KOREAN JOURNAL OF PACKAGING SCIENCE & TECHNOLOGY
Vol. 30, No. 3 241~248 (2024)
https://doi.org/10.20909/kopast.2024.30.3.241

Stress Analysis on Palletized Unit-load of Various Pallet Stacking Patterns in Corrugated Packages

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Abstract In current scenario of supply chains, the palletized unit-load (PUL) is a major form of storage and distribution for packaged products. The packaging materials used for the unitization of PUL products are mainly corrugated packages and the stability of the unit-load is primarily related to the compressive strength of the corrugated package. Studies dealing with the interaction between the pallet and stacked packages have been conducted since long time; however, the results of studies dealing with the stability and stress distribution of PUL according to the pallet stacking pattern (PSP) are insufficient. In this study, the stability and design factors of PUL were analyzed through a stress analysis using block, alternate-row, and pinwheel PSP as targets. As a result of the experiment and finite element analysis (FEA), the stress acting on the bottom-surface of the lowest-layer packages was mainly concentrated near the four vertical edges in the block PSP. However, in the alternate-row and pinwheel PSP, where the upper and lower corrugated packages were interlocked, the stress distribution tendency toward the vertical panels appeared owing to the distribution of the stacking load. In addition, the maximum stress reduction and stress distribution effects of shrink-wrap packaging were also the most significant in the block PSP. Considering only the stability and strength of the PUL of the corrugated packages, a mixed pattern of blocks in the lower layer and interlock PSP in the upper part is considered effective.

Keywords Corrugated package, Pallet-based unit-load, Pallet stacking pattern, Finite element analysis, Packaging

Introduction

Accurately understanding and implementing the pallet stacking pattern (PSP) are crucial for businesses in various industries, from manufacturing and distribution to retail. It also notably impacts warehouse space management, product protection during distribution, transportation costs, and overall operational efficiency.

In general, PSP can view blocks, alternate-rows, and pinwheel patterns as basic types and various modifications and mixed patterns can be applied based on this basic type. Depending on the PSP, not only the stacking efficiency, but also the pressure distribution and stability vary owing to the interaction between the stacked packages or between the stacked packages and the pallet. The PSP determinants include product size and weight, weight distribution, product and package characteristics, access to individual packages, and transportation conditions[1,2].

In current scenario of supply chains, the palletized unit-load (PUL) is a major form of storage and distribution for packaged products. In the PUL, the packaging material applied to the unitization of a product is mainly a corrugated package, and, principally, the stability of the PUL is mostly related to the compressive strength of the corrugated package. Therefore, accurately predicting the required compressive strength of corrugated packages for various distribution conditions (such as environmental conditions, overhang with pallets, stacking period, and PSP) has been an important topic of research. In addition, several researchers have studied various interactions between pallets and stacked corrugated packages.

In the PUL, the bottom-corrugated packages are subjected to high compressive stress under the harshest conditions and the pallet directly supports these corrugated packages. Therefore, various physical interactions exist between pallets and corrugated bottom-packages. In other words, factors, such as pallet overhang, pallet deckboard gaps, and top deck stiffness affect the strength of stacked corrugated packages[3-11].

When configuring a PUL, pallet overhang may be intentionally caused to increase the storage space efficiency by increasing the stacking efficiency of the pallets; however, unin-

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tended overhang may occur because of the horizontal impact caused by incorrect handling during shipping[5]. Levans[3] investigated the decrease in compressive strength due to the overhang of the length and width of the corrugated package and the overhang of the two edges in contact with them, and reported that a linear relationship exists between the lost corrugated package perimeter and the compressive strength. Monaghan and Marcondes[4] also investigated the reduction in compressive strength owing to the overhang of the length and width of the corrugated package and reported that the loss of compressive strength was large even for a small proportion of overhang. DiSalvo[5] analyzed the effect of various palletizing factors, such as pallet overhang, pallet gap, interlock stacking, or a combination of these factors on the compressive strength of the corrugated package. When pallet overhang, the most important one among the factors, was approximately 25% compared to the corrugated package perimeter, a decrease in strength of approximately 42.1% was reported. More recently, Singh et al.[12-14] analyzed the effect of the pallet overhang of a three-layer stacked corrugated package and the lateral offset of the middle layer on the compressive strength of the corrugated package. In addition, Kim et al.[11] reported that the overhang of the long side of the corrugated package had a substantial decrease in compressive strength owing to the increased loss of the supported corrugated package perimeter compared with the overhang of the short side, and the adjacent-side overhang had a unique effect owing to the loss of structural support from an additional corrugated package corner. Although the results of the above studies were limited to those derived under limited conditions, it is clear that pallet overhang remarkably affects the stability of the PUL. The Korean Industrial Standards[15] stipulate 69 modules that are highly consistent with these standard pallets to increase consistency with standard pallets (1100×1100 mm, 1200×1000 mm) for through transportation and to secure the stability of the PUL.

Several research results deal with the interaction between the pallet and stacked corrugated packages, but those on stability and stress distribution by PSP could not be confirmed through the literature. Therefore, this study aimed to analyze the stability and design factors of PUL through stress analysis according to the PSP of corrugated packages. Experiments and finite element analysis (FEA) were conducted simultaneously.

Experiment Design and Methods

1. FEA for PUL

1.1. FE modeling and procedures

The specifications of the target corrugated package during the FEA for the PUL were as follows: L×W×D = 240 ×180×130 mm in outer-dimension, 123.71 kg/m^3 of the material density of the corrugated package itself, and 35.68 kg/m^3 of packaging density. The other specifications are listed in Table 1.

In this study, block, alternate-row, and pinwheel PSP, which are the basic types of PSP in corrugated package, were set as targets. Fig. 3 shows the FE modeling results for the PUL by PSP.

In the FE modeling of the PUL, the number of individual corrugated packages per floor was 12 (3×4) (block and alternate-row) or 8 (pinwheel pattern), and seven-layer stacking was applied to all the PULs. The preprocessor applied to the FE model was ANSYS Workbench[16], and the numbers of nodes and grids of the FE model were 95,144 and 16,297 for the block PSP; 95,144 and 16,297 for the alternate-row PSP; and 63,683 and 10,896 for the pinwheel PSP, respectively.

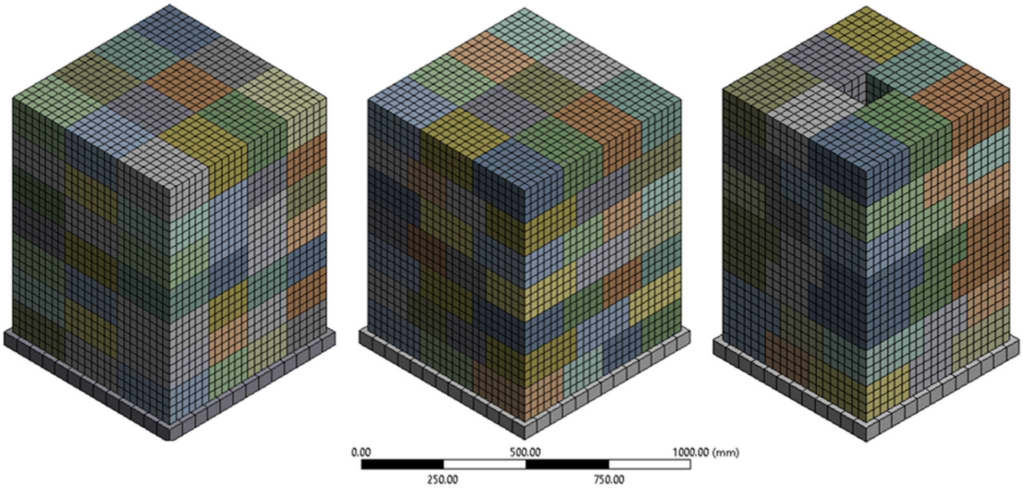
In general, the containment force of the unit-load by a stretch-wrapping machine is determined by the movement speed of the carriage, rotational speed of the turntable, prestretch of the stretch films (linear low-density polyethylene, LLDPE), and wrapping pattern[17]. The containment force generated by the shrink-wrap packaging acts as a horizontal pressure on the corrugated packages located at the four vertical edges of the unit-load. Therefore, in this study, to express stretch wrapping as a simplified FE model, an angle [web (a,b)×thickness = 50×50×5 mm] was added to the four vertical edges of the FE model for the unbounded PUL shown in Fig. 1 and a uniform horizontal pressure was applied. Fig. 2 shows the FE modeling results for the shrink-wrap packaged PUL, where the numbers of nodes and grids of FE models was 98,820 and 16,809 for block PSP; 98,820 and 16,809 for alternate-row PSP; and 67,579 and 11,440 for pinwheel PSP, respectively.

Fig. 3 shows the boundary and constraint conditions applied in FEA. Frictional contact conditions were assigned between the packages and between the angles and cprrugated packages [18]; the motion of the pallet was constrained in all directions, but

Table 1. Specifications of the individual corrugated package applied to the FEA

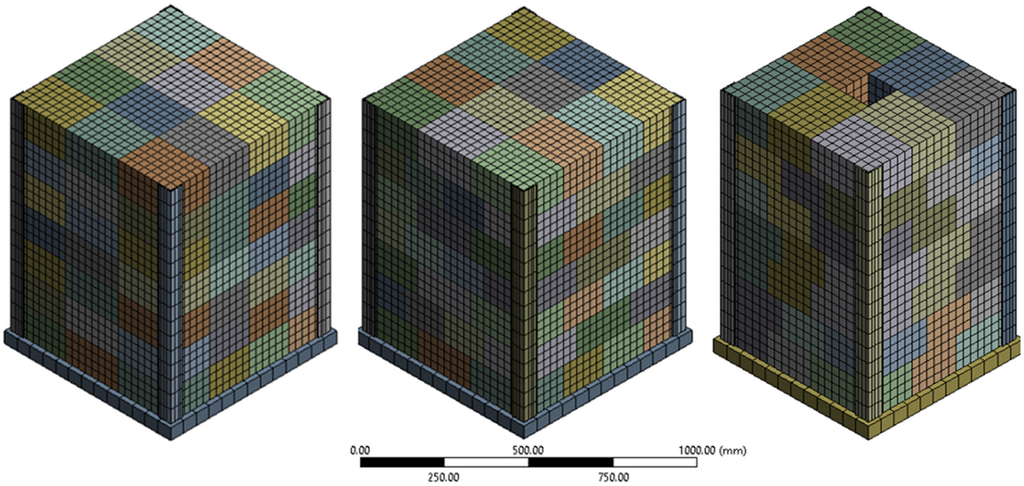
Type[1]	Board combination[2]	Dimensions of A-flute	Thickness of paperboards	Total thickness & weight
A/F-SW	KLB175/K180/KLB175	- (wavelength) 9.00 mm - (height) 4.60 mm - (tack-up factor) 1.560	- (KLB175) 0.22 mm - (K180) 0.24 mm	- (board) 5.1 mm - (package) 0.1684 kg

Note: 1) A/F-SW = A flute-single-wall corrugated board.
2) KLB175 [18% *UKP* (unbleached kraft pulp) + 20% American old corrugated container (*AOCC*) + 62% Korean old corrugated container (*KOCC*)], K180 (100% *KOCC*).



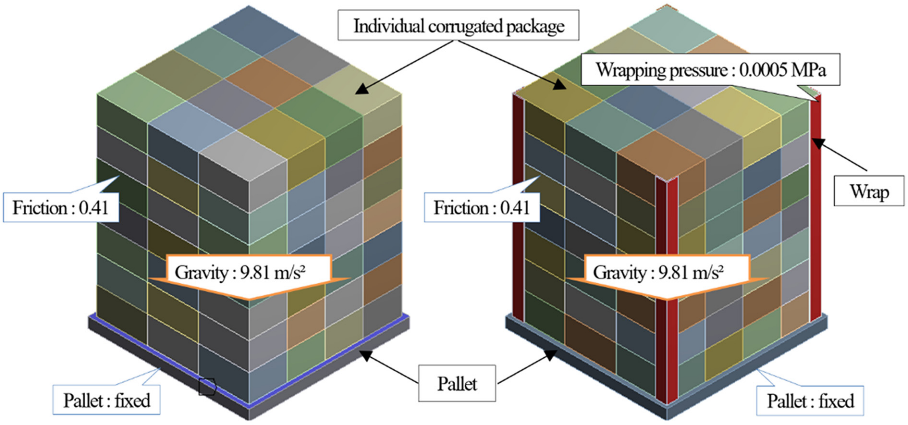
(a) Block PSP (b) Alternate-row PSP (c) Pinwheel PSP

Fig. 1. Meshed 3D models for unbounded PUL of corrugated package.



(d) Block PSP (e) Alternate-row PSP (f) Pinwheel PSP

Fig. 2. Meshed 3D models for the shrink-wrap packaged PUL.



(a) Non wrapping (b) Wrapping

Fig. 3. Boundary and constraint conditions: block PSP.

not the motion of all stacked corrugated packages.

During the FEA, 35.68 kg/m^3 of a packaging density of the corrugated package was imposed as a weight using the distributed mass function of the postprocessor (ANSYS Workbench[16)]).

1.2. Material properties

Assuming that the material properties of the corrugated package during FEA are isotropic, 137.06 MPa of Young's modulus, 22.25 MPa of shear modulus, and 0.087 of Poisson's ratio were applied. These values were the averages of the equivalent material properties of an orthotropic material previously reported by Park et al.[19)]. Conversely, in the FEA for the shrink-wrap packaged PUL, the angle was regarded as a rigid body and the properties of structural steel (7,850 kg/m^3 of density, 200 GPa elastic modulus, and 0.3 Poisson's ratio) were applied.

2. Experiment for PUL

2.1. Experimental corrugated package

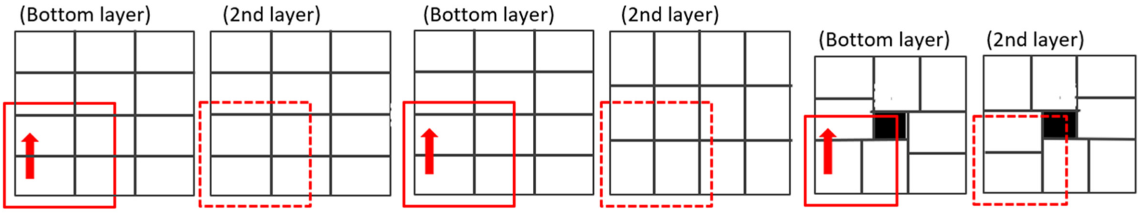
The specifications of the corrugated packages applied to the configuration of the three types of PUL adopted in this study were the same as those of the FEA: A/F-SW corrugated board of the material and L×W×D = 240×180×130 mm in outer-dimensions. The other specifications are listed in Table 2.

Each corrugated package was filled with approximately 2 kg of rough rice to achieve a packaging density of 3500 N/m^3. This value was determined by referring to the package dimensions and packaging density [(apple) 3312 N/m^3, (Korean melon) 3665 N/m^3] of the packaging unit with 10 kg (apples

Table 2. Specifications of the individual corrugated package applied to the experiment

Type[1)]	Board combination[2)]	Dimensions of A-flute	Thickness of paperboards	Total thickness & weight
A/F-SW	SK180/K180/SK180	-(wavelength) 9.00 mm -(height) 4.60 mm -(tack-up factor) 1.560	-(SK180) 0.22 mm -(K180) 0.24 mm	-(board) 5.34 mm -(package) 0.1710 kg

Note: 1) A/F-SW = A flute-single-wall corrugated board.
2) SK180 [20% outer liner containing unbleached kraft pulp (*UKP*)+ 80% Korean old corrugated container (*KOCC*), K180 (100% *KOCC*)



(a) Block PSP (b) Alternate-row PSP (c) Pinwheel PSP

Fig. 4. Pressure measurement position by target PSPs.

(a) Bottom-layer (b) Second-layer

Fig. 5. Pressure measurement method of PUL: Pinwheel PSP.

2.2. Experimental devices and methods

The pressure mapping system used to measure the pressure of the PUL was Tactulus [SENSOR PRODUCTS INC. (SPI, USA)] and the basic specifications are as follows: 0~34 kPa of the pressure range, 25.4×25.4 mm of the sensor size, 3.2 mm of the spaces between sensors, and 1854×762 mm of the sensing area.

In the PUL of the corrugated package, the pressure measurement positions were selected at two locations: between the bottom-layer packages and the pallet to measure the pressure distribution transmitted to the pallet loading surface and between the bottom-layer packages and the second layer packages to measure the pressure distribution according to the contact conditions of the upper and lower corrugated packages.

Considering the size of the sensing area of the pressure-mapping system and the repeatability of the PSP, one-quarter of the pallet occupancy area for each PUL was set as the measurement range (Fig. 4). The occupancy area not covered by the pressure mapping system was leveled by placing a cardboard of the same thickness as the pressure mapping system (Fig. 5).

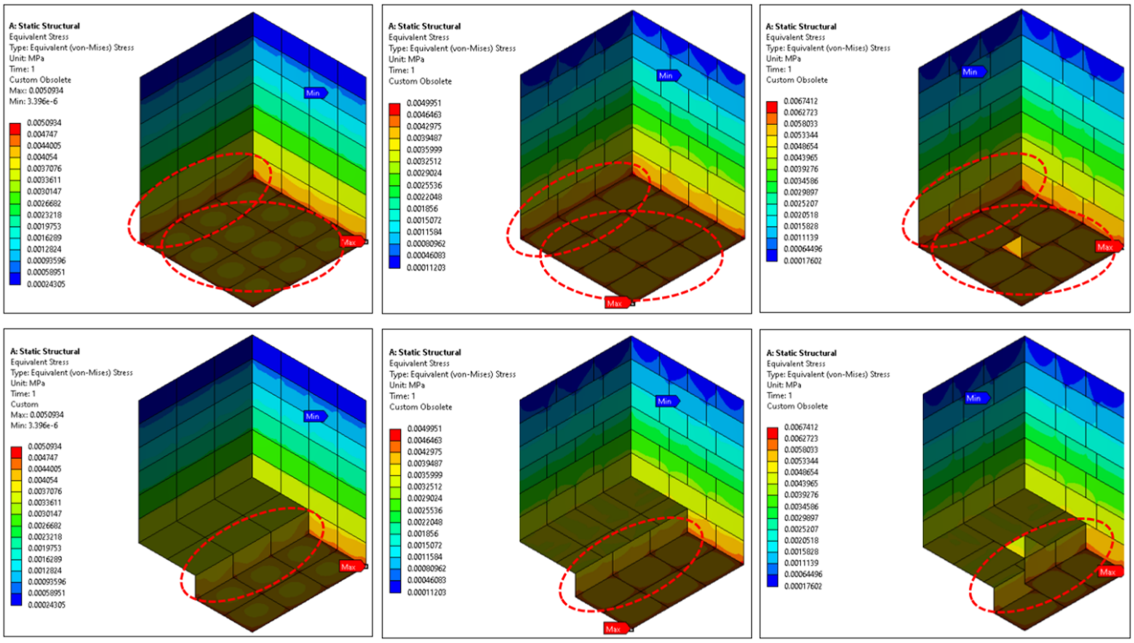
Results and Discussion

1. FEA simulation for PUL

Fig. 6 shows the FEA results for the unbounded PUL (Fig. 1) for each target PSP. Based on the stress distribution generated on the bottom-surface of the lowest-layer packages under the harshest conditions in the PUL, in the case of the block PSP, in which the four vertical edges which are the most rigid parts in the individual corrugated package match up and down, the stress concentration mainly occurred at the four vertical edges. However, in the alternate-row and pinwheel PSP, where the upper and lower packages are interlocked, the stacking load is distributed, and the stress distribution tends toward the vertical panels of the corrugated package. This phenomenon was more pronounced in the inner packages than that in the outer packages of PUL.

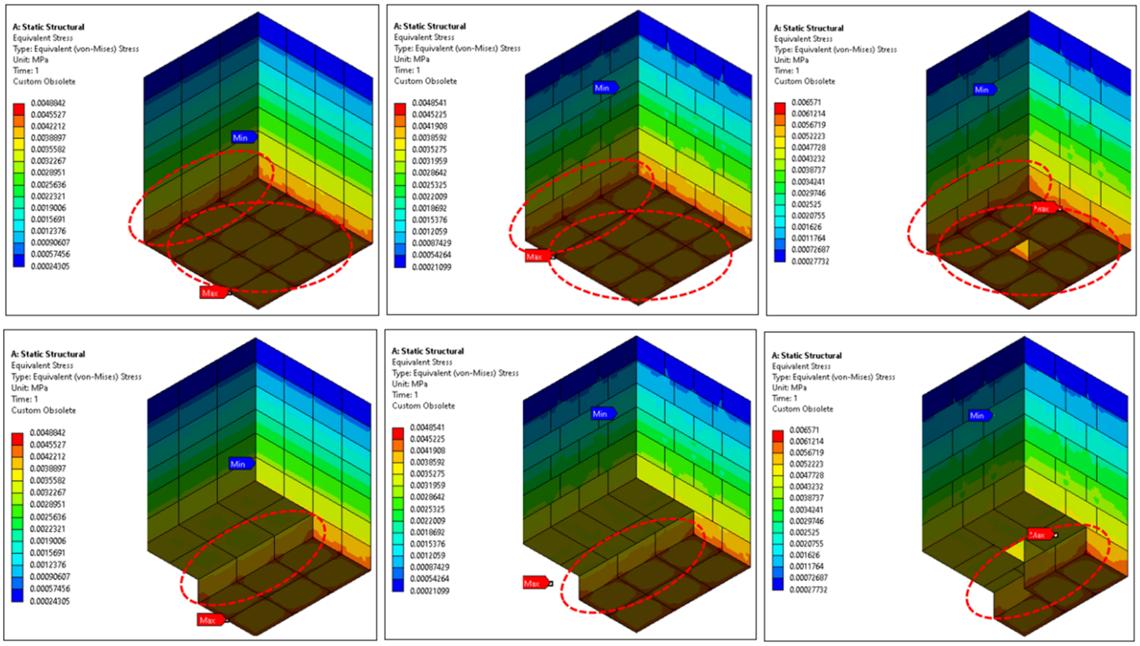
However, as a result of the FEA for the shrink-wrap packaged PUL (Fig. 7), the block PSP had the largest reduction of approximately 4.1% (5.0934 → 4.8842 GPa) compared with the unbounded PUL, based on the maximum stress acting on the bottom-surface of the lowest-layer packages and the pinwheel PSP had the smallest reduction of approximately 2.5% (6.7412 → 5.5710 GPa). Particularly, in the case of the block PSP packaged by shrink-wrap, the tendency of the stress concentration near the four vertical edges to be dispersed toward the vertical panels was more significant than that of the other PSPs.

The stress dispersion effect due to shrink-wrap packaging was evident in the inner packages of the block PSP; however, the dispersion effect in the interlocked alternate-row and pinwheel PSP was insignificant. However, it was confirmed through several repeated FEA that the difference in maximum stress generated in the corrugated packages according to the wrapping pressure of the shrink-wrap was weak in all target PSP in this study.



(a) Block PSP (b) Alternate-row PSP (c) Pinwheel PSP

Fig. 6. FEA results for unbounded PUL.



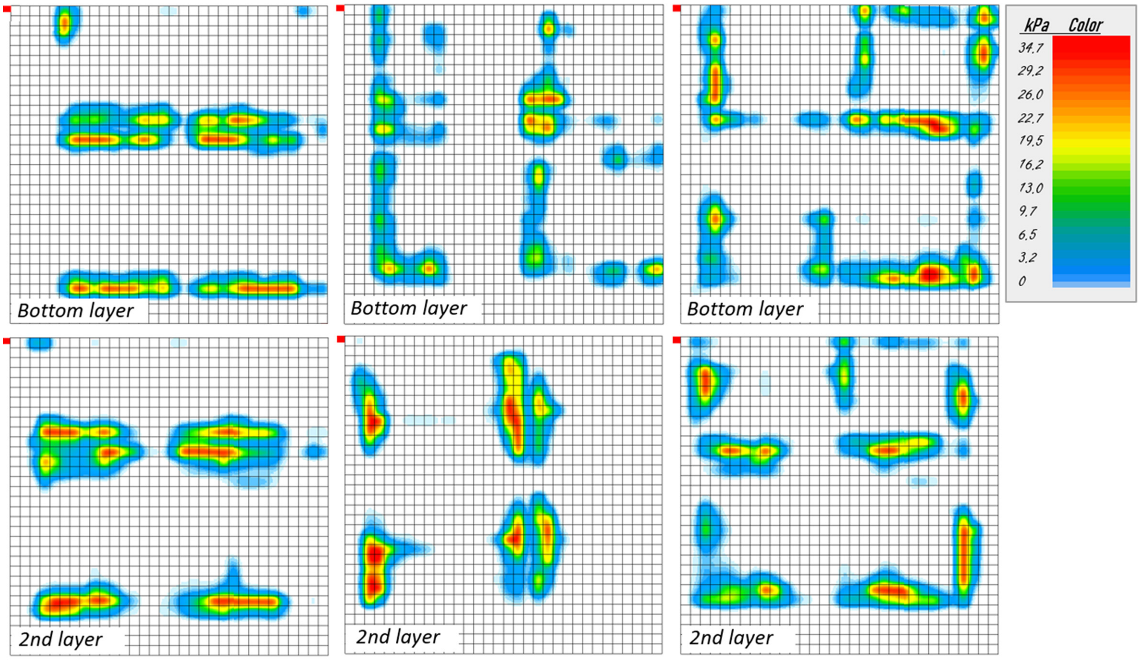
(a) Block PSP (b) Alternate-row PSP (c) Pinwheel PSP

Fig. 7. FEA results for the shrink-wrap packaged PUL.

2. Comparison with the experimental study

Corrugated packages with the same size and packaging density as the target corrugated package in the FEA for PUL were manufactured to measure the stress acting on the contact surface between the bottom packages and pallet and between the bottom-packages and second-layer packages for the three PSPs, as shown in Fig. 8.

Among the three PSPs, in the two PSPs other than block PSP, the stacking load was distributed to the vertical edge and the vertical panel by the interlock of the upper and lower cor-



(a) Block PSP (b) Alternate-row PSP (c) Pinwheel PSP

Fig. 8. Measurement results of pressure distribution by PSP of PUL.

rugated packages and as a result, the stress dispersion effect was evident. In other words, in the block PSP, the stress was concentrated on the long-side surface of the individual corrugated package, whereas in the alternate-row and pinwheel PSP, the stress was distributed on the long- and short-side surfaces of the corrugated package. These results were in good agreement with the FEA results; however, there was a limit to the lack of capacity of the pressure mapping system used for a more detailed quantitative analysis through experimental results.

In general, most of the compressive strength of an individual corrugated package is determined by the stiffness of the four vertical edges [20,21]. In the case of block PSP, a large portion of the stacking load is supported through these vertical edges because the vertical edges of the upper and lower corrugated packages are consistent; therefore, it is advantageous in terms of the robustness and uniformity of the PUL. However, it is disadvantageous in terms of stability because of the behavior of the stacked corrugated packages splitting vertically. In addition, a risk of stiffness loss was observed in corrugated packages when the vertical edge supporting a large stacking load coincides with the gaps between the pallet deckboards and when pallet overhang occurs. However, in the alternate-row and pinwheel PSP, the stacked upper and lower corrugated packages interlock with each other; thus, no vertical splitting of the stacked corrugated packages occurs, which is advantageous in terms of unit-load stability. Even though, as the stacked upper and lower corrugated packages support the stacking load with the most rigid and weak parts in contact with each other, the stiffness of the corrugated packages decreases. Therefore, considering only the stability and robustness of the PUL of the corrugated package, constructing a unit-load in a pattern mixed with block PSP in the lower layers and interlock PSP in the upper layers is advantageous. For example, if the outer dimension of the corrugated package is L×W = 366×275 mm (No. 11-47 in the 1100×1100 mm module size, transport package sizes by modular coordination on KS T 1002 [15]), a PSP that is a mixture of blocks and alternate-row PSPs can be constructed, which can achieve the stability and robustness of the unit-load.

Conclusions

In the current product supply chains, PUL is a major form of storage and distribution for packaged products. Therefore, understanding and implementation of PSP are directly or indirectly related to warehouse space efficiency, product protection, and transportation costs. In this study, stress analysis was performed through FEA and experiments on the PUL of three types of PSP, and the design factors of the PUL were analyzed in terms of stability and strength. A more specific summary of the results is as follows:

1) As a result of the FEA, the stress on the bottom-surface of the lowest-layer corrugated packages was mainly concentrated near the four vertical edges in the block PSP; however, the alternate-row and pinwheel PSP, which are interlock patterns, showed a tendency to distribute stress toward the vertical panel. This trend was also proven by the experimental results; that is, in block PSP, stress concentration occurred on the L×D surface of the corrugated packages, whereas in alternate-row and pinwheel PSP, stress was distributed on the L×D and W×D surfaces.

2) In the shrink-wrap packaged PUL, the maximum stress generated on the bottom-surface of the lowest-layer of the corrugated packages decreased by approximately 4.1% (5.0934 → 4.8842 GPa) in block PSP and 2.5~2.8% in other patterns compared to the unbound PUL. In addition, the stress dispersion effect of shrink-wrap packaging was most remarkable in internally located corrugated packages in the PUL of the block PSP.

3) Block PSP is advantageous in terms of the robustness and uniformity of the PUL; however, it has an unfavorable pattern in terms of stability owing to the splitting phenomenon of stacked corrugated packages. In contrast, the alternate-row and pinwheel PSP, which are interlock patterns, are advantageous in terms of stability; however there is a concern of strength deterioration owing to unfavorable contact between stacked corrugated packages. Therefore, considering only the stability and strength of the PUL of the corrugated packages, a mixed pattern of block PSP in the lower layer and interlocking PSP in the upper part is considered beneficial.

Acknowledgements

This research was conducted with the support of the Cooperative Research Program for development of data application technology for postharvest management of the agricultural and livestock products (Project No. PJ017050042024), Rural Development Administration (RDA).

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투고: 2024.11.17 / 심사완료: 2024.11.28 / 게재확정: 2024.12.03