Original Paper

Method for Controlling Damage to Products Subjected to Cumulative Fatigue Considering Damage Degree at Each Layer in Stacked Packaging

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To devise a method for controlling the damage to products considering the degree of damage per shock (*d*) at each layer in stacked packaging, we laid board- or sheet-like cushioning materials between each layer or outside the bottom of the boxes and studied the effects they had on the velocity change (*Vc*), the peak acceleration (*PAcc*), and *d* at each layer in the stacked packaging. The results of a drop test indicated that the values of *Vc* and *PAc*c corresponding to the drop shock at each layer in the stacked packaging can indeed be controlled by laying the board- or sheet-like cushioning materials between each layer or outside the bottom layer. Estimation results, obtained by a multiple regression analysis for the calculation of a specific *d*, indicated that the layer having the maximum *d* (d_{Max}) could be changed using the cushioning materials, although the average *d* (d_{Av}) throughout the packaging was not so changed. These results will contribute to the development of a mixed packaging system for products with varying fragility, damaged by cumulative fatigue.

Keywords: cumulative fatigue, multiple regression analysis, peak acceleration, repetitive shock, velocity change

1. Introduction

In a previous study, we demonstrated that the combination of the velocity change (*Vc*) and peak acceleration (*PAcc*) due to a dropping shock changed variously by the differences among the layers in stacked packaging for strawberries damaged by cumulative fatigue[1)]. Accordingly, the degree of damage to the fruit per shock (*d*) varied according to the layer differences. These results indicated that the differences in the combinations of *Vc* and *PAcc* corresponding to different layers should be considered in order to prevent products inside stacked packaging from being damaged because of cumulative fatigue due to repetitive shock. The sensitivity of products inside stacked packaging to a single shock has been thoroughly studied[2,3)]. However, few reports consider methods for controlling the damage to products inside stacked packaging due to cumulative fatigue caused by repetitive shock.

The aim of this study was to propose a method to control product damage, considering *d* at each layer in stacked packaging. When using packaging in actual transport, controlling measures are easily applied. To control *d* at each layer, we laid board- or sheet-like cushioning materials between each layer of boxes and outside the bottom of the boxes.

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2. Theory

2.1 Summary of experiment and analysis

First, we examined whether *Vc* and *PAcc* at each layer were changed by laying board- or sheet-like cushioning materials between each layer or outside the bottom layer. Next, we estimated the resulting changes in the *d* values. The *d* values corresponding to the combination of *Vc* and *PAcc* were estimated by multiple regression analysis.

2.2 Multiple regression analysis for estimation of *d* values corresponding to the combination of *Vc* and *PAcc*

Assuming damage boundary curves (DBCs) corresponding to a specific *d*, each *d* value is determined according to two parameters: *Vc* and *PAcc*. Therefore, multiple regression analysis was performed with *Vc* and *PAcc* as explanatory variables and *d* as the objective variable. We attempted to lead the equation of multiple regression to cross each DBC (Fig. 1) as follows:

$$d = aVc + bPAcc + c, \qquad (1)$$

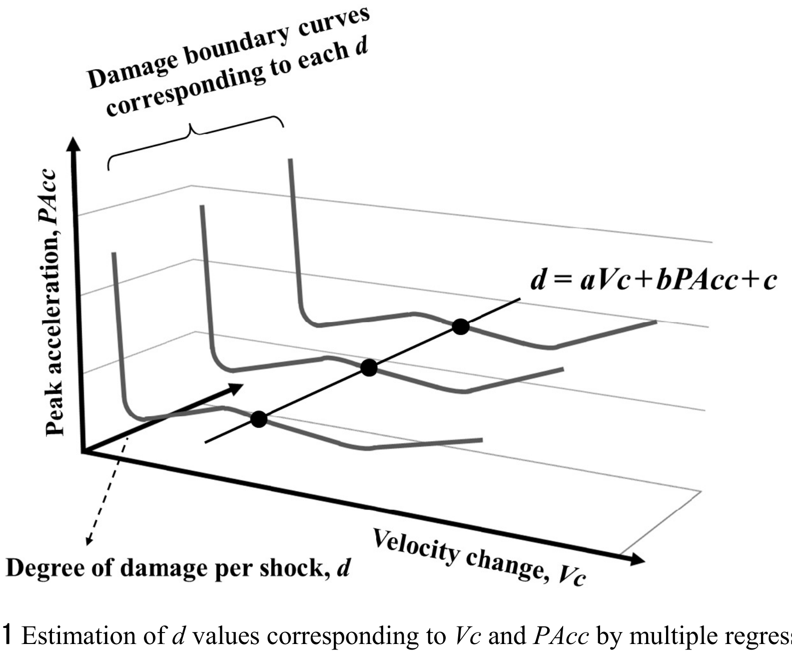

Fig. 1 Estimation of *d* values corresponding to *Vc* and *PAcc* by multiple regression analysis.

where *a*, *b,* and *c* are constants. The data of *Vc*, *PAcc*, and *d* for the multiple regression analysis were obtained from a previous report[1)], which considered a drop test for strawberries inside five-layered stacked packaging (Table 1). To confirm the significance of the regression equation, an analysis of variance (ANOVA) was performed. Both analyses were performed using statistical software (Excel Toukei 2012, Social Survey Research Information; Tokyo, Japan). **We used multiple regression analysis only for estimating the *d* values because the DBCs cannot be drawn from the analysis.**

Table 1 Data of velocity change (*Vc*), peak acceleration (*PAcc*), and degree of damage per shock (*d*) of strawberry fruit[1)] for multiple regression analysis

Layer[z]	Drop height (m)	*Vc* (m/s)	*PAcc* (m/s^2)	*d*
1	0.03	0.94[y]	194.7[y]	0.022[x]
	0.05	1.49	313.4	0.028
	0.10	1.87	442.0	0.052
	0.15	2.22	624.8	0.066
	0.20	2.56	914.1	0.092
	0.25	3.02	989.7	0.115
2	0.05	1.48	139.2	0.022
	0.10	1.95	260.9	0.037
	0.15	2.32	371.6	0.052
	0.20	2.55	498.6	0.061
3	0.05	1.65	124.5	0.021
	0.10	2.07	220.9	0.029
	0.15	2.50	386.6	0.058
	0.20	2.78	421.1	0.070
4	0.05	1.68	107.5	0.020
	0.10	2.14	210.4	0.031
	0.15	2.77	340.3	0.058
	0.20	3.06	450.5	0.070
5	0.05	1.66	117.8	0.029
	0.10	2.46	177.7	0.035
	0.15	2.91	284.3	0.047
	0.20	3.42	459.3	0.077

[z]1: Bottom of five-layered corrugated fibreboard boxes.
5: Top of five-layered corrugated fibreboard boxes.

[y]Obtained from 11-12 replications.

[x]Obtained from 5 replications.

3. Experiment

3.1 Condition for *Vc* and *PAcc* measurements in drop test with each material

The dummy sample used to measure *Vc* and *PAcc* was a five-layered stack of corrugated fibreboard boxes (external dimensions: 355 mm × 254 mm × 75 mm) each containing four 300–320-g clay-packed polyethylene terephthalate resin-made trays (external dimensions: 166 mm × 117 mm × 40 mm). A 20-mm-thick layer of foamed urethane sheets was placed on each tray to stop its rebound. Each box was fastened by two plastic bands, and then the boxes were stacked. The bottom and top boxes were defined as the 1^{st} and 5^{th} layers, respectively. The total weight of the stacked packaging was ~6.5 kg.

The board- or sheet-like cushioning material used to control *Vc* and *PAcc* **should be easily obtainable** and not change the total weight of the packaging. In addition, it should be sufficiently hard **to**

avoid the collapse of the cargo. Thus, we used a foamed plastic board (FPB), a corrugated plastic board (CPB), and a foamed rubber sheet (FRS). The thickness of each material was 5 mm. The specifications of each material are given in **Table 2**. Each material was laid between the layers or outside the bottom layer (**Fig. 2**). The condition wherein the material was laid outside the bottom layer was labelled “0-1.” Similarly, when the material was laid between the 1st and 2nd, 2nd and 3rd, 3rd and 4th, and 4th and 5th layers, the conditions were labelled “1-2,” “2-3,” “3-4,” and “4-5,” respectively.

Table 2 Specifications of tested materials for controlling *Vc* and *PAcc*

Material	Made from...	Density (g/cm^3)^z
Foamed plastic board, FPB	Polyvinyl chloride	0.54
Corrugated plastic board, CPB	Polypropylene	0.91^y
Foamed rubber sheet, FRS	Natural rubber	0.32

^{z}Each value was measured by a gas pycnometer (AccuPyc II 1340, Micrometrics, USA) .
^{y}Value of the material in itself.

Fig. 2 Cushioning material for controlling *Vc* and *PAcc*; laying the corrugated plastic board between the 2nd and 3rd layers (CPB-2-3).

previous reports[1,4]. That is, a three-dimensional accelerometer (2366 W; Showasokki, Tokyo Japan; size: 8.0 mm × 7.0 mm × 5.5 mm; weight: 1.2 g) was attached to the internal centre of one of the tray bottoms using double-sided tape and kept in place by the weight of the clay. The dummy sample, i.e., the five-layered stack of boxes, was dropped perpendicularly by hand. Then, the *Vc* and *PAcc* were measured. **In our previous study on strawberry fruit, we found that a drop height of around 0.2 m was enough to damage the fruit during transport[5]. Thus, the drop height was set to 0.1 m.** In the “0-1” condition, the distance between each layer of material and the counterface surface was adjusted to 0.1 m. The counterface surface was a 10-mm-thick silicone rubber sheet (density: 0.27 g/cm^3, compression stress at 25% distortion: 126.1 kPa) on an iron board **to reduce the *PAcc***. The measurement conditions were as follows: sampling interval, 500 μs; data, 2000 points; filer mode, automatic; trigger level, 0.4%; and pre-trigger, 5%. These conditions were set using a shock measurement and analysis system (SMH-12, Shinyei Technology, Kobe, Japan), connected to the accelerometer and shock vibration analysis software (SMS-500M, Shinyei Technology).

The *Vc* and *PAcc* data without any materials were obtained from the previous report[1)] and shown in **Table 1** and were used for the control condition.

3.2 Estimation of *d* at each layer

The values of *Vc* and *PAcc* obtained from the measurement results of **3.1** were substituted into Equation (1). Thus, the *d* values obtained from dropping were estimated for each material. The average and maximum *d* values of the all 5 layers were also calculated: d_{Av} and d_{Max}, respectively.

4. Results and Discussion

4.1 Multiple regression analysis for estimation of *d* values corresponding to the combination of *Vc* and *PAcc*

From the result of the multiple regression analysis of the data shown in **Table 1**, we obtained the following equation with a high coefficient of correlation:

$$d = 1.51\text{E-}02Vc + 7.85\text{E-}05PAcc - 1.32\text{E-}02 \ (r = 0.9848). \qquad (2)$$

The results of the ANOVA showed that the *P* value, indicating the significance, was 3.68E-15; this value is sufficient to explain the significance of Equation (2). Therefore, this equation is reliable for estimating *d* according to the combination of *Vc* and *PAcc*.

4.2 Effects of each material and its position on the *Vc* and *PAcc* at each layer

The data of *Vc* and *PAcc* in each layer for each material are shown in **Tables 3 and 4**, respectively. Each *Vc* value tended to be large in the upper layer compared with the lower layer, which supports the previous report[1)]. The combination of *Vc* and *PAcc* changed variously with each material (**Fig. 3**). Thus, it was suggested that the hardness of the whole packaging and/or each layer was changed by using each material when it was assumed as a spring. It was also reported that the transmissibility of the acceleration at the upper layer was larger than that at the lower layer when a half-sine shock pulse was applied to the stacked packaging[2)]. Thus, in the current study, it was suggested that the transmissibility of the acceleration at each layer was changed by using each material laid at a different position. Moreover, in this study, the material of the counterface surface for the drop test was an elastic silicone rubber sheet; its elastic properties might affect the combination of *Vc* and *PAcc* at each layer. To clarify this issue, further studies are needed.

Table 3 Effects of each cushioning material and its position on the *Vc* (m/s) at each layer (Drop height: 0.1m)

Cushioning material	Position of each material	Layer				
		1	2	3	4	5
No material (Control)[z]	-	1.87 ± 0.03[y]	1.95 ± 0.03	2.07 ± 0.04	2.14 ± 0.02	2.46 ± 0.03
FPB	0-1	1.73 ± 0.03	2.07 ± 0.03	2.08 ± 0.03	2.30 ± 0.05	2.51 ± 0.08
	1-2	1.87 ± 0.05	1.93 ± 0.04	2.18 ± 0.02	2.43 ± 0.03	2.53 ± 0.03
	2-3	1.86 ± 0.06	1.90 ± 0.01	1.92 ± 0.03	2.43 ± 0.06	2.42 ± 0.02
	3-4	1.94 ± 0.05	2.34 ± 0.04	2.43 ± 0.04	2.30 ± 0.03	2.60 ± 0.04
	4-5	1.74 + 0.03	2.14 ± 0.02	2.38 ± 0.03	2.52 ± 0.03	2.65 ± 0.04
CPB	0-1	1.61 ± 0.06	2.12 ± 0.02	2.32 ± 0.03	2.34 ± 0.08	2.36 ± 0.09
	1-2	2.06 ± 0.01	1.69 ± 0.03	2.21 ± 0.03	2.35 ± 0.06	2.33 ± 0.05
	2-3	1.83 ± 0.01	1.93 ± 0.04	2.10 ± 0.02	2.14 ± 0.05	2.21 ± 0.03
	3-4	2.16 ± 0.03	2.08 ± 0.04	2.09 ± 0.02	2.37 ± 0.02	2.50 ± 0.03
	4-5	2.11 ± 0.03	2.03 ± 0.02	2.11 ± 0.03	2.37 ± 0.01	2.05 ± 0.07
FRS	0-1	1.77 ± 0.03	2.00 ± 0.02	2.16 ± 0.01	2.30 ± 0.06	2.55 ± 0.05
	1-2	1.82 ± 0.03	1.82 ± 0.03	2.00 ± 0.02	2.35 ± 0.04	2.40 ± 0.05
	2-3	2.10 ± 0.05	1.98 ± 0.02	2.14 ± 0.02	2.45 ± 0.04	2.49 ± 0.07
	3-4	2.05 ± 0.04	2.04 ± 0.01	2.15 ± 0.03	2.32 ± 0.05	2.34 ± 0.05
	4-5	2.09 ± 0.05	2.04 ± 0.02	2.16 ± 0.03	2.24 ± 0.01	2.51 ± 0.03

[z]Each value was obtained from the previous report[1)].

[y]Average ± SE (n = 6).

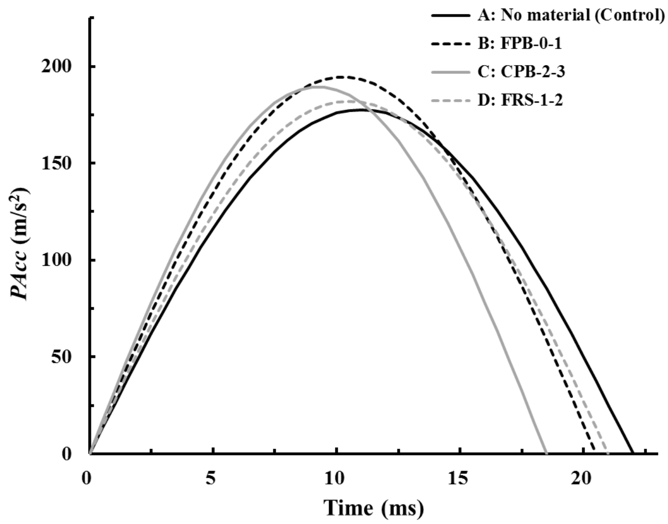

Fig. 3 Shock pulses at the 5th layer under the following conditions: no material (Control; A), FPB-0-1 (B), CPB-2-3 (C), and FRS-1-2 (D).

The data for "no material" were obtained from the previous report[1)].

The *Vc*s for A, B, C, and D are 2.46, 2.51, 2.21, and 2.40 m/s, respectively.

4.3 Estimation of *d* at each layer

The *d* values calculated according to the results in Tables 3 and 4, along with Equation (2), are indicated in Table 5. For each material, the *d* values at the 1st and 4th layers tended to be larger than those of the control because the *Vc* and/or *PAcc* values in those layers tended to be large compared with the control. Therefore, in most cases, it was estimated that the d_{Max} values at each layer were larger than the control. On the other hand, a decrease in the *d* values compared with the control was observed at the 2nd **and 3rd** layers in several conditions, corresponding to a decrease in the *Vc* and/or *PAcc* values compared with the control. Thus, it was estimated that the d_{Av} values were not changed by using the material, except in the FPB-3-4 and 4-5 conditions.

The trends in the *d* values at each layer in the FPB-0-1, CPB-2-3, and FRS-1-2 conditions are shown in Fig. 4. For the FPB-0-1 condition, the d_{Av} value was the same as that of the control. However, the d_{Max} value was smaller than that of the control because the *d* value at the 1st layer decreased compared with the control. For the CPB-2-3 and FRS-1-2 conditions, each d_{Max} value was larger than that of the control because the *d* values at the 1st layer increased compared with the control. However, in both conditions, the *d* values decreased compared with the control in the layers above the 2nd layer. Therefore, the d_{Av} values were the same as those of the control.

Table 5 The *d* values at each layer estimated by *Vc* and *PAcc* values, and Equation (2)

Cushioning material	Position of each material	Layer 1	2	3	4	5	Average (d_{Av})	Maximum (d_{Max})
No material (Control)[z]	-	0.05	0.04	0.04	0.03	0.04	0.04	0.05
FPB	0-1	0.04	0.04	0.03	0.04	0.04	0.04	0.04
	1-2	0.06	0.03	0.04	0.04	0.04	0.04	0.06
	2-3	0.06	0.03	0.03	0.04	0.04	0.04	0.06
	3-4	0.06	0.04	0.04	0.04	0.04	0.05	0.06
	4-5	0.06	0.04	0.04	0.04	0.04	0.05	0.06
CPB	0-1	0.05	0.04	0.04	0.04	0.04	0.04	0.05
	1-2	0.06	0.03	0.04	0.04	0.04	0.04	0.06
	2-3	0.06	0.03	0.03	0.03	0.04	0.04	0.06
	3-4	0.06	0.04	0.04	0.04	0.04	0.04	0.06
	4-5	0.06	0.03	0.04	0.04	0.03	0.04	0.06
FRS	0-1	0.05	0.04	0.04	0.04	0.04	0.04	0.05
	1-2	0.06	0.03	0.03	0.04	0.04	0.04	0.06
	2-3	0.07	0.04	0.04	0.04	0.04	0.04	0.07
	3-4	0.06	0.04	0.04	0.04	0.04	0.04	0.06
	4-5	0.07	0.04	0.04	0.04	0.04	0.04	0.07

[z]Each value was calculated by Equation (2). Therefore, all values are not the same as those shown in the previous report[1)].

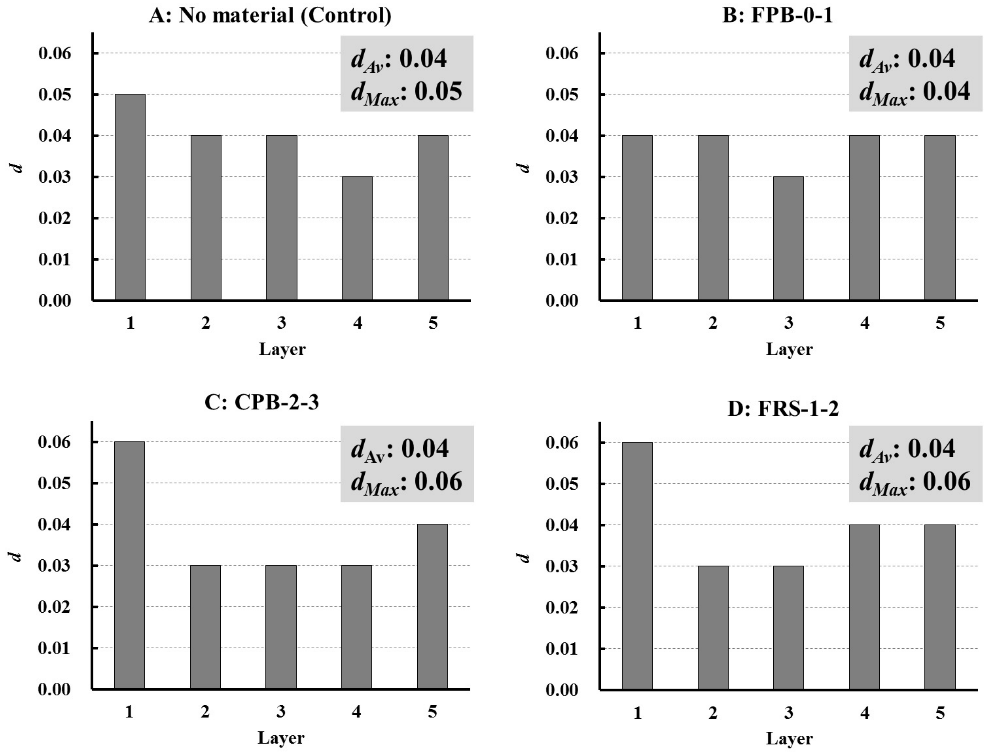

Fig. 4 Varying *d* by laying board- or sheet-like cushioning materials at each layer.

5. Conclusion

Our results indicate that the values of *Vc* and *PAcc* due to drop shock at each layer in stacked packaging can be controlled by laying board- or sheet-like cushioning materials between each layer or outside the bottom layer. Moreover, our results suggest that the layer with the maximum *d* (d_{Max}) could be changed variously using these materials, although the average *d* (d_{Av}) throughout the packaging was not so changed.

6. Future Prospects

We suggest applying the current results to strawberries damaged by cumulative fatigue. For strawberries, the difference in the firmness caused by the differences in the cultivar[6)] or harvested period[7)] links directly to the sensitivity to shock during transport. Thus, a non-destructive method to distinguish the firmness of strawberries has been developed[8)]. The application of the aforementioned non-destructive method has been limited to arranging the fruit depending on the destination[9)] because there was no mixed packaging system for fruits with different firmness.

On the other hand, our results will contribute to the development of a mixed packaging system for fruits with different fragilities, wherein the fruits can be placed at different layers depending on their firmness (Fig. 5). The control range of *d* can be widened by using board- or sheet-like cushioning materials, although it seems that the mixed packaging might be sufficient without these materials (Table 5). Our future research will focus on applying the present results in designing cushioning packaging for products that are damaged by cumulative fatigue.

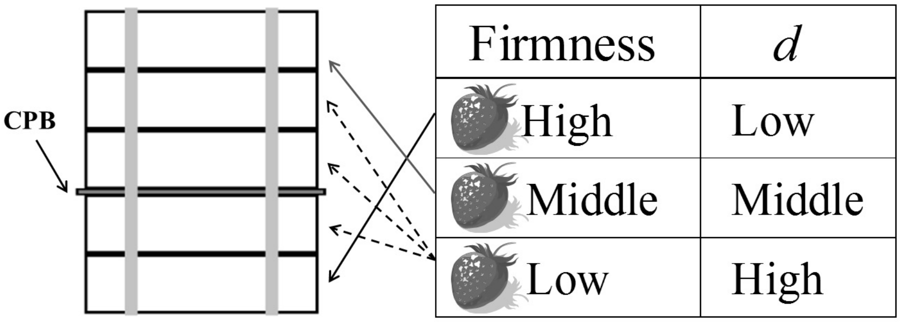

Fig. 5 Concept of mixed packaging style for products having different sensitivities to repetitive shock. Here, a corrugated plastic board is laid between the 2nd and 3rd layers of boxes (CPB-2-3; case C in Fig. 4).

Acknowledgements

A part of this study was supported by the Scheme to Revitalize Agriculture and Fisheries in Disaster Area through Deploying Highly Advanced Technology of the Ministry of Agriculture, Forestry and Fisheries of Japan. We thank Akira Michishita, an assistant manager at Shimadzu Corporation, for supporting the density evaluation of each material and Naoko Hasegawa of the technical staff at the National Food Research Institute for supporting the drop test.

References

1) Kitazawa, H. and Saito, K.: J. Pack. Sci. Tech., 23(4), 277–285. (2014).
2) Nakajima, T., Saito, K., Kubo, M. and Teragishi, Y.: J. Pack. Sci. Tech., 8(3), 123–134. (1999).
3) Nakajima, T., Saito, K., Kubo, M. and Teragishi, Y.: J. Pack. Sci. Tech., 9(1), 33–46. (2000).
4) Kitazawa, H., Saito, K. and Ishikawa, Y.: Pack. Tech. Sci. 27(3), 221–230. (2014).
5) Kitazawa, H., Ishikawa, Y., Lu, F., Hu, Y., Nakamura, N. and Shiina, T.: Hort. Res. (Japan), 9(2), 221–227. (2010).
6) Salentijn, E. M. J., Aharoni, A., Schaart, J. G. Boone, M. J. and Krens, F. A.: Physiol. Plant., 118(4), 571–578. (2003).
7) Kitazawa, H., Sato, T., Ishikawa, Y., Nakamura, N. and Shiina, T.: Food Preserv. Sci., 36(6), 265–269. (2010).
8) Kashiwazaki, M., Nagasuge, T., Soutome, H., Nakajima, M. and Omori, S.: J. Jpn. Soc. Agric. Mach., 71(6), 90–97. (2009).
9) Kashiwazaki, M., Nagasuge, T., Soutome, H., Nakajima, M. and Omori, S.: J. Jpn. Soc. Agric. Mach., 69(6), 49–56. (2007).

(Received **15** October 2014)
(Accepted 6 February 2015)

Method for Controlling Damage to Products Subjected to Cumulative Fatigue
Considering Damage Degree at Each Layer in Stacked Packaging

多段積み包装における段ごとの損傷度を考慮した蓄積疲労により損傷する物品の損傷制御方法の提案

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多段積みされた包装において、段ごとの衝撃 1 回あたりの損傷度（*d*）を考慮することによって、物品の損傷を制御するための方法を提案するために、本研究では多段積み包装における各包装容器と包装容器の間もしくは包装全体の最底面への板またはシート状の緩衝材の配置が、段ごとの速度変化（*Vc*）、ピーク加速度（*PAcc*）および *d* に及ぼす影響を評価した。落下試験の結果より、板またはシート状の緩衝材を用いることにより、各段における *Vc* と *PAcc* を様々に変化させることができることが明らかとなった。また、これらの変化に伴い、各段における *d* がどのように変化するのかを重回帰分析を用いて推定したところ、包装全体における *d* の平均値（d_{AV}）は、殆ど変化しないものの、*d* が最大（d_{Max}）となる段が様々に変化する可能性が示唆された。これらの結果は、異なる易損性を持つ、蓄積疲労により損傷する物品を混載することを可能とする包装設計の実現に貢献するものと期待された。

キーワード：蓄積疲労、重回帰分析、ピーク加速度、繰り返し衝撃、速度変化