Investigating the Feasibility of a Cushion Selection Method on Polyethylene Based on a Predictive Model

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Abstract. Cushion materials are very popular and widely used in various applications. Cellular solid has been used for cushioning for many years due to its low weight and high energy absorption capacity. Cushioning selection is the process of selecting a cushioning material to sufficiently cushion an object. There are a few cushion selection methods available in literature. The objective of this report is to investigate the feasibility of a cushion selection method based on predicting the impact absorption capacity from static compressive stress-strain data. This is achieved by comparing the predicted dimensionless deceleration (G) and the measured G. Polyethylene (foam) samples were used to conduct the compression test and drop test. For polyethylene, the predicted G showed higher accuracy at low drop height and became lower accuracy with increasing drop height. A dynamic factor C was introduced to account for the difference. From this report, researchers may explore the feasibility of this cushion selection method on polyethylene or even conduct experiments on other cellular solid specimens in the future.

1. Introduction
Cushioning materials have been applied to prevent valuable goods or human body parts from being damaged for many years, due to their low price, environmental friendliness [1]. It means that cushioning materials play an important role in our daily life and how to select and use material for cushioning becomes an essential issue in recent years. Earlier cushioning methods were in the form of variations of polymer foam peanuts [2], corrugated fiber board [3], bubble wraps [4] and so on. They are widely used in a long, unstable transportation and protect glasswork, electronic products etc. However, foams, whose structure can be considered to be a cellular solid, come into people’s eyes for cushioning due to their high efficiency, low weight in contrast to other cushions these days.

Because of the various microstructures of different cellular solids, designers should select a proper kind of cellular solid for specific application. For cushion selection, the cushioning curves are required. Cushioning curves represents a material’s ability to reduce shock transmission to a product [5]. To obtain the best effect of cushioning, the material with the smallest G level should be chosen among several materials. Shock is measured in terms of G level, which is the measured deceleration divided by gravitational acceleration (9.81 m/s^2). G is plotted against the static stress (σ_s) due on the cushion, which is the ratio of the load due on the cushion to the contact area (between the load source and the cushion). Figure 1 is an example of a cushioning curve. As observed, the G level is plotted against the static stress (σ_s). There is a unique cushioning curve for each material, drop height (H) and foam height (Ly).
Figure 1. Cushioning curve for 3D printed honeycomb for drop-height of 100 mm [6].

The cushioning curve is acquired by conducting a set of experiments. The resulting G level measured by a drop test machine is then plotted, which corresponds to a static stress ($\sigma_s$) value on the curve. Performing various drop-tests of different weights will result in a set of plotted points which are then fitted with a best fit curve to obtain the final cushioning curve [7]. More drop-tests are required to obtain a cushioning curve with higher accuracy.

A new method is designed for cushion selection, which is based on the stress-strain curve in compression test. From the static stress-strain curve, cushioning curve can be obtained and G values for any static load can be acquired. This method is the least time consuming and most cost-effective method as a simple static compression test can generate a range of cushioning curves.

Although the method is designed, there are still some unknown realms about this kind of cushion selection method, which should be explored on the basis of experiments. Hence, in order to analyze and optimize this method for cushion selection, more data should be collected in experiments.

The objective of this project is to compare the G values obtained experimentally and mathematically (from static compressive stress-strain data). This comparison can help to evaluate the feasibility and establish necessary adjustments to obtain a G value from static compressive stress-strain data.

2. Method to Get Cushion Curve from Static Compression Data

To generate a cushion curve with high accuracy, the drop test should be done lots of times and too many specimens should be used, which is time consuming and very costly. Hence, another method to generate cushion curve has been suggested.

Gruenbaum and Miltz proposed the use of static compressive stress-strain data to predict the cushioning curve for a range of drop-height and foam height [8]. This method is the least time consuming and most cost-effective method as only a simple static compression test is required. However, the accuracy of the cushioning curves decreases with increasing drop-height and decreasing foam height [8]. This method assumes that for any drop-height (H), the amount of energy absorbed during a drop-test is the same during static compression. This is illustrated in Figure 2 and Equation 1.
Figure 2. Energy absorbed during static compression equals to the energy absorbed during drop test [8].

\[ P, E = mgH = AL_y \int_0^e \sigma \, d\varepsilon \]  

where \( Ly \) is the height of the foam, \( A \) is the contact area of the foam and \( \sigma \) is the static stress value which is a function of strain.

From Equation 1 and knowing that \( \sigma_s \) is weight (mg) divided by contact area, Equation 2 is obtained.

\[ \sigma_s = \frac{mg}{A} = \frac{L_y}{H} \int_0^e \sigma \, d\varepsilon \]  

Fragility value or G level is basically the dimensionless deceleration value as a ratio of gravitational acceleration. This can be calculated with Equation 3.

\[ G = \frac{a_{\text{deceleration}}}{g} = \left( \frac{F_{\text{reaction}}}{m} \right) \frac{1}{g} = \frac{\sigma A}{mg} = \frac{\sigma}{\sigma_s} \]  

where \( \sigma \) is the corresponding static stress value if the foam is compressed up till a certain strain. From Equations 1 to 3, a curve of G vs \( \sigma_s \) can be plotted which is, in fact, the cushioning curve. Foam height (\( Ly \)) and drop-height (\( H \)) are considered as constants. Therefore, adjusting these values provides a range of cushioning curves.

3. Methodology

3.1. Experimental Procedures

3.1.1. Compression test on polyethylene (PE) foams. Universal Testing Machine, Instron 5569 was used to test specimens at a strain rate of 100 mm/min during the static compression test. Each specimen has a contact area of 50 mm by 50 mm, with the height of 50 mm approximately. Ten specimens were cut off from a whole foam board with a pen knife, and then measured by a vernier caliper. In order to minimize experimental errors, 5 best specimens were selected for the test.

Figure 3 shows the specimen under testing.
3.1.2. Drop test on polyethylene (PE) foams. Before conducting the drop test, the PE foams were cut into 90 mm * 100 mm rectangle shape, with 50 mm height. To calculate the acceleration, we used the Cadex Twin Wire 1000 kg Machine. The total mass of drop system is 3291g. Before drop test, the velometer on the machine should be calibrated. The surface of drop system and the surface of the specimen should be made as close as possible, which is the zero position during the test, as shown in Figure 4.

The specimens were tested at the drop height of 15 at first. Then the drop height was changed to 30cm and 45cm to conduct the experiment respectively. The velocity was recorded for further calculation.

3.2. Calculation Procedure
The method of obtaining cushioning curves from stress-strain curve is as covered in Section 2. For this project, the following steps were taken to calculate the $G$ value from stress-strain curve.

Combining Equation 2 and 3:
For a foam compressed up till a certain strain value of $\varepsilon = b$, Equation 4 can then be further simplified to Equation 5.

$$ G = \frac{\sigma_b}{W_b} \left( \frac{H}{L_y} \right) $$

(5)

The static loading $\sigma_s$ can be simplified to Equation 6.

$$ \sigma_s = W_b \left( \frac{L_y}{H} \right) $$

(6)

From Equation 5 and 6, the $G$ value, corresponding to drop test $G$ value, can be deduced for certain static loading, at each drop height and specimen height.

4. Results and Discussion

4.1. Results Obtained

After the compression test, the static stress-strain curve and energy absorption capacity curve can be obtained with the raw data. Figure 5 shows the curve of one of the PE specimens. According to the total weight of the drop system and the dimensions of PE, the static stress $\sigma_s$ can be calculated. With Equation 6, the energy absorption capacity for the drop height 15 cm, 30 cm, 45 cm can be obtained. From PE stress-strain curves and energy absorption curves, the stress $\sigma_b$ corresponding to $W_b$ at each drop height can be obtained, and the mean $\sigma_b$ at each drop height can be calculated. Finally, according to Equation 5, the $G$ calculated from static stress-strain curve could be obtained for further analysis.

![Figure 5. PE specimen 2 stress-strain curve and energy absorption capacity curve.](image)
After the drop test, the measured G was obtained from the velocimeter with simple calculation, and the mean measured G at each drop height can be calculated for further analysis.

4.2. Analysis

After the data processing, the G values of polyethylene (PE) foams, which were calculated from the static stress-strain curve and measured from the drop test, are shown in Table 1.

| Height (cm) | G (calculated) | G (measured) |
|------------|----------------|--------------|
| 15         | 16.87          | 23.01        |
| 30         | 29.57          | 41.96        |
| 45         | 42.89          | 66.70        |

The G values at different drop height could be found in Figure 6. In the graph, the difference between measured and calculated G value increases when the drop height becomes larger. This means that the accuracy becomes lower when the drop height increases. The calculated G cannot predict G value at large drop height, which can be explained by introducing dynamic factor c to the calculated G [9].

The dynamic factor is a function of speed (strain rate) and displacement (strain) of the deformation on the foam which can be directly translated to strain and strain rate [10]. The dynamic factor $c(\dot{x}, x)$ could be derived from Equation 7, 8, 9, 10, 11, 12

\[ m\ddot{x} = F(x) + F_{\text{dynamic}}(\dot{x}, x) \]  
\[ \sigma_s A/g \ddot{x} = \sigma(x)A + F_{\text{dynamic}}(\dot{x}, x) \]  
\[ \sigma_s/g \ddot{x} = \sigma(x) + \sigma_{\text{dynamic}}(\dot{x}, x) \]
Strain rate $\dot{x}$ accounts for the drop height, the higher the drop-height, the higher the potential energy and therefore, higher strain rate during impact. The strain $x$ accounts for the height of the structure ($L_y$). Small height of the structure will cause large strain during drop test. Hence, a more accurate $G$ value from static stress-strain curve could be obtained by combining the calculated $G$ and the dynamic factor $c$.

The dynamic factor can also be predicted from the experiment data. Table 2 shows the dynamic factor value at each drop height.

| Height (cm) | Dynamic factor |
|-------------|----------------|
| 15          | 1.36           |
| 30          | 1.42           |
| 45          | 1.56           |

Figure 7 shows the predicted dynamic factor $c$ at different drop height, which could be presented by Equation 13. But for more accurate value, more tests on different drop heights and foam heights should be conducted.

$$c = 0.0002h^2 - 0.0045h + 1.3915$$ (13)
5. Conclusion
The objective of this project is to compare the G values obtained experimentally and mathematically (from static compressive stress-strain data). PE foams were proposed for the project. Compression test and drop test were conducted on the materials to obtain the calculated G and the measured G.

Two methods for cushion selection are compared and shown in Table 3.

| Methods                        | A   | B   |
|--------------------------------|-----|-----|
| Accuracy                       | High| Medium|
| Time-consumption               | High| Low |
| Cost                           | High| Low |

Method A: Cushion selection method based on drop test.
Method B: Cushion selection method based on compression test.

For PE foams, the accuracy in cushion selection method based on compression test is lower than the drop-test method due to the error associated with the dynamic effect. But cushion selection method based on compression test is less time-consuming and more cost-effective as only a simple static compression test is required. However, the accuracy of this method is lower with drop height increasing, because of the strain rate increasing in dynamic factor. Researchers can conduct more experiments to determine the effect of the foams height on the accuracy of predicted model in the future, which affects the second variable in dynamic factor.

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