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Simplified Performance Evaluation Methods for Cushioning Materials

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Abstract. To quantitatively evaluate the performance of cushioning materials, cushion curve is indispensable. However, a desired cushioning effect may not be available sometimes when we use the cushion curve to design transport package. In addition, massive dynamic compression tests must be carried out to plot the cushion curve traditionally. Thus, it costs large amounts of manpower and material resources. Therefore, we used expanded polyethylene and laminated-board cushion as test materials to represent typical cushioning materials, and proposed simplified performance evaluation methods for cushioning materials based on a certain dynamic compression tests. By comparing with the experimental results, the results showed that: To get more accurate packaging design, the effect of shearing should not be ignored when we use the cushion curve; Moreover, for both plastic and paper cushions, new performance evaluation methods can reduce test numbers of the dynamic compression test on large-scale and have enough accuracy and feasibility when actual packaging design.

Introduction

To accomplish optimum package, cushion curve (combination of static stress–peak acceleration curve and static stress–strain curve) is often used in packaging field [1, 2]. Using the cushion curve, we can calculate the minimum thickness of the cushioning materials swiftly. If there is not a ready-made cushion curve (Fig. 1) on hand for a cushioning material, the packaging designer should plot it by himself. However, traditional plotting method is dependent on massive repeated dynamic compression tests. Furthermore, using self-made cushion curve based on the traditional method, we may not accomplish desired cushioning effect. Therefore, to quantitatively evaluate the performance of the cushion materials, it is necessary to search a new simplified method that not depends on the large number dynamic compression tests. According to literature, many simplified methods [3-8] for the cushion curve were proposed so far, nevertheless, precision evaluation of those methods were not completely carried out.

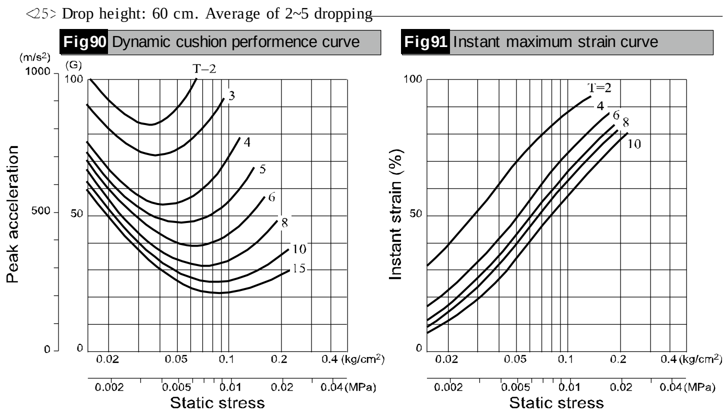
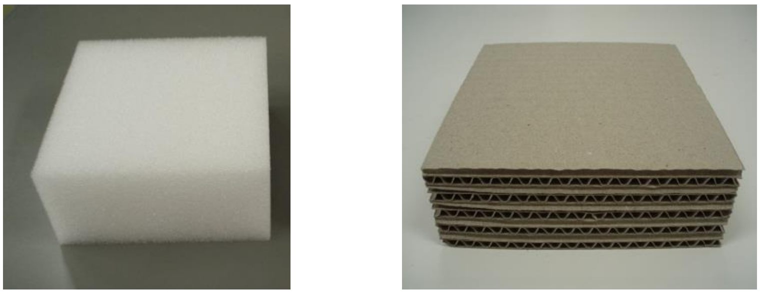


Fig. 1 Ready-made cushion curve [9]

Plastic cushion and paper cushion are extensively applied in packaging field [10]. Their representative cushioning materials are expanded polyethylene (EPE) and corrugated fiberboard. Therefore, EPE and laminated-board cushion (LBC) was used as test materials to represent plastic and paper cushions in this study (Fig. 2).

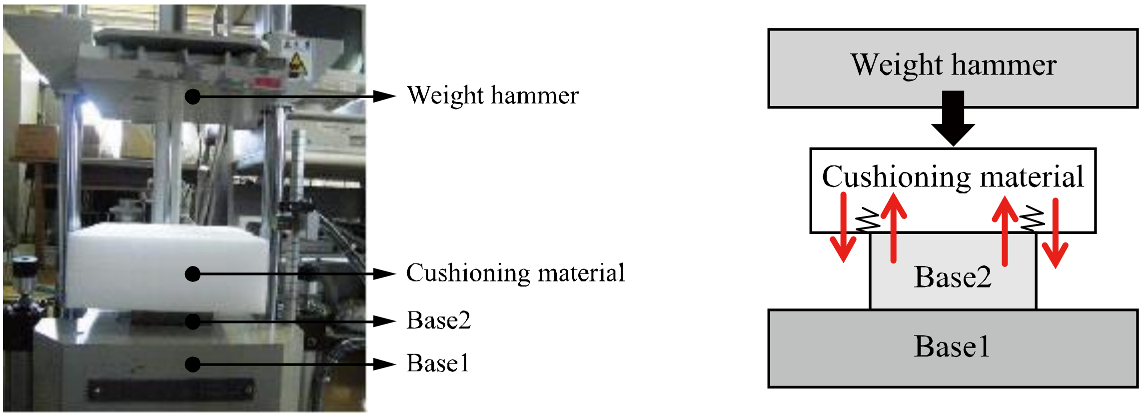


(a) (b)

Fig. 2 Two kinds of cushioning materials. (a) Plastic cushion, (b) Paper cushion.

Cushion Curve with Shearing

When we use the cushion curve to design transport package, desired cushioning effect may not be available sometimes. Considering an effect of shearing happens when shock or vibration hazards occur, the reason is considered due to the effect of shearing. Therefore, the cushion curve with shearing is discussed in this section.



(a) (b)

Fig. 3 Dynamic compression test with shearing. (a) Dynamic compression test, (b) Illustration of the effect of shearing

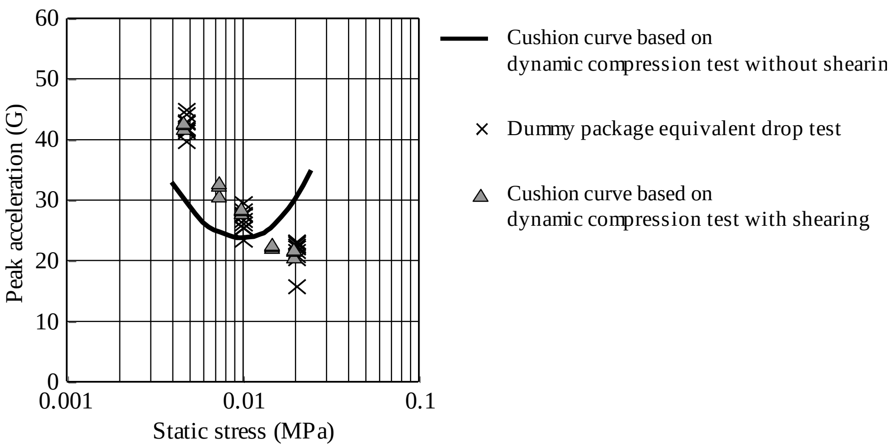


Fig. 4 Comparison between experimental results and cushion curves with and without shearing

EPE (25 times expanded rate, 178×178×80 mm) as shown in Fig. 2(a) was used as the test material. A dynamic compression test with the effect of shearing was carried out (Fig. 3(a)) [11]. A test configuration following Fig. 3(b) was set to yield the effect of shearing. An iron plate (Base2: 100×100×63 mm) was fixed on the table of the test equipment (Base1) and EPE was placed on the iron plate. Test conditions were set as: the drop height h was 0.6 m, 5 consecutive droppings were performed, 5 points of the static stress was plotted, 3 tests under the same conditions were carried out for each point.

Based on the experimental data, we plot the cushion curve with shearing as shown in Fig. 4. Moreover, a cushion curve without shearing based on a test (h: 0.6 m, the thickness of the test material t: 80 mm) and the result of dummy package (content: 20 kg, 400×400×300 mm; cushioning material: 8 corner pads, 80×80×80 mm) equivalent drop test [12-17] based on the test conditions above are also provided.

According to Fig. 4, the results of dummy package equivalent drop test and the cushion curve with shearing are almost identical. Hence, it can be say that the shearing should be a major reason that the desired cushion effect is not available. Therefore, to get more accurate packaging design, the effect of shearing should not be ignored when we use the cushion curve.

Simplified Performance Evaluation Method for Plastic Cushions

C curve (it is also called dynamic stress–dynamic cushion factor curve) is another cushioning performance curve that is often used in packaging field [1]. The C curve can be plotted by using data of one dynamic compression test. A cluster of thin lines in Fig. 5(a) is the strain–dynamic stress curve of EPE under different thickness of test materials and the free fall height conditions. Using the data of Fig. 5(a), we plot C curves of EPE as shown in Fig. 5(b). A conclusion that the strain–dynamic stress curve of the plastic cushion has a unification characteristic was proposed [3-6]. According to Fig. 5(b), the C curve of EPE has a unification characteristic, too. It further verifies aforementioned conclusion.

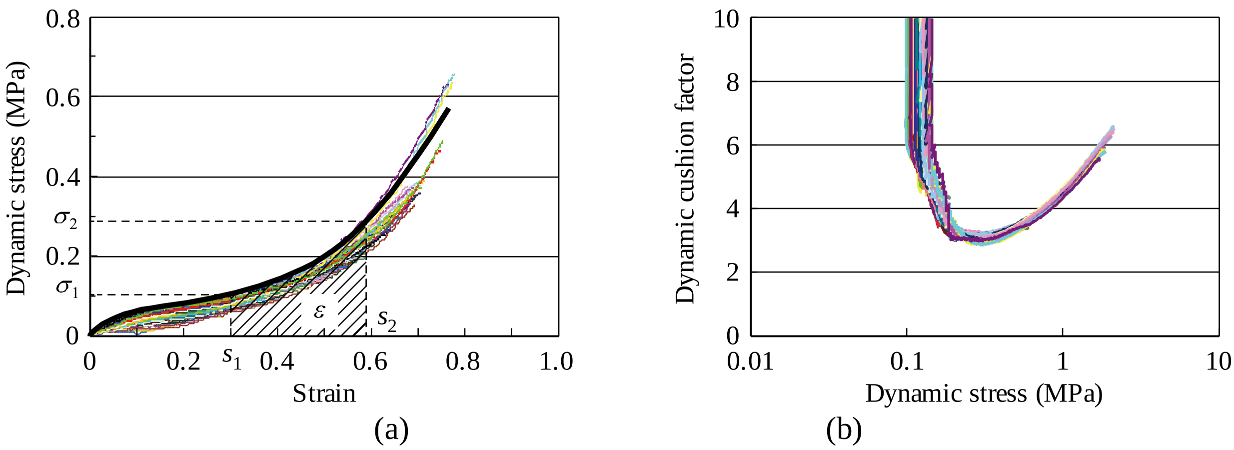


Fig. 5 Strain–dynamic stress and C curves of EPE. (a) Strain–dynamic stress curve, (b) C curve

According to packaging dynamics [18], the dynamic cushion factor C is defined as $C = \sigma_d/\varepsilon = A_c t/h$. Rearranging this equation, the acceleration equation is available:

$$A_c = C\frac{h}{t}, \tag{1}$$

where σ_d is the dynamic stress, ε is the absorbable impact energy per unit area and A_c is the peak acceleration.

The dynamic strain σ_d is expressed as $\sigma_d = mg \cdot A_c/P = \sigma_s \cdot A_c$. We get the static stress equation after this equation is rearranged:

$$\sigma_s = \frac{1}{A_c}\sigma_d, \tag{2}$$

where m is the mass of weight hammer, g is the acceleration of gravity, σ_s is the static stress and P is the pressure area.

Considering the unification characteristic of the strain–dynamic stress curves of EPE, we use one curve to represent others (bold line in Fig. 5(a)). ε is equal to the area of the shadow figure in Fig. 5(a) [18]. Its area can be calculated approximately by $\varepsilon = (\sigma_1 + \sigma_2)(s_2 - s_1)/2$. Rearranging this equation, the strain equation s is

$$s = s_2 - s_1 = \frac{2\varepsilon}{\sigma_1 + \sigma_1}. \quad (3)$$

If the C curve of a cushioning material is known, meanwhile t and h are also given; we can plot the cushion curve according to Eqs. (1), (2) and (3) simply.

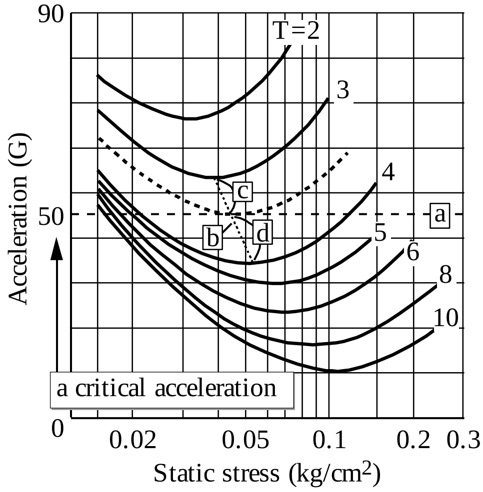


Fig. 6 Example of calculating thickness of cushioning material using cushion curve

Generally, there are two methods to calculate the minimum thickness of the cushioning material t_{min} for a certain drop height and acceleration when packaging design. One is a method using the lowest point of the cushion curve; the other is a method using the lowest point of the C curve. An example of calculating t_{min} using the cushion curve shows in Fig. 6. Using the peak acceleration–static stress curve of cushion curve, we draw a line 'a' from a critical acceleration, and then connect the lowest points of two adjacent cushion curves of line 'a' and get line 'b'. Line 'b' is broken up into two parts by an intersection: lines 'c' and 'd'. According to proportion of lines 'c' and 'd', we can calculate t_{min} [1]. Using these two methods, we calculated t_{min} for equal free fall heights and accelerations, as shown in Fig. 7. Horizontal axis shows the thickness t_0 calculated by the ready-made cushion curve [9], vertical axis shows the thickness t_c calculated by the C curve. It can be known that the two results are almost the same roughly. However, the error between the two results becomes large gradually with respect to the increase in the thickness of the cushioning material.

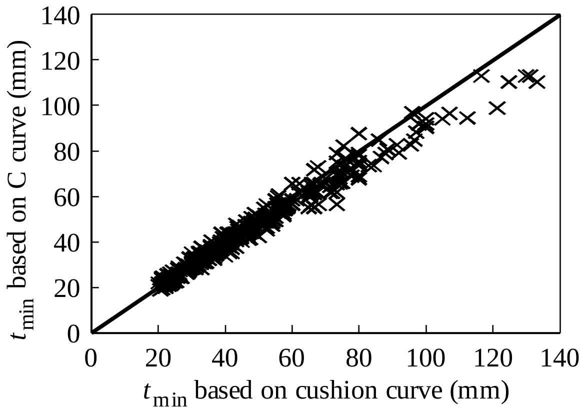


Fig. 7 Comparison of two calculating methods for t_{min}

To quantitively discuss the error between t_c and t_0, Fig. 8 is plotted. Horizontal axis is the set-up acceleration and vertical axis is the difference of thicknesses $t_c - t_0$. Considering that the thickness of the cushioning material increases or decreases in 10 mm increments when packaging design, we highlight the part that $t_c - t_0$ is larger than 10 mm, and know $t_c - t_0$ becomes large when the set-up acceleration is smaller than 50 G. To plot the ready-made cushion curve, test conditions of the dynamic compression test are usually set as: h = 0.6 m, t = 40 mm. Peak acceleration of the dynamic compression test using these test conditions is still larger than 65 G even in small acceleration region. Hence, the lowest point of the C curve based on the dynamic compression test under above conditions cannot express the cushioning performance in small acceleration region correctly. Moreover, $t_c - t_0$ becomes larger in small acceleration region. Therefore, we should make careful judgment on the test condition of the dynamic compression test when the cushioning characteristic of the C curve is used.

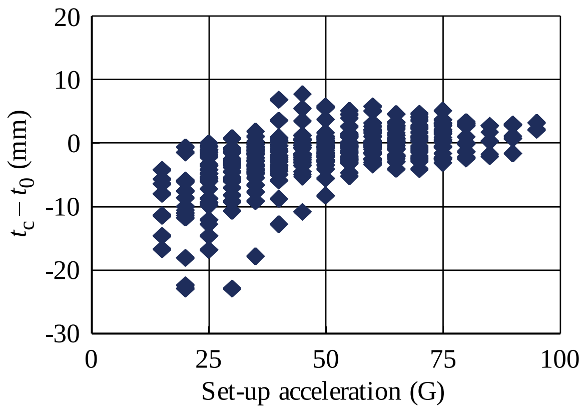


Fig. 8 Difference of thicknesses in different acceleration regions

Simplified Performance Evaluation Method for Paper Cushions

Three types LBC (5, 8 and 10 layered boards) as shown in Fig. 2(b) were used in this study. Pressure areas of three types LBC were 15×15 cm^2 and belonged to 'A' flute. Fig. 9 shows the strain–dynamic stress curves of LBC based on dynamic compression tests. Test conditions were set as follows: 5 layered LBC: hammer weight was 6 kg and 3 times for each test; 8 layered LBC: hammer weight was 7 kg and 3 times for each test; 10 layered LBC: hammer weight was 4 kg and 6 times for each test.

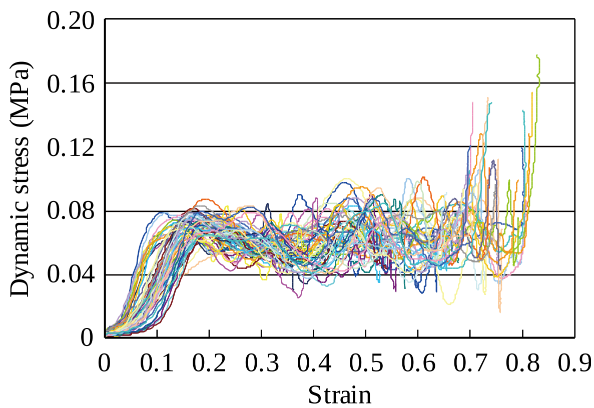


Fig. 9 Strain–dynamic stress curves of LBC

It can be seen that strain–dynamic stress curves of LBC considerably differ. Hence, it is not possible to use one curve as same as the plastic cushion to represent others. Therefore, we proposed a method that using an average stress–strain curve to calculate the strain and the acceleration. To ensure that the packaging design has sufficient safety in terms of acceleration, we also calculated an average+3σ strain–dynamic stress curve (σ: standard deviation). The definite integral of the strain–dynamic stress curve is ε. Hence, if let $\varepsilon = E_p$ (E_p: absorbable energy calculated by the potential energy that based on m and h), we can calculate the peak acceleration and the strain. The calculating process is shown in Fig. 10: First, based on the average strain–dynamic stress curve, the strain corresponding to ε is derived. Second, according to average and average+3σ strain–dynamic stress curves, the peak acceleration until the strain becomes the calculating value is calculated.

According to Fig. 10, comparing the calculating strain and acceleration with the experimental data, it is known that although the calculating strain matches the experimental data, the calculating acceleration is small than the experimental data when the average strain–dynamic stress curve is used and large than the experimental data when the average+3σ strain–dynamic stress curve is used. Hence, we must determine that based on which of these curves to let the calculating results approach the experimental data. The investigate results show that the average+σ strain–dynamic stress curve is optimum. Therefore, if the average strain–dynamic stress curve and the standard deviation can be available, we can evaluate the cushioning performance of LBC swiftly.

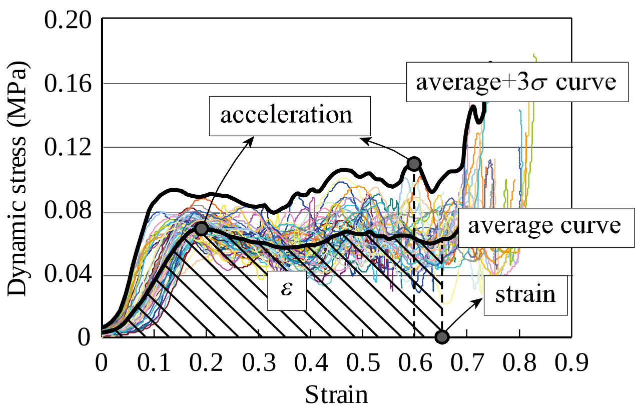
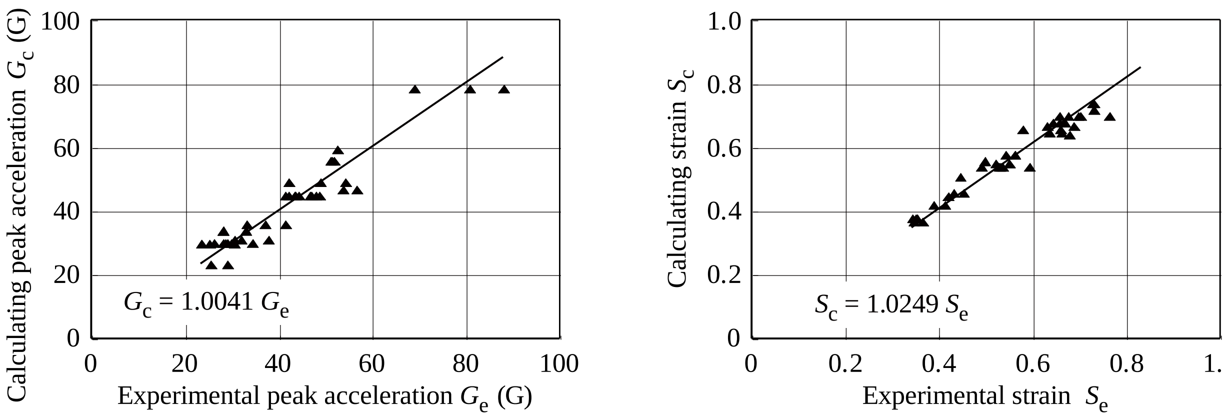


Fig. 10 Estimation of the strain and the peak acceleration of LBC

Fig. 11 shows acceleration and the strain comparisons of LBC between calculating results and experimental data based on 20 dynamic compression tests. It is known that $G_c = 1.0041\ G_e$, $S_c = 0.0249\ S_e$. For both the acceleration and the strain, there is approximate linear relationship between calculating results and experimental data. Thus, it can be say that the proposed method has enough precision to evaluate the cushioning performance of LBC.



(a) (b)

Fig. 11 Comparison between calculating results and experimental data. (a) Comparison of peak acceleration, (b) Comparison of strain

Conclusions and Further Study

Using EPE as the test material to represent the plastic cushion, a dynamic compression test with shearing was carried out. The experimental results proved that the shearing may be a major reason that the desired cushion effect is not available and the effect of shearing should not be ignored when we use the cushion curve. Furthermore, based on a unification characteristic of the C curve, a simplified plotting method for the cushion curve was proposed. Meanwhile, we proved that we should make careful judgment on the test condition of the dynamic compression test when the cushioning characteristic of the C curve is used. Using LBC as the test material to represent the paper cushion, we proved that the strain–dynamic stress curve of LBC has not a unification characteristic. According to the law conservation of energy, we can derive the dynamic cushioning performance of LBC under any conditions if the average strain–dynamic stress curve and the standard deviation are known.

By comparing calculating results with the experimental data, it is proofed that the cushion curve of the plastic cushion based on the simplified method has enough precision; On the other hand, for the paper cushion, although a certain numbers strain–dynamic stress curves are still needed, the test times reduce substantially than traditional method.

The dynamic compression test is important test to evaluate the performance of cushioning materials. Nevertheless, a shock test is often used as a substitution when the dynamic compression test cannot be adopted. According to standard JIS [19], the two tests are equivalent. Using the optimum σ_s of cushion curve, the equivalence of the two tests will be addressed in future studies.

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