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Viscoelastic modeling of apples under quasi-static loading using finite element method to investigate the causes of bruising

B. Ghasemi[1]- A. Hemmat[2*]- A. Ghasemi[3]- A. Habini Rad[4]

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Introduction: Apple is one of the most important horticultural crops of Iran. Its production in the country stands in the second place after citrus. Iran holds the fourth place in the world production of apples and gains a major share in the export of this product. Therefore, it is necessary to enhance the quantity and quality of the fruit in order to maintain and promote its position among the countries importing this product from Iran. Most of the mechanical damages to fruits and vegetables occur due to contact stresses under static, quasi-static and impact loading. To obtain stress distribution inside the fruit we can use finite element analysis. The aim of this study was to simulate the behavior of the apple as a viscoelastic body subjected to quasi-static loading and also to determine the failure criteria (maximum normal stress or shear stress) of apple flesh to estimate its susceptibility to mechanical bruising.

Materials and methods: In this study, Golab kohanz apple was used. Two samples were removed from each apple using a core sampler, one was used for uniaxial compression and the other was used for confined compression test using Instron universal tension and compression machine. Spherical indenter and parallel plate tests were performed in order to study apple susceptibility to bruising at four deformation levels (1, 2, 3 and 4 mm) and the bruise volume was then measured after 24 hours. Stress-strain curves were plotted and then, the elastic and viscoelastic properties were obtained. Then, by using the data obtained from apple properties, the apple was modeled in Abaqus software as spherical and cylindrical shapes with viscoelastic behavior subjected to quasi-static loadings.

Results and Discussion: The normal stress distribution of the modeled apple in the shape of a cylindrical sample is shown in Fig. 4. The value of maximum normal stress was obtained (0.51 MPa) at the contact point of the loading plate with the sample. Experimental and modeled stress-strain curves are shown in Fig. 5. Up to the bio-yield point, the two curves are nearly matched; and beyond that point, there are some overestimations in the predicted stress values.

The location and pattern of failure have often been used to explain the cause of failure in fruits. When specimens of fruit are subjected to a uniaxial compression, the failure often occurs the maximum shear stress plane. Failure patterns in the tested samples indicate that the failure occurs due to shear stresses. Another explanation that has been used by researchers for shear failure is the bruising position inside the fruit after loading. The position of bruising in most of the tested apples was a distance away from the apple surface (Fig. 7).

According to the experiments results at the three deformation levels of 2, 3, and 4 mm, the maximum generated normal stress inside the apple was above the point of failure of the cylindrical samples. Based on the empirical results, the bruising was almost zero for the apples subjected to one or two mm deformation (Fig. 9a). The experimental value of the shear strength of the Golab kahanz apple was obtained to be 0.23 MPa. The maximum shear stress inside the modeled apple due to the two mm deformation was 0.195 MPa, which was lower than the shear strength of the apple. On the other hand, by applying three and four mm of deformation, the maximum shear stresses were obtained to be 0.24 and 0.26 MPa, respectively, indicating that the induced stress exceeded the shear strength of apple flesh; therefore, the bruising was observed in the flesh of these apples. The location of the maximum shear stress corresponds to the location of bruising in the tested samples as shown in Fig. 9b.

According to the obtained results from the modeling in the finite element software, we can use this software in order to recognize and investigate the damages in agricultural products during different loading conditions (Harvesting, transportation, packaging and storage).

1, 3 & 4- Graduated student, Department of Agricultural Machinery Engineering, College of Agriculture, Isfahan University of Technology, Isfahan

2- Prof., Department of Agricultural Machinery Engineering, College of Agriculture, Isfahan University of Technology. Isfahan

(*- Corresponding Author Email: ahemmat@cc.iut.ac.ir)

Conclusions: In this work, Golab apple was considered as a viscoelastic material and its behavior under quasistatic loading was modeled using finite element method. Elastic, viscoelastic properties and shear strength of apple flesh were obtained and used in the simulation. Comparison of modeling and experimental results shows that the model simulates the behavior of apples during quasistatic loading well. The location of bruise occurrence in the flesh of tested apple and the location of maximum shear stress in the simulated apple was the same. Therefore, the maximum shear stress criterion can be used to estimate the susceptibility of apple varieties to internal bruising under quasistatic loading. Modeling of apple as a viscoelastic sphere in Abaqus software assuming constant bulk modulus could properly simulate apple behavior under quasistatic loading.

Keywords: Apple, Finite element, Quasi-static loading, Viscoelastic properties