking place during lifting. Force  $P$  is the force resisting the uprooting of the beet and is formed by the root anchoring and the root weight. During the investigation of the root friction coefficient due to the wedge action this force is equal to the root weight. From the Appendix, Figure 1, the following equations can be derived:

$$P = 2*(U-FRW)*\cos \alpha/2 \quad (1)$$

$$U = Q \sin \alpha/2 \quad (2)$$

$$FRW = FR_w*Q*\cos \alpha/2 \quad (3)$$

Using equations (2) and (3) in equation (1) :

$$P=2*( Q \sin \alpha/2 - FR_w*Q*\cos \alpha/2)* \cos \alpha/2 \quad (4)$$

and

$$FR_w = (2*Q*\tan \alpha/2 -(P/\cos^2 \alpha/2))/2*Q \quad (5)$$

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**Table 1. Friction coefficient of beet root and metals from Burmistrova et al (1956).**

<b>Applied force N:</b>	<b>Own weight</b>	<b>29.4</b>	<b>58.9</b>	<b>117.7</b>
Machined steel	0.54	0.37	0.37	0.32
Sheet steel	0.63	0.44	0.43	0.37

**Table 2. Beet MR used for the experiments characteristics for the two years.**

<b>Characteristic</b>	<b>Mean</b>	<b>Standard deviation</b>
Diameter at soil level, mm	75.87	16.69
Maximum MR diameter, mm	83.01	16.23
MR length, mm	322.59	56.96
Angle at plane normal to line, °	27.69	7.14
Angle at line plane, °	27.54	8.10
Volume, cm <sup>3</sup>	564.34	264.23
Net mass, Kg	0.62	0.32
Specific mass of MR Kg/m <sup>3</sup>	1100	170

**Table 3. Strength of secondary beet roots and rootlets in tension**

<b>Dependent variable</b>	<b>Dependent Variable mean</b>	<b>Independent Variable</b>	<b>Independent t variable mean</b>	<b>Equation</b>	<b>R<sup>2</sup></b>
Force	39.55 N	Section area at failure mm <sup>2</sup>	14.93	Y=7.865 +2.12X	0.82
Stress	4.41 MPa	Section area at failure mm <sup>2</sup>		Y=0.36-0.12X	0.22
Stress		Section area at failure mm <sup>2</sup>		Y=1.81e <sup>-0.31X</sup>	0.52

**Table 4. Strength of beetroot Parts In Tension and Compression.**

<b>Statistics</b>	<b>Inner Parts of Root Tensile Strength MPa</b>	<b>Outer Parts of Root Tensile Strength MPa</b>	<b>Inner Parts of Root Compression Stress MPa</b>	<b>Outer Parts of Root Compression Stress MPa</b>
Mean $\bar{x}$	2.1	2.8	3.05	2.77
Standard Deviation	0.91	1.00	0.49	0.37
Observations	28	25	13	15
Range	0.65-4.29	1.4-4.46	2.50-4.00	2.10-3.30
t values calculated	t calc 2.62		t calc 1.65	

t values theoretical for p=0.025 , n=51 t= 2.01, and n=26, t=2.056

**Table 5. Shear strength of beet root and the relationships of shear stress and breaking area**

<b>Shearing normal to grooves shearing 27 observations</b>			
<b>Dependent Variable</b>	<b>Independent Variable</b>	<b>Equation</b>	<b>R<sup>2</sup></b>
Shear Stress	Area at breaking	Y=0.84-0.00026A	0.22
$\bar{x}$ =0.69MPa	$\bar{x}$ =538.68 mm <sup>2</sup>		
SD=0.13	SD=234.72		
<b>Shearing to grooves side 28 observations</b>			
<b>Dependent Variable</b>	<b>Independent Variable</b>	<b>Equation</b>	<b>R<sup>2</sup></b>
Shear Stress	Area at breaking	Y=0.80-0.00013A	0.15
$\bar{x}$ =0.68 MPa	$\bar{x}$ =923.79 mm <sup>2</sup>		
SD=0.13	SD=391.82		

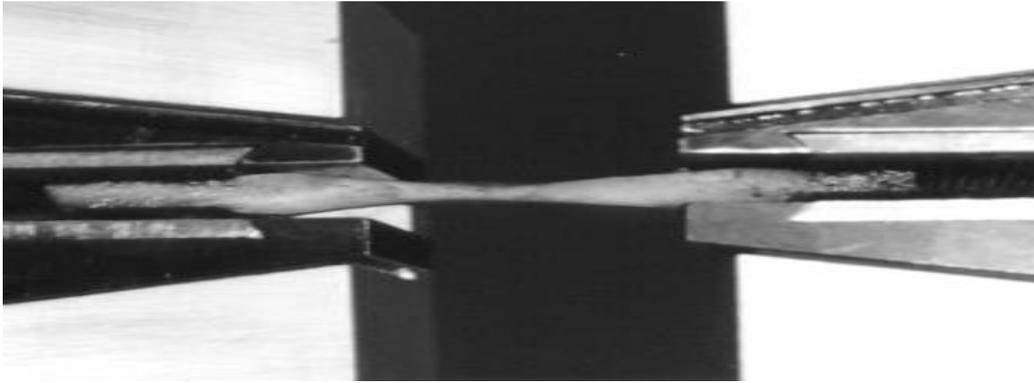
**Table 6. Results of bending experiment with couple applied in grooves plane.**  
Relationships of maximum stress at the outer layer (20 observations).

<b>Dependent Variable</b>	<b>Independent Variable</b>	<b>Equation</b>	<b>R<sup>2</sup></b>
Stress	Breaking section axis at couple plane Y	Y=12.47-0.23x	0.81
Mean	mean 38.1mm		
3.60 MPa			
Stress	Breaking section area	Y=7.00-0.0024x	0.38
	Mean 1434 mm <sup>2</sup>		
Stress	Breaking section axis normal to couple plane	Y=10.88-0.15x	0.61
	mean 49.4 mm		

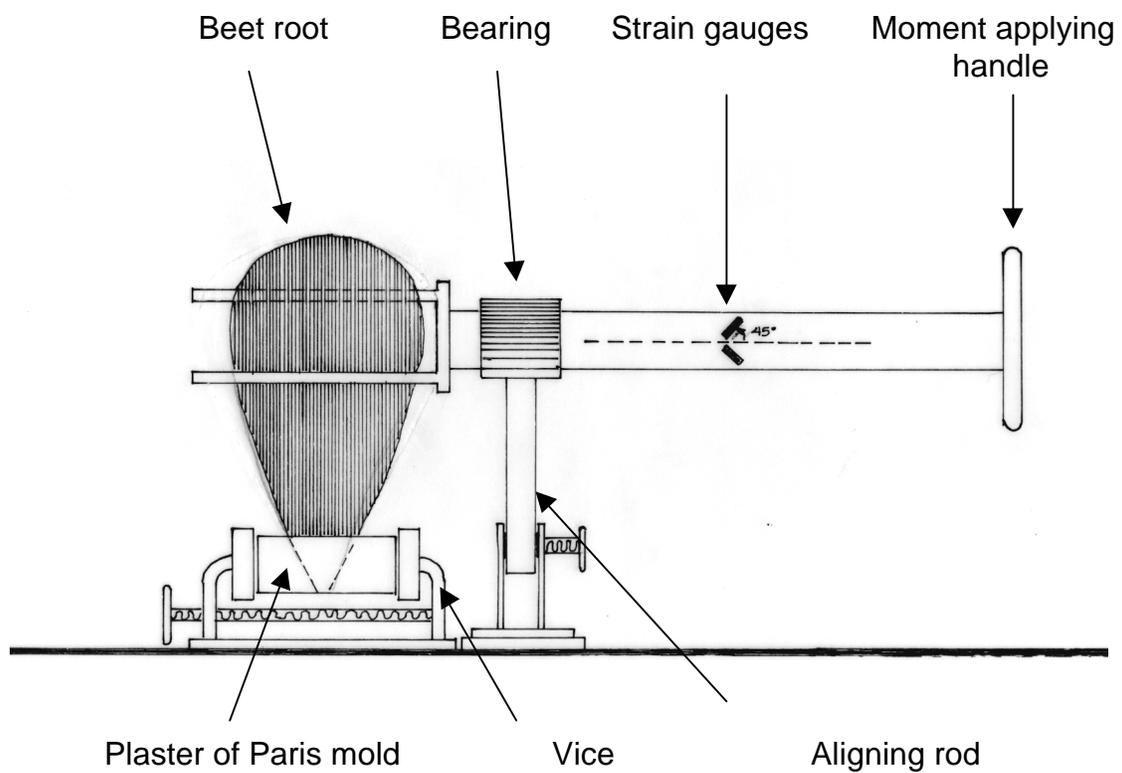
Stress	Breaking section area	$Y=16.65*e^{-0.11x}$	0.49
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**Table 7. Results of bending experiment with couple applied in the normal to grooves plane.** Relationships of maximum stress at the outer layer (20 observations).

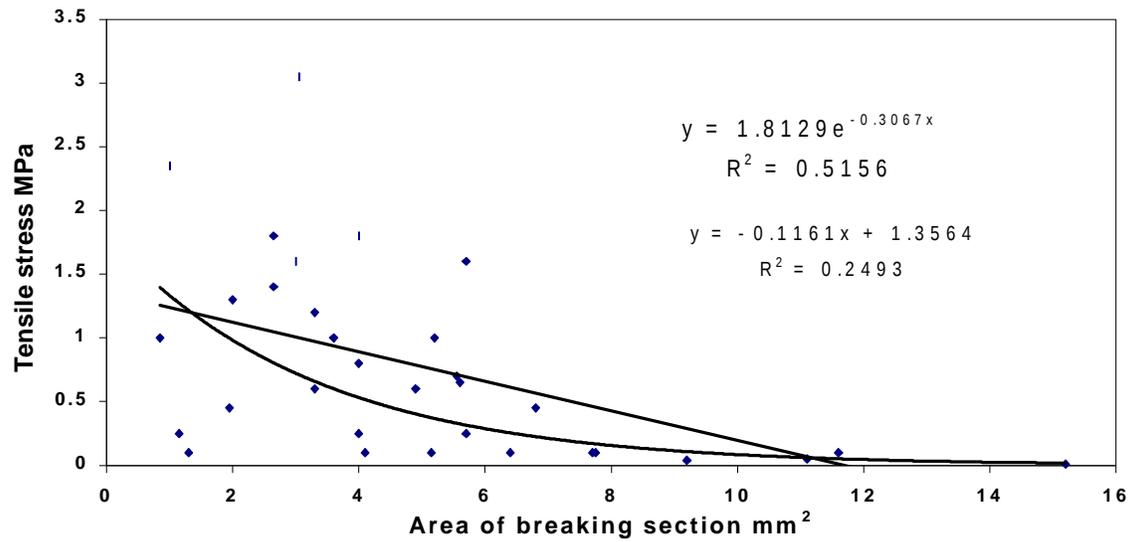
<b>Dependent Variable</b>	<b>Independent Variable</b>	<b>Equation</b>	<b>R<sup>2</sup></b>
Stress	Breaking section axis at couple plane	$Y=7.31-0.096x$	0.74
Mean 2.71MPa	Mean 47.8 mm <sup>2</sup>		
Stress	Breaking section area Mean 1459 mm <sup>2</sup>	$Y=4.86-0.0015x$	0.62
Stress	Breaking section axis normal to couple plane Mean 37.2 mm	$Y=5.99-0.088x$	0.52
Stress	Breaking section area	$Y=18.37e^{-0.15}$	0.76
Stress	Breaking section area	$Y=27.93X^{-0.83}$	0.63



**Figure 1. Sugar beet specimen tested in tension**



**Figure 2. Draft of the equipment setting for the bending experiment**



**Figure 3. Strength of root and rootlets of sugar beet. Stress vs breaking area in tensile tests**



**Figure 4. Specimen from the inner part of the root failing in a diagonal plan.**



**Figure 5. Specimen from the outer part of the root failing by buckling.**



**Figure 6. Beet root failing in bending within the plaster of Paris.**



Figure 7. Beet root failing in bending outside the plaster of Paris.

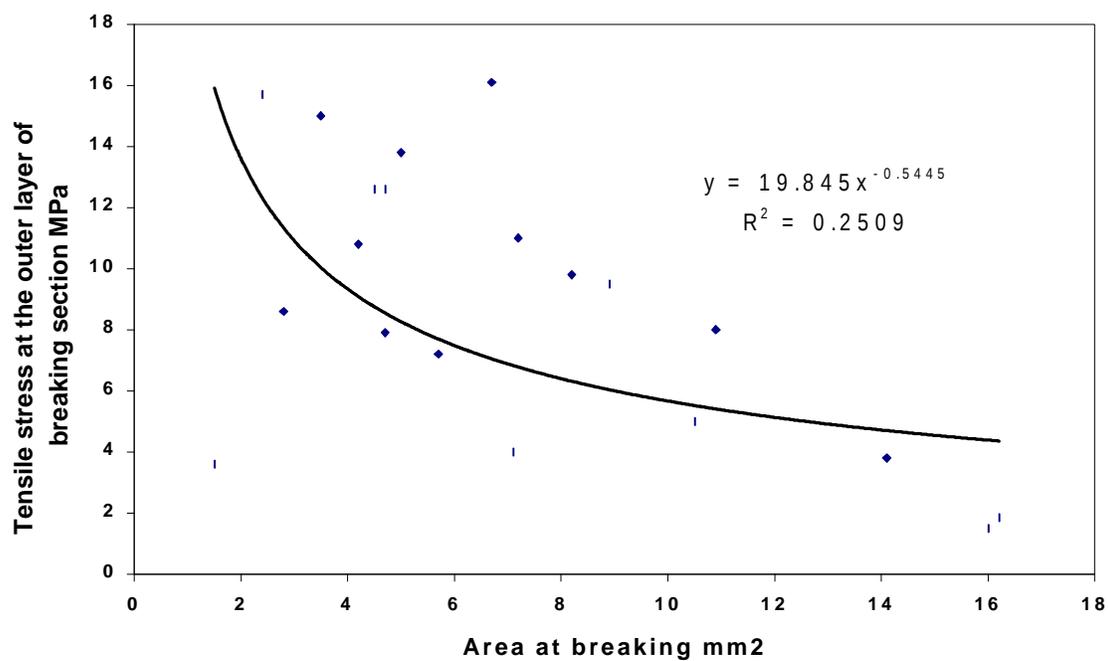
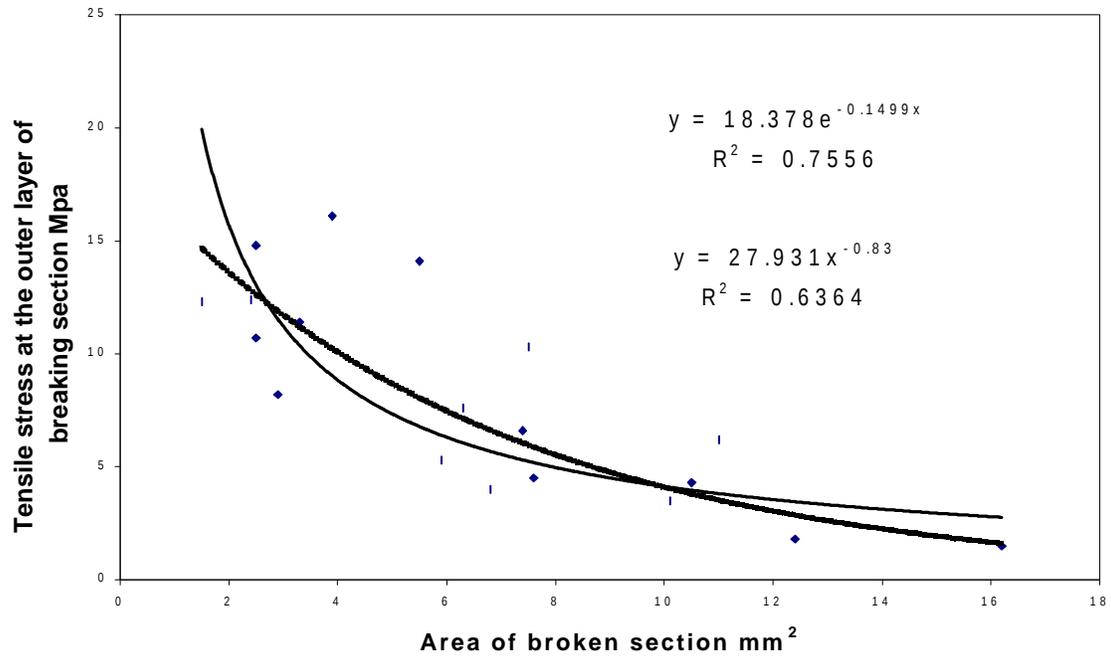


Figure 8. Stress vs area at breaking. Moment applied at grooves plane.



**Figure 9. Stress vs area at breaking in bending experiments. Moment applied in normal to the grooves plane.**