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Effects of Sinusoidal Vibration Fatigue on Compression Strength of Corrugated Fiberboard Container for Packaging of Fruits

Hyun Mo Jung†, Jong Kyoung Kim[1], and Man Soo Kim[2]

Division of Packaging·Design, Kyongbuk Science University
[1]School of Packaging, Michigan State University
[2]Department of Biosystem Machinery Engineering, Chungnam National University

Abstract The compression strength of corrugated fiberboard containers for packaging the agricultural products rapidly decreases because of various environmental conditions during distribution of unitized products. Among various environmental conditions, the main factors affecting the compression strength of corrugated fiberboard are absorption of moisture, long-term accumulative load, and fatigue caused by shock and vibration. An estimated rate of damage for fruit during distribution is about 30~40% owing to the shock and vibration. This study was carried out to characterize the durability of corrugated fiberboard containers for packaging the fruits and vegetables under simulated transportation environment. After the packaging freight was vibrated at various experimental conditions, the compression test for the packaging was performed. The compression strength of corrugated fiberboard containers decreased with loading weight and vibration time. The multiple nonlinear regression equation ($R^2 = 0.9198$) for predicting the decreasing rate of compression strength of corrugated fiberboard containers were developed using four independent variables such as input acceleration level, input frequency, loading weight and vibration time.

Keywords Compression strength, Corrugated fiberboard, Shock, Vibration fatigue

Introduction

Damage in agricultural products is mostly caused by breakage of outside packaging container. Since the compression strength of agricultural packaging is important, it is standardized by KS (Korean industrial standard) and other regulations, such as ASTM and ISO. Compression strength of corrugated fiberboard containers is determined by the quality and constitution of corrugating mediums and linerboards as well as outside dimension rate of the containers. Hence, the compression strength of container is generally managed by ring crush and edgewise compression strength (ECS) of the stencil paper.

The compression strength of corrugated fiberboard containers is excessively decreased by many factors while going through the distributional process after production. The most important among those factors are double-layered water absorption, long-term accumulative load, and fatigue caused by shock and vibration during transportation. The strength of corrugated fiberboard containers used is very important for companies to maintain a good image. With the opening of the international agricultural market, the use of corrugated fiberboard containers is expected to see a continuous increase. Therefore, it is necessary to conduct various kinds of research aimed to improve the durability and compression strength of corrugated fiberboards. It is worth mentioning that the rate of mechanical damage to fruit during post-harvest handling is estimated at 30~40%.

Rouillard and Sek[1)] did sinusoidal sweep vibration test using hydraulic servo actuator to measure resonance frequency of corrugated fiberboard containers. As a result, there was resonance occurred at about 14.5 Hz, and they reported the breakage of corrugated fiberboard containers after about 20 minutes by doing sinusoidal dwell test of 0.7 G acceleration level for resonance frequency. To acquired basic materials about vibration during distribution and pallet designing of packaging, Timothy and Marshall[2)] did a sinusoidal sweep vibration test on pallet packaging in 3~50 Hz frequency. The result reported that forms and load weight of pallet affect the resonance frequency.

McKee et al.[3)] reported that about 64% of load is supported in the 4 perpendicular corners of the container, and the remaining 36% is supported by the side panel of the box. So, perpendicular compression strength and bending stiffness are the main factors to determine compression strength. Gartaganis[4)], Koning[5)] and Leake[6)] reported that ECS method could cal-

†Corresponding Author : Hyun Mo Jung
Division of Packaging·Design, Kyongbuk Science University, 159, Bongsan-ri, Kisan-myeon, Chilgok-gun, Gyeongbuk, 718-851 Korea
E-mail : <hmjung@kbcs.ac.kr>

culate compression strength of containers from compression strength of corrugated fiberboard sample, without much influence by dimensions of container.

In Korea, several kinds of ongoing research are being conducted with the objective of improving the quality of corrugated fiberboards. Most of these studies focus on change in compression strength by many factors like temperature, humidity, and dimensions of the containers. Some of the recent studies are on optimization of compression strength by mechanical methods like finite-element analysis[7]. However, there is almost no existing research study on compression strength by vibration during distribution process. Hence, we proposed to consider the durability of corrugated fiberboard containers for fruits by vibration time, loading weight, and input frequency about acceleration levels during transportation.

Materials and Methods

In this experiment, we selected the corrugated fiberboard containers made with stencil paper that is commonly used in Korean fruit packaging. We aimed to analyze compression strength by vibration fatigue as in Table 1. The dimensions of the corrugated fiberboard containers were similar to those used for pear packaging. The packaging unit was 15 kg_f as specified by the agricultural production standard applied in Korea. We used the containers after maintaining it equilibrium in a large thermo-hygrostat for more than 48 hours with a temperature of 23 ± 1^oC and relative humidity of 50% according to ASTM D685[8].

In order to analyze compression strength of corrugated fiberboard containers by vibration with transportation time in Korea, loading weight, and input frequency, we put the experimental container on the vibration table, and slided the load panel with certain weight in the larger container, so as to apply perpendicular load on the experimental container as a form of dead load as shown in Fig. 1. With this condition, we did a compression test after applying vibration for a certain time with three frequency types of 20, 45, and 70 Hz in three acceleration levels of 0.25, 0.5, 1 G_{rms}, which is the acceleration level of the truck itself on the pavement. We fixed the experiment container and loading container so that they would not to be separated during the vibration test. The compression test had a loading rate of 12.7 mm/min with ASTM D642[9]. We repeated vibration and compression tests five times over, and the measuring result was represented as remaining average value except for the maximum and minimum value.

In this research, we used hydraulic vibration actuator (Engineering-Korea HVT-2, 700 kg_f, 300 Hz) as in Fig. 2 (a) to make vibration experiment with stable acceleration level. Fig. 2 (b) represents compression experiment on the same sample container using compression tester (DAEYOUNG, 5 ton) after vibration test.

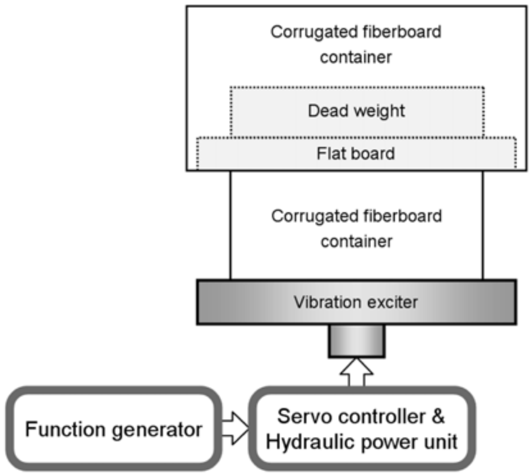

Fig. 1. Schematic diagram of the vibration test system.

Results and Discussions

1. Relationship between compression strength and vibration fatigue of corrugated fiberboard containers

In order to analyze change in compression strength of corrugated fiberboard containers with respect to loading weight, vibration frequency, and vibration time, we did the vibration and compression tests. Fig. 3 represents force-displacement curve of corrugated fiberboard container before the vibration test. Compression strength was the maximum in force-displacement curve. Table 2 represents the decreasing rate of compression strength of the corrugated fiberboard containers by loading weight, vibration frequency, vibration time, and

(a) Vibration test (b) Compression test

Fig. 2. Vibration and compression test apparatus for corrugated fiberboard containers.

Table 1. Type and physical properties of corrugated fiberboard container tested

Type	Flute	Symbol	Paper combination	Dimension (L × W × D, mm)
RSC (0201)	AB/F	DW	$KA^{180}/K^{180}/K^{180}/K^{180}/K^{180}$	550 × 366 × 280

*DW denotes double wall corrugated fiberboard

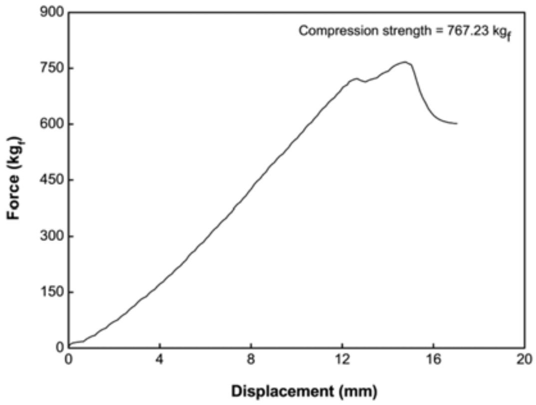

Fig. 3. Force-displacement curve of corrugated fiberboard container.

acceleration level based on compression strength without any application of vibration. As shown in Table 2, compression strength decreased by loading weight and vibration time; and change in compression strength by input frequency was shown by a low frequency range with severe vibration displacement.

With higher input acceleration level, the decreasing rate in compression strength was higher. This implies that compression strength decrease in long-term distribution is directly related to the damage of packaged fruits due to breakage of corrugated fiberboard containers. This is because large vibration displacement occurs when frequency range is low and because acceleration level is high during transportation.

2. Modeling of decreasing rate of compression strength by vibration fatigue during transportation

In order to predict the decreasing rate of compression strength of corrugated fiberboard containers during transportation, we developed multiple nonlinear regression models with independent variables of input frequency, vibration time, and loading weight by input acceleration level.

As demonstrated in Table 3, each coefficient of multiple determination of multiple regression model developed by acceleration level was shown as 0.9475, 0.9707, and 0.9479. Analysis of variance of these values represented the high significance in every model. Also, in the correlation analysis of input frequencies, loading weight, vibration time and decreasing rate of compression strength of containers, loading weight (0.6837) had higher correlation than vibration time (0.4924) in case of acceleration level of 0.25 G_{rms}. Input frequency (−0.4243) had lower correlation at the low acceleration level.

At an acceleration level of 0.5 G_{rms}, loading weight (0.5831) as compared to the vibration time (0.4481), and input frequency (−0.5130) as compared to vibration time had high correlation with decreasing rate of compression strength. At an acceleration level of 1 G_{rms}, loading weight (0.6141) as compared to vibration time (0.4283), and input frequency (−0.4714) as compared to vibration time had higher correlation with decreasing rate of compression strength. As shown in the

Table 3. Coefficients of multiple nonlinear regression model for the decreasing rate of compression strength in acceleration level

Variables	$DR = exp(a \times F + b \times T + c \times W + d)$		
	0.25 G_{rms}	0.50 G_{rms}	1.00 G_{rms}
a	−0.01431	−0.02237	−0.01948
b	0.00893	0.00981	0.00859
c	0.01889	0.01981	0.01996
d	−0.37142	0.36299	0.61716
R^2	0.9475	0.9707	0.9479

*DR denotes decreasing rate , F denotes input frequency, T denotes vibration time and W denotes loading weight.

Table 2. Decreasing rate (%) of compression strength of corrugated fiberboard containers by vibration fatigue

Input frequency (Hz)	Vibration time (min)	Acceleration level (G_{rms})											
		0.25				0.50				1.00			
		Loading weight (kg_f)											
		10	30	50	70	10	30	50	70	10	30	50	70
20	30	0.28	1.16	2.38	2.48	0.75	1.75	3.25	5.25	0.98	2.66	4.19	6.87
	60	0.82	1.45	2.46	3.31	1.25	2.50	4.75	7.00	1.93	3.48	5.84	8.45
	90	1.34	2.16	3.18	4.62	2.25	4.25	6.00	9.00	3.14	4.79	7.23	11.78
	120	2.01	2.58	4.60	5.35	3.75	5.75	8.50	12.00	4.25	6.58	9.35	15.45
45	30	0.19	0.62	1.04	1.68	0.41	1.23	1.76	2.45	0.62	1.62	2.58	3.76
	60	0.42	0.96	1.58	2.01	0.92	1.48	2.76	3.42	1.57	2.49	3.46	4.45
	90	0.93	1.42	1.94	2.65	1.45	2.28	3.19	4.82	2.45	3.31	3.98	5.74
	120	1.32	1.63	2.48	3.51	2.23	3.10	4.28	5.56	3.18	3.85	4.86	6.76
70	30	0.16	0.36	0.89	1.59	0.32	0.84	1.54	2.38	0.46	1.25	2.29	3.47
	60	0.29	0.74	1.45	1.98	0.76	1.27	1.96	2.58	1.21	2.14	3.16	3.87
	90	0.62	1.22	1.62	2.45	1.19	1.83	2.40	2.92	1.87	2.85	3.42	4.65
	120	1.12	1.40	1.98	2.97	1.86	2.29	2.71	3.92	2.69	3.17	3.97	4.98

*Values were averaged

results, within the same condition, decreasing rate of compression strength was larger in lower frequency than higher frequency. Also, when input acceleration was high, decreasing rate of compression strength was also high.

We set input acceleration level (*AL*), input frequency (*F*), loading weight (*W*), and vibration time (*T*) as independent variables and developed multiple nonlinear regression models with decreasing rate of compression strength of corrugated fiberboard containers as dependent variable. As shown by the results in Table 4, coefficient of multiple determinations was 0.9198 in a model with four independent variables - a little lower in value than the model with three independent variables. However, this model indicated the highest significance, as seen in the analysis of variance in the model shown in Table 5. Considering domestic distribution time, in the correlation analysis of four different individual variables and compression strength decreasing rate of corrugated fiberboard container, loading weight (0.5366) was the highest followed by input frequency (−0.4172), vibration time (0.3903), and input acceleration level. The reason for the small correlation coefficient of input acceleration is a small difference between acceleration levels. When we expanded the range of acceleration level, input acceleration and correlation coefficient were also larger. When vibration time was long enough, correlation between the decreasing rate of compression strength and vibration time was the strongest.

On correlation analysis, loading weight was determined to have the most influence on decrease in compression strength of corrugated fiberboard containers. Therefore, when outside packaging containers of lower level packaged freight during transportation of pallet materials get vibration fatigue, there is an excessive decrease in compression strength. Breakage of the containers affect the stability of pallet packaged freight and also cause damage to packaged products. By applying this result, we can estimate the optimum level of loading for agricultural packaging during distribution and minimize damage of agricultural products by optimum package designing.

Table 4. Coefficients of multiple nonlinear regression model for decreasing rate of compression strength by vibration fatigue.

Variables	$DR = exp(a \times AL + b \times F + c \times T + d \times W + e)$				R^2
	Coefficients	Standard error	t-ratio	Prob(t)	
a	0.87830	0.05023	17.48518	0.0	0.9198
b	−0.01961	0.00093	−21.09857	0.0	
c	0.00898	0.00051	17.56705	0.0	
d	0.01975	0.00086	22.88112	0.0	
e	−0.25463	0.08490	−2.99915	0.00321	

*AL denotes input acceleration level.

Table 5. Analysis of variance of multiple nonlinear regression model for decreasing rate of compression strength by vibration fatigue.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob (F)
Regression	4	766.8787021	191.7196755	398.5315**	0.00
Error	139	66.8680729	0.481065273		
Total	143	833.746775			

Conclusions

We also did a vibration and compression experiment about corrugated fiberboard containers to analyze the decreasing rate of compression strength of packaging containers by vibration time, loading weight, and input frequency about acceleration level occurred during transportation. The decreasing rate of compression strength of corrugated fiberboard containers was larger in lower frequency than higher frequency and when input acceleration was high, the decreasing rate of them was also high with same conditions, and loading weight was determined to have the most influence on decrease in compression strength of corrugated fiberboard containers on correlation analysis, and a multiple nonlinear regression models ($R^2 = 0.9198$) of compression strength decrease of corrugated fiberboard containers for packaging of fruits by vibration fatigue was developed with independent variables of input acceleration (*AL*), input frequency (*F*), loading weight (*W*), and vibration time (*T*).

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