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MODELING OF CARROT ROOT WITH THE USE OF PHOTOELASTICITY METHOD

Summary

This paper presents elastooptical method for assessment of carrot root displacement under impact load. The main purpose of this study involved an analysis of cross-section model of carrot root performance. The investigation by means of the polariscope was conducted. In each phase under load, a characteristic isochromatic pattern distribution was determined. Tested model was made of the polyurethane elastomer which provided mechanical properties similar to biological features. Stress distribution in selected cross-sections as well as in two mutually perpendicular σ_x and σ_y directions was also determined. On basis of the results a cross-section model of carrot root has been performed.

***Keywords**: carrot root, isochromatic fringe, photoelasticity method, strength properties*

MODELOWANIE KORZENIA MARCHWI PRZY UŻYCIU METODY ELASTOOPTYCZNEJ

Streszczenie

W pracy przedstawiono elastooptyczną metodę oceny przemieszczenia korzeni marchwi pod obciążeniem udarowym. Głównym celem badania była analiza przekrojowego modelu wydajności korzenia marchwi. Przeprowadzono badanie za pomocą polariyskopu. W każdej fazie pod obciążeniem określono charakterystyczny rozkład wzoru izochromatycznego. Testowany model został wykonany z elastomeru poliuretanowego, który zapewniał właściwości mechaniczne podobne do właściwości biologicznych. Określono również rozkład naprężeń w wybranych przekrojach oraz w dwóch wzajemnie prostopadłych kierunkach σ_x i σ_y. Na podstawie wyników wykonano model przekroju korzenia marchwi.

***Słowa kluczowe**: korzeń marchwi, prążek izochromatyczny, metoda fotoelastyczności, właściwości wytrzymałościowe*

1. Introduction

The importance of modeling in studies involving biological products seems to be incontestable. In most cases mathematical models including various degree of complexity were performed. Particularly, the structural models which are based on general laws of physics were usually tested. Unfortunately, construction of biological models causes a lot of problems because of reliable theory shortage [1, 2]. A significant diversity in strength properties of this material depends mainly on species, variety and shape of the object. Furthermore, high accuracy of material investigation should involve a phenomenon occurring in its internal structure [3, 4]. One of method performed in assessing of interactions between these elements can be an analysis of the physical properties in tested object. However, a lack of proper material which reproduces tested object with high accuracy involving strength properties as well as linear dimensions resulted in poor studies. This state was changed by dynamic development in chemical industry in which materials including temporary double refraction effect with various strength properties and highly complicated shapes occurred. Bronwen [5] for instance, analyzed a microstructure of carrot root during drying process and then compared obtained results to properties of fresh vegetables. During harvest, transport or handling, vegetables as well as fruits are exposed to damage, bruise or crack. To determine a degree of destruction, a bruise volume can be measured [6]. Hence, determination of more reliable models of biological material should be investigated [7]. According to Grotte et al. [8] and Manjunatha [9] an assessment of mechanical properties of biological material components and testing them under different compressive load in many cases seems to be impossible.

The elastooptical method as well-known in determining of displacement in tested material is based on specific properties of light. On the one hand, this technique consists in continous observation of changes which occur in examined object (especially internal structure) under load, on the other it hand provides useful information about stress concentration and deformation tested sample [10].

Primarily, in modeling of biological material, the elastooptical method has not been applied because of difficulties in correct material selection. Arnold et al. [11] analyzed a contact stress in the point of single-layered model of the wheat grain during contact against fixed surface. This model was made of epoxide resin which was characterized by high accuracy. Stopa [12] conducted a similar study. He used the epoxide resin in order to build internal structure of carrot root, bean seed as well as wheat grain [12, 13]. All the mentioned papers demonstrate a grain model which made from the epoxy resin. Significant differences in strength properties between biological origin and applied in modeling materials, were verified by implementation of the same Young's modulus coefficient as well as the Poisson constant. However, sometimes this approach generates many problems with results interpretation. Since Kanyanta et al. [14] applied the polyurethane elastomer in modeling of biological material, conducted investigtions enabled more reliable results and conclusions.

According to statistics, in the near future, a rapid increase in carrot consumption in various forms is expected. Carrot, in many countries around the world is one of the most popular agricultural product classified to root group. It represents biological material with high water content. Carrot root is characterized by layered structure which represents different strength properties on each layer. Due to cross-sectional shape of this vegetable, a crucial issue is how to solve a problem of excessive surface pressure, also how to identify stress-concentration area which leads to plant tissue damage. In addition, elongated shape of the carrot root enables to construct disc model matching in the elastooptical technique.

The elastooptical method enables to conduct qualitative measurement of interaction occurring between each part of the model under impact load accompanied by stress concentration. Quantitative measurement leads to determination of direction, stress values, deformations and their displacements. In turn, isochromatic images allow to determine the value of stresses, while isocelline to assess their direction [15]. After demonstration of close relationship between results of the elastooptical method with actual tests, it was possible to perform investigation under dynamic load conditions using a high-speed camera. This investigation involved evaluation of specific isochromatic images in cross-section model of carrot root including each phase of stress process. The following elements of the model were taken into account: shape of loading element, shape of cross-section and different strength properties of carrot root components (core and bark). There was also defined an importance of each layer in transfer of compressive load.

2. Object, purpose and course of research

The primary purpose of this study was to validate a real object for possible evaluation [16]. Authors adopted flat stress to this model (stress course in direction of the longitudinal axis omitted). This model was made of the polyurethane elastomer, because on the one hand meets all requirement in aspect of model construction and on the other hand is characterized by double-refraction effect typical in these tests. Due to complex structure and principles of correct modeling (especially for core and for intercellular space in bark layer) a numerically controlled instrument was used. While measuring of dimension of carrot root cross-section, the coefficient (k_l) was 2. A mean external diamater of tested sample was 100 mm, whereas core was 53 mm. A model thickness equaled 13 mm and enabled maintanance of flat state of stress (in disk-shaped model) as well as provided optical sensitivity.

In investigation, the elastic optical polariscope equipped with light source, working in range of the Instron 5566 was implemented (Fig. 1). The direction of acting force was put along modeled plane.

During test, isochromatic patterns in bark and in core were recorded by means of digital camera. Measurements conducted under various loads ranged from 0 to 50 N at fixed intervals of time. This fact enabled the elimination of stress relaxation influencing isochromatic pattern distribution. In tests, the following types of carrot root cross-sections were adopted: simplified – round shape of core as well as outer layer of bark, quadrangular and star-shaped (Fig. 2) [17]. These models subjected to load by means of stress testing machine equipped with working head in range up to 1 kN. Additionally, flat-shaped loading element was implemented.

In order to determine an impact of strength properties of tested object on isochromatic distribution, several models including various material properties were constructed. Conducted analysis indicated that model consisted of bark and core made from polyurethane elastomer involving three different strength properties was chosen: $E_{k1} = E_{r1} = 2.24$ MPa: $E_{k2} = E_{r2} = 3.48$ MPa, $E_{k3} = E_{r3} = 4.48$ MPa.

3. Measurement results

An impact of tested cross-section on isochromatic distribution by means of four different shaped models, including similar strength properties for core and for bark layer: $E_k = 3.48$ MPa, $E_r = 3.48$ MPa was conducted. Obtained isochromatic images under load F = 5.0 N at the moment when first isochromatic line in the core appeared as well as under maximum load F= 15 N, whereas the photoelastic image was just clearly identified, these results were presented in Fig. 3.

Fig. 1. Polariscope used in measurements [17]
Rys. 1. Polaryskop użyty do pomiarów [17]

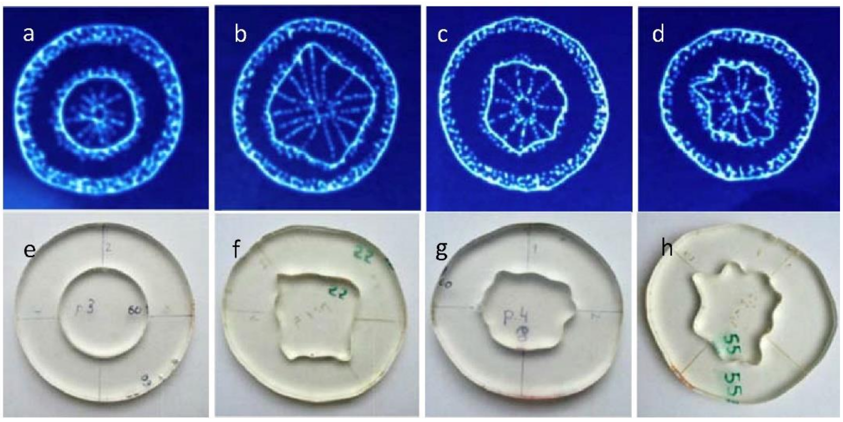

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Fig. 2. Cross-sectional shapes of carrot root with their models: a, e – round; b, f – quadrangular; c, g – lightly star-shaped; d, h – strong star-shaped

Rys. 2. Kształty przekrojów poprzecznych korzenia marchwi oraz ich modele: a, e – okrągły; b, f – czworokątny; c, g – o zarysie gwizady; d, h – w kształcie gwiazdy

For comparison, at F = 5.0 N, total load only the bark layer transferred. In the root core an isochromatic line expressed fractional values. Maximum number of isochromatic fringe orders in the bark at that moment was 9. In the round model (Fig. 3) isochromatic line distribution symmetrical shape took and was accompanied by three line orders. The critical points observed on the vertical axis corresponded with force direction and covered several points on the horizontal axis.

Rectangular model (Fig. 3) characterized symmetry in the vertical as well as in the horizontal axis. As a consequence, a width of stress field was similar to core length involving direction of compressive force. For comparison, on the periphery of bark and core layers the isochromatic line occurred on fragmentary order. Specific, irregular feature of isochromatic lines distribution was presented as star-shaped core (Fig. 3). Obtained results showed, that stress distribution depended mainly on shape of the core. On periphery of the bark and core layer a maximum isochromatic fringe order ranged from m = 1 to m = 1.5.

An increase in load up to F = 15 N (Fig. 3) was accompanied by deflection in bark layer and caused an increase in number of isochromatic fringe in core, especially in the area of contact with the bark on the vertical axis. For instance, in round model (Fig. 3) an isochromatic line image was similar to stress distribution.

The strength properties of the bark and the core layers significantly influenced the behavior of the real object under given load. Several studies have shown that the real objects were characterized by greater mechanical properties, hence smaller damage under compressive loads were observed [18]. Stronger parameter of cells in this model reduced more efficiently damages in observed points.

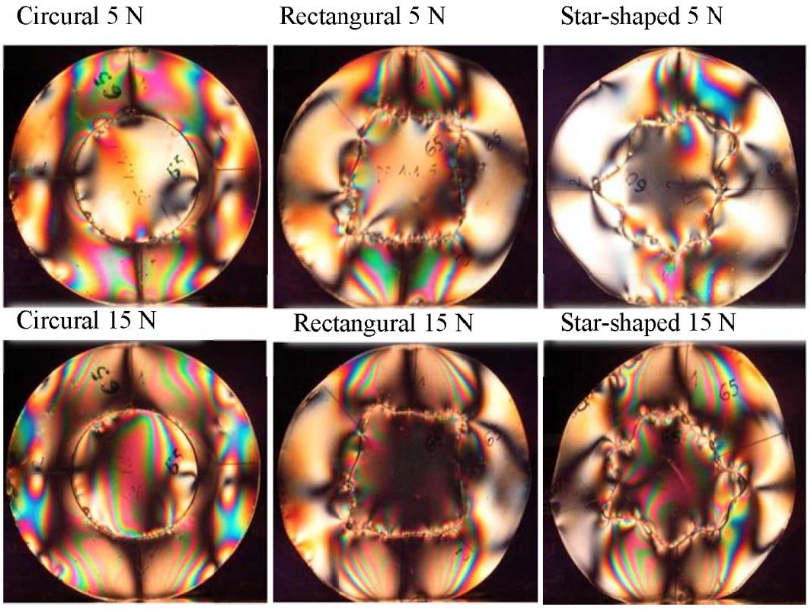

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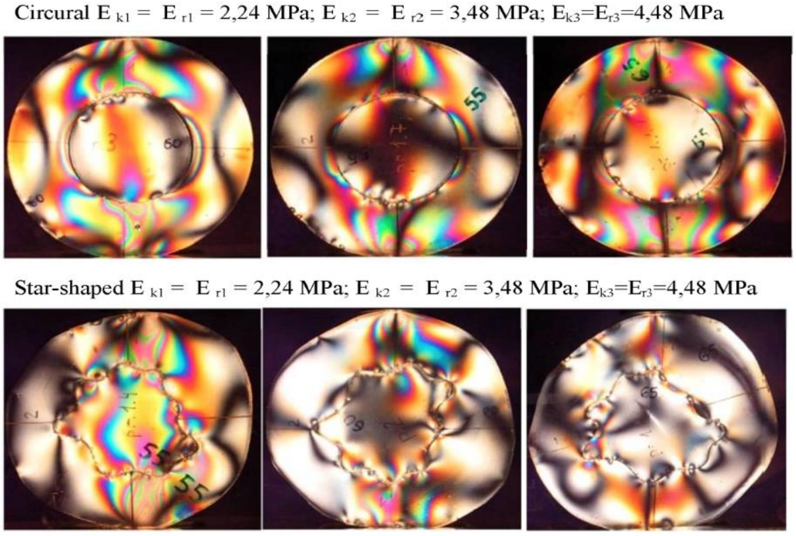
Fig. 3. Isochromatic pattern images for various shaped models, loads and strength properties. Comparative analysis. Isochromatic pattern – colour lines, isoclina pattern – black lines

Rys. 3. Obrazy wzoru izochromatycznego dla różnych kształtów, obciążeń i właściwości wytrzymałościowych modeli. Analiza porównawcza. Wzór izochromatyczny – linie kolorowe, wzór izokliny – czarne linie

Fig. 4 shows whole isochromatic fringes model of round carrot root sample, which includes similar strength properties of layer in the core as well as in the bark under constant load F= 5 N. Furthermore, a model which was characterized by the lowest Young's modulus (E_{k1} = E_{r1} = 2.24 MPa, Fig. 4) clearly shows impacting bark part on root core structure. Consequently, on bark layer a compressive stress state featured by different courses (curved, collapsed) was observed.

Fig. 5 displays isochromatic fringes distribution model characterized by round cross-section shape including dissimilar strength properties of core and bark. On core layer the Young's modulus was 2.24 MPa and on bark layer a number of isochromatic lines order was 7 (Fig. 5e) while in core (Young's modulus E_r = 3.48 MPa) equaled 5. As consequences, significant influence of core layer on bark layer (Fig. 5f) was observed. From conducted study follows that tested core characterized by poor mechanical properties has not transferred load. Stress concentration in this field was significanlty smaller. In addition, an impact of bark layer strength properties on isochromatic lines distribution in round-symmetrical model was investigated. In this test, three different Young's modules (E_{k1} = 4.48 MPa, E_{k2} = 3.48 MPa, E_{k3} = 2.24 Mpa) were considered. On Figs. 5a and 5d there are showed isochromatic fringes distribution at the highest Young's modulus E_{c1} = 4.48 MPa. From this study, it follows that maximum number of isochromatic line orders in core has not resulted from bark layer properties.



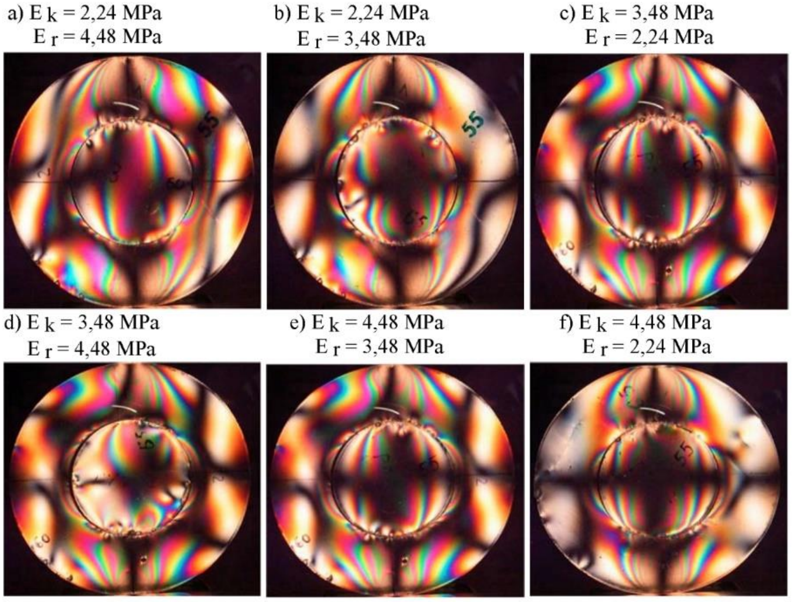
Circural E_{k1} = E_{r1} = 2,24 MPa; E_{k2} = E_{r2} = 3,48 MPa; E_{k3}=E_{r3}=4,48 MPa

Star-shaped E_{k1} = E_{r1} = 2,24 MPa; E_{k2} = E_{r2} = 3,48 MPa; E_{k3}=E_{r3}=4,48 MPa

Source: own work / Źródło: opracowanie własne

Fig. 4. Isochromatic pattern distribution images of circular-shaped and star-shaped model under load 5 N. Isochromatic pattern – colour lines, isoclina pattern – black lines

Rys. 4. Obrazy rozkładu izochromatycznego modelu w kształcie koła i gwiazdy pod obciążeniem 5N. Wzór izochromatyczny – linie kolorowe, wzór izokliny – czarne linie



a) E_k = 2,24 MPa
E_r = 4,48 MPa

b) E_k = 2,24 MPa
E_r = 3,48 MPa

c) E_k = 3,48 MPa
E_r = 2,24 MPa

d) E_k = 3,48 MPa
E_r = 4,48 MPa

e) E_k = 4,48 MPa
E_r = 3,48 MPa

f) E_k = 4,48 MPa
E_r = 2,24 MPa

Source: own work / Źródło: opracowanie własne

Fig. 5. Isochromatic pattern distribution for circular model including various strength properties of bark and core under load 15 N. Isochromatic pattern – colour lines, isoclina pattern – black lines

Rys. 5. Rozkład wzoru izochromatycznego modelu kołowego o różnych właściwościach wytrzymałościowych kory i rdzenia, pod obciążeniem 15N. Wzór izochromatyczny – linie kolorowe, wzór izokliny – czarne linie

A quantitative analysis involves determination of isochromatic fringes distribution only in bark layer including different strength and biological properties or their variable behavior under load. To consider layered structure of carrot root, behaviour of bark layer during transferring load should be more specifically identified. For this purpose, a stress distribution which is based on the Frocht technique was applied. It allowed for (δ_1-δ_2) difference analysis where stress values including isochromatic and isoclinic lines distribution were presented as σ_x and σ_y in A-A and B-B cross-sections. (Fig. 6). A stress calculation along primarily selected stress sections may be carried out involving a difference in stress values, typical in photoelasticity. Stress distribution was determined under radial load, at F=15 N and corresponded to load value at which quality analysis conducted.

To determine range of core influence on stress distribution in bark layer, a model without core was tested.

Fig. 7 displays a stress distribution σ_y in cross-section A-A where modeled strength properties at E_k = E_r = 3.48 MPa, with core - $\sigma_{y(r)}$ and without core - σ_y were taken. This diagram presents stress distribution in characteristic way expressed as curve. Above presented studies confirm that maximum value in tested model without core was σ_y = 0.06 MPa whereas, in model with core has not exceed σ_y = 0.04 MPa. The highest value of stress (involving negative value) in the internal part of bark layer was observed and amounted σ_y = -0.18 MPa in model without core and σ_y = -0.11 MPa in model with core.

It means that core has not changed a course of stress curves in the horizontal section along the A-A line, but only caused a decrease of its maximum value. As follows from given results, an effect of bark layer on stress distribution shape on horizontal cross-section A-A in core has not been observed.

Stress distribution results σ_x and σ_y in B-B cross-section are displayed in Fig. 8. In this model without core a complex stress state in bark layer occurred (Fig. 8). Stress values σy described by means of positive sign on the whole cross-section, as opposed to σx stress values expressed with negative signs. In addition, an increase of stress values, caused significantly lower strength values (σy_{max} = -0.037 MPa) than stress calculated at level (σx_{max} = 0.19 MPa).

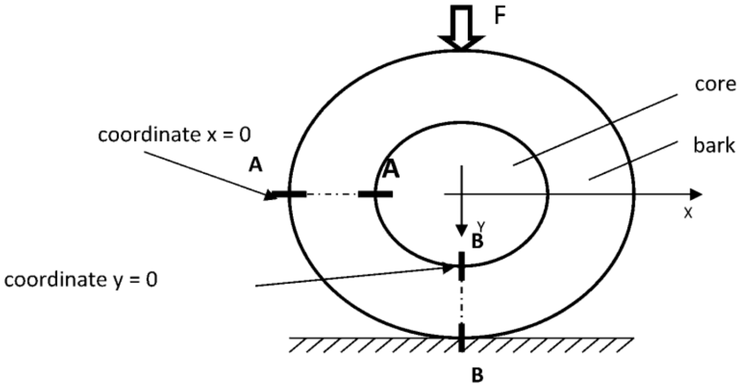


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Fig. 6. A diagram including circular carrot root cross-section model under load. A-A cross-section of the bark thickness in x direction, B-B cross-section of the bark thickness in y direction, F – load

Rys. 6. Schemat zawierający model przekroju kołowego korzenia marchwi pod obciążeniem. A-A – Przekrój grubości kory w kierunku x, przekrój B-B grubości kory w kierunku y, F – obciążenie

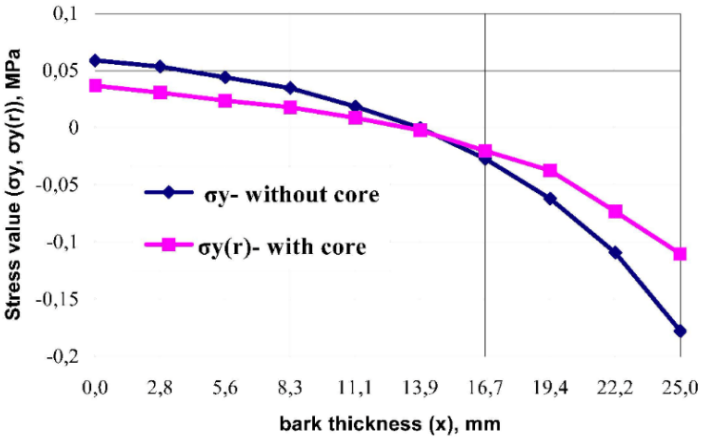

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Fig. 7. The σ_y stress graph – section A-A without core σ_y and with core σ_y(r). —■— Normal stress distribution in A-A section of bark thickness in y direction in model with core. —◆— Normal stress distribution in A-A section of bark thickness in y direction in model without core

Rys. 7. Wykres naprężenia σy - sekcja A-A bez rdzenia σy i z rdzeniem σy (r). —■— Normalny rozkład naprężeń w odcinku A-A grubości kory w kierunku y w modelu z rdzeniem. —◆— Normalny rozkład naprężeń w odcinku A-A grubości kory w kierunku y w modelu bez rdzenia

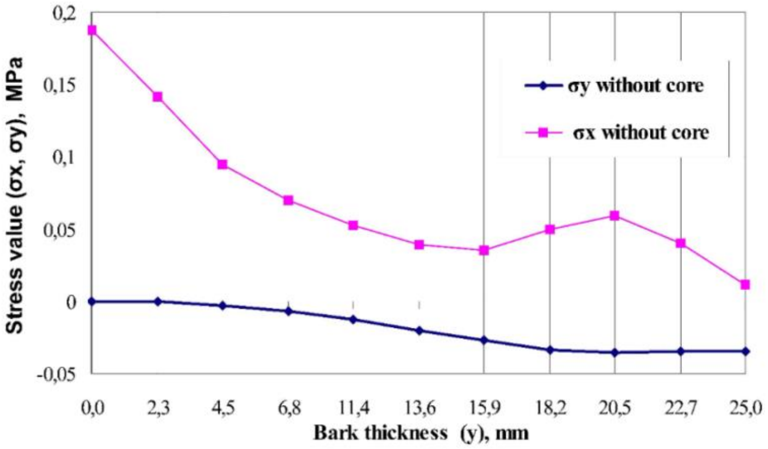

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Fig. 8. The σ_y and σ_x stress graph in section B-B (without core). —■— Normal stress distribution in B-B section of bark thickness in x direction in model without core. —◆— Normal stress distribution in B-B section of bark thickness in y direction in model without core

Rys. 8. Wykres naprężeń σy i σx w sekcji B-B (bez rdzenia). —■— *Normalny rozkład naprężeń w przekroju B-B grubości kory w kierunku x modelu bez rdzenia.* —◆— *Normalny rozkład naprężeń w przekroju B-B grubości kory w kierunku y w modelu bez rdzenia*

As follows from linear courses of stress, the highest transfer of load was observed in model without core. Relatively low values of stress σ_y are justified through significant contact area of bark layer with core as well as bottom fixed surface of testing machine.

4. Conclusions

In cross-section model of carrot root, a distribution of isochromatic fringes significantly depends on shape of the loading element only in the contact points. A round shaped element determined only one critical point where isochromatic lines increased. Growth in radius of the round loading element has not influenced order number but changed their shape. During tests with flat element consisting of two areas of isochromatic lines were formed and its value increased in the corners (load F = 5 N). During test with flat element, a isochromatic lines distribution located in the corners has not contacted a model (flats: l_4 = 7 mm, l_5 = 10 mm and l_6 = 12 mm) and corresponded to distribution obtained while impacting of not-limited surface.

5. References

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