2000

Effect of cushion geometry on package performance

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EFFECT OF CUSHION GEOMETRY ON PACKAGE PERFORMANCE

A Thesis

Presented to

The Faculty of the Department of Nutrition and Food Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Arunkumar Madanagopal

December 2000

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ABSTRACT

THE EFFECT OF CUSHION GEOMETRY ON PACKAGE PERFORMANCE

by Arunkumar Madanagopal

Although the shock performance of cushioning material is determined by testing rectangular blocks with a square base, it is unlikely that the same shapes will be used in packaging fabrication. As the shock performance of a cushion may vary according to cushion/product configuration, experiments were carried out to investigate the effects on shock transmission of: (A) tapered angles of cushion blocks and (B) position of impact on the cushion block. A Lansmont cushion tester was used to simulate impact forces that a cushion package encounters during handling. For part A, trapezoidal blocks of expanded polyethylene (EPE) cushions with four different tapered angles (15° , 30° , 45° , and 60°) and a rectangular cushion block with a square base as control, all having same volume with fixed thickness and width, were used. For part B, five different impact positions were used.

Results of part A of this study showed that the effective area used to distribute shock by trapezoidal cushion blocks was different from the area used by the control cushion block. Results of part B of this study showed that the area of the cushion used to distribute shock increased as the position of impact moved towards the center of the cushion block. These results have considerable relevance in designing the effective area of the cushion block to achieve desired shock performance of the package.

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PREFACE

The following is a publication style thesis. Chapters 1 and 3 are written according to guidelines outlined in the *Publication Manual of the American Psychological Association*, 4th edition, 1994. The second chapter is written in journal format and will be submitted to *Packaging Technology and Science*.

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List of Acronyms, Abbreviations, and Variables

ASTM	= American Society for Testing and Materials
EPE	= Expanded Polyethylene
SL_o	= Static Load (Control Block)
psi	= Pounds per Square Inch
lb	= Pounds
in.	= Inch
W	= Weight of the Product
A	= Bearing Area of the Cushion
SL_{α}	= Static Load on a Trapezoidal Cushion Block with given Taper Angle
RH	= Relative Humidity
SL₄₅	= Static Load on a Trapezoidal Cushion Block with a Taper Angle of 45°
SL_{af}	= Static Load Adjusting Factor
Pcf	= Pounds per cubic feet

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

Introduction

In designing a protective packaging using cushions, a packaging engineer searches through a variety of cushion curves to select a cushion with suitable thickness and area to adequately protect the product from mechanical shocks. Cushion curves describe the level of deceleration transmitted through a given thickness of a cushion material as a function of static loading on the cushion, its thickness and drop height (Schueneman, 1993). The deceleration is defined as the maximum intensity of shock transmitted to an object when it is dropped flat from a specified height on top of a cushion. Static loading is defined as the ratio between the weight of the product and bearing area of the cushion.

The cushion area required for adequate protection is determined using optimum static loading. When a contact area of a product is considerably larger than the required cushion area for shock protection, a ribbed cushion configuration may be used. Introduction of ribs may result in buckling which occurs when the length or width of a cushion is less than its thickness for most plastic cushions. Buckling can be dealt with by changing the shape of the ribs to tapered blocks or trapezoidal blocks (Marcondes & Schueneman, 1999).

Since cushion curves are generated using rectangular blocks with square base, when the shape of a cushion block changes to trapezoid the effective area is no longer the bearing area of cushion block with the products. As most of the work done in tapered or

trapezoidal blocks and rib configuration has been intuitive in nature (Schueneman, 1993), the part A of this research was dedicated to the study of shock performance of trapezoidal cushion blocks.

When the contact area between product and cushion is smaller than the area of the cushion, the shock performance of the package may vary. Position of the product on the cushion may also influence the cushion's performance. The part B of this research focuses on effects of the impact position on shock transmission performance of a cushion block.

Objectives

The objective of this research is to examine the shock transmission performance of a cushion block:

Part A. If its shape changed from rectangular block with square base to trapezoid.

Part B. With respect to the position of the object on the cushion.

Significance

In the package design phase, a packaging engineer determines the required area and thickness of the cushion based on its shock transmission properties. These properties are published by the manufacturers of the cushion as cushion curves. Using the test procedure developed by the American Society for Testing Materials the cushion curves are plotted based on the dynamic properties of rectangular cushion blocks with a square base (ASTM 1998). However, when the cushions are fabricated in the form of ribs that are trapezoidal in shape, there is no recognized procedure for determining the area and thickness of cushions in these shapes.

For a given thickness, the dynamic properties of a cushion depend on the area of cushion available to distribute the dynamic force caused by a mechanical shock.

Introduction of tapered angles and variation in position of the product on the cushion can change the bearing area of the cushion and may change its shock transmission properties.

As there is no recognized procedure to account for these variations, this study focused on investigating:

- A. Effective area used by the trapezoidal shaped cushion blocks compared to rectangular cushion blocks with a square base to transmit shock.
- B. Effective area used by cushion blocks with respect to position of impact to transmit shock.

Review of Literature

During distribution, packages are subjected to mechanical shock from mishandling such as dropping, throwing, and kicking. A mechanical shock, however brief, may cause damage to the product. In order to protect the product from damages, a resilient medium such as polymeric foam is placed between the product and outer package. An optimum package system consists of a product of known ruggedness and cushion which together provide sufficient resistance to damage from impacts likely to be encountered in the distribution (Schueneman, 1993).

Mechanical Shock

A mechanical shock is characterized by a sudden change in velocity of a product, resulting in a high deceleration over a short period of time (Brandenburg & Lee, 1985). Fragility of a product is determined by the intensity of mechanical shock the product can

withstand without being damaged. The objective of good cushioning design is to absorb enough mechanical shock to keep the resultant force below the fragility level of the product. In an impact, the kinetic energy of a product compresses or deflects the cushion and is represented by the following equation:

$$E = \frac{1}{2} K d_m^2 \quad (1)$$

Where

E = Energy absorbed by the cushion, lb-in.

K = Stiffness of the cushion, lb/in.

d_m = Dynamic deflection of the cushion, in.

By deflecting, a cushion increases the duration of impact by providing space through which a product in motion is brought to rest (see Figure 1.1). This action reduces the rate of deceleration, thereby mitigating the influence of impact. Figure 1.2 shows a comparison between a shock pulse as received by the outer package (input shock pulse) and the shock pulse received by the cushioned product.

Cushion Curve

The ability of a cushion to mitigate the shock is usually presented as a cushion curve. A cushion curve shows how a particular cushioning material of a given thickness behaves at different impact conditions. Cushion curves are generated by dropping a series of known weights onto a cushion sample from a specified height and measuring the amount of shock experienced by the weights as they impact the cushion. Cushion curves

are available for a variety of drop heights, thickness and usually for single and multiple impacts. The ASTM method D-1596 specifies how the test method must be performed. Most of the cushion curves have a general shape as shown in Figure 1.3.

Figure 1.1. Cushion Deflection

A cushion curve describes the level of deceleration transmitted through a given thickness of cushion material as a function of static loading on the cushion and drop height. Deceleration is the maximum intensity of shock transmitted to an object when it is dropped flat from a specified height on top of a cushion. Static loading is the ratio

between the weight of the object and the bearing area of the cushion. Static load is given by:

$$S.L = W / A \quad (2)$$

Where

S.L = static loading, psi

W = weight of the product, lb

A = area of the product, in².

Figure 1.2. The effect of cushion on mechanical shocks

ASTM Test Procedure

As per ASTM D1596, a procedure developed by American Society for Testing and Materials (ASTM), cushion curves are developed by dropping predetermined weights onto a block of cushion of known thickness and area from a given drop height. This procedure recommends that the test specimens be right square prisms or other

configuration as desired with the maximum length and width dimensions less than the corresponding drop platen dimension. However, this procedure does not cover trapezoidal shaped test specimens. Manufacturers of cushion materials use this procedure and publish cushion curves for the cushion material they produce. In addition to cushion curves, transmissibility and stress strain curves represent cushion material's vibration transmission and compression properties respectively. This research is limited to shock performance of expanded polyethylene (EPE) cushions.

A cushion package design process begins with determining the thickness of the cushion material necessary to achieve the desired shock protection. Cushion curves are also used to determine the optimal area and thickness of cushion material.

Figure 1.3. Generic cushion curve

Buckling

If the ribs become too tall or thin in design, buckling occurs. Buckling is the non-uniform compression of a cushion. When buckling occurs, the energy of impact is not transferred evenly throughout the cushion, and its cushion performance is unpredictable. To avoid buckling, cushion blocks should be stable enough to return to their original position to provide protection during more than one drop (Hatae, 1988). Studies have shown that when minimum bearing area is less than 1.33 times the design thickness of cushion, buckling occurs (Peaché, 1998). According to Marcondes and Schueneman (1999), buckling may be dealt with by changing the shape of the cushion to a tapered or trapezoidal block.

Contact area

In ribs design, static loading is the ratio between the weight of the product and area of the cushion that effectively bears the product weight (the effective contact area). According to Marcondes and Schueneman (1999), the effective contact area is:

1. The actual contact area for rectangular cushion blocks (see Figure 1.4) if the product is in full contact with this area of cushion.
2. The average between two parallel surface areas for trapezoidal cushion blocks (see Figure 1.5) if the product is in full contact with one of these areas (top or bottom).

3

As shown in Figure 1.5, the actual area of trapezoidal cushion which is in physical contact with the product is less than the effective or design contact area. Hence, the product loading on the top surface is higher than the effective static loading. In this case,

deflection of the upper part of the block occurs very rapidly at the onset of dynamic force input. As deflection of the cushion material continues in response to the force input, the effective static loading decreases. Ideally this deflection and change in static loading is expected to occur at a rate which is optimum for shock performance of the cushion (Schueneman, 1993).

Figure 1.4. Contact area of rectangular cushion blocks

Figure 1.5. Contact area of trapezoidal cushion blocks

Though cushion curves are generated using rectangular blocks, in reality the cushion geometry could be different in order to account for product/package geometry, buckling and other practical issues. Howard (1999), found that it is difficult to effectively arrive at the cost-effective cushioning solution by simply using published performance data such as cushion curves. He suggested that if the cushion design is shaped differently than a rectangular block then the “in-package shocks” might vary significantly from the cushion curves. Part A of this research focuses on the effects of contact area of cushion on the shock performance of the design.

Sometimes by design, the area of the cushion required will be more than the area of the product. In such cases, the effective contact area may vary with the position of the product on the cushion. Consequently, the effective static loading may vary from the design static loading. As the effective contact area changes with change in the position of the product on the cushion, the shock performance of the design could also vary. Part B of this research focuses on the effects of position of impact on the shock performance of cushion blocks.

CHAPTER 2
JOURNAL ARTICLE

Authors Title Page

Effect of Cushion Geometry on Package Performance

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ABSTRACT

Although the shock performance of cushioning material is determined by testing rectangular blocks with a square base, it is unlikely that the same shapes will be used in packaging fabrication. As the shock performance of a cushion may vary according to cushion/product configuration, using expanded polyethylene (EPE) cushion blocks experiments were carried out to investigate the effects on shock transmission of: (A) tapered angles of cushion blocks and (B) position of impact on the cushion block. A Lansmont cushion tester was used to simulate impact forces that a cushion package encounters during handling. For part A, trapezoidal blocks of EPE foams with four different tapered angles (15° , 30° , 45° , and 60°) and a rectangular cushion block with a square base as control, all having same volume with fixed thickness and width, were used. For part B, five different impact positions were used.

Results of part A of this study showed that the effective area used to distribute shock by trapezoidal cushion blocks was different from the area used by the control cushion block. Results of part B of this study showed that the area of the cushion used to distribute shock increased as the position of impact moved towards to the center of the cushion block. These results have considerable relevance in designing the effective area of the cushion block to achieve desired shock performance of the package.

Keywords: Cushion, shock, trapezoid block, EPE foam, tapered angle

Running headline: Effect of cushion geometry on package performance

INTRODUCTION

A protective package is an interface between the fragile product and potentially harmful hazards in the distribution environment. A mechanical shock, associated with drops or other mishandling of packaged product, is considered to be the most severe hazard that a protective package must mitigate. Such a mechanical shock, however brief, may cause damage to the product. Fragility of a product is the intensity of mechanical shock it can withstand without being damaged.

The objective of a good cushioning design is to absorb the necessary mechanical shock and keep the resultant force below the fragility level of the product. A mechanical shock is characterized by sudden change in velocity of a product, resulting in high deceleration over a short period of time [1]. In an impact, the kinetic energy of a product compresses or deflects the cushion. By deflecting, a cushion increases the duration of the impact by providing space through which a product in motion is brought to rest. This action reduces the rate of deceleration and thereby mitigates the impact of mechanical shock.

The ability of a cushion to mitigate the shock is usually presented as a cushion curve. As per ASTM D1596 [2], a procedure developed by American Society for Testing and Materials (ASTM), cushion curves are developed by dropping predetermined weights onto a block of cushion of known thickness and area from a given drop height. This procedure recommends that the test specimens shall be right square prisms or other configuration as desired with the maximum length and width dimensions less than the corresponding drop platen dimension. Cushion curves describe the level of shock

transmitted by a given thickness of cushion block as a function of static loading on the cushion and drop height. Static loading is defined as the ratio between the weight of the product and bearing area of the cushion.

In designing a protective packaging using cushions, a packaging engineer searches through a variety of cushion curves to select a cushion with suitable thickness and area to adequately protect the product from mechanical shocks. When a contact area of a product is considerably larger than the cushion area required for shock protection, ribbed cushion may be used. The introduction of ribs may result in buckling which occurs when the length or width of a cushion is less than its thickness. Studies have indicated that when the minimum bearing area is less than 1.33 times the design thickness of cushion, buckling occurs [3]. To avoid buckling, the cushion should be stable enough to return to its original position and provide protection during more than one drop [4]. Buckling can be dealt with by changing the shape of the cushion to a tapered or trapezoidal block [5]. However, there is no recognized procedure which would guide a designer to a certain rib configuration. Most of the work done in this area has been intuitive in nature [6].

When the shape of a cushion block changes to a trapezoid, the bearing area of the cushion block also changes. In this case, the static loading is the ratio between the weight of the product and the area of the cushion that effectively bears the product weight (the effective contact area). The effective contact area is [5]:

- the actual contact area for rectangular cushion blocks if the product is in full contact with this area of cushion.

- the average between two parallel surface areas for trapezoidal cushion blocks if the product is in full contact with one of these areas (top or bottom).

Although cushion curves are generated using rectangular blocks, in reality the cushion geometry could be different from the rectangular or square prism in order to account for the center of gravity of product, buckling and other practical issues. It is difficult to effectively arrive at the cost-effective cushioning solution by simply using the published performance data such as cushion curves [7]. If the cushion design is shaped differently than a rectangular block then, the “in-package” shock loads might vary significantly from the cushion curves. Part A of this research focused on the effects of the contact area of cushion on the shock performance of the design.

Sometimes by design, the area of the cushion required will be more than the area of the product. In such cases, the effective contact area varies with the position of the product on the cushion. Consequently, the actual static loading may vary from the design static loading. As the effective contact area changes with the change in the position of the product on the cushion, the shock performance of the design could also vary. Part B of this research focused on the effects of the position of impact on the shock performance of the cushion.

EXPERIMENTAL DESIGN

Material and Design Overview

A. Tapered blocks

DOW Chemical’s expanded polyethylene foam (EPE) known as ETHAFOAM™ 220 brand, with density 2.2 lb/ft³ was used for this study. A 2 inch thick rectangular foam

block with a square base was used as a control. Two inch thick trapezoidal foam blocks with four different tapered angles (15° , 30° , 45° , and 60°) were used (see Figure 2.1). The area of the control block and effective contact area of tapered blocks was 36 in^2 . Four static load settings (0.2, 0.5, 1.0, and 1.5 psi) and a 36" drop height were used in this study. The volume of the control block and trapezoidal blocks was 72 in^3 .

B. Impact Position

Four inch wide and 2inch thick EPE cushion blocks, ETHAFOAM™ 220 with density lb/ft^3 , were used. Starting from one edge, impact position was moved towards the center of the cushion incrementally by 0.75 inch using five different lengths (6", 6.75", 7.50", 8.25" and 9") of blocks (see Figures 2.2). Three weight settings (18, 36, and 54 lb) and a drop height of 36" were used in this experiment.

All of the cushion blocks used were stored in ambient conditions, approximately 23°C and 50% RH, until they were utilized for the experiment. Following conditioning, these samples were tested for shock performance and the results were analyzed.

ASTM D1596 test procedure, Dynamic Shock Cushioning Characteristics of Packaging Material [2], was utilized for testing shock performance of the cushion blocks. Before testing, an accelerometer was fixed on the platen of the cushion tester to measure the shock response of the cushion blocks. Furthermore, the weights on the platen were adjusted to obtain the desired static loading for each set of drops. Using velocity sensor software, the drop height of 36" was set for all parts of this study. This software accounts for friction between the platen and guide bars and indicates the drop height equivalent. The platen was dropped from a height more than 36" and a trial and error method was

used until an actual drop height of 36" was determined using this software. The software determines the equivalent drop height by calculating the impact velocity. The impact velocity is calculated by measuring the time it takes for a 0.5" blade to travel through an infrared sensor.

Samples Used for Testing

A. Tapered blocks

For each static loading set up, five samples of control and tapered blocks per taper angle were tested. A cushion tester platen with predetermined weights was dropped five times on each of the samples. A one-minute gap between successive drops was maintained. Peak acceleration transmitted and duration for each impact were recorded using an instrumentation system. In this part of the study the static loading of rectangular cushion blocks (control block) with a square base was calculated as follows:

$$S.L_o = W/A \quad (1)$$

Where

$S.L_o$ = Static Loading, psi

W = Weight of the product, lb

A = Bearing area of the cushion, in².

Static loading on the trapezoidal cushion blocks was calculated based on the effective contact area [2] and the formula as follows (see Figure 2.1):

$$S.L_o = 2W/(A_T + A_B) \quad (2)$$

Where

$S.Lo$ = Static loading, (psi)

W = Weight of the product, lb

A_T = Area of the Top face, in².

A_B = Area of the base, in².

B. Impact Position

Impact position was changed incrementally from one edge of the block to the center by 0.75 inch. The impact of the platen was localized by using a wooden block of area 3" x 4" attached to the center of the platen. Three weight settings (18, 36, and 54 lb) were used by adding weights to cushion tester platen. Cushion deflection was measured using high-speed video equipment. The platen was dropped once on each of these five samples. Peak acceleration transmitted and duration for each drop were collected using a shock data acquisition system.

Equipment

A. Tapered blocks

All of the testing was conducted using a Lansmont Cushion tester, Model 23, with additional weights for varying static loading. Lansmont Test Partner TP3 and Velocity Sensor Version 1.01p software were used to record shock pulses. A PCB accelerometer (sensitivity = 10 mV/g) was fixed on the platen to measure the shock response of each impact.

B. Impact position

In addition to the set up mentioned previously, a Red Lake Motion Scope 500 camera was used to take the images of deflection. A Red Lake Motion Scope recorder was used to record the deflection of the cushion block during an impact. The images were observed using Microsoft Windows Power Point version 97 and analyzed visually.

Data Analysis

A. Tapered blocks

Once all testing was complete, the data were organized and cushion curves for 1st and for 2nd - 5th impacts were plotted (see Figures 2.3 and 2.4) (peak acceleration versus static loading) to analyze effects of taper angles on shock performance of the cushion blocks. Cushion curves of the control and tapered blocks were compared to identify the shock response with respect to effective contact area.

B. Impact position

To study the effects of position of impact on the shock performance of a cushion, images of cushion deflection were analyzed to identify the pattern of shock transmission. Cushion curves for all of the impact positions (see Figure 2.5) were plotted to compare the shock response of cushion blocks with respect to impact position.

DATA AND RESULTS

A. Tapered blocks

The effects of taper angle or trapezoidal shape on the shock performance of the control and tapered cushion samples were summarized and plotted as cushion curves. (see Tables 1 and 2 and Figures 2.3 and 2.4). Like typical cushion curves, these curves

showed relatively high acceleration transmission at lower static loading (0.2 psi). This is due to the light weight placed on the cushion tester platen which is not sufficient to deflect the cushion to its optimum working length. The cushions are rigid during impact and resemble dropping a product onto a rigid surface. It was observed that at 0.2 psi static loading the cushion block with a taper angle 60° transmitted the highest acceleration followed by the control sample and blocks with taper angles 45° , 15° and 30° (see Figures 2.3 and 2.4).

Between static loading 0.5 and 1.0 psi all cushion blocks, except the block with a taper angle of 60° , behaved similarly and their acceleration transmission was the lowest. This indicated that the falling platen induced sufficient force to deflect the cushion and to cause the deceleration to spread over a longer period of time.

As the static load was increased to 1.5 psi, the cushion blocks were over loaded and the falling platen made the cushion bottom out. Cushion blocks with a taper angle 60° transmitted the highest acceleration followed by cushion blocks with taper angles 45° , 30° , and 15° . The control block transmitted the lowest acceleration at this static loading.

B. Impact Position

The effect of impact position on the shock transmission of cushion blocks is summarized in Table 3. Results (see Figure 2.5) indicated that as the impact position moved towards the center of the cushion block the level of shock transmission was reduced. The slow motion video study indicated that the impact force was transmitted at an angle extending from the edges of the wooden block during an impact. The effective volume of cushion increased as the impact position moved from one edge of the cushion

towards the center. As the volume increased, the level of shock transmission decreased. It was also observed that not all cushion volume was used to transmit the impact energy. The effective volume used depended upon the angle at which the impact was transmitted from the edge of the wooden block.

DISCUSSION

A. Tapered blocks

Cushion curves of trapezoidal blocks (see Figures 2.3 and 2.4) showed that the peak acceleration transmitted varied when shapes of cushion blocks changed from rectangular to trapezoid. This indicated that when the shape changed, the effective contact area used to distribute the impact force was different from the calculated effective contact area. In this study, the area of control block and effective contact area of trapezoidal blocks were kept constant. From these results, it can be inferred that equivalent contact area is not enough for accurate designing especially if the tapered angle is increased towards 60° or more. Therefore, a static load adjusting factor must be incorporated in the design. The “Static Load Adjusting Factor” is defined as:

$$S.L_{af} = S.L_{\alpha}/S.L_o \quad (3)$$

Where

$S.L_{af}$ = Static Loading Adjusting Factor

$S.L_{\alpha}$ = Static loading (for a given taper angle), psi

$S.L_o$ = Static loading (rectangular shape), psi

By comparing the cushion curves of a trapezoid block and control block (see Figure 2.6), the static loads required to transmit a given level of shock by these blocks can be predicted. Using these static loads and Equation 3, the Static Load Adjusting Factor was obtained. Using this procedure, a Static Load Adjusting Factor for each of the tapered angles used in this study were determined (see Tables 4,5,6 and 7). In the absence of cushion curves for trapezoidal shaped cushions, the design static load can be obtained by multiplying this factor to the desired static loading from the published cushion curves. However, it might be beneficial to do further research to see whether a trapezoidal shaped cushion transmits a desired level of shock if its effective contact area were adjusted by the static load factor.

Analyzing shock pulses indicated that raise and decay time were almost equal at 0.2 psi static loading (see Figure 2.7). As the static loading increased to 1.5 psi, the difference between raise and decay time widened. Although the raise and decay time increased as the static loading increased, raise time was higher than the corresponding decay time at the higher static loading end. This indicated that the higher weight on the platen at higher static loading was able to deflect the cushion more than the weight at lower static loading. As the platen traveled more through the cushion, the raise time increased. But as the higher weight deformed the cushion and reduced its thickness the distance for rebound reduced accordingly. This resulted in reduction of decay time and a wider difference between raise and decay time at higher static loading.

B. Impact Position

The high-speed video analysis indicated that the area used by the cushion increased as the impact position moved towards the center of the cushion. As the area increased, the level of shock transmitted decreased. In cases where the product contact area was less than cushion top area, the required static load depended on effective contact area. The effective contact area in this case was calculated with a taper angle of maximum 45° [5] (see Figure 2.8). The calculated effective contact area and actual area used by the cushion to transmit shock are shown in Table 8. As the impact position moved towards the center, the area of the cushion used was slightly greater than the calculated area. From this result, it can be inferred that the impact force was extended at an angle just under 45° .

The tests were conducted only on EPE cushions of the dimension 6" x 6" x 2" and using a drop height of 36". Hence, generalization or inference on the effect of other materials and sizes might not be valid.

CONCLUSION

Results of these experiments confirmed that the shock performance of the cushion blocks varied with cushion shapes and cushion/product configuration. Although, the effective contact area and volume of cushion blocks used in this study were the same, cushion blocks with taper angle 30° and 15° transmitted the lowest shock between static loading 0.5 and 1.0 psi. This is the workable range of the cushion. Results of the effect of the impact position (Part B) indicated the importance of placement of product on the

cushion. For a given level of impact, the area used by the cushion varied with the position of impact.

In packaging cushion design these results can be used as a tool to determine the correct area of cushion, when using published cushion curves. In particular, the Static Load Adjusting Factor derived by comparing cushion curves can be used as an aid in predicting the design static load. An application example using this principle follows.

Determination of design static load for a trapezoidal shaped cushion.

Suppose a packaging engineer wants to design a trapezoidal rib with a 45° taper angle for a product with a weight (W) of 50 lb, fragility (G_c) of 44 g, and a drop height (DH) of 36". The following steps can be used to determine the design static load.

1. Using cushion curves for EPE 2.2 pcf and DH = 36" (see Figure 2.9), find the optimum static load (SL_o) to bear 44 g shock.

For example, from Figure 2.9 it can be predicted that the optimum static load to absorb a shock to 44 g is 1.0 psi (SL_o). If this static loading is used to calculate the effective cushion area (average of top and bottom area), then the area of the cushion required is as follows:

$$W/SL_o = 50 \text{ lb}/1.0 \text{ psi} = 50 \text{ in}^2.$$

Using the Table 6 find the static load adjusting factor (SL_{45}/SL_o) for corresponding design static load (SL_o). The static load adjusting factor (SL_{45}/SL_o) is 0.908 for the corresponding static load of 1.0 psi (SL_o)

2. Multiply optimum static load (SL_o) by the static load adjusting factor (SL_{45}/SL_o) to obtain the design static load (SL_{45}) for trapezoidal rib with 45° taper angle.

$$SL_{45} = SL_0 \times SL_{45}/SL_0 = 1 \times 0.908 = 0.908 \text{ psi}$$

The required effective area for the rib is as follows:

$$W \times SL_{45} = 50/0.908 = 55.06 \text{ in}^2.$$

This indicates that the effective contact area required is 5.06 in² more than effective contact area calculated by averaging top and bottom areas.

As it can be seen from the application example and results of this study, area used by the cushion blocks vary with shape and position of impact. Although the published cushion curves provide an excellent starting point for designing cushions, it would be appropriate if the effective area were determined according to the shape of the cushion and position impact.

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Figure 2.1 . Effective contact area of trapezoidal cushion block

Figure 2.2. Impact position

Table 1. Data of 1st impact on tapered and control cushion blocks

Static Load (psi)	Peak acceleration (g)				
	Taper angles				
	0°	15°	30°	45°	60°
0.2	72.6	69.5	63.2	71.0	78.1
0.5	53.4	51.2	49.6	52.0	57.6
1.0	54.3	53.4	55.3	56.6	69.2
1.5	69.2	77.8	77.4	82.6	97.6

Figure 2.3. Cushion curves 1st impact, for taper angles 0° to 60°

Table 2. Data on 2nd to 5th impact on tapered and control cushion blocks

Static Load (psi)	Peak acceleration (g)				
	Taper angles				
	0 ^o	15 ^o	30 ^o	45 ^o	60 ^o
0.2	79.5	77.4	70.0	78.8	79.8
0.5	62.6	62.6	62.0	66.1	73.4
1.0	73.1	71.9	74.3	75.7	93.0
1.5	90.6	100.0	105.7	113.5	134.2

Figure 2.4. Cushion Curve 2nd-5th impact, for taper angles 0° to 60°

Table 3. Shock transmission with respect to impact position

Sample Dimension	Weight (lb)					
	18		36		54	
	A _{peak} (g)	Duration (ms)	A _{peak} (g)	Duration (ms)	A _{peak} (g)	Duration (ms)
6" x 6"x 2"	45.6	25.70	66.5	23.10	104.5	14.90
6.75" x 6"x 2"	45.4	25.40	64.3	23.90	96.6	16.50
7.50" x 6"x 2"	45.0	24.90	64.2	23.90	95.2	16.70
8.25" x 6" x 2"	43.9	25.50	62.9	23.80	88.8	18.70
9" x 6"x 2"	43.8	24.90	55.9	25.00	83.2	17.30

Figure 2.5 Cushion Curve for Impact Position

Figure 2.6 Static Load Adjusting Factor

Table 4. Static Load Adjusting Factor for taper angle 15°

1 st Impact		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 15°) SL ₁₅ (psi)	Static Load Adjusting Factor $\frac{SL_{15}}{SL_0}$
0.4	0.366	0.915
0.6	0.466	0.776
0.8	0.446	0.557
1.0	0.400	0.400
1.2	1.158	0.965
1.4	1.300	0.928
1.5	1.358	0.905
2 nd -5 th Impact		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 15°) SL ₁₅ (psi)	Static load Adjusting Factor $\frac{SL_{15}}{SL_0}$
0.4	0.567	0.945
0.6	0.567	0.945
0.8	0.733	0.916
1.0	0.925	0.925
1.2	1.183	0.985
1.4	1.300	0.928
1.5	1.348	0.898

Table 5. Static Load Adjusting Factor for taper angle 30°

1st Impact		
Static load (Control Block) SL₀ (psi)	Static Load (Taper angle 30°) SL₃₀ (psi)	Static Load Adjusting Factor $\frac{SL_{30}}{SL_0}$
0.4	0.292	0.730
0.6	0.392	0.653
0.8	0.367	0.458
1.0	0.975	0.975
1.2	1.108	0.923
1.4	1.258	0.900
1.5	1.350	0.890
2nd-5th Impact		
Static load (Control Block) SL₀ (psi)	Static Load (Taper angle 30°) SL₃₀ (psi)	Static Load Adjusting Factor $\frac{SL_{30}}{SL_0}$
0.4	0.300	0.750
0.6	0.501	0.835
0.8	0.758	0.948
1.0	0.958	0.958
1.2	1.117	0.931
1.4	1.233	0.881
1.5	1.283	0.855

Table 6. Static Load Adjusting Factor for taper angle 45°

1 st Impact		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 45°) SL ₄₅ (psi)	Static Load Adjusting Factor $\frac{SL_{45}}{SL_0}$
0.4	0.375	0.937
0.6	0.483	0.805
0.8	0.800	1.000
1.0	0.908	0.908
1.2	1.033	0.860
1.4	1.192	0.851
1.5	1.275	0.850
2 nd -5 th Impact		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 45°) SL ₄₅ (psi)	Static Load Adjusting Factor $\frac{SL_{45}}{SL_0}$
0.4	0.375	0.937
0.6	0.483	0.805
0.8	0.800	1.000
1.0	0.908	0.908
1.2	1.033	0.860
1.4	1.192	0.851
1.5	1.275	0.850

Table 7. Static Load Adjusting Factor for taper angle 60°

1 st impact *		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 15°) SL ₆₀ (psi)	Static Load Adjusting Factor $\frac{SL_0}{SL_{60}}$
1.2	0.6	0.5
1.3	0.825	0.634
1.4	0.9	0.642
1.5	1	0.666
2 nd -5 th impact*		
Static load (Control Block) SL ₀ (psi)	Static Load (Taper angle 15°) SL ₆₀ (psi)	Static Load Adjusting Factor $\frac{SL_0}{SL_{60}}$
1.0	0.500	0.500
1.2	0.725	0.604
1.4	0.883	0.631
1.5	0.958	0.639

* Points beyond static load 1.0 were not possible to predict.

Figure 2.7. Raise Vs Decay Time

Figure 2.8 Effective area used when cushion bearing area is more than product area

Table 8. Area used by the cushion blocks with respect to position of impact.

Weight (lb)	Impact Position	Calculated area (sq. in)	Actual area (sq. in)
18	Corner	16	15.9
	0.75" from corner	17.5	17.22
	1.5" from corner	19	18.69
	2.25" from corner	20	18.70
	3" from corner	20	18.82
36	Corner	16	15
	0.75" from corner	17.5	16.9
	1.5" from corner	19	18.8
	2.25" from corner	20	18.4
	3" from corner	20	18.6
54	Corner	16	14.7
	0.75" from corner	17.5	16.98
	1.5" from corner	19	17.8
	2.25" from corner	20	18.1
	3" from corner	20	18.2

Figure 2.9. Cushion Curve for 2" thick EPE cushion (DH=36" and 1st Impact)

Chapter 3

SUMMARY AND RECOMMENDATIONS

Summary

Effects on shock transmission of (a) tapered angles of cushion blocks and (b) position of impact on the cushion block were investigated using Dow Chemical's two inch thick expanded polyethylene (EPE) cushion blocks known as ETHAFOAM 220 brand with density of 2.2 lb/ft^3 . Trapezoidal shaped cushion blocks were used because they are a standard shape used in cushion packaging design. The test was conducted at San Jose State University Packaging Laboratory using a Lansmont cushion tester Model 23, with Lansmont Test partner TP3 and Velocity Sensor Version 1.01p software (see Appendix A). In addition, a Red Lake Motion Scope 500 camera was used to record the effect of impact position on shock transmission of cushion blocks.

Tapered blocks

Trapezoidal shaped cushion blocks with four taper angles (15° , 30° , 45° , and 60°) and a rectangular cushion block with a square base (control) were used (See Appendix B). The area of the control block and effective contact area of the trapezoidal cushion blocks were kept at 36 in^2 . Four static load settings (0.2, 0.5, 1.0, and 1.5) were used. Five repetitions of each shape were tested at each static load setting and five drops were performed on each sample. A one-minute gap between successive drops was maintained.

Data on peak acceleration transmitted and duration for each impact were collected using an instrumentation system. The static loading of the rectangular cushion block

(control block) with a square base and trapezoidal cushion blocks were calculated using Equation 1 & 2 in chapter 2.

Impact position

Four inch wide and 2 inch thick EPE cushion (ETHAFOAM 220, 2.2 lb/ft³) blocks were used. Starting from one end, the impact position was moved towards the center of the cushion by 0.75 inch increments using five different lengths (6", 6.75", 7.50", 8.25" and 9") of foams (see Appendix C). Three weight settings (18, 36, and 54 lb) were used in this experiment. Impact of the platen was localized by using a wooden block of area 3" x 4" attached to the center of the platen. The platen was dropped once on each of the five samples. Data on peak acceleration transmitted and duration for each sample were recorded using a shock data acquisition system.

ASTM D 1596, Dynamic Shock Cushioning Characteristics of Packaging Material, was utilized to test shock performance of the cushion blocks (ASTM, 1998). All blocks used were stored in ambient conditions, approximately 23⁰ C and 50% RH, until they were utilized in the experiment.

Once all testing was completed, the data were organized and cushion curves for 1st and for 2nd to 5th impacts were plotted (peak acceleration versus static loading) to analyze the effects of taper angles on shock performance of the cushion blocks (see Appendix D). Cushion curves of control and tapered blocks were compared to identify the shock response with respect to the effective contact area. To study the effects of position of impact on shock performance of the cushion, cushion curves for the 1st impact

were plotted. Images of cushion deflection were analyzed using Microsoft Windows Power Point version 97.

Tapered blocks

Cushion curves (see Appendix D) revealed that as the shapes of the cushion blocks changed from rectangular to trapezoid, the peak acceleration transmitted varied. This indicated that, when the shape changed, the effective contact area used to distribute the impact force was different from the calculated effective contact area. In the cushion packaging design process, cushion curves published by the manufacturers of cushion material are used to determine the area of the cushion needed. These curves are plotted using rectangular cushion blocks with a square base, similar to the one used as a control block in this study. In fabrication when trapezoid shaped ribs become necessary, the effective contact area of the ribs will be determined using these published cushion curves. As results of this study indicated, the effective contact area is not enough for accurate designing, especially as tapered angles increased towards 60° . Therefore a “Static Loading Adjusting Factor” must be incorporated in design.

By comparing the cushion curves of a trapezoid block and a control block, the static loads required to transmit a given level of shock by these blocks were predicted. Using these two static loads, the Static Load Adjusting Factor was obtained using the Equation 3 in chapter 2. In the absence of cushion curves for trapezoidal shaped cushions, the design static load can be obtained by multiplying this factor to the desired static loading from the published cushion curves.

Analyzing shock pulses indicated that the raise and decay time increased as the static loading increased, and raise time was higher than the corresponding decay time at higher static loading. This indicated that the higher weight on the platen at higher static loading was able to deflect the cushion more than the weight at lower static loading. As the platen traveled more through the cushion, the raise time increased. But as the higher weight deformed the cushion and reduced its thickness, the distance for rebound reduced accordingly. This resulted in reduction in decay time and wider difference between raise and decay time at higher static loading.

Impact position

The results showed that as the impact position moved towards the center of the cushion block, the level of shock transmission was reduced. The high-speed video analysis indicated that the area used by the cushion increased as the impact position moved towards the center of the cushion (see Appendix E). This was expected because the static loading range for all drops were higher than the static loading for minimum acceleration (around 0.5-0.6 psi). In cases where the product contact area is less than the cushion bearing area, the required static load depends on effective contact area. The effective contact area in this case was calculated with a taper angle of maximum 45° (Marcondes & Schueneman, 1999). The actual area used was determined using the high-speed video analysis. This indicated that as the impact position moved towards the center, the area of the cushion used was slightly less than the calculated area. From this result, it can be inferred that the impact force was extended at an angle just under 45° .

Recommendation

In packaging, cushion fabrication ribs with trapezoidal shapes are common. And when the cushion design area is more than product contact area, in order to account for center of gravity and other practical factors, the product can be placed on the cushion at different positions. As the results of this study indicated, the effective area used by the cushion blocks to distribute shock vary with shape and position of impact. The results of this study can be used to adjust the area of cushion, when using published cushion curves. In particular, the Static Load Adjusting Factor derived by comparing cushion curves can be used as an aid to predict the design static loading.

Further studies are necessary to see whether a trapezoidal shaped cushion block transmits required level of shock, when its effective contact area is adjusted by the Static Load Adjusting Factor. Further research is recommended to determine whether a cushion block transmits the desired level of shock when impact position is moved away from the geometric of the center of the cushion block. Different materials and sizes should also be investigated to produce overall conclusions.

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APPENDICES

APPENDIX A
CUSHION TESTER SET UP

Figure A.1. Cushion tester set up

Figure A.2. Drop height adjustment for friction

APPENDIX B

CUSHION BLOCKS

Figure B.1 to B.5 show the cushion blocks used for testing

Figure B.1. Control cushion block

Figure B.2. Trapezoidal cushion block with 15° taper angle

Figure B.3. Trapezoidal cushion block with 30° taper angle

Figure B.4. Trapezoidal cushion block with 45° taper angle

Figure B.5. Trapezoidal cushion block with 60° taper angle

APPENDIX C

IMPACT POSITION

Figure C.1 to C.5 show impact position used in testing

Figure C.1. Impact position starting from left edge

Figure C.2. Impact position 0.75" from left edge

Figure C.3. Impact position 1.50" from left edge

Figure C.4. Impact position 2.25" from left edge

Figure C.5. Impact position 3" from left edge

APPENDIX D**SUMMARY OF TEST RESULTS OF PART (A)**

Figure D.1 and D.12 and tables D.1 to D.5 shows the results

Table D.1

Data of 1-5 Impacts on Control Block

Static load (psi)	I Impact Peak acceleration (g)		II Impact Peak acceleration (g)		III Impact Peak acceleration (g)		IV Impact Peak acceleration (g)		V Impact Peak acceleration (g)		Average of 2-5 impacts (g)	S.D of 2-5 Impacts (g)
	Average	S.D	Average	S.D	Average	S.D	Average	S.D	Average	S.D		
0.2	72.6	1.4	78.5	2.0	79.0	1.7	79.8	1.2	82.1	3.5	79.5	1.6
0.5	53.4	4.0	58.9	1.4	62.1	1.1	63.6	1.7	65.8	1.4	62.6	2.9
1	54.3	2.4	67.2	3.5	74.8	3.7	75.2	4.4	76.5	4.5	73.1	4.2
1.5	69.2	3.8	82.3	4.5	83.9	5.3	87.0	4.5	104.3	4.8	90.6	10.1

Table D.2

Data of 1-5 Impacts on Trapezoidal block with 15° taper angle

Static load (psi)	I Impact Peak acceleration (g)		II Impact Peak acceleration (g)		III Impact Peak acceleration (g)		IV Impact Peak acceleration (g)		V Impact Peak acceleration (g)		Average of 2-5 impacts (g)	S.D of 2-5 Impacts (g)
	Average	S.D	Average	S.D	Average	S.D	Average	S.D	Average	S.D		
0.2	69.5	1.8	75.3	3.4	77.4	5.9	78.8	6.7	78.4	7.9	77.4	1.6
0.5	51.2	0.4	60.0	1.0	61.8	0.9	63.9	1.0	65.0	1.4	62.6	2.3
1	53.4	5.3	66.2	6.6	69.4	4.4	80.9	4.0	82.3	0.7	71.9	8.1
1.5	77.8	6.7	91.1	4.3	98.8	8.6	101.0	9.3	110.3	2.6	100.0	7.9

Table D.3

Data of 1-5 Impacts on Trapezoidal block with 30° taper angle

Static load (psi)	I Impact Peak acceleration (g)		II Impact Peak acceleration (g)		III Impact Peak acceleration (g)		IV Impact Peak acceleration (g)		V Impact Peak acceleration (g)		Average of 2-5 impacts (g)	S.D of 2-5 Impacts (g)
	Average	S.D	Average	S.D	Average	S.D	Average	S.D	Average	S.D		
0.2	63.2	2.9	68.7	1.0	69.2	2.1	69.6	2.4	72.7	3.7	70.0	1.8
0.5	49.6	0.4	58.5	1.5	61.9	0.8	63.2	0.8	64.5	0.7	62.0	2.6
1	55.3	5.3	64.7	9.2	72.5	7.6	72.8	6.3	73.8	12.6	74.3	4.2
1.5	77.4	6.7	96.7	8.8	107.3	8.7	105.1	9.5	114.0	6.5	105.7	7.1

Table D.4

Data of 1-5 Impacts on Trapezoidal block with 45° taper angle

Static load (psi)	I Impact Peak acceleration (g)		II Impact Peak acceleration (g)		III Impact Peak acceleration (g)		IV Impact Peak acceleration (g)		V Impact Peak acceleration (g)		Average of 2-5 impacts (g)	S.D of 2-5 Impacts (g)
	Average	S.D	Average	S.D	Average	S.D	Average	S.D	Average	S.D		
0.2	71.0	1.8	76.3	2.4	79.4	2.6	79.0	1.3	80.5	2.4	78.8	1.8
0.5	52.0	0.8	62.5	0.9	65.9	1.1	67.7	1.0	68.6	0.9	66.1	2.7
1	56.6	7.9	69.5	3.0	71.7	2.9	78.4	2.1	87.9	7.4	75.7	8.3
1.5	82.6	4.3	110.0	2.2	114.5	4.7	114.6	3.8	115.0	7.4	113.5	2.4

Table D.5

Data of 1-5 Impacts on Trapezoidal block with 60° taper angle

Static load (psi)	I Impact Peak acceleration (g)		II Impact Peak acceleration (g)		III Impact Peak acceleration (g)		IV Impact Peak acceleration (g)		V Impact Peak acceleration (g)		Average of 2-5 impacts (g)	S.D of 2-5 Impacts (g)
	Average	S.D	Average	S.D	Average	S.D	Average	S.D	Average	S.D		
0.2	78.1	1.2	77.1	1.4	79.7	3.3	81.0	3.3	81.2	3.2	79.8	1.9
0.5	57.6	1.3	69.5	1.6	72.3	1.4	75.5	1.1	76.6	1.7	73.4	3.2
1	69.2	7.8	85.3	9.1	89.4	8.0	94.1	7.5	101.2	4.7	93.0	6.8
1.5	97.6	7.7	125.1	8.0	131.9	9.1	135.2	8.2	140.0	9.8	134.2	6.3

Figure D.1.1. Cushion curves 1st Impact, for taper angles 0° to 60°

Figure D.2. Cushion curves 2nd-5th Impact, for taper angles 0° to 60°

Figure D.3. Cushion curve for control block (1st Impact)

Figure D.4. Cushion curve for control block (2nd-5th impact)

Figure D.5. Cushion curve for trapezoidal block with taper angle 15° (1st impact)

Figure D.6. Cushion curve for trapezoidal block with taper angle 15° (2^{nd} - 5^{th} impact)

Figure D.7. Cushion curve for trapezoidal block with taper angle 30° (1^{st} impact)

Figure D.8. Cushion curve for trapezoidal block with taper angle 30° (2^{nd} - 5^{th} impact)

Figure D.9. Cushion curve for trapezoidal block with taper angle 45° (1st impact)

Figure D.10. Cushion curve for trapezoidal block with taper angle 45° (2^{nd} - 5^{th} impact)

Figure D.11. Cushion curve for trapezoidal block with taper angle 60° (1^{st} impact)

Figure D.12. Cushion curve for trapezoidal block with taper angle 60° (2^{nd} - 5^{th} impact)

APPENDIX E**HIGH SPEED ANALYSIS (PART B)**

Tables E.1 to E.15 show area used by the cushion blocks with respect impact position.

Table E.1. Cushion deflection (Static loading 0.5 psi, Impact position-Left corner)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=18
	t= 2		t= 20
	t= 4		t= 24
	t= 6		t= 26
	t= 8		t= 28
	t= 10		t= 30
	t= 12		
	t= 14		
	t= 16		

Table E.2. Cushion deflection (Static loading 0.5 psi, Impact position 0.75" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=18
	t= 2		t= 22
	t= 4		t= 26
	t= 6		t= 28
	t= 8		t= 30
	t= 10		
	t= 12		
	t= 14		

Table E.3. Cushion deflection (Static loading 0.5 psi, Impact position 1.50" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 18
	t= 4		t= 20
	t= 6		t= 22
	t= 8		t= 24
	t= 12		t= 26
	t= 14		t=28

Table E.4. Cushion deflection (Static loading 0.5 psi, Impact position 2.25" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
t= 2		t= 18
t= 6		t= 20
t= 8		t= 22
t= 10		t= 24
t= 12		t= 26
t= 14		t=28

Table E.5. Cushion deflection (Static loading 0.5 psi, Impact position 3" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=18
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 12		t= 28
	t= 14		
	t=16		

Table E.6. Cushion deflection (Static loading 1.0 psi, Impact position- left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t=0		t=16
t=2		t=20
t=4		t=22
t=6		t=24
t=8		t=26
t=10		t=28
t=12		t=30
t=14		

Table E.7. Cushion deflection (Static loading 1 psi, Impact position 0.75" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t=0		t=18
t=2		t=20
t=4		t=22
t=6		t=24
t=8		t=26
t=12		t=28
t=14		t=30
t=16		t=32

Table E.8. Cushion deflection (Static loading 1.0 psi, Impact position 1.5" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 10		t= 28
	t= 12		t=30
	t= 14		t=32

Table E.9. Cushion deflection (Static loading 1.0 psi, Impact position 2.25" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 10		t= 28
	t= 12		t=30
	t=14		t=32

Table E.10. Cushion deflection (Static loading 1.0 psi, Impact position 3" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t=0		t=16
t=2		t=20
t=4		t=22
t=6		t=24
t=8		t=26
t=10		t=28
t=12		t=30
t=14		t=32
		t=34

Table E.11. Cushion deflection (Static loading 1.5 psi, Impact position- left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
t= 2		t= 18
t= 4		t= 20
t= 6		t= 22
t= 8		t= 24
t= 10		t= 26
t= 12		t=28
		t=30

Table E.12. Cushion deflection (Static loading 1.5 psi, Impact position 0.75" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 10		t= 28
	t= 12		t=30
	t=14		t=32

Table E.13. Cushion deflection (Static loading 1.5 psi, Impact position 1.5" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
t= 2		t= 20
t= 4		t= 22
t= 6		t= 24
t= 8		t= 26
t= 10		t= 28
t= 12		t=30
t=14		t=32

Table E.14. Cushion deflection (Static loading 1.5 psi, Impact position 2.25" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 10		t= 28
	t= 12		t=30
	t=14		t =32

Table E.15. Cushion deflection (Static loading 1.5 psi, Impact position 3" from left edge)

Forward Motion	Time (msec)	Rebound	Time (msec)
t= 0		t=16
	t= 2		t= 20
	t= 4		t= 22
	t= 6		t= 24
	t= 8		t= 26
	t= 10		t= 28
	t= 12		t=30
	t=14		t=32