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FEA 시뮬레이션 기법을 이용한 수출용 한국 배 포장 트레이 및 완충패드 최적 포장설계

Optimum Packaging Design of Packaging Tray and Cushion Pad of Korean Pears for Exporting using FEA Simulation

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〈Abstract〉

Among the many packaging materials used in cushion packaging, there is a lack of optimum design for packaging trays and cushion pads used in pear packaging for export and domestic distribution. It causes over-packaging due to excessive material input, and can be solved by applying various parameters needed to optimize the design of the packaging tray and cushion pad considering the packaging material and the number of pears in the box. In the case of a cushion pad for pears, the economic efficiency of material and thickness should be considered. Therefore, it is possible to design a packaging tray and cushion pad depending on eco-friendly packaging materials (PLA, PET) used by applying appropriate design parameters. The static characteristics of the materials used for the packaging of pears were analyzed using FEA (finite element analysis) simulation technique to derive the optimal design parameters. In this study, we analyzed the contact stress and deformation of PET, PLA tray (0.1, 0.5 1.0, 1.5 and 2 mm) and PET foam (2.0, 3.0 and 4.0 mm) with pears to derive appropriate cushion packaging design factors. The contact stress between the pear and PET foam pad placed on PLA, PET trays were simulated by FEA considering the bioyield strength (192.54±28 kPa) of the pears and safety factor (5) of packaging

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design, which is the criterion of damage to the pears. For the combination of PET tray and PET foam buffer pad, the thickness of the PET foam is at least 3 mm, the thickness of the PET foam is at least 1.0 mm, the thickness of the foam is at least 2 mm, and if the thickness of the PET tray is at least 1.5 mm, the thickness of the foam is at least 1 mm, suitable for the packaging design. In addition, for the combination of PLA tray and PET foam pad, the thickness of the PET foam was not less than 2 mm if the thickness of the PLA tray was 0.5 mm, and 1 mm or more if the thickness of the PLA tray was not less than 1.0 mm, the thickness of the PET foam was suitable for the packaging design.

Keywords : Pear, PET tray, PLA tray, PET foam, Packaging, Contact stress, Contact deformation, FEA

1. Introduction

The distribution of agricultural products in Korea has changed greatly recently. Consumers' buying patterns have become more diverse and skewed toward high-end products due to increased demand for high-quality, safe agricultural products. As such, the logistics processing of agricultural products during distribution should consider large quantities of supplies, prices and changing product characteristics. Special packaging is needed because agricultural products can be easily damaged. During post-harvest storage, fruit quality is degraded and to reach consumers, it goes through numerous steps, including screening, packaging and processing. Fruit damage can be caused by fungi and bacteria, rats and other pests, improper temperatures and humidity, poor handling, chemical processes in fruits, etc. In particular, fruit softens and reduces its shelf life after the physiological aging process after the harvest.

For improvements to be made in the handling system or related tools, a deep understanding of the strength of the motion and force resulting from the excess of negligence during the various handling processes is required. Finite Element Method (FEM) has been used to investigate the effect of mechanical loads on fruits before developing a prototype of the intended design. Simulation tests were conducted to visualize the deformation behavior over time. Various studies have been reported on the use of FE to study the effects of compression and falling forces on fruit.

To prevent damage caused by impact during the distribution of agricultural products, tray cup pads, plastic foam material, are mainly used, and demand is increasing every year. However, the optimum packaging design of tray cup pads is not applied but is being used indiscriminately. Furthermore, this mechanical behavior, which leads to material properties are the primary input to any complex finite element problem. Modeling these materials behavior is a key factor. Over the past few decades, the behavior of polymers has been studied by several researchers.

FEA (Finite element analysis) has been used in the simulation of many mechanical and biological systems. In addition, Amoeedo and Lee (1992) assumed that the stress depends on the strain rate, temperature and a set of internal variables and developed a constitutive model to study yielding, strain softening, hardening on amorphous polymers, and study the initial visco plastic and nonlinear hardening of semi crystalline polymers. Aruda and Boyce (1993) conducted tests on PC, PMMA and developed a 3 D constitutive model to predict a flow strength and deformation behavior of expanded polymer materials. Ziaei-Rad (2008) developed a model to predict time dependent material properties of polymers, the same model was implemented to study friction in polymers during compression testing.

Tray cup pads of packaging cushion material are manufactured and used as various materials, and their use is increasing every year due to the increase in the domestic delivery service market. However, various research approaches are needed for the optimal design of packaging cushions according to the distribution environment of agricultural delivery services.

In this study, the static characteristics of PET and PLA trays and PET foam materials, eco-friendly packaging materials applied to the packaging of export pears were analyzed using FEA a simulation technique to derive optimal design parameters. In addition, by applying appropriate design parameters considering the amount of fruit and the distribution environment, the appropriate fruit tray cup pad can be designed.

2. Materials and Methods

2.1 Theoretical aspects

In the general case of two bodies in contact subjected to a perpendicular force (P) on the contact surfaces the outline of the contact surface is an ellipsis, which transforms into a circular surface or a strip in extreme situations. The distribution of the stress on the contact surface is given by the ordinates of the ellipsoid built on the contact surface with the maximum stress at the center of the ellipsis. If the spherical body of radius R is in contact on a flat surface, the contact stress is:

$$\sigma_{\max} = 0.388 \times \sqrt[3]{PE^2 \cdot \frac{1}{R^2}} \tag{1}$$

where E is the apparent elastic modulus. The radius a of contact circle and the depth of maximum contact point d is:

$$a = 1.109 \times \sqrt[3]{\frac{P}{E} \cdot R} \tag{2}$$

$$d = 1.231 \times \sqrt[3]{\left(\frac{P}{E}\right)^2 \cdot R} \qquad (3)$$

2.2 Experimental methods

In this study, 3D modeling and FEA (final element analysis, Ansys Workbench 18.1) are used for optimal packaging design of packaging trays and cushion pads for the export of Korean pears. The optimal packaging materials were selected in the use of pear export-packaging materials in the theoretical analysis of PET, PLA tray applied the PET foam pad, and FEA of each material resulted in packaging materials according to the appropriate thickness design based on the contact stress and displacement between the pear and cushion pads. We designed trays, considering the fixed and cushioning effects of export pears.

Fig. 1 Design of packaging tray and cushion pad for export pears

Also, it is designed to place three pears into one tray, as shown in Fig. 1, reflecting the tendency to purchase small amounts of fruit in overseas markets. In addition, a semi-permanent PET foam molded on the inside floor of the tray is designed to prevent compression damage caused by shock and vibration during transport of the pear. In this study, the contact stress and deformation with pears were analyzed by application of the thickness of PET, PLA tray (0.1, 0.5, 1.0, 1.5, and 2.0 mm) and PETfoam (2.0, 3.0 and 4.0 mm) to derive appropriate cushion packaging design factors.

Pears of the 'Nittaka' cultivar (harvested in October 2019 in Cheonan, Korea) were sorted and packaged in the local packaging center and then stored at 5±1℃ with 85±5% relative humidity for 3 days before the experiment. Compression tests were conducted to establish the criteria for damage caused by impact on pears for export. To measure the bioyield strength of pears, a 5 mm/min loading rate was applied to the upper surface of pears cut in half and a

Fig. 2 Compression tester of the pears

compression test performed using a cylindrical compression jig (10 mm diameter following ASABE S368.3 using a universal compression machine (SY-005, Sunyoung Systec Co., Daejeon, Korea) as shown in Fig. 2.

The geometric shapes of PET and PLA trays and PET foam were modeled as cosine functions, and for simplicity, the connection point between PET and PLA trays and PET foam was modeled using the sharing method for points (nodes). In the event of large deformation, pinball areas were allocated to increase convergence, giving acceptable intervals between surfaces. The models were meshed to produce 17,231 finite elements for PET and PLA tray, 8,370 finite elements for PET foam, while the total number of nodes was 34,341 for PET and PLA tray, and 17,145 for PET foam. The number of nodes and elements according to the thickness of the sample was the same. Fig. 3 show examples of the meshed FE models for PET and PLA tray and PET foam following the requirements of each standard. The material properties including general, elastic properties are shown in Table 1.

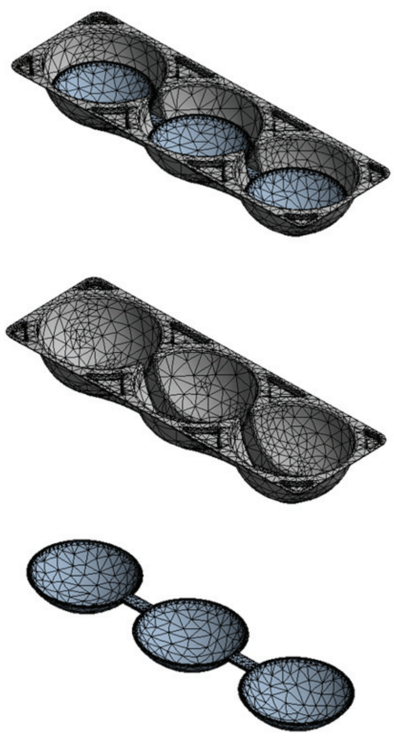


Fig 3. The meshed 3D models for FE simulation of PET/PLA tray and PET foam

Before selecting the mesh size, the mesh convergence study was conducted to reassure that the employed mesh element size is neither time consuming nor leading to any discretization error. In this simulation, the mesh study includes five different element mesh sizes. Table 2 was von Mises stress of different mesh size of PET tray (1 mm) and PET foam (1 mm) using FEA. It can be seen from Table 2 that stress is similar for the

Table 1. Material properties of PET, PLA trays and PET foam components used for the FEA

Samples	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Shear modulus (MPa)	Yield strength (MPa)
PET	1,335	1,254.74	0.4	448.12	155.26
PLA	1,240	1,043.21	0.38	380.91	104.41
PET foam	105	36.24	0.1	21.10	0.87

* PET by Vaidya (2009), PLA by Humaira et al. (2019) and PET foam by Fathi (2018).

Table 2. von Mises stress of different mesh size of PET tray (1 mm) and PET foam (1 mm) using FEA

Mesh size (mm)	von Mises stress (kPa)
1.6	195.2
1.7	196.5
1.8	193.2
1.9	192.8
2.0	192.1

mesh size ranging from 1.6 to 2.0 mm. By considering the least number of distorted elements and the time taken to run the simulation, mesh size of 1.6 mm was chosen for the remaining study.

3. Results and Discussion

3.1 Bioyield strength of the pears

The force-deformation curve of pear measured by compression tests, with the bioyield strength indicating a firmness factor as shown in Fig. 4. Generally, the soft texture of fruits and vegetables is a consequence of many factors such as the loss in cell turgor pressure and vascular air and the degradation of cell wall constituents and polysaccharides (Lakshminarayana, 1980). Texture degradation has been closely correlated to ripening. During ripening, there is a rapid enzyme synthesis and subsequent SSC release, which would explain the greater softening in ripe fruit. In this experiment, the damage criteria by contact stress of export pears were set to bioyield strength that is the value of dividing the bioyield point (N) derived from the force-deformation curve by the area of contact with a cylindrical compression jig (10 mm diameter following ASABE S368.3), And the measured bioyield strength was 192.54± 28 kPa.

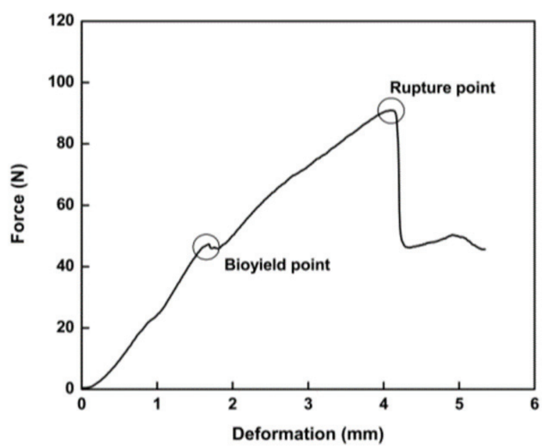
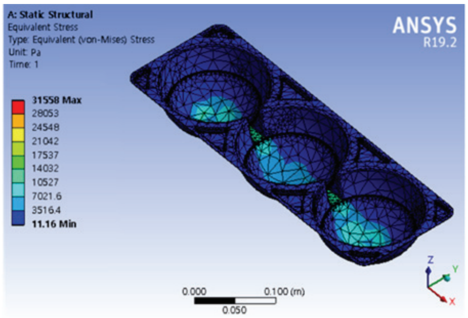


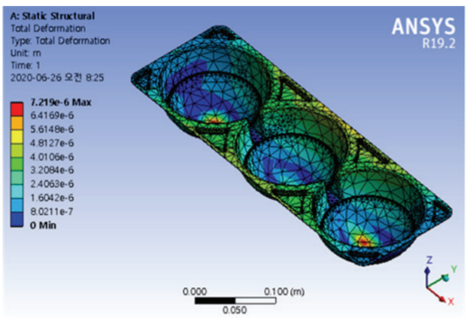
Fig. 4 Force-deformation curve of pear by compression test

3.2 FEA of PET, PLA tray considering the effects of cushion material

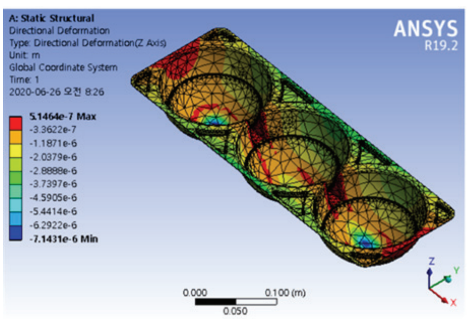
The FEA of PET, PLA tray analyzed static contact stress and deformation of the pear and tray in the absence of the cushion material, and Figs. 5 and 6 show the results of the FEA (the contact stress and deformation) on the tray material PET, PLA and the pear that was placed on the designed thickness-specific PET and PLA tray and the weight of pear was approximately 4.9 N.



(a) Contact Stress

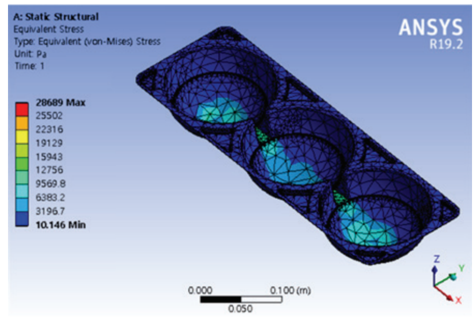


(b) Total Deformation

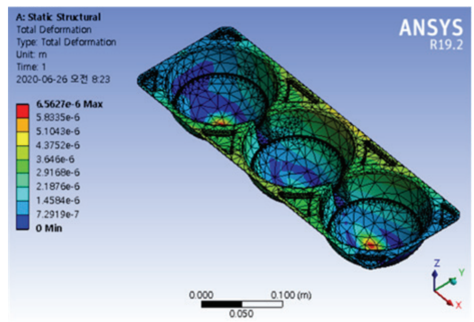


(c) Z-directional Deformation

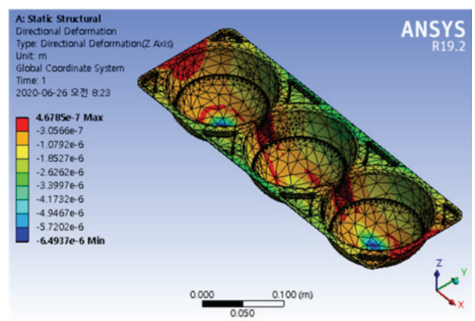
Fig. 5 Contact stress and deformation of PET tray and PET foam pad by FEA



(a) Contact Stress



(b) Total Deformation



(c) Z-directional Deformation

Fig. 6 Contact stress and deformation of PLA tray and PET foam pad by FEA

Tables 3 and 4 show the results of the contact stress and contact deformation analysis for PET, PLA tray and PET foam pad through analysis according to the thickness of the materials. In this experiment, the firmness (bioyield strength, 192.54±28 kPa) of the pear measured was set as the criterion for damage caused by contact. Physical environments such as shock and vibration in transit are designed by applying the safety factor of 4～5 in the packaging design (Kim, 2010), and the results of the analysis of static conditions

Table 3. Results of contact stress between pear and PET/PLA tray with PET foam (Safety factor : 5)

Thickness (mm)	Contact Stress (kPa)					
	PET			PLA		
	PET foam			PET foam		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
0.1	264.3	248.2	223.2	259.7	239.5	214.5.5
0.5	224.3	198.3	186.2	213.4	183.2	163.4
1.0	195.2	167.9	153.2	163.8	144.5	134.6
1.5	163.2	139.4	124.5	143.5	124.3	113.5
2.0	135.1	114.6	102.4	120.7	115.3	98.4

Table 4. Results of contact deformation between pear and PET/PLA tray with PET foam (Safety factor : 5)

Thickness (mm)	Contact Deformation (10^{-6}mm)					
	PET			PLA		
	PET foam			PET foam		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
0.1	37.1	39.1	41.2	35.4	36.1	37.2
0.5	36.3	37.5	38.1	33.2	34.9	35.7
1.0	35.4	36.0	37.3	30.4	32.5	34.6
1.5	34.5	34.1	36.4	28.7	30.2	31.5
2.0	33.9	33.2	35.2	26.4	27.6	29.3

and the safety factor (5) of the physical environment were also applied in this study.

Analysis of the contact stress between pear and PET foam of thickness of 1, 2, and 3 mm placed on PET, PLA trays of thickness of 0.1, 0.5, 1.0, 1.5, and 2.0 mm indicated that applying the bioyield strength of pears and the safety factor of packaging design. For the combination of PET tray and PET foam buffer pad, the thickness of the PET foam is at least 3 mm, the thickness of the PET foam is at least 1.0 mm, the thickness of the foam is at least 2 mm, and if the thickness of the PET tray is at least 1.5 mm, the thickness of the foam is at least 1 mm, suitable for the packaging design. In addition, for the combination of PLA tray and PET foam pad, the thickness of the PET foam was not less than 2 mm if the thickness of the PLA tray was 0.5 mm, and 1 mm or more if the thickness of the PLA tray was not less than 1.0 mm, the thickness of the PET foam was suitable for the packaging design.

4. Conclusions

In this study, to perform the optimum packaging design of packaging trays and cushion pads for exporting Korean pears, we used 3D modeling and FEA techniques. The optimum packaging materials were selected from the theoretical analysis of PET, PLA tray applied PET foam Pad for using packaging materials of exporting pears and the best packaging materials were derived based on FEA analysis results of each material, the contact stress and deformation between the pear and cushion pad. For the combination of PET tray and PET foam buffer pad, the thickness of the PET foam is at least 3 mm, the thickness of the PET foam is at least 1.0 mm, the thickness of the foam is at least 2 mm, and if the thickness of the PET tray is at least 1.5 mm, the thickness of the foam is at least 1 mm, suitable for the packaging design. In addition, for the combination of PLA tray and PET foam pad, the thickness of the PET foam was not less than 2 mm if the thickness of the PLA tray was 0.5 mm, and 1 mm or more if the thickness of the PLA tray was not less than 1.0 mm, the thickness of the PET foam was suitable for the packaging design.

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