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Static and Dynamic FEM Simulation of Packaging Tray Cup Pad for Korean Pears

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Abstract Among the many packaging materials used in cushion packaging, there is a lack of optimum design for the tray cup pad used in fruit packaging for export and domestic distribution. It causes over-packaging due to excessive material input, and this could be solved by applying various parameters needed to optimize the design of the tray cup pad considering the packaging material and the quantity of fruits in the box. In the case of a tray cup for fruits, the economic efficiency of material and thickness should be considered. Therefore, it is possible to design a tray cup pad depending on the packaging material used by applying appropriate design parameters. The static and dynamic characteristics of the materials used for packaging of pears were analyzed by using the FEM (finite element Method) simulation technique to derive the optimal design parameters. And by applying the appropriate design parameters considering the quantity of fruit and distribution environment, it is possible to design an appropriate fruit tray cup pad. In this study, as a result of simulating the contact stresses between the fruit and the tray cup for the PP, PE, and PS materials used in the fruit tray cup, the material with the lowest contact stress was PP and the value was found to be 398 Pa. The contact displacement between fruit and tray cup using this material was about 0.0463 mm, which was the lowest value compared with other materials. Also the resonance frequency band of tray cup made of PP material was below 36.81 Hz, and the strain energy was below 12.20 J. The resonant frequency band of the pear is more than 80 Hz and it could be applied to all the tray cup materials as compared with the resonance band of 38.81 Hz or less which is the resonance band of all tray cup pads for packaging. Finally, PP is the most suitable material for the tray cup pad.

Keywords Pear, Tray cup pad, Packaging, Contact stresses, Resonance frequency

1. Introduction

The distribution of agricultural products in Korea has changed substantially in recent years. The purchasing patterns of consumers have become more diverse and skewed towards upscale products, as exemplified by the increased demand for high-quality and safe agricultural products. As such, logistical handling of agricultural products during distribution must take into consideration large volumes, prices, and changing product characteristics. Because agricultural products can be easily damaged, they require special packaging. Fruit quality declines during storage after harvesting, and to reach consumers fruit products must go through numerous steps including sorting, packaging, and processing. Fruit damage can occur from mold and bacteria, rats, and other pests, inappropriate temperature and humidity, poor handling, and chemical processes within fruit. Particularly after harvesting, the physiological post-ripening process leads to fruit softening, diminishing storage life. In order to prevent damage caused by impacts during transportation of agricultural products, tray cup pads which are plastic foam materials, are mainly used and the demand is increasing every year. However, the optimum packaging design for the tray cup pads is not applied and is used indiscriminately. Although research papers on packaging cushion materials have been published, most of them are experiment papers, and most of them are theoretical analysis papers on corrugated fiberboard.

Experimental methods for investigating the performance and properties of the corrugated fiberboard and corrugated fiberboard-based products have limitations from time and eco-

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nomic perspectives. In addition, it is almost impossible to quantitatively analyze the effect of each component of the corrugated fiberboard on the edgewise compression test (ECT). Therefore, computer simulation techniques like FEM recently have been used to analyze various characteristics including the ECT of corrugated fiberboards (Gilchrist et al. (1999), Haj-Ali et al. (2009), Rahman and Abubakr (2004), Armentani et al. (2006), Park et al. (2010), Jiménez and Liarte (2003), Biancolini(2005)).

Tray cup pads of packaging cushion materials is manufactured and used in various materials, and its usage is increasing every year due to the increase in the domestic parcel delivery service market. However, various research approaches are needed for the optimum design of packaging cushion according to the distribution environment of parcel delivery service for agricultural products.

In this study, the static and dynamic characteristics of the materials used for packaging of pears were analyzed by using the FEM (finite element Method) simulation technique to derive the optimal design parameters. And by applying the appropriate design parameters considering the quantity of fruit and distribution environment, it is possible to design an appropriate fruit tray cup pad.

2. Materials and Methods

In this study, the packaging system for home delivery service developed is a type in which the cushioning material is inserted and packed on the upper and lower sides of the tray cup. In this study, the design of the cushion for the package was designed to maximize the effects of fixing and cushioning the designed tray cup. The optimum packaging materials were selected from the theoretical analysis of PE, PP, PS tray cups used as packaging materials for apples and pears and the best packaging materials were derived based on the FEA analysis results of each material and static and dynamic analysis were applied to each material by FEA analysis software (ANSYS Ver. 18.1) in this study.

We propose a method for the development of a tray cup considering the effects of fixing and cushioning of apples and pears for delivery, as shown in Figures (1). It is designed so that more than 2/3 of the fruit for home delivery service is fixed in the groove of the tray cup and the damage stress caused by the contact between the fruits is not generated. In addition, the bottom of the groove is designed as a circular shape so that the fruit can be stably contacted with the left and right sides, and the center of gravity is designed so that the center of gravity is not tilted to one side. For FEA, the initial conditions of the bottom fixing and the boundary conditions applying the pear weight to the contact surface on groove part of tray cup pad.

3. Results and Discussion

3.1 FEA of the tray cup considering the effects of fixing and cushioning

The finite element analysis (FEA) of the designed tray cup pads allows the analysis of stress, deformation and resonance occurring during distribution and strain energy in the resonance frequency band. The bioyield strength, bio G-factor, and resonant frequency of the pears presented by Jung (2003) were applied. Figure (2) shows the results of the FEA analysis on the contact stress between the tray cup pad and the entry fruit of polypropylene (PP) material when about 0.5 kg_f of pears were placed in the tray cup pad with 7 grooves developed for the home delivery service. As shown in the figure, the maximum contact stress is about 384 Pa, which is significantly lower than the bioyield strength of the pears (181.54 ~201.76 kPa).

Figure (2) shows the results of the FEA analysis for the contact displacements of the PP (polypropylene) material when about 0.5 kg_f of pears were inserted into the tray cup pads with 7 grooves for home delivery service. As can be seen from the figure, the displacement of the contact part between the fruit and the tray cup pad was about 0.0392 mm, which was significantly lower than that of the tray cup pad by about 0.5 mm. It was judged that the thickness of the tray cup pad was sufficient for the applied fruit (pear).

Table (1) shows the results of analysis of contact stress and

Table 1. Results of contact stress and displacement analysis for tray cup of 7, 8 and 9 pears

	7 Fruits Tray	8 Fruits Tray	9 Fruits Tray
Contact Stress (Pa)	384	398	413
Contact Displacement (mm)	0.0392	0.0463	0.0547

Fig. 1. Design of packaging tray cup pads (7, 8 and 9 grooves) for pears.

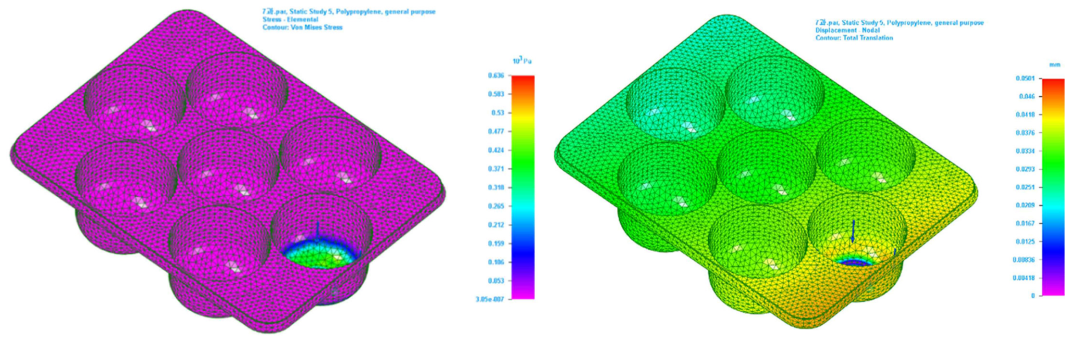

Fig. 2. Stress and deformation analysis of PP material tray cup for 0.5 kgf of pears using FEA.

contact displacement for tray cup pads of 7, 8 and 9 pears. The higher the number of fruits inserted, the higher the contact stress and the greater the contact displacement. The small contact stress means that the fruit and the stratum come into contact with a larger area, and when the contact area is large, the contact displacement is consistent with the tendency to decrease.

Figures (3) and (4) show the resonance point and strain energy of PP (polypropylene) material by FEA analysis when about 0.5 kg_f of pears are inserted in tray cup. In the case of the simulation, 4 resonance points (9,23, 26.81, 30.77, 36.81 Hz) occurred in the frequency range of 5 ~ 150 Hz. It is considered that this is a suitable frequency band for the delivery by the frequency band which is far out of the range of 62.5 ~ 108.6 Hz which is the resonance frequency band of pears proposed by Jung (2003).

In general, when the resonance frequency of the tray cup pad for packaging and the resonance frequency of the fruit to be inserted in the tray cup are presented in the same frequency band, resonance occurs due to the vibration generated during transportation, resulting in a larger vibration amplitude, The design factors for resonance must be applied to the plastic-based packaging material.

As shown in the results of the analysis of the strain energy at the 4 resonance points. The strain energy is an index of the force generated by the resonance, which means that the large strain energy can cause a large deformation (distortion) due to resonance. As can be seen in the figures, the maximum strain

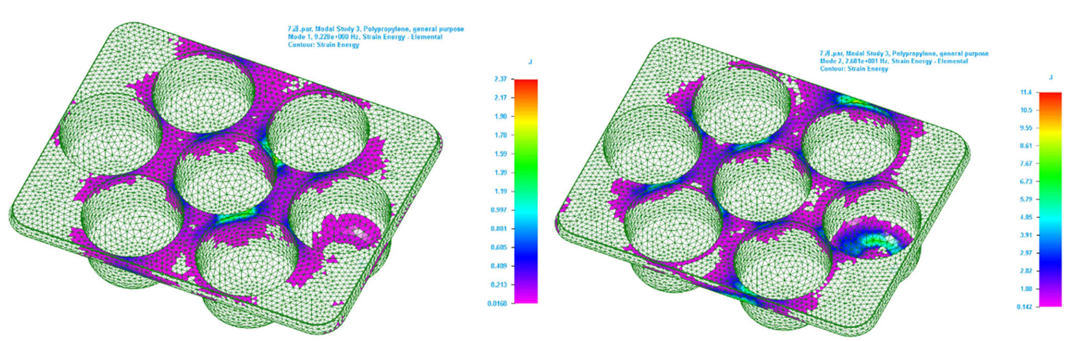

Fig. 3. Strain energy of first and second resonance point of PP material tray cup pad for 0.5 kgf of pears using FEA.

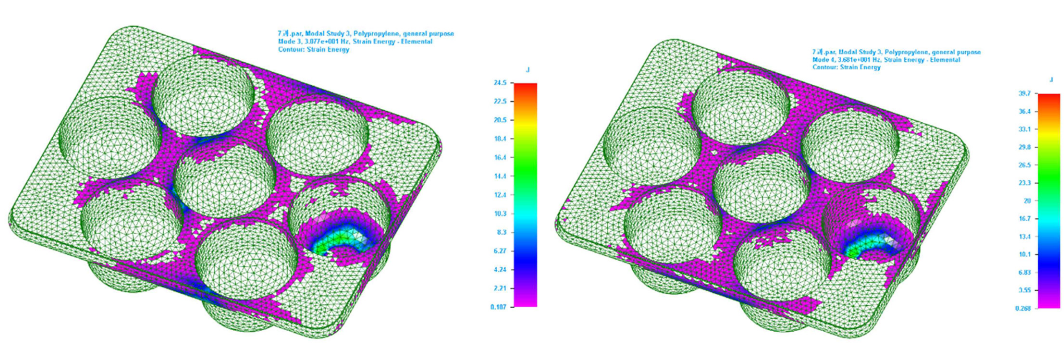

Fig. 4. Strain energy of third and fourth resonance point of PP material tray cup pad for 0.5 kgf of pears using FEA.

Table 2. Results of resonance frequency and strain energy analysis for tray cup pad of 7, 8 and 9 pears

No.	7 Fruits Tray		8 Fruits Tray		9 Fruits Tray	
	Resonace Frequency (Hz)	Strain Energy (J)	Resonace Frequency (Hz)	Strain Energy (J)	Resonace Frequency (Hz)	Strain Energy (J)
1	9.23	1.89	7.14	0.49	9.08	0.78
2	26.81	8.61	19.24	2.67	27.57	4.08
3	30.77	10.30	22.31	5.82	28.18	5.92
4	36.81	12.20	27.00	7.82	32.16	6.52

energy at the first resonance point of 9.23 Hz is 1.89 J, the second resonance point of 26.81 Hz is 8.61 J, the third resonance point of 30.77 Hz is 10.3 J, and the fourth resonance point of 36.81 Hz is 12.2J. which occurs at the upper part of tray cup pad. If the height of the tray cup pad is designed to be low, the strain energy accumulated in the edge of the groove is transmitted to the fruit during the distribution of the parcel, which causes damage.

Analysis results show that the resonance frequency increases and the strain energy of the design is also increased. This means that when the frequency is increased at the same acceleration level, the strain that receives vibration is subjected to a larger impact acceleration, so that the strain energy is greatly measured. As shown in figures, the large impact energy of the bottom surface is larger than that of the bottom surface. The results of the FEA analysis were not considered in this study.

Table (2) shows the results for the resonance frequency and strain energy for the pear tray cup pad. As shown in the table, the deformation energy at the resonance point tends to decrease as the number of fruits is increased. Generally, the resonance is consistent with the tendency that the larger the area occupying the horizontal part of the tray cup pad is, the larger the strain energy is measured. Also, as the resonance frequency increases, the strain energy tends to increase. This result shows that when the frequency is increased at the same acceleration level, the stress by vibration is subjected to a larger impact acceleration, so that the strain energy is measured to a large extent.

3.2. FEA according to the tray cup pad materials

The tray cup pad analysis of pears for the home delivery service designed with polyethylene (PE) and polystyrene (PS) material was performed by using finite element analysis (FEA) as shown in Figure (5) and (6). In order to compare and

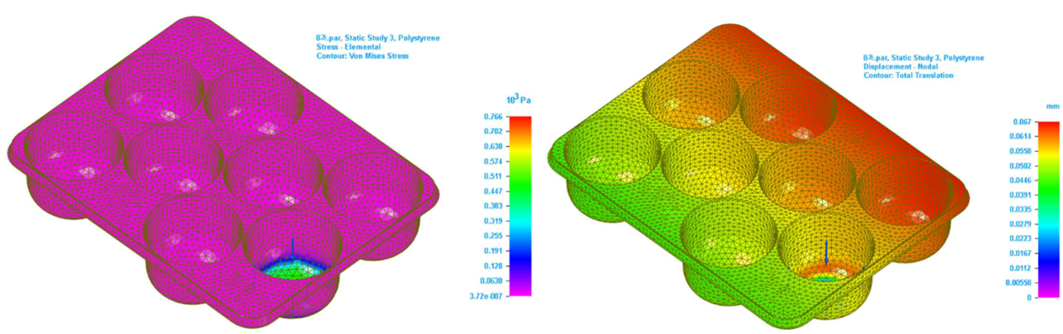

Fig. 5. Stress and deformation analysis of PE material tray cup pad for 0.5 kgf of pears using FEA.

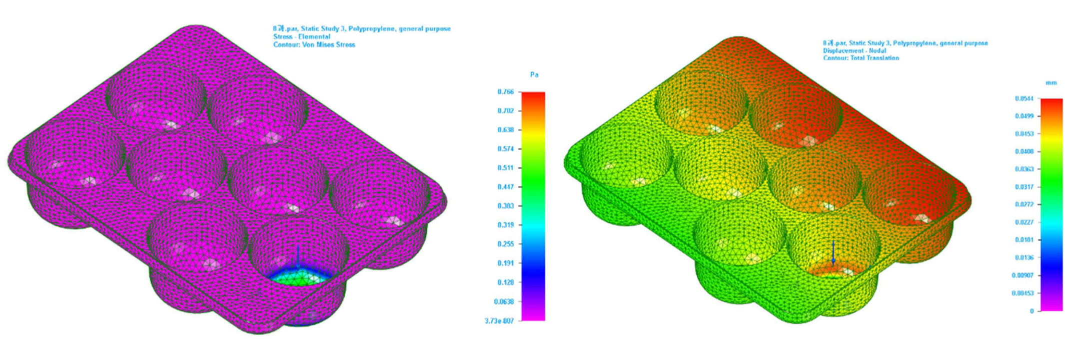

Fig. 6. Stress and deformation analysis of PS material tray cup pad for 0.5 kgf of pears using FEA.

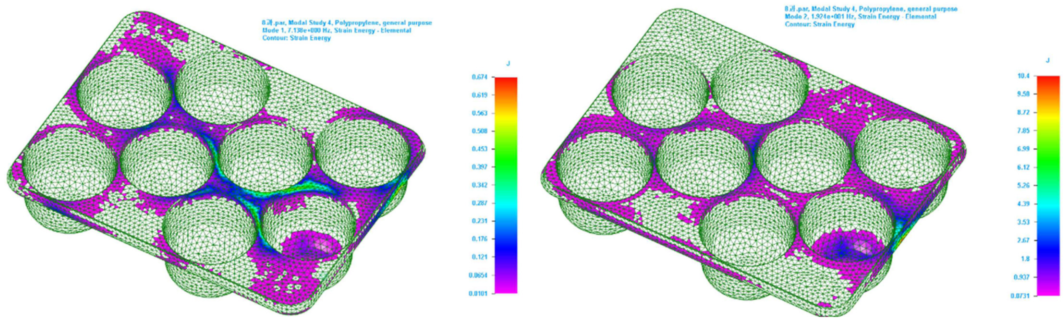

Fig. 7. Strain energy of resonance band of PE and PS material tray cup pad for 0.5 kg of pears using FEA.

Table 4. Results of resonance frequency and strain energy analysis for tray cup pads according to materials of 8 pears

No.	PP		PE		PS	
	Resonace Frequency (Hz)	Strain Energy (J)	Resonace Frequency (Hz)	Strain Energy (J)	Resonace Frequency (Hz)	Strain Energy (J)
1	7.14	0.49	7.19	1.46	6.34	0.37
2	19.24	2.67	8.50	0.45	17.35	1.08
3	22.31	5.82	10.68	1.02	20.11	2.81
4	27.00	7.82	12.33	0.98	23.34	3.94

analyze the analysis results of the tray cup pad designed with PE (polyethylene), and the effect of finite element analysis for each material was analyzed.

Finite element analysis of PE and PS materials tray cup pad for 8 fruits were performed as shown in Figure (7). The strain energy at the resonance point was measured higher in the PP material with good material properties of the elastic modulus and yield strength.

This result implies that the impact force on the fruit contacted by the material with good elastic modulus and yield strength is greater. Therefore, in the case of currently used tray cup pad, the design height is low, and the tray cup is brought into contact with the corner of the upper groove where the deformation energy is concentrated, so that the fruit may be damaged during the delivery of the parcel. Therefore, the fruit must be designed so that the side portion does not come into contact with the upper groove edge of the tray cup pad. Table (3) shows the contact stress and contact displacement of each tray cup pad by FEA, and the smallest value was obtained from PP material. The resonance frequency of the tray cup pads was measured in PP more than other materials, and value of strain energy was also measured in PP most as shown in Table (4). Strain energy is defined as the energy required for deformation, and the use of a material with a high energy generated by the material is a way to reduce the damage to the cushion materials due to the shock and vibration during transportation.

4. Conclusions

Summarizing the results, it means that impact force is more effective on the fruit to which the cushioning material having good elastic modulus and yield strength properties is applied, and the probability of damages is also increased.

In addition, damage to fruit due to vibration in the low frequency band of the distribution environment occurs. Therefore, it is a principle of proper packaging design that the resonance frequency band is designed to be larger than the resonance frequency of the cushioning material in the packaging design. Therefore, as the number of fruits put into the tray cup pad increasing, the value of contact stress and contact displacement increased, and PP material was the best among the PP, PE, and PS materials in case of considering the home delivery service of pears by FEM.

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