

Original Paper ~~~~~

Modified Equivalent Drop Test for Structural Corrugated Fiberboard Cushioning

Chen ZHONG* and Katsuhiko SAITO**

Previous studies have shown limitations of the conventional equivalent drop theory, and therefore, a friction equivalent drop theory was proposed. We prove that applying the friction equivalent drop theory to structural cushioning materials (SCM) using a corrugated sleeve as a test material can correct errors of equivalent tests. However, a full proof of this conjecture remains to be obtained. Therefore, further investigation is performed to obtain a robust conclusion for this new theory. In this study, we first consider the influence of stress. Shock and dynamic compression tests are carried out using different weight dummies. New data collection and data analysis methods are also proposed. The experimental results showed that there is a correction effect when we apply the friction equivalent drop theory to the corrugated sleeve. Finally, we evaluated quantitatively the correction effects.

Keywords : packaging, transport, cushioning, corrugated fiberboard, equivalent drop

1. Introduction

Dynamic compression and shock tests are two important test methods used to evaluate the cushioning performance of transport packaging. Theoretically, if the cushion is assumed to follow a linear mass–spring model, then the dynamic compression and shock tests yield the same results for equal free fall heights (Fig. 1(a))^{1), 2)}. This result is known as the ‘conventional equivalent drop theory’ (conventional theory). Saito *et al.*^{3), 4)} proved that the conventional theory has limitations that cause experimental errors, and thus, they developed a damping equivalent drop theory (damping theory) by introducing a viscous damping model (Fig. 1(b)).

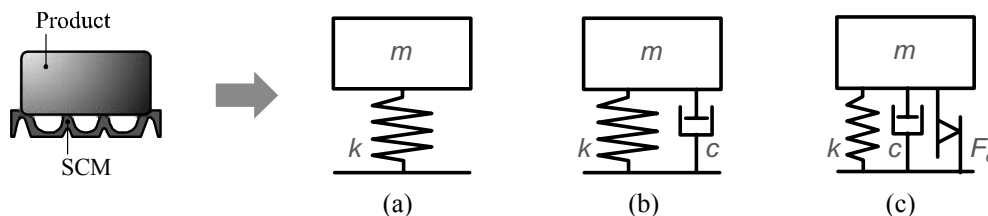


Fig. 1. Three models. (a) Linear model, (b) Viscous damping model, (c) Friction model

* Ph.D. Candidate. Graduate School of Maritime Sciences, Kobe University, Fukaeminami, Higashinada, Kobe 658-0022, Japan

** Corresponding Author, Professor. Transport Packaging Laboratory, Kobe University, 5-1-1, Fukaeminami, Higashinada, Kobe 658-0022, Japan

E-mail: ksaito@maritime.kobe-u.ac.jp, Tel: +81-78-431-6341

Earlier studies by Zhong *et al.*^{5), 6)} have shown that applying the damping theory using a quasi-linear cushion can improve the equivalent precision of tests. However, this theory is not applicable to SCM⁷⁾. Therefore, Zhong *et al.*^{8), 9)} proposed a friction model (Fig. 1(c)) and developed a ‘friction equivalent drop theory’ (friction theory). Under the friction theory, $A_{ff\max}$ and $A_{cs\max}$ (the peak response accelerations of the dynamic compression and shock tests, respectively) are expressed by **Eqs. (1) and (2)**, and a correction condition is given by **Eq. (3)**:

$$A_{ff\max} = u_{ff} \cdot \omega_n \cdot V + \mu_{ff} \cdot \omega_n \cdot V_F, \quad (1)$$

$$A_{cs\max} = u_{cs} \cdot \omega_n \cdot V_c, \quad (2)$$

$$V_{\text{new}} = \frac{u_{cs}}{u_{ff}} V_c - \frac{\mu_{ff}}{u_{ff}} V_F, \quad (3)$$

where ω_n is the natural angular frequency, u_{ff} , u_{cs} and μ_{ff} are correcting coefficients, V is the impact velocity of the mass, V_c is the velocity change on the shock table, V_F is the velocity related to friction and V_{new} is the corrected impact velocity.

Zhong *et al.*¹⁰⁾ proved that the application of the friction theory using a corrugated sleeve as a test material could solve the aforementioned issue. However, this conclusion was based on only one material (corrugated fiberboard) and one design configuration (a corrugated sleeve with the same equivalent free-fall height and weight dummy). Therefore, to obtain a robust conclusion, it is necessary to consider other factors such as stress, test material and free fall height. The influence of these three factors can be investigated by varying the weight dummy, using pulp mould as the test material and changing the free fall height of the mass. In this study, we address the influence of stress.

2. Materials and Tests

2.1 Test equipment and materials

■ Test equipment:

To perform the shock and dynamic compression tests, we used a shock machine (Yoshida Seiki Co., Ltd.. JAPAN) and a dynamic compression tester (Yoshida Seiki Co., Ltd.. JAPAN), respectively. An acceleration analysis instrument, termed the ‘Shock Manager’ (Yoshida Seiki Co., Ltd.. JAPAN), was used to measure the response accelerations of the two tests.

■ Corrugated sleeve:

A corrugated sleeve, created by folding by a corrugated fiberboard (‘A’ flute, LB210/MC120/LB 210), was used as test material (Fig. 2). Based on previous studies⁸⁾⁻¹⁰⁾ and considering the technical specifications of the test equipment^{11), 12)}, its dimension was determined to be 180×180×80 mm.

■ Weight dummy:

Based on the research of NAKAGAWA¹³⁾, we used nine weight dummies ranging between 4 kg and 12 kg, in one kilogram increments. The length and width of the nine weight dummies were held constant (220×220 mm), but their thicknesses were different (Fig. 3).

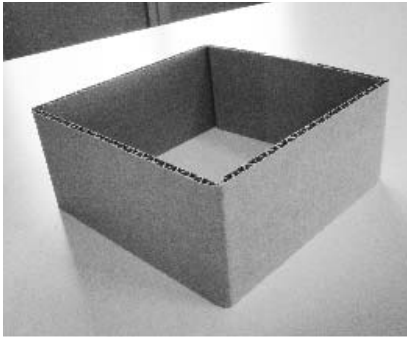


Fig. 2. Corrugated sleeve

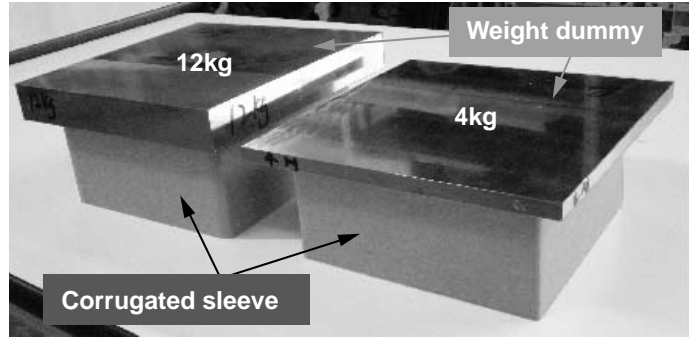


Fig. 3. Weight dummies with corrugated sleeves

2.2 Test method

■ Test flow:

The flow of the test was as follows:

1. Perform tests (using weight dummies in the range of 4–12 kg)
 - 1-1. Shock test
 - 1-2. Dynamic compression test (based on the conventional theory)
 - 1-3. Correction of V (based on the data obtained in steps 1-1 and 1-2)
 - 1-4. Dynamic compression test (based on V_{new} obtained in step 1-3)
2. Process and analyse experimental data
3. Assess test results

■ Data collection:

To compare the influence of stress, the free fall height H was set to 0.6 m and was held constant⁷⁾. The equation $V_{th} = \sqrt{2gH}$ was used to obtain the theoretical impact velocity of the mass $V_{th} = 3.43$ m/s. According to the conventional theory, $V_c = V_{th}$, which implies that $V_c = 3.43$ m/s.

In earlier studies^{5), 6), 8)-10)}, the data were adopted only when V or $V_c = 3.43$ m/s for both tests. However, when the tests were carried out, a large number of data was measured with V or $V_c \neq 3.43$ m/s. Therefore, in this study, to improve the accuracy of the test results, we used statistics to take full advantage of these data. Here, the effective impact velocity V and the effective velocity change V_c were redefined in the range of 3.43 ± 0.1 m/s.

According to the statistical theory, to ensure the reliability of the results, a test population must be larger than 30 samples¹⁴⁾. Therefore, in steps 1-1, 1-2 and 1-4, we collected 40 sets of data for each test.

■ Test method:

Using weight dummies in the range of 4–12 kg, we performed the shock and dynamic compression tests. For each weight dummy, the test method applied was as follows:

First, we performed the shock test and recorded V_c and A_{csmax} . Second, based on the conventional theory and using the impact pulse of the shock test in step 1-1, we carried out the dynamic compression test and recorded V and A_{Fmax} . Third, similar to previous studies^{9), 10)}, we corrected V using the data recorded in steps 1-1 and 1-2. In certain cases, the resulting V_{new} was out of the range of 3.43 ± 0.1 m/s. Fourth, if V_{new} was not within the range 3.43 ± 0.1 m/s, the dynamic compression test was re-performed to measure the new peak response acceleration corresponding to the V_{new} .

2.3 Friction

The hysteresis loop of the friction model shown in Fig. 4 is based on a previous study⁹⁾. The area enclosed by the hysteresis loop is called the loss energy. The loss energy E_n is expressed as

$$E_n = \pi c \omega_n A^2 + 4F_c A, \quad (4)$$

where c is the damping coefficient, F_c is the friction, and A is the displacement.

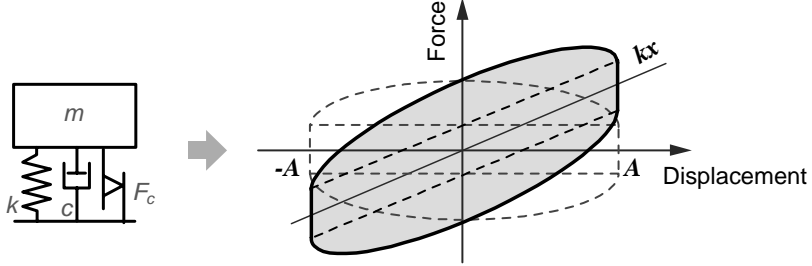


Fig. 4. Hysteresis loop of the friction model

By rearranging Eq. (4), we obtain

$$F_c = \frac{1}{4} \frac{E_n}{A} - \frac{\pi}{4} c \omega_n A. \quad (5)$$

Furthermore, by substituting $\omega_n = \sqrt{k/m}$ and $c = 2\sqrt{km}$ in Eq. (5), we obtain

$$F_c = \frac{1}{4} \frac{E_n}{A} - \frac{\pi}{2} k A, \quad (6)$$

where k is the spring constant.

According to literature^{15), 16)}, the hysteresis loops of the friction model are the complete nested hysteresis loops (Fig. 5). Thus, the term E_n/A in Eq. (6) is constant. Furthermore, because k is constant, from Eq. (6) we predict that if the increase in the weight dummy causes a large change in A , then F_c will decrease.

From the experimental data of the dynamic compression test obtained using weight dummies in the range of 4–12 kg, we can draw the hysteresis loops of the corrugated sleeve. Fig. 6 shows the hysteresis loops when using 4 kg, 8 kg and 12 kg weight dummies. Based on this figure we can make two observations. (1) The upper parts of the hysteresis loops are almost identical. The ratio E_n/A is almost the same for all dummy weights from 4 kg to 12 kg and is approximately equal to 2000 N. (2) The displacement values for the weight dummies are $A_{4\text{kg}} \approx 7$ mm, $A_{8\text{kg}} \approx 16$ mm and $A_{12\text{kg}} \approx 23$ mm. Hence, by increasing the weight dummies, parameter A also increases.

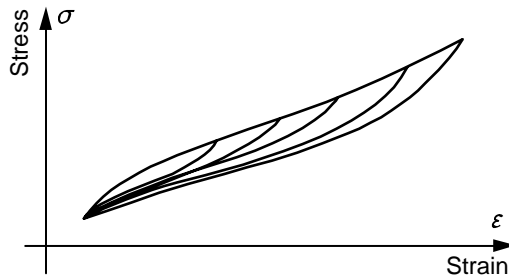


Fig. 5. Complete nested hysteresis loops^{15), 16)}

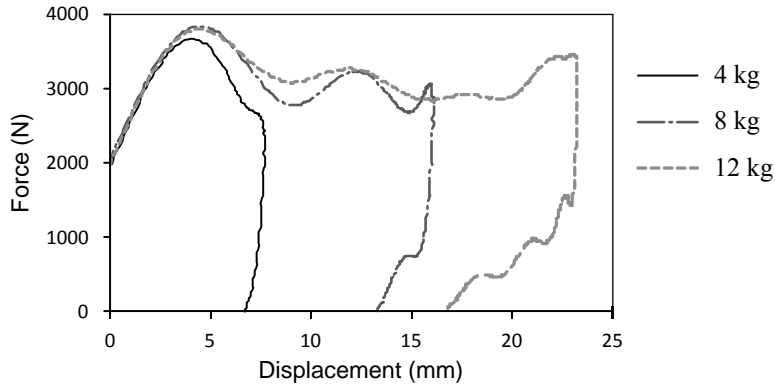


Fig. 6. Hysteresis loops of the corrugated sleeve for 4 kg, 8 kg and 12 kg weight dummies

3 Difference in Peak Response Accelerations of the Two Tests

■ Definition of difference in the peak response accelerations of the two tests

Difference in the peak response accelerations of the two tests (dGs) is an important indicator for our study. According to dGs, we can know the correction effect of the friction theory roughly. dGs is expressed as

$$dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V). \tag{7}$$

■ Calculation of dGs

There are two types of $A_{ff\ max}(V)$ corresponding to before and after the correction of V : $A_{ff\ max}(V_{old})$ and $A_{ff\ max}(V_{new})$, respectively. Therefore, **Eq. (7)** has two cases: $dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V_{old})$ and $dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V_{new})$.

An example of calculating $dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V_{old})$ is presented in Table 1. The experimental data is too large to show completely in the example, thus, only a part of data is shown in Table 1. First, the test results of both tests are listed in order of V_c or V . Second, values of $A_{cs\ max}(V_c)$ and $A_{ff\ max}(V_{old})$ corresponding to the same value of V_c or V are grouped together (blocks with same colour). Third, we calculate dGs by the formula $A_{cs\ max}(V_c) - A_{ff\ max}(V_{old})$ using all the data in each group.

Table 1. Example of calculating $dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V_{old})$. Weight dummy: 6 kg

Shock Test		Dynamic Compression Test (Conventional theory)		dGs	
V_c (m/s)	$A_{cs\ max}(V_c)$ (G)	V_{old} (m/s)	$A_{ff\ max}(V_{old})$ (G)	Velocity (m/s)	$A_{cs\ max}(V_c) - A_{ff\ max}(V_{old})$ (G)
3.36	62.3	3.36	53.7	3.36	8.6
3.36	60.4	3.36	55.6	3.36	6.7
3.37	60.4	3.37	54.5	3.36	6.7
3.37	58.5	3.38	57.0	3.36	4.8
3.38	61.2	3.38	55.2	3.37	5.9
3.39	64.2	3.39	57.3	3.37	4.0
3.39	60.4	3.39	55.8	3.38	4.2
3.40	61.8	3.40	59.3	3.38	6.0
3.40	63.5	3.40	57.7	3.39	6.9
3.40	56.8	3.40	54.0	3.39	8.4

An example of calculating $dGs = A_{cs\ max}(V_c) - A_{ff\ max}(V_{new})$ is presented in Table 2 (portion of data). First, based on the friction theory¹⁰⁾, we calculate V_{new} using the data of the shock test (block

①). Second, the old test results (the results when V_{new} is within the range 3.43 ± 0.1 m/s) and the new test results (the results when V_{new} is outside the range 3.43 ± 0.1 m/s) of the dynamic compression test are listed in block ②. Third, $A_{cs\max}(V_c)$ corresponding to a special V_{new} and $A_{ff\max}(V_{new})$ when V equals to this special V_{new} are grouped together (blocks with the same colour) and are taken for permutation and combination (block ③). Finally, we calculate dGs by the formula $A_{cs\max}(V_c) - A_{ff\max}(V_{new})$ using all the data in a group (block ④).

Table 2. Example of calculating dGs = $A_{cs\max}(V_c) - A_{ff\max}(V_{new})$. Weight dummy: 6 kg

①		②		③			④	
Shock Test	Corrected Impact Velocity	Dynamic Compression Test (Friction theory)		Data Arrangement			dGs	
$A_{cs\max}(V_c)$ (G)	V_{new} (m/s)	V_{new} (m/s)	$A_{ff\max}(V_{new})$ (G)	$A_{cs\max}(V_c)$ (G)	V_{new} (m/s)	$A_{ff\max}(V_{new})$ (G)	Velocity (m/s)	$A_{cs\max}(V_c) - A_{ff\max}(V_{new})$ (G)
60.4	3.49	3.48	56.5	60.4	3.49	58.5	3.49	1.9
60.4	3.51	3.49	58.5	60.4	3.51	60.7	3.51	-0.3
64.2	3.51	3.49	62.8	64.2	3.49	62.8	3.49	0.9
62.5	3.43	3.47	59.5	60.4	3.51	60.7	3.51	-0.3
61.8	3.48	3.49	59.5	64.2	3.49	62.8	3.51	-2.4
62.4	3.43	3.43	57.2	61.8	3.48	56.5	3.51	3.5
63.1	3.52	3.55	59.3	62.5	3.43	57.2	3.51	1.4
60.3	Data of $A_{ff\max}(V_{old})$ when $V=3.43$ m/s			62.4		58.0	3.48	5.3
63.5						55.4	3.43	5.3

4 Test Results

4.1 Probability distribution of dGs

Using the statistical theory¹⁴⁾, if the friction theory can be applicable to SCM when stress varies, the probability distribution of dGs after the correction should get even closer to 0.

Based on the experimental data, the probability distribution of dGs is shown in Fig. 7. Averages and standard deviations of dGs among weight dummies are also shown in right bottom of Fig. 7. By comparing the nine bar charts, the following conclusions are drawn. (1) When a light weight dummy is used, dGs is large before and after the correction. (2) dGs reduces gradually with respect to the increase in the weight dummy. (3) dGs with the highest probability after the correction is closer to 0 than before the correction. This behaviour is more prominent as the weight dummy becomes heavier. By comparing the data of deviations, we can know that both averages and standard deviations of dGs scatter between 0.78 and 3.18. Although averages and standard deviations of dGs when using 5, 9, 11 and 12 weight dummies are smaller than before the correction, these when using 4, 6, 7, 8 and 10 weight dummies are larger than before the correction. Therefore, it can be said that the friction theory has a little effect to deviation. Additionally, it must be pointed out that numbers of the bar for aggregating data are not the same among weight dummies due to the varied deviations under different weight dummies.

Based on the bar charts of the probability distribution of dGs, we can qualitatively conclude that the friction theory is applicable to SCM under different stresses. However, we cannot derive a specific value for the correction effect of the friction theory. In other words, we cannot evaluate quantitatively the effects of the friction theory only based on the bar charts. Therefore, in this study, we investigate a new evaluation method.

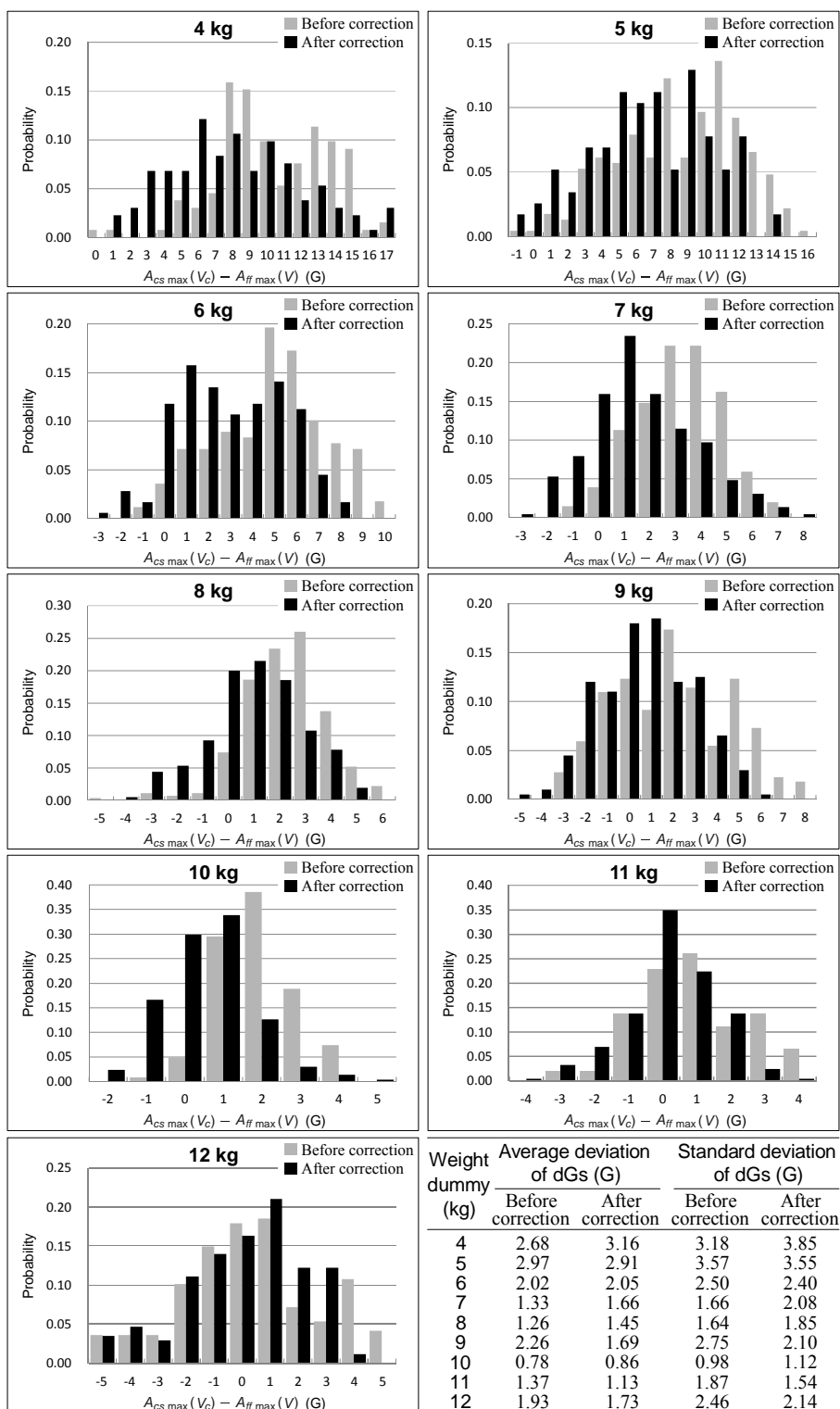


Fig. 7. Probability distribution, average deviation and standard deviation of dGs among weight dummies

4.2 Evaluation of correction effect

■ Data normalization:

Figure 8 shows examples of response accelerations of the shock and dynamic compression tests using 5 kg and 12 kg weight dummies. It can be seen that the peak response accelerations of the same test under different stresses considerably differ. In other words, the comparison basis of evaluating the correction effect varies. Therefore, the test results cannot be directly compared. To remove the influence of the different comparison basis, we need to perform data normalization.

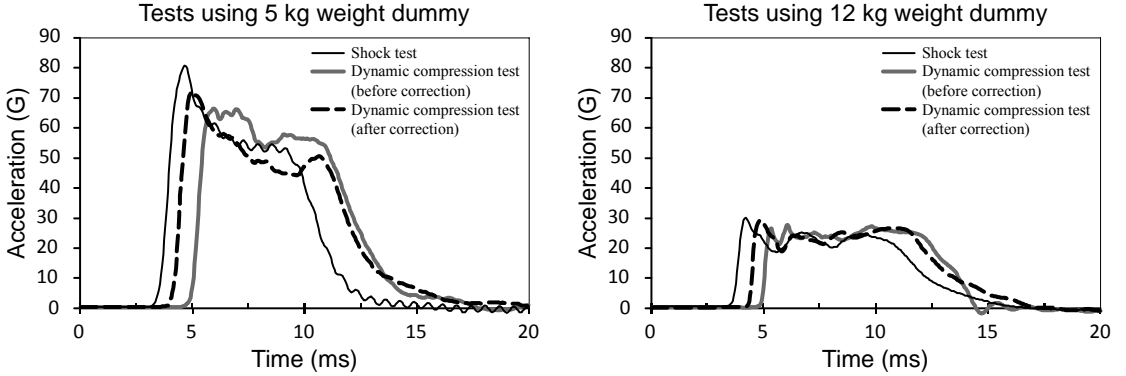


Fig. 8. Response accelerations of the two tests using 5 kg and 12 kg weight dummies

To perform data normalization, we first need to determine the true value of the peak response acceleration. We measure two types of peak response accelerations, $A_{cs\max}(V_c)$ and $A_{ff\max}(V)$, and need to determine which of these types represent the true value of the peak response acceleration. According to the aforementioned test method, we know that when $H=0.6$ m, $V_{th}=3.43$ m/s. Therefore, the peak response acceleration of the dynamic compression test when $V=3.43$ m/s, $A_{ff\max}(V=3.43)$ must represent the true value. Actually, several $A_{ff\max}(V=3.43)$ measurements were obtained during the dynamic compression test. Therefore, for data normalization, the average value of $A_{ff\max}(V=3.43)$ must be calculated.

According to the analysis above, the data normalization equation Γ is defined as follows:

$$\Gamma = \frac{\sum_n (A_{cs\max}(V_c) - A_{ff\max}(V))}{A_{ff\max}(V=3.43)}. \quad (8)$$

Considering two types of $A_{ff\max}(V)$, **Eq. (8)** is broken up into two equations, as shown in **Eqs. (9)** and **(10)**:

$$\Gamma_{\text{before}} = \frac{\sum_n (A_{cs\max}(V_c) - A_{ff\max}(V_{\text{old}}))}{A_{ff\max}(V=3.43)}, \quad (9)$$

$$\Gamma_{\text{after}} = \frac{\sum_n (A_{cs\max}(V_c) - A_{ff\max}(V_{\text{new}}))}{A_{ff\max}(V=3.43)}. \quad (10)$$

Here, $A_{cs\max}(V_c)$ is the peak response acceleration of the shock test when V_c is equal to a specific value (for example, $V_c=3.45$ m/s). Furthermore, $A_{ff\max}(V_{\text{old}})$ is the peak response acceleration of

the dynamic compression test based on the conventional theory when V is equal to the aforementioned V_c (i.e. $V = 3.45$ m/s). Similarly, $A_{ff_{max}}(V_{new})$ is the peak response acceleration of the dynamic compression test based on the friction theory when $V = V_{new}$ (V_{new} is calculated when $V_c = 3.45$ m/s based on the friction theory, using the data obtained from the shock test).

■ Correction indicator

Only considering the peak response acceleration of each test, Fig. 8 can be generalised to Fig. 9(a). After data normalization, Fig. 9(a) changes to Fig. 9(b). Using parameter Γ we can compare the correction effect under different stresses. However, we cannot use $\Gamma_{before} \square \Gamma_{after}$ to evaluate the correction effect, because according to Fig. 9(b), the error levels under different weight dummies differ widely.

We address this issue by proposing a new correction indicator Δ , defined as

$$\Delta = \frac{\Gamma_{before} - \Gamma_{after}}{\Gamma_{before}} \times 100 \% \tag{11}$$

By using the correction indicator Δ , Fig. 9(b) is changed to Fig. 9(c).

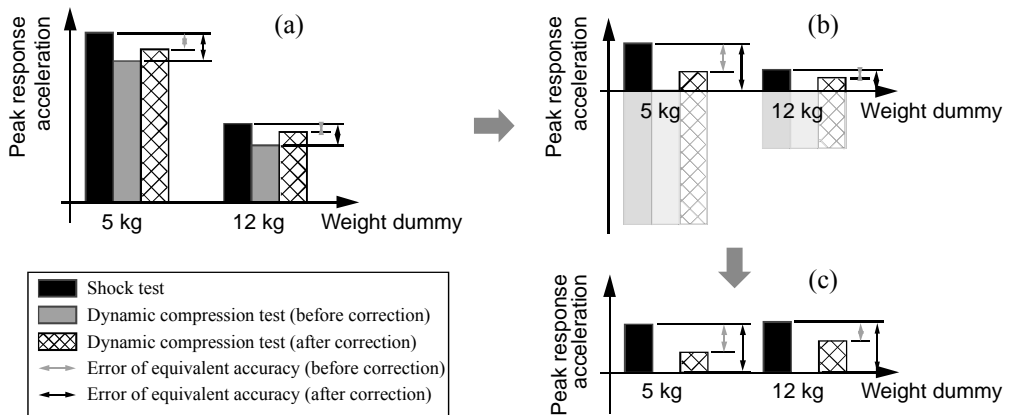


Fig. 9. Schematic representation of correction indicator

5 Discussions

The experimental results are summarised in Table 3. Column ① lists the weights of the dummies used. Column ② contains the average of $A_{ff_{max}}(V=3.43)$. Column ③ shows the average of the friction under different stresses. The data in column ④ corresponds to the results obtained using the method presented in the section ‘Calculation of dGs’. The data presented in column ⑤ is the result of normalizing the data in columns ② and ④, Column ⑥ lists the correction indicator calculated by Eq. (11).

Using the data of column ②, we plot the cushion curve (solid points in Fig. 10). It is known that as the dummy weight increases, the peak response accelerations of the dynamic compression test decreases. Based on the equivalent drop theory, the same trend holds true for the shock test. To confirm the lowest point of the cushion curve, we performed additional experiments. In particular, we used a 15 kg weight dummy, as shown by hollow points in Fig. 10, which was within the technical specifications of our test equipment^{(11), (12)}. From Fig. 10, we can see that the point

corresponding to the 15 kg weight dummy is not the minimum, i.e. in this study it was not possible to obtain the lowest point of the cushion curve.

Table 3. Experimental results and comparison of the correction indicator

① (kg)	② (G)	③ (N)	④ (G)		⑤		⑥
			before ^a	after ^b	before	after	
4	80.3	62	10.55	8.04	13.15%	10.02%	23.80%
5	67.0	51	8.76	6.62	13.08%	9.89%	24.41%
6	57.2	39	5.02	3.00	8.79%	5.24%	40.34%
7	50.0	31	3.33	1.64	6.66%	3.28%	50.77%
8	45.0	26	2.37	1.00	5.27%	2.22%	57.89%
9	40.5	20	2.20	0.68	5.44%	1.69%	69.01%
10	36.8	14	1.96	0.53	5.32%	1.45%	72.81%
11	34.5	14	0.84	0.17	2.45%	0.48%	80.30%
12	30.4	12	0.40	0.06	1.31%	0.20%	84.73%

① Dummy weights.

② Average of the peak response accelerations of the dynamic compression test when $V = 3.43$ m/s.

③ Friction.

④ Average of dGs.

⑤ Proportion of the equivalent errors of the two tests.

⑥ Correction indicator Δ (a larger value indicates better correction effect).

a: Before correction using the friction theory.

b: After correction using the friction theory.

Based on the data of column ③, the friction curve is plotted in Fig. 11. As mentioned above, under different stress values, the friction did not remain constant, but instead decreased as the weight dummies became heavier.

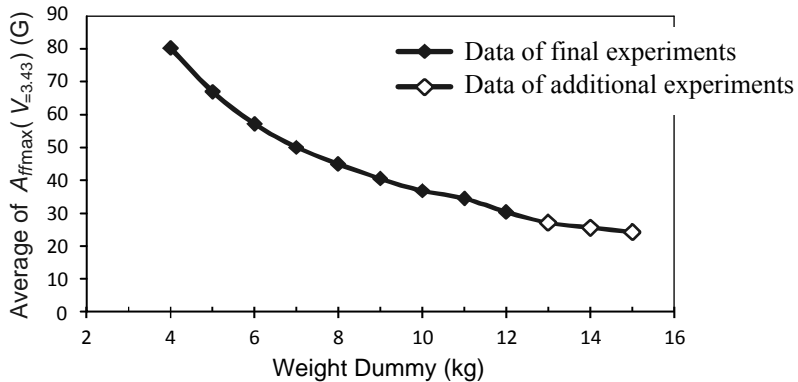


Fig. 10. Cushion curve

Using the data of column ⑥, we plot the correction indicator curve of the friction theory shown in Fig. 12. The correction indicator is denoted by a percentage. This number represents the degree by which the friction theory can improve the equivalent precision of the two tests with respect to the results before the correction. A larger value indicates a better correcting effect. From Fig. 12, it can be seen that the correction effect corresponding to the 4 kg and 5 kg weight dummies is approximately 20%, and that corresponding to the 12 kg weight changes to approximately 80%. Considering this result along with the cushion curve, we conclude that as we approach the lowest

point of the cushion curve, the correction effect improves. Therefore, the correction effect becomes more apparent as the weight dummy increases.

There is a little correction effect when we use a light weight dummy. This result is attributed to the fact that the corrugated sleeve is constructed from nonlinear cushioning material. It should be pointed out that the correction effect of the area around the lowest point of the cushion curve is more significant than that of the left area, because the left area of the cushion curve is barely used¹⁾.

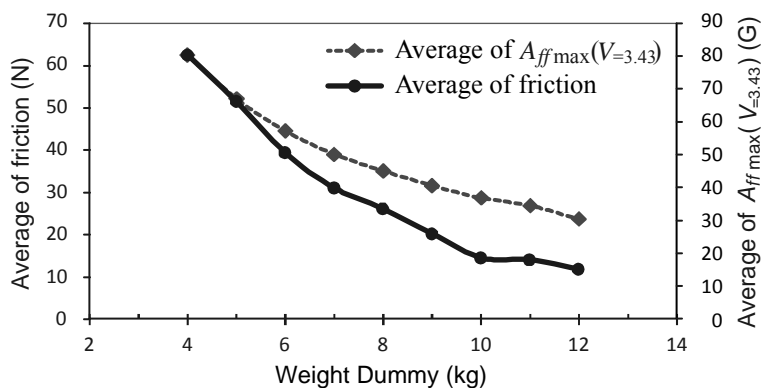


Fig. 11. Friction curve

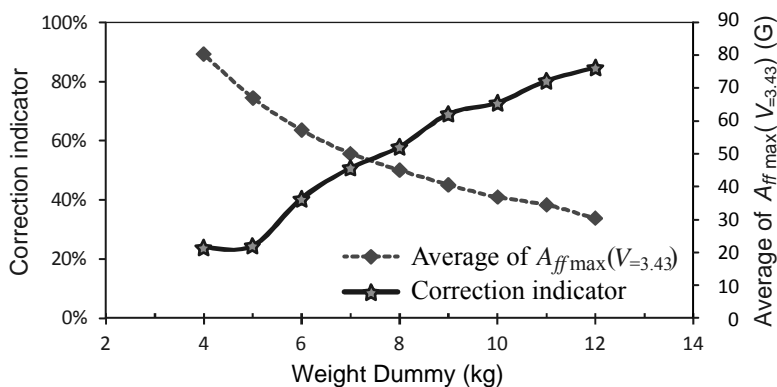


Fig. 12. Correction indicator curve

6 Conclusions and Further Study

To verify the feasibility of applying the friction equivalent drop theory to SCM, the influence of stress was investigated in this study. A corrugated sleeve was used as a test material and weight dummies in the range of 4–12 kg were employed to calculate the stress. In addition, we investigated the effects of friction. Based on the hysteresis loop of the friction model, we predicted that friction decreases when stress increases and validated this prediction through test results. Moreover, we proposed new data analysis and results evaluation methods using statistics. The experimental results showed that although the equivalent errors of the two tests can be corrected by applying the friction equivalent drop theory, the correction effects were not the same under different stresses. The correction effect becomes more prominent as we approach the lowest point of the cushion curve.

Considering that packaging designers typically use the lowest point of the cushion curve to design transport packages, the results of our study have important practical significance.

The influence of the test material will be addressed in future studies. We will consider pulp mould as the test material because of its nonlinear cushioning characteristics and extensive use in transport packaging.

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(Received 12 April 2012)
(Accepted 16 May 2012)

構造体段ボール緩衝材に対する改良等価落下試験

仲 晨、斎藤 勝彦

落下衝撃から包装内容品を保護するための緩衝材の性能は、動圧縮試験によって評価されるが、複雑な形状の構造体緩衝材では、動圧縮試験ができないため、衝撃試験装置を用いた等価落下試験で評価される。これまでの研究により、従来の等価落下試験における等価自由落下高さは精確ではないことが指摘されている。その原因として、緩衝系に減衰の影響が無視できないことが挙げられる。したがって、我々は減衰と摩擦の影響を考慮した理論に基づいた等価落下試験の方法を提案し、段ボールから作られたスリーブを試験材料として、摩擦等価落下モデルによる等価落下試験を行い、摩擦等価落下理論により両試験の等価度が上がることを実験的に確認した。また、摩擦等価落下理論の有効性を十分に確認するためには、様々な要因を考慮しなければならないが、これまでの実験的確認は限定的であったことから、本研究では、様々な静的応力条件下での等価落下試験と動圧縮試験を行った。その結果、摩擦等価落下理論は構造体段ボール緩衝材に適用できること、及びその改善効果を定量的に示すことができた。

キーワード： 包装、輸送、緩衝、段ボール、等価落下