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JOONGMIN SHIN

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Gary Burgess
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CORRUGATED CUSHION VS. EPS; A COMPARSION OF CUSHION PROPERTIES

BY

JOONGMIN SHIN

A THESIS

Submitted to
MICHIGAN STATE UNIVERSITY
in partial fulfilment of the requirements
for the degree of

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2004

ABSTRACT

CORRUGATED CUSHION VS. EPS; A COMPARSION OF CUSHIONPROPERTIES

BY

JOONGMIN SHIN

Cushioning systems, which are cushion material and its designed configuration, are important to protect fragile items since they act as buffers between the impact force and the fragile product. As cushion materials, several plastic foams are commonly used in industry. Among plastic cushion materials, EPS is the oldest synthetic and the most widely used cushion material with a multitude of applications with various advantages. It is utilized for a variety of products, which require a careful protection such as consumer electronics and furniture. However, utilization of the material has been causing a solid waste problem and pollution. Thus, as an alternative cushion material to EPS, a corrugated cushion, which is considered environmentally friendly and cheap material, was put into drop tests and, and its impact shock attenuation was investigated. Two types of a corrugated cushion were constructed, "flat crush mode" and "edge crush mode". Flat and free fall drop data were recorded and compared to the dynamic shock of EPS cushion. In addition, the published cushion curves and corrugated cushion design formulas were compared to the actual shock G. For laboratory parts, a cushion tester, free drop tester, and EDR were used to evaluate their overall cushion properties.

The results show that the corrugated cushion gives an excellent protection for items that are subjected to the limited number of drops. Also, there is a potentiality to improve its cushion properties through changing its designs.

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ACKNOWLEDGEMENTS

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CHAPTER 1. INTRODUCTION

Cushioning systems (cushion material and its designed configuration) are incorporated in package-product systems to protect fragile items. When a package is dropped on a rigid surface, the cushion system which is contained in the package acts as a buffer between the impact force and the fragile product. The product does not stop as abruptly as the outer container impacts the ground. The cushion allows it to slow down gradually [1]. Therefore, cushioning systems are important to protect fragile products in distribution. For cushioning materials, there are several plastic fabricated foams that are widely used in industry; Expanded Polystylene (EPS), Polypropylene foam, Polyethylene foam, and Urethane foam. EPS is considered the standard cushioning material used in consumer product applications, and represents the baseline against which the other materials are compared [2]. Among plastic cushion materials, EPS is the oldest synthetic and the most widely used cushion material with a multitude of applications, since it is light weight, has a high strength to weight ratio, and low moisture absorption properties. EPS is utilized for a variety of products which require protection, like consumer electronics, furniture, and so on. However, the solid waste problem with EPS makes its utilization a concern. Moreover, environmentally friendly materials are being supported by the government in terms of recycling laws.

The environmentally friendly cushioning material, corrugated board, was introduced in the early 1950's. Corrugated board has three layers of paper assembled using a series of arches, which gives it compression resistance and reasonable rigidity to support heavy weights. This structure provides an almost unlimited combination of board types, flute sizes, weights, adhesive types, coatings, and so on. One easy way to make corrugated cushions from corrugated board is to attach each layer using glue. In this research, two types of cushions were constructed; the "flat crush mode" and the "edge crush mode". For the same size cushion, the edge crush mode can support heavier products, but the flat crush mode, and the flat crush mode gives lower G values compared to the edge crush mode.

Corrugated board can be a very useful cushion material. It is environmentally friendly with an unbeatable record for recycling and recovery as well as economical cost. However, corrugated cushions tend to produce higher shock levels than EPS as the number of drops increases because the mode of deformation is one of crushing (permanent deformation) rather than elastic compression and recovery as with foam cushions. Moisture sensitivity is another problem. Since paper is susceptible to moisture gain, corrugated cushions lose their resilience and elasticity at high relative humidity conditions. Corrugated cushions will also be too brittle in extremely low relative humidity conditions. Finally, as a marketing issue, consumer perception is a problem. People think a corrugated cushion is usually used for cheap products because it is a cheap material. Therefore, the use of corrugated board as a cushion has been limited, and has been neglected in research aimed at evaluating corrugated board as a cushion. Through this study, corrugated cushions will be compared as a cushioning material to EPS, and will be evaluated for their shock transmission properties. Conventional cushion curves for EPS and design formulas for corrugated cushions will be tested for their accuracy and ability to produce effective cushions. The detailed objectives of this study are as follows:

1. Check the accuracy of published cushion curves for EPS.

The published shock transmission characteristics (ASTM D-1596) of EPS cushion may not be accurate. Some are more than 10 years old before they are checked again. Material composition may change over this long time. Using the cushion tests, the actual shock transmission characteristics will be evaluated and compared to the published curves.

2. Design and test corrugated fiberboard cushions

- Evaluate the accuracy of corrugated cushion design formulas.

The cushioning characteristics of corrugated cushions can be estimated using simple design formulas for the number of useful drops, the dynamic shock G, and the dynamic deflection. However, there has been no recent research to verify these design formulas. This study will evaluate the accuracy of corrugated cushion design formulas.

- Recovery properties of corrugated cushions.

EPS is used by many consumer product manufacturers because of its multiple-impact protective properties. Corrugated cushions are not regarded as being resilient, losing all of their cushioning properties after several drops. Its lack of resilience makes it perceived as a cheap packaging material. However, there is still the possibility that corrugated cushions retain enough resilience to be useful.

-Comparison of dynamic shock G values for different alignments of the flutes in corrugated cushions.

Corrugated fiberboard cushions will be constructed of layers having their flutes oriented three different ways; aligned parallel flutes, perpendicular parallel flutes, and misaligned flutes. The G values from each will be measured and compared to each other.

3. Compare cushioning performance between EPS and corrugated cushions, with actual product in drop tests.

Impact G value is one of the most important parameters used to estimate cushion properties. An impact data recorder packaged in both EPS and corrugated cushions will be used to compare the two.

CHAPTER 2. LITERATURE REVIEW

2.1 "Edge Crush Test" and "Flat Crush Test" on corrugated board

The edge crush test (ECT) measures the edgewise compressive strength, parallel to the flutes, of a short column of corrugated board. According to TAPPI T 402[ref], the edge crush test is performed as in Figure 1. The edgewise compression resistance of corrugated board is used to estimate box compression strength. The flat crush test (FCT) is a measure of the ability of the corrugated board to resist being crushed under the action of a compressive force perpendicular to the surface. Figure 2 shows the test procedure for measuring flat crush resistance. The flat crush strength is critically important to corrugated board because it is closely related to the strength of the fluted medium. A stronger medium gives a higher flat crush strength. This reduces crushing during conversion and product use [5]. The strength of the medium however decreases with multiple drops.

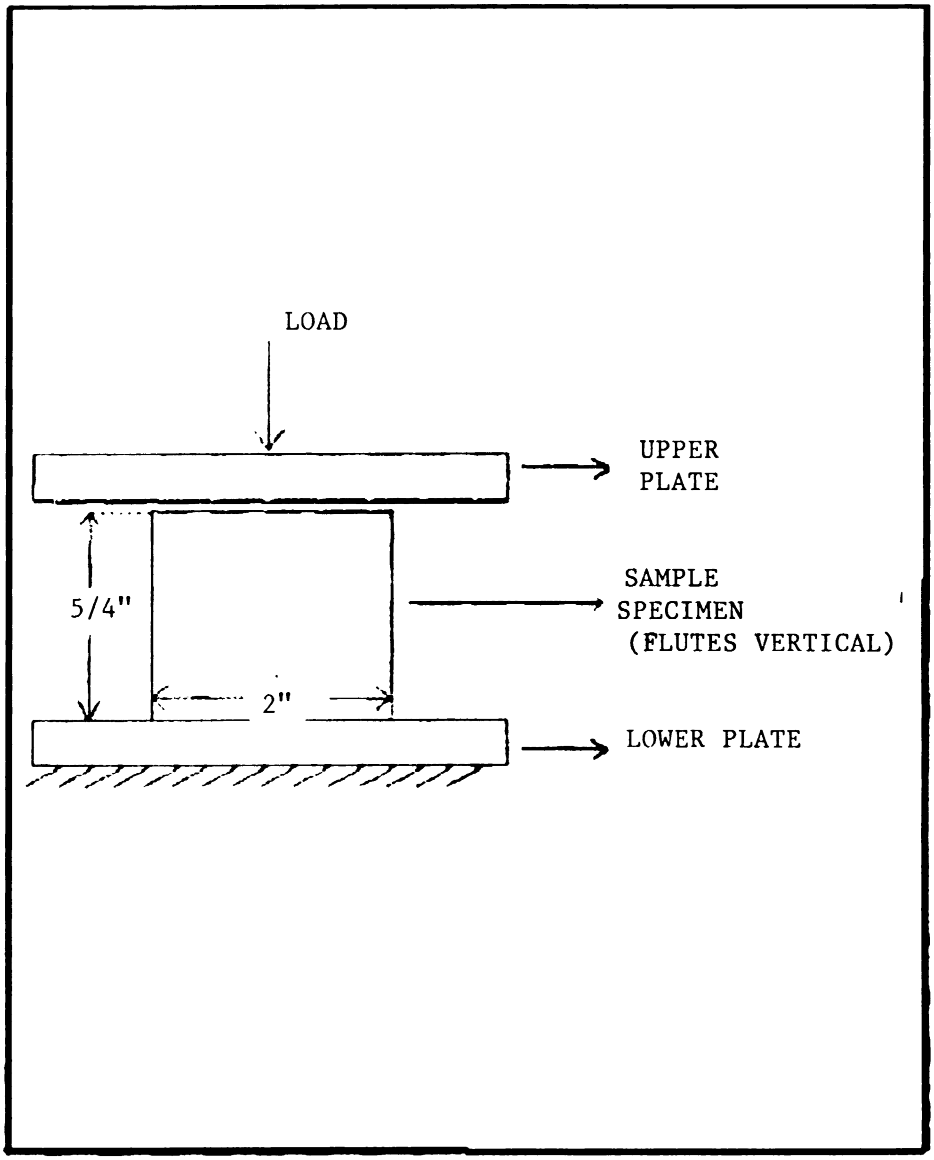


Figure 1: Edge Crush Test

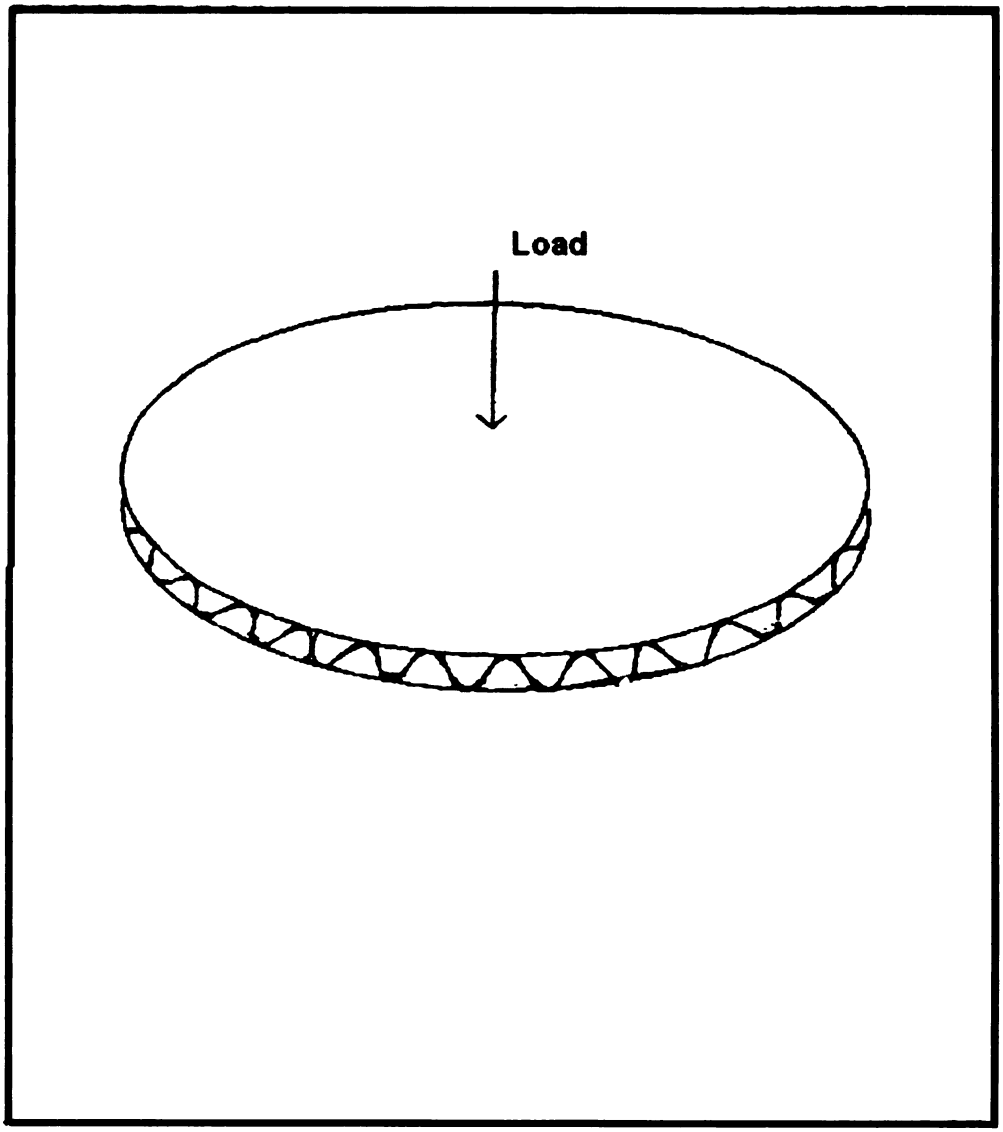


Figure 2: Flat Crush test

2.2 Corrugated cushion design formulas

There is not much published on corrugated board used as a cushioning material. Consequently, there are no widely used cushion curves to predict shock transmission characteristics for the material. However, through several formulas, it is possible to estimate the shock G value without them. To estimate the G value, we need a measure of the resistance to compression. This is provided by both the ECT and FCT values for the board. When medium in layer balance along with newton's law, the resulting design equations are:

$$G = \frac{ECT \times L}{W} \text{ if edge crush mode, or}$$

$$G = \frac{FCT \times A}{W} \text{ if flat crush mode} \tag{1.1}$$

$$\text{Dynamic deflection} = \frac{h}{G} \tag{1.2}$$

$$\text{Shock duration} = \frac{1}{G}\sqrt{\frac{2h}{g}} \tag{1.3}$$

$$\text{Number of useful drops} = \frac{\textit{Cushion thickness}}{\textit{dynamic deflection}} \tag{1.4}$$

The ECT and FCT values along with the cushion geometry (length or area) and product weight (wt) provide enough information about the material to determine G in any situation involving flat drops onto cushions operating in the edge crush and flat crush modes respectively. The formulas are derived by using Newton's second law, which states that:

$$F = W \times G \tag{1.5}$$

F =peak impact force on the product

W = weight of the product

G = peak acceleration of the product expressed as a multiple of gravity, g

g = acceleration due to gravity = 386.4 in/sec^2

So G can be determined from:

$$G = \frac{F}{W} \tag{1.6}$$

Newton's third law states that the force exerted by the corrugated cushion on the product is equal in magnitude and opposite in direction to the force exerted by the product on the cushion. In the edge cushion mode, the force on the cushion acts to crush it. In the process of crushing it, this force is:

$$F = ECT\ (lb/in) \times L\ (in) \tag{1.7}$$

Where L means "edge length" for a cushion. It is the total length of edge the falling weight acts upon. For example, a ten layer edge crush cushion where each layer has a length of 2.5" would have a total edge length of 25 inch.

Through Newton's first and second laws, equation (1.6) becomes:

$$\text{Edge crush } G = \frac{ECT(lb/in) \times L(in)}{W(lb)} \tag{1.8}$$

The same method is used to derive the flat crush G. The reaction force is given by:

$$F = FCT\ (lb/in^2) \times A\ (in^2) \tag{1.9}$$

where A is the area of board the falling weight acts upon. For example, a ten layer flat crush cushion where each layer measures 2" x 3" has an area of 6 in^2.

Substitution into equation (1.6) yields:

$$\text{Flat crush } G = \frac{FCT(psi) \times Area(in^2)}{product\ weight(lb)} \tag{1.10}$$

Formula (1.10) shows that in the flat crush mode, only the bearing area is needed to estimate the peak G in a drop. No matter how many layers are in a flat crush cushion, the peak G is predicted to be independent of the number of layers.

If a corrugated cushion "bottoms out" after several drops, the predictions are invalid. This can be determined by evaluating the dynamic deflection in a drop. In order to calculate dynamic deflection, the following energy balance is manipulated: potential energy= weight x drop height = force x dynamic compression.

The force is the same as before: ECT x L for an edge crush cushion and FCT x A for a flat crush also.

$$\text{Dynamic deflection} = \frac{Wh}{F} = \frac{Wh}{Wg} = \frac{h}{G} \tag{1.11}$$

Substituting the forces from equations (1.7) and (1.9) gives:

$$\text{Dynamic deflection (for ECT mode)} = \frac{W(lb) \times h(in)}{ECT \times L(in)} \tag{1.12}$$

$$\text{Dynamic deflection (for FCT mode)} = \frac{W(lb) \times h(in)}{FCT \times A(in^2)} \tag{1.13}$$

If the force required to crush corrugate board remains relatively constant, as the board cushiones, a relatively constant acceleration should be experienced by the falling weight. Thus, the allowable number of drops can be predicted by calculating the dynamic deflection in each drop using equation (1.12) and (1.13) and treating this as a permanent deflection. The cushion bottoms out when these deflection accumulate to the thickness of the cushion. Dividing the thickness by this amount:

$$\text{The number of useful drops} = \frac{\textit{Cushion thickness}}{\textit{dynamic deflection}} \tag{1.14}$$

This assumes that the dynamic deflection is a permanent deflection. Equations (1.10) and (1.13) predict that the number of layers has no effect on the flat crush G or its dynamic deflection, but it does affect the number of useful drops because the thickness depends on the number of layers.

2.3 Humidity effects

The performance of corrugated board depends on humidity conditions.

As humidity increases, the board gets weaker. The following Table 1 shows the relationship between strength at a reference humidity of 50% RH and the strength at any other relative humidity. At 85% RH for example, a box is only 60% as strong as at 50% RH. Since box compression strength is proportional to the ECT of the board used to make it, this means that the ECT of the board is only 60% of its value under that conditions of 50% RH.

RH	Percent strength retained
0%	125 %
25%	110 %
50%	100 %
75%	80 %
85%	60 %
90%	50 %

Table 1. Corrugate board strength vs relative humidity (RH)

Humidity affects the performance of corrugated cushions the same way. The ECT and FCT are adjusted using the same strength retention factors. According to equations 1.8 & 1.10, the G values should also be adjusted by the same account. So the peak G at % RH should be 60% of the peak G at 50% RH. The G goes down because the cushion is softer. This is good. But the dynamic deflection increases proportionally giving fewer useful drops.

2.4 The Environmental Data Recorder (EDR)

The "Environmental Data Recorder" is a portable data recording system for making dynamic field measurements. Using the EDR lets us measure what actually happens in a drop. This sensor records shock pulses using a tri-axial accelerometer. It records G in the X, Y, and Z directions. The unit itself and the three shock pulses are shown in Figure 3. The unit records three shock pulses for every drop and later combines this information to arrive at the drop height and other relevant information through the use of software. These recorders are packaged in rugged aluminum housings for use in harsh environments, and engineered for high shock and vibration survivability while fully operable over a large temperature range.

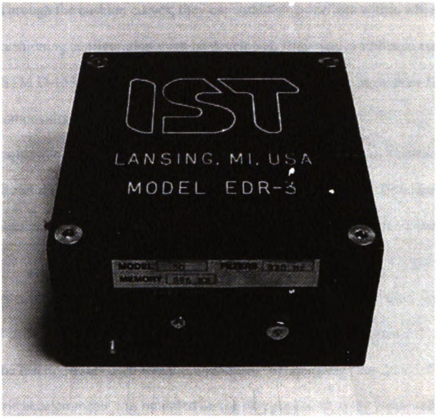


Figure 3. Environmental Data Recorder

CHAPTER 3. MATERIALS AND EXPERMENTAL DESIGN

3.1. verification of EPS cushion curves

Traditionally, packaging engineers design cushions by combination knowledge of a product's fragility level, and weight, and dynamic cushioning curves for the cushion material. Through the cushion curves, they can establish guidelines within which an effective cushioning configuration must be developed. However, established cushion curves (ASTM D-1596) may not be accurate because they may be more than 10 years old. Material composition may be changed during that period.

Shock transmission properties of cushioning materials are measured on a cushion tester. Figure 4 shows the set up that was used in this research. 1.5 inch thick EPS cushion were cut to dimensions 8" x 5", and tested using two different drop heights of 18 and 30 inches. Each sample was subjected to 5 impacts and the "1st impact" G and "2~5 impact" G's were recorded. Weights of 40lbs, 32lbs and 20lbs were used to set the "static stress" 1.0psi, 0.8 psi and 0.5 psi for each height. So, the total number of drops was 2 x 5 x 3 x 5= 150. The test apparatus used was a LANSMONT MODEL 23 Drop tester. A piezoelectric accelerometer was mounted on the dropping head of the tester and the signal was carried by a shielded cable to a "Piezotron" charge amplifier and then on to a twelve bit analog to digital card on an computer. The peak acceleration of the platen was recorded together with the corresponding static load. Test Partner (LANSMONT CORPORATION) was used to analyze the shock pulses. An example of the acceleration, shock pulse, velocity and displacement recorded in an impact is shown in Figure 4.

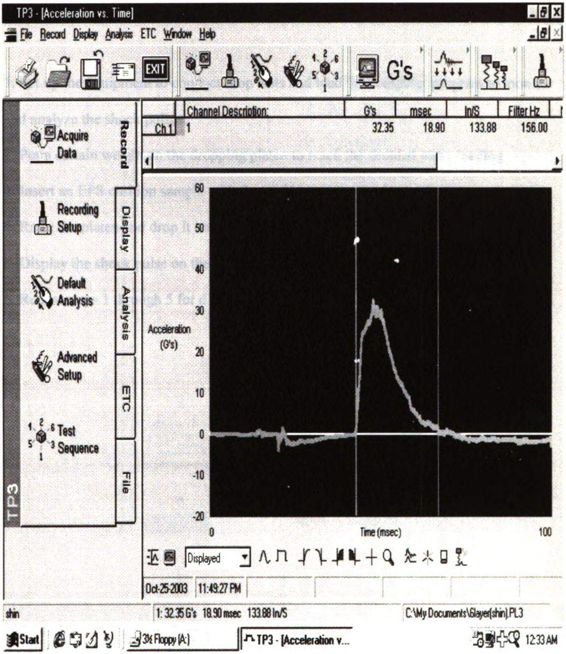


Figure 4. A shock pulse record from corrugated cushion

ASTM D1596 was used as a guideline for all testing. The drop tests onto the EPS cushion samples were performed as follows:

1. Set up the equipment to conduct drop tests and load the computer program to monitor and analyze the shock pulses.
2. Put a certain weight on the dropping platen to reach the decided static loading.
3. Insert an EPS cushion sample with the cushion tester (see Figure 5)
4. Raise the platen and drop it onto the cushion.
5. Display the shock pulse on the monitor and read the peak deceleration value.
6. Repeat steps 1 through 5 for different thicknesses, static stresses and drop heights.

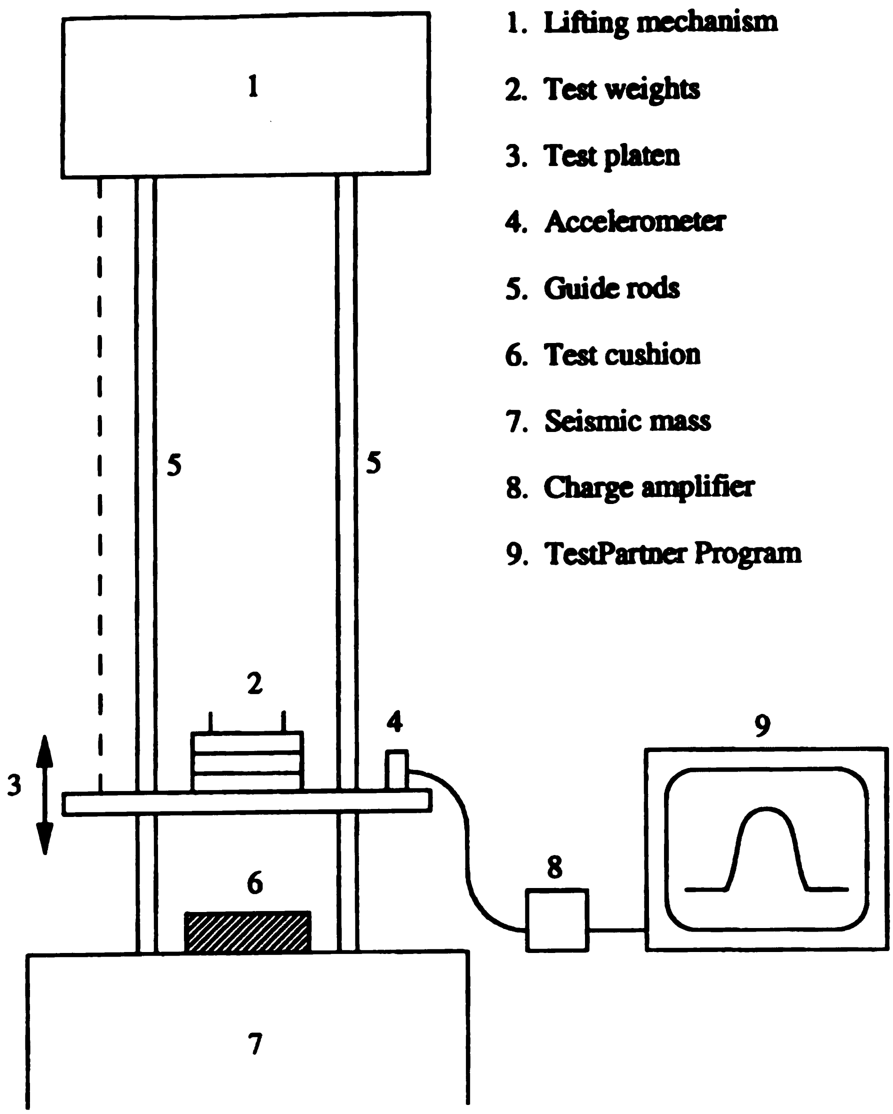


Figure 5. Dynamic Cushion Tester for Drop test

The actual drop heights used on the machine were not 18" and 30" because there is friction between the guide rode and platen. Consequently, actual platen drop height is slightly greater than the free fall drop height to compensate for the friction. So equivalent drop heights based on the impact velocity were used in place of actual drop heights. The cushion tester used a photoelectric sensor which is mounted just above the impact surface of the cushion. It measured the amount of time, which is called gate time, for a ½" wide trigger blade mounted on the dropping head to pass through it. This time value can then be substituted into the following equation

$$V= \frac{d}{t} \tag{3.1}$$

where,

V= impact velocity (in/sec)

d= width of the trigger blade= ½"

t= gate time (sec)

The equivalent free fall drop height h corresponding to this impact velocity must be obtained from:

$$h= \frac{V^2}{2g} \tag{3.2}$$

where,

h= free fall height

V= impact velocity (in/sec)

Table 2 shows the gate times and impact velocities required to produce 18" and 30" free fall heights.

Table 2. Gate times vs free fall drop height

Gate Time (ms)	Impact Velocity (in/sec)	Free Fall Drop Height (in)
4.27 ± 0.02	117.9 ± 0.57	18 ± 0.17
3.30 ± 0.02	152.3 ± 0.91	30 ± 0.36

3.2. Corrugated board cushions

Several tests were performed to compare corrugate fiberboard cushion properties with EPS. All corrugated cushion samples were pre-conditioned for at least 24 hours at standard conditions of 72 F, 50% RH. The board flute type used C-flute, the middle in profile shape of the three commonly used profiles, A, B and C flutes. All cushion modes were designed so that cushions were longer in the machine direction except for "shock absorbance of corrugated board in three different arrangements" (section No. 3.2.3)

3.2.1 Flat and edge crush tests

TAPPI Standard T808 om-86 and ASTM D2808-90 were used to determine the ECT and FCT. Twenty pre-conditioned specimens were cut by a TMI standard circular sample cutter and TMI standard edge crush sample cutter. A 400 Series TMI Crush Tester, Model no. 17-36 was used to determine FCT and ECT data. Tests were conducted in accordance with the applicable standards, except for dipping the edges of the board sample in molten paraffin for the ECT test. This was done to be closer to actual resistant forces in nature during drop tests.

3.2.2 The effect of number of layers in the FCT mode

According to the formula [1.10], the number of layers in a flat crush cushion in theory should have no effect on the G as long as the impact does not completely flatten the flutes. The force required to crush one layer is the same as the force required to crush whatever number of layers because the force is transmitted unchanged through the stack of layers. However, "edge crush" cushions are completely different. The number of layers are strongly related to G value because they affect the edge length. To demonstrate the effect of cushion layers in the FCT mode, different numbers of layers of corrugated board was subjected to constant static loading impacts. To avoid the flutes flattening, weights of 32 lbs, 20 lbs, and 13 lbs were used. Five different corrugated fiberboard cushions in layers of three, four, five, six, and seven were constructed and tested using an 18 inch fixed drop height. Regardless of the thickness of cushion used, each layer had the same contact area. The cushion sizes tested were 8" X 5". Each cushion was assigned one flat drop and replicated, so that the static loadings were kept constant at 0.325psi, 0.5 psi, and 0.8 psi. The test apparatus used was a LANSMONT MODEL 23 cushion tester. Therefore, the total drops were 3 x 5 x 5= 75 times in this test. The shocks recorded by the software were filtered at 125 Hz. The reason 125 Hz was chosen as a filter frequency is that normal shock duration was 20 ms. Then the shock pulse frequency was 1/(2 x 0.020)= 25 Hz and the recommended filter frequency is 5 times the shock pulse frequency.

3.2.3. Shock transmission of FCT cushions in three different arrangements

In the FCT cushion mode, flute strength, which is its main resistance against compressive forces applied perpendicular to its surface, is used to attenuate shock values. To investigate whether there are any differences in the shock levels transmitted by corrugated cushions due to differences in the alignment of the flutes in the corrugated board cushion, tests were performed on three sets of square 1 inch thick 8 in x 8 in C-flute corrugated fiberboard cushions: "mis-aligned flutes", "perpendicular flutes", and "aligned flutes".

To construct 1inch thickness of corrugated fiberboard cushion, six layers of C-flue corrugated board were glued together using spray adhesive.

The "mis-aligned flutes" pattern is shown in Figure 6. The layers were glued together, and their peaks and valleys were lined up.

The "perpendicular flutes" cushions were constructed with layers placed in an alternating fashion, so the flutes were perpendicular to each other as shown in Figure 7. The "aligned flutes" cushions were constructed as in Figure 8, with the peaks of a layer aligned with valleys of another layer.

The effect of flute alignment was evaluated using a drop height of 18 inches on a LANSMONT MODEL 23 cushion tester with a piezoelectric accelerometer. The platen weights were 51 lbs, 32 lbs, and 13 lbs so that the static loadings were kept constant at 0.2 psi, 0.5 psi, and 0.8 psi. Each cushion was subjected to five consecutive drops with 1 min waiting time. The shock values were recorded after filtering at 125 Hz. These values were then averaged over the five cushions tested for each cushion mode. The design giving the lowest G was selected and used in comparison tests with EPS cushions.

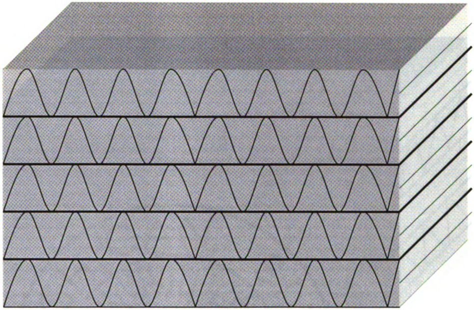


Figure 6. Mis-aligned flute cushion

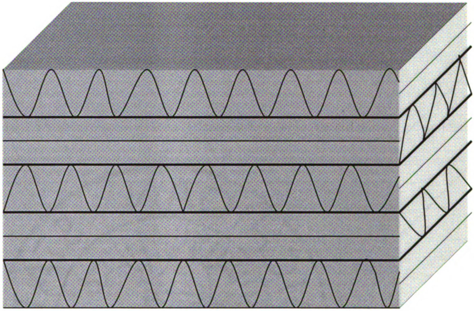


Figure 7. Perpendicular flute cushion

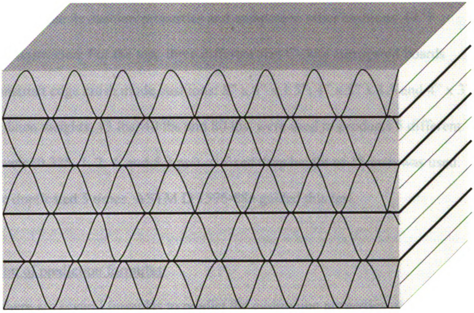


Figure 8. Aligned flute cushion

3.2.4 Shock transmission for ECT cushion

The "edge crush" mode is very strong and is suitable for cushioning heavy weight products. To investigate its cushion properties and compare to other cushions, ECT cushions were constructed. For the test, three different size C-flute corrugated boards were cut to construct edge crush mode cushions: 8" x 5" x 1.5", 4" x 5" x 1.5 and 4" x 3" x 1.5. Three platen weights, 13 lbs, 40 lbs and 80 lbs, were used to products 5 different static stress levels (0.325, 1, 2, 4, and 5.3 psi). A fixed drop height of 18 inch was used. All drops were duplicated 5 times. ASTM D 1596-88a guided this test.

3.2.5 Evaluation of prediction formulas

In Chapter 2, there are several formulas to predict the cushioning properties of corrugated cushions. As outlined earlier, the following formulas predict what happens in a drop:

$$G = \frac{ECT \times L}{W} \text{ for edge crush mode}$$

$$G = \frac{FCT \times A}{W} \text{ for flat crush mode} \qquad (3.3)$$

$$\text{Dynamic deflection} = \frac{h}{G} \qquad (3.4)$$

$$\text{Number of useful drops} = \frac{Cushion\ thickness}{dynamic\ deflection} \qquad (3.5)$$

The above formulas were used to predict read G, dynamic deflection, and number of drops. The predictions were then compared to actual data.

3.3. Comparison between EPS and corrugated board cushions

A comparison between EPS and corrugated cushions was performed.

To construct the best corrugated fiberboard cushion, all test results from section 3.2 were considered to design the corrugated cushion which would be compared with EPS. Once a cushioning configuration had been developed, however, the package designer cannot fully predict how a cushioning system will behave and perform in an actual package product application. Therefore, the design must be evaluated for performance in a specific application. For the performance evaluation, the International Safe Transit Association (ISTA) Pre-Shipment test procedure was used to evaluate this design and to compare to EPS. For the test, The EDR-3C from IST was used as the product in order to measure the G's transmitted in a drop.

The sensor recorded all acceleration-time histories and shock duration for each drop series. The program, DynaMax, was used to download all data from the EDR-3C. Every drop was filtered at 125 Hz (no lower than 5 times the basic pulse frequency) to eliminate "noise". The overall procedure for this test is as follows:

1. As in Figure 9, identify and label the following surfaces of the package-EDR3C system: top as '1'; right side as '2'; bottom as '3'; left side as '4'; front as '5'; and back as '6'. Figure 9 shows the labeling of surfaces of the system.

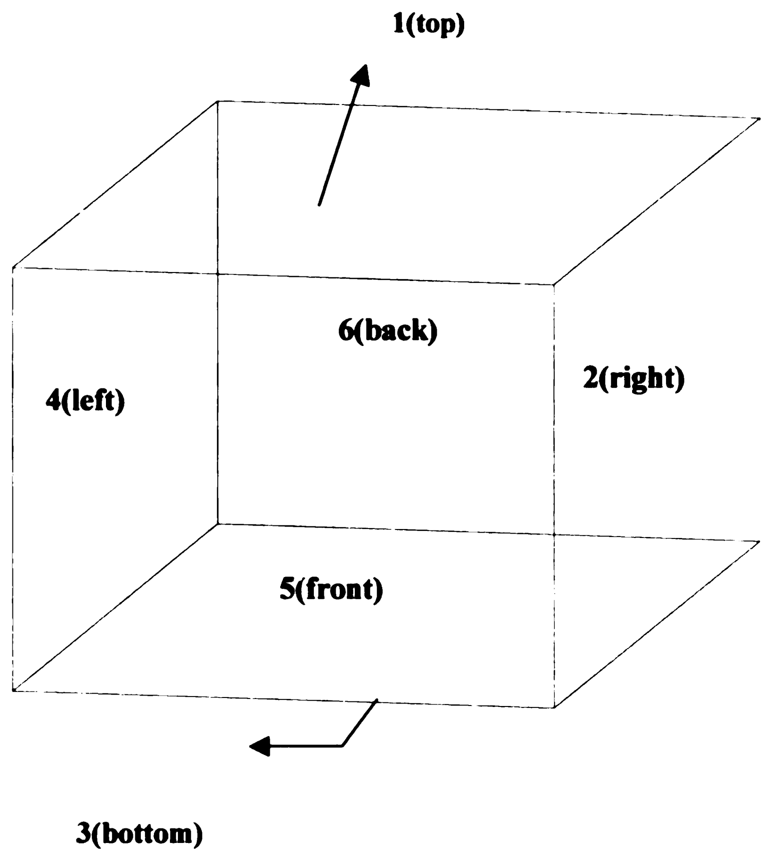


Figure 9. Identification of number for surface of the package-EDR3C system

2. Identify edges by the number of those two surfaces forming that edge. For example, the edge forming the top and right side is identified as 1-2.

3. The drop height shall be set based on package-EDR3C system weight; 1 through 20.99lbs, 30 inch; 21 through 48 lbs, 24 inches; 41 through 60.99 lbs, 18 inches; and 61 lb up to and including 100.00lbs, 12 inches. (specification do exist for heavier product). The weight of package-EDR3C was less than 30 lbs. so the drop height was set to 30 inches.

4. Drop or impact the package-product system as specified under following sequence

   (1) Flat on one of the smallest face

   (2) Flat on the other of the smallest face

   (3) Flat on one of the medium face

   (4) Flat on the other of the medium face

   (5) Flat on one of the largest face

   (6) Flat on the other of the largest face

   (7) Corner drop (3 corner).

5. Inspect both the package and the product. The EDR was regarded as the product. All shock responses were recorded and downloaded into the computer through a USB cable. The Dynamax software was used to analyze shock pulses. The shock pulses were displayed by the computer program. (See figure 10).

ISTA standards include the influence of vibration tests on the effectiveness of a package design. However, the effect of vibration is considered minimal because the EDR is light weight product. Vibration tests were therefore omitted from the evaluation of cushioning comparison test between EPS and corrugate fiberboard cushion.

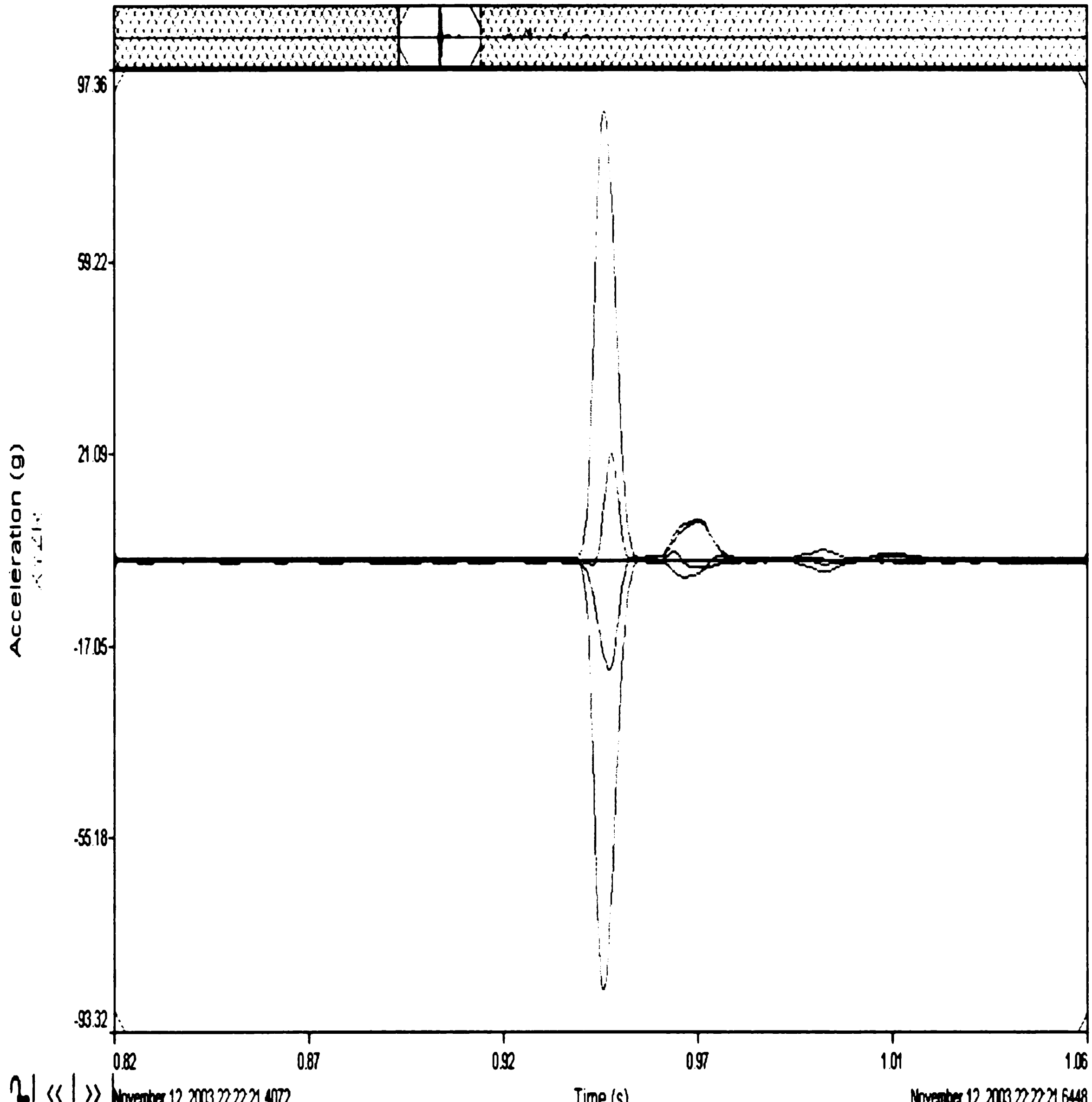


Figure 10. Analyzed shock pulse from software

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Verification of cushion curves

The validation tests which were used to check the accuracy of the published EPS cushion curves. By using the dynamic cushion tester, several test combinations were performed to be compared to the cushion curves; 2 drop heights x 3 static stress levels (psi) x 2 thicknesses. And then all results were reported as peak acceleration levels (G). Table 1 shows the averaged peak acceleration levels (G) obtained from EPS cushions. In the first drop, the results revealed that almost all predicted shock transmission values using the cushion curves were much higher than actual test values except for 1.0 psi at 18" height. At 1.0 psi, the prediction from the cushion curves corresponded to the actual test result. However other results were significantly different.

In the 2~5th multiple drop, the overall prediction was better than for a single drop prediction. The predicted values at 0.5 and 0.8 psi corresponded to within 10%. However other predictions were all significantly different. The cushion curves were published by ACRO (a brand name of EPS) , which are for their EPS. The EPS used to do the tests may have been from a different manufacture. So, basically, it is hard to conclude that the predictions from the cushion curves were not accurate by both comparison to test data. However, this study revealed that using published cushion curves is not practical, since its variability depends on the manufacturer of the cushion. Moreover, ASTM D 1596 says "the reproducibility standard deviation is ranged from 9 to 18% of the mean depending on the type and loading of the cushion, and on the type of equipment used by laboratories".

Table 3. Predicted shock transmission value vs. actual shock transmission value at 18 and 30 inches (Values listed are Mean/ Standard deviation)

EPS (18" height)						
Static Stress	1st			2-5 th		
	Predict(G)	Actual(G)	Error rate (%)	Predict(G)	Actual(G)	Error (%)
0.5	53	30.42 /2.07	74.24	68	40.03/1.15	69.87
0.8	40	25.08 /4.14	59.52	56	30.76 /2.37	82.06
1.0	35	35.01 /2.44	0.02	55	42.85 /1.11	28.37
EPS (30" height)						
Static Stress	1st			2-5 th		
	Predict(G)	Actual(G)	Error rate (%)	Predict(G)	Actual(G)	Error (%)
0.5	66	46.72	41.27	79	74.06	6.67
0.8	57	49.72	14.63	70	71.33	1.86
1.0	52	37.76	37.72	72	55.25	30.31

4.2 Shock transmission vs. the number of layers

Table 4 shows average shock transmission values for the different number of layers in FCT cushion. The result shows that the number of layers does influence the G values. but not very much. G's were around 40 in all tests, except for the 3-layer cushion. The 3-layer cushions showed a little higher value than other test results, probably became they began to be bottom out after the second drop. The results show that G's tended to decrease as the number of layers increased. Figure 11 shows the same comparison.

Static stress (psi)	Sample No.	3 layers	4 layers	5 layers	6 layers	7 layers
0.325	1	45.02	38.51	40.24	33.62	37.57
	2	49.01	43.84	39.45	37.37	37.54
	3	50.84	43.14	45.62	35.99	42.38
	4	48.36	44.66	40.13	42.28	40.19
	5	51.32	38.67	38.57	32.35	38.76
	6	47.24	45.88	42.35	40.17	32.43
	Average	48.63	42.45	41.06	36.96	38.15
	Stdev	2.34	3.13	2.56	3.80	3.34
0.5	1	80.51	47.91	40.85	38.57	50.44
	2	79.14	52.61	45.16	39.57	49.66
	3	77.54	51.28	49.00	45.26	47.92
	4	79.24	49.27	52.36	52.07	45.43
	5	79.51	55.26	49.26	41.26	49.27
	6	78.36	47.73	50.16	49.28	47.28
	Average	79.05	50.68	47.80	44.34	48.33
	Stdev	1.01	2.95	4.13	5.49	1.83
0.8	1	137.96	137.10	55.55	37.21	32.22
	2	145.32	128.21	52.33	32.22	35.07
	3	136.42	127.70	58.32	35.39	39.25
	4	132.36	125.63	52.36	33.28	31.92
	5	138.25	130.25	55.93	39.25	30.25
	6	129.35	118.25	51.26	31.25	31.28
	Average	136.61	127.86	54.29	34.77	33.33
	Stdev	5.50	6.14	2.73	3.08	3.32

Table 4. Shock transmission value vs. number of layers.

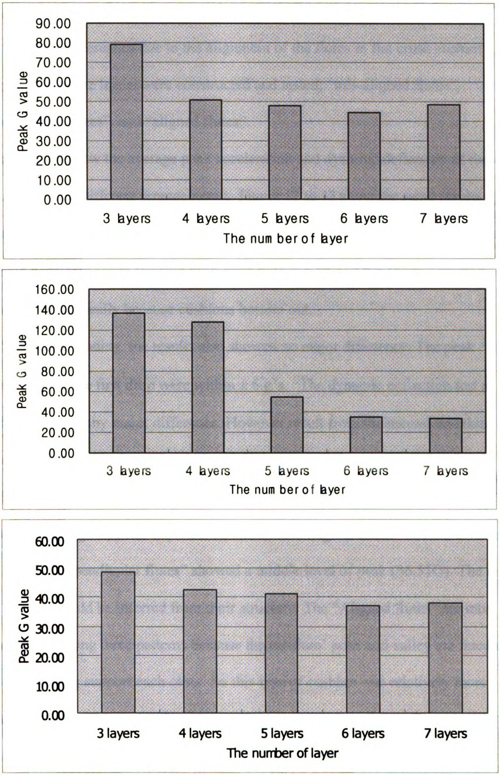


Figure 11. Shock transmission values vs. number of layers

4. 3. Shock transmission vs. layer arrangement

To investigate differences due to the alignment of the flutes in flat crush cushions, three arrangements of the layers were constructed and tested; "mis-aligned flutes", "perpendicular flutes", and "aligned flutes".

Tables 5 and 6 show the average peak acceleration and dynamic deflection of flat crush cushions in three different arrangements. Figure 12 to 13 show the same results. At 0.2 psi static loading, the results showed no significant difference among the three patterns. The peak accelerations in the first drop were within ± 4g's. After the fourth drops, the G values rise dramatically because cushions bottom out.

At 0.5 psi static loading, the results also showed no major difference. The peak accelerations in the first drop were within ± 6 g's. The dynamic deflection test at 0.5 psi also did not show any major difference. However result from the second and third drops showed more dynamic deflection in "mis-aligned flutes" than "aligned flute".

At 0.8 psi static loading, the arrangements revealed different characteristics. "Aligned flutes" had the highest peak G (48.65G), while "mis-aligned flutes" had the lowest peak of 30.22 G. "Perpendicular flutes" showed a middle level of peak (36.51G). The reason for this result could be inferred from their structure. The "Aligned flutes" are most rigid cushion type among three patterns because the medium' peak and valley are lined up well and keep a strong support each other. So this type of cushion was relatively more resistant in multiple drops but had high peak G's. "mis-aligned flutes" were arranged in a completely opposite way, the peaks and valleys of the corrugate board missed their lines and got more dynamic deflection than other two arrangement patterns. After all, it had the most shock attenuating characteristics. "perpendicular flutes" showed intermediate levels between "mis-aligned flutes" and "Aligned flute". Its dynamic shock was higher than "mis-aligned flute, and lower than the others.

In multiple drops, "aligned flutes" showed better performance although they had the highest shock transmission in the first drop. The dynamic deflection at 0.8 psi was lower than "mis-aligned" flutes. In the 2nd drop at 0.8 psi, the thickness of "aligned flue" mode was 0.98" while the "mis-aligned" was 0.90". Therefore, the result was proved "aligned flutes" are more durable for multiple drops.

At 0.8 psi, cushions exceeded their maximum limit after the third consecutive drop. All of the peak transmittance was more than 170 G. So, further drop tests were omitted. For future research, more layers of corrugated board and higher static loadings should be considered to give clearer results.

Table 5. Peak acceleration of flat crush cushions in three different arrangements (value listed mean/standard deviation)

Static stress (psi)	Arrangement	1st drop	2nd drop	3rd drop	4th drop	5th drop
0.2	Aligned flutes	43.07/2.90	49.8/2.90	59.02/4.21	142.21/4.81	173.77/5.58
	Perpendicular flutes	40.92/0.91	44.57/2.86	64.18/2.57	146.57/8.17	184.03/6.69
	Miss-aligned flutes	39.45/1.47	47.6/3.31	66.35/2.28	143.36/5.00	190.18/6.14
0.5	Aligned flutes	37.78/2.19	51.31/3.25	162.89/5.04	204.19/1.76	238.77/6.88
	Perpendicular flutes	42.77/1.46	65.65/5.98	184.78/9.96	207.3/3.22	230.86/3.51
	Miss-aligned flutes	43.69/4.37	59.82/7.51	171.04/2/42	196.19/2.58	219.36/10.74
0.8	Aligned flutes	48.65/1.15	101.74/2.19	170.01/9.07	x	x
	Perpendicular flutes	36.51/2.44	108.18/1.47	208.86/17.32	x	x
	Miss-aligned flutes	30.22/1.22	123.18/4.44	173.75/7.34	x	x

Table 6. Dynamic deflection of flat crush cushions in three different arrangements

Static stress (psi)	Arrangement	0st drop	1st drop	2nd drop	3rd drop	4th drop
0.2	Aligned flutes	0.66	0.61	0.54	0.52	0.49
	Perpendicular flutes	0.66	0.61	0.55	0.52	0.51
	Miss-aligned flutes	0.66	0.63	0.57	0.54	0.51
0.5	Aligned flutes	1.32	1.27	1.16	1.07	0.95
	Perpendicular flutes	1.32	1.27	1.13	1.06	0.94
	Miss-aligned flutes	1.32	1.23	1.12	1.04	0.93
0.8	Aligned flutes	1.32	1.17	0.98	0.92	x
	Perpendicular flutes	1.32	1.14	0.95	0.91	x
	Miss-aligned flutes	1.32	1.03	0.90	0.89	x

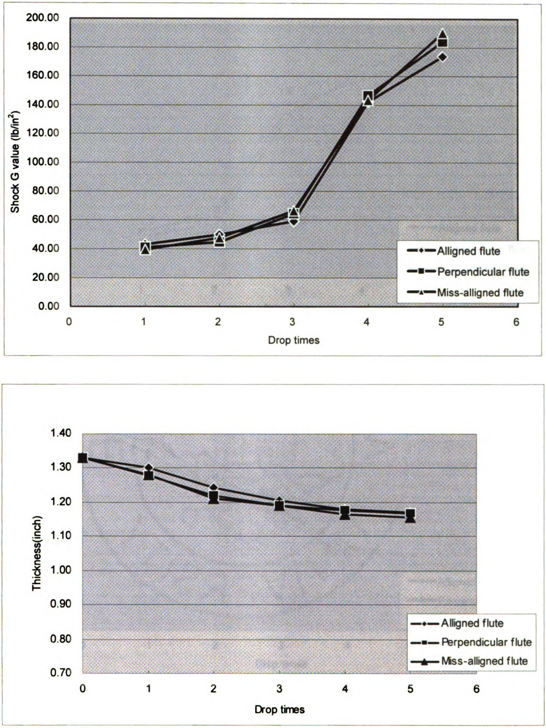
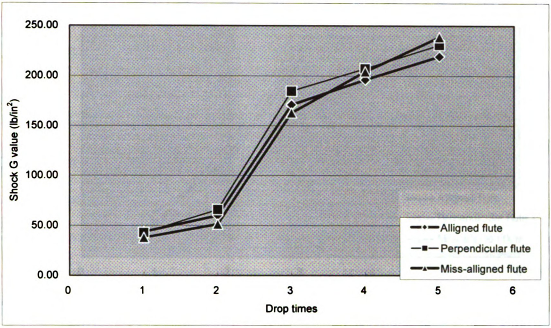


Figure 12. Shock G's and dynamic deflections of corrugated cushions in three arrangements. (Drop height=18", Static stress=0.2 psi)



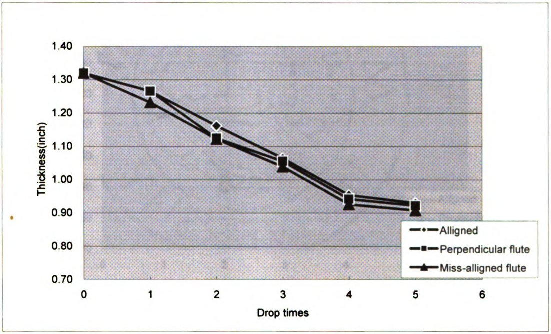
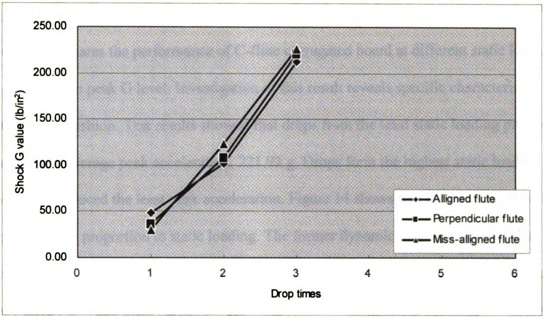


Figure 13. Shock G's and dynamic deflections of corrugated cushions in three arrangements. (Drop height=18", Static stress=0.5 psi)



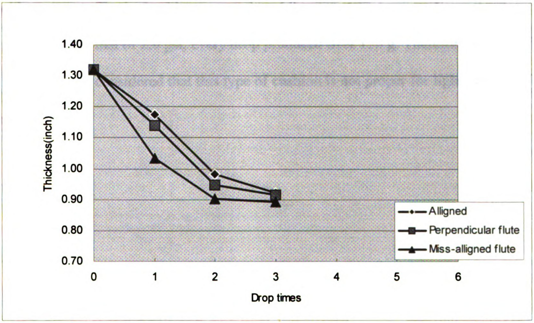


Figure 14. Shock G's and dynamic deflections of corrugated cushions in three arrangements. (Drop height=18", Static stress=0.8 psi)

4.4 Shock transmisson of edge crush mode(ECT) cushions

Table 7 compares the performance of C-flute corrugated board at different static loads by examining the peak G level. Investigation of this result reveals specific characteristics of ECT mode cushion. Test results showed that drops from the least static loading produced the highest average peak acceleration, 221.93 g. Drops form the highest static loading (test #5) produced the least peak acceleration. Figure 14 shows that the peak accelerations are in inverse proportion to static loading. The former dynamic drop test showed flat crush mode cushions would easily bottom out in high energy absorption impacts because they have exceeded their energy absorbing capacity. Edge crush mode cushions, however, could attenuate effectively at least more than 4.0 psi of static loading. From the static loading 0.325 to that of 2.0 psi, every drop produced over 150 g. Therefore edge crush mode cushion is considered that this type of cushion is not proper for light products, but heavy products.

Table 7. Peak G's for edge crush mode cushion (Values listed are mean/standard deviation)

Test No.	Area	weight	Static Load	Drop height	Thickness(in)	Peak G
1	8x5	13	0.325	18"	1.5	221.93/9.83
2	8x5	40	1	18"	1.5	164.37/4.53
3	8x5	80	2	18"	1.5	159.79 /1.15
4	4x5	80	4	18"	1.5	88.75 /5.07
5	3x5	80	5.3	18"	1.5	52.67/6.91

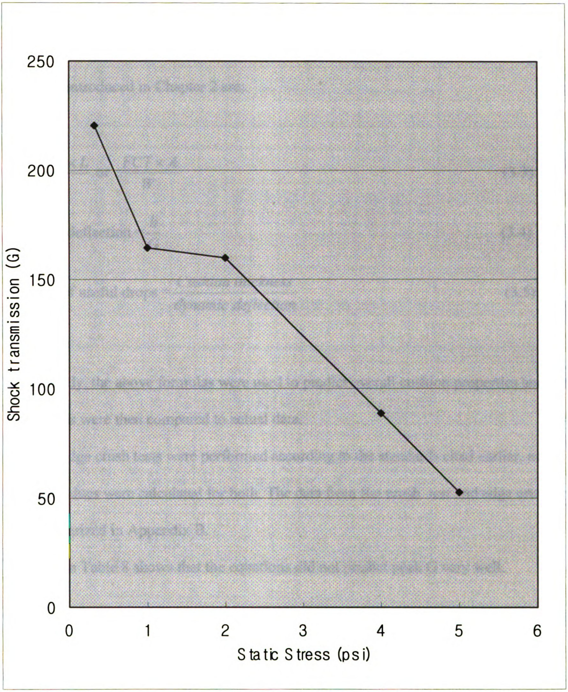


Figure 14. Shock transmission of edge crush mode cushions.

4.5 Evaluation of prediction formulas

The mathematical formulas to predict G and number of useful drops were tested. The formulas introduced in Chapter 2 are:

$$G = \frac{ECT \times L}{W} \text{ or } \frac{FCT \times A}{W} \tag{3.3}$$

$$\text{Dynamic deflection} = \frac{h}{G} \tag{3.4}$$

$$\text{Number of useful drops} = \frac{\textit{Cushion thickness}}{\textit{dynamic deflection}} \tag{3.5}$$

In this study, the above formulas were used to predict overall cushion properties and the predictions were then compared to actual data.

Flat and edge crush tests were performed according to the standards cited earlier, and average values were calculated for both. The data from flat crush test and edge crush test are summarized in Appendix B.

The data in Table 8 shows that the equations did not predict peak G very well.

Table 8. Predicted G's vs. Actual G's

	Area (in^2)	weight (lbs)	Static Load (psi)	Predicted peak G (g)	Actual peak G (g)	Drop height (in)	# of useful drop (predicted)	# of useful drop (actual)
ECT	40	13	0.325	582.61	221.93	16	56.396	x
	40	13	0.325	582.61	220.49	18	56.396	x
	40	40	1	189.35	164.37	18	18.329	x
	40	80	2	94.67	159.79	18	9.164	7
	20	40	2	94.67	202.24	32	9.164	6
	20	80	4	47.34	88.75	18	4.582	3
	15	80	5.3	35.50	52.67	18	3.437	2
FCT	64	13	0.2	166.46	43.69	18	6.103	5
	40	13	0.325	104.04	40.00	18	8.381	4
	40	20	0.5	67.62	46.07	18	4.959	3
	40	32	0.8	42.27	34.05	18	3.522	2

4.6 Corrugated vs. EPS cushions

Through several laboratory test results above, the proper design was selected for comparison tests between corrugated cushions and EPS.

First of all, since ECT mode cushions are not suited for light items, FCT mode cushions were not used for this study because EDR3C weighs less than 3 lbs. In former tests, it was proved that shock transmissions of corrugate cushions in FCT mode were similar to each other, regardless of the number of layers, until they became bottomed out. Also, the arrangement of layers did not affect the result much. Even though result showed "mis-aligned" flutes were slightly better than other two cushion modes, the difference was small at low static loadings. Therefore, the design used for this comparison test was 9 layers to match the same thickness to EPS cushion. Table 9 summarizes the maximum G's experienced by the EDR3C during the drop test sequence; the measured G for each of the six flat surfaces of the package-product system is presented. The maximum G experienced by the product was 125.5 g's on the bottom surface for the EPS cushion and 135.8 g's for the corrugated cushion. There results showed that the ability of corrugated cushions to attenuate shocks is comparable with EPS at this static stress.

The effect of consecutive drops on cushioning performance was also investigated. For light weight products, more than five drops should be conducted to find out when performance of the materials starts to deteriorate. The cushioning performance kept constant peak G values.

Table 9. Corrugated vs. EPS cushion

Drop (EPS)	Thickness	Drop height	Max G’s using EPS	Max G’s using Corrugate cushions
Bottom	1.5	18	125.532	135.882
Top	1.5	18	112.271	135.678
Left	1.5	18	83.06	76.586
Right	1.5	18	82.626	74.749
Front	1.5	18	99.126	110.435
Back	1.5	18	105.41	90.738
Corner	1.5	18	56.522	44.294

CHAPTER 5. CONCLUSIONS

Through this study, several corrugated cushion properties and performance comparisons between EPS and corrugated board were investigated.

The conclusions reached in this research are:

1. Cushion curves may not always be practical method to predict G's. A new approach should be developed for other commercialized EPS cushions.

2. As long as a drop onto an FCT cushion does not came the cushion to bottom out (compact the paper into a solidness), the dynamic shock exceeds cushion's attenuation, G's is not influenced by the number of layers of corrugated board in FCT mode.

3. G's can be improved or grow worse by aligning the layers in an FCT cushion.

- The mis-aligned cushion mode has the best shock attenuation value in the first drop performance and worst in multiple drops.
- The aligned cushion mode has the worst shock attenuation value in the first drop performance and worst in single drop.

4. Peak G prediction formulas for corrugated cushions are not accurate.

5. The performance test using EDR revealed that corrugated cushions provide excellent protection for items that are subjected to a limited number of drops.

6. it is not clear whether corrugated board is more economical than EPS, because:

- EPS can be molded but corrugated board can not; making the construction of corrugated cushion more labor required.
- Performance issues with corrugated board like moisture sensitivity, fatigue, dusting and consumer acceptance are difficult to evaluate

Appendix A

Table A1. Peak accelerations for EPS at 18 inch drop height

Static Stress (psi)	Sample	1st	2nd	3rd	4th	5th	2-5th (ave)
0.5	1	30.23	38.31	39.64	40.15	39.84	39.49
	2	32.95	39.74	40.14	40.32	43.56	40.94
	3	27.49	39.31	36.24	40.36	42.78	39.67
	4	29.73	40.25	36.46	40.27	37.46	38.61
	5	31.69	39.42	39.46	41.58	45.34	41.45
	Average	30.42	39.41	38.39	40.54	41.80	40.03
	Stdev	2.07	0.71	1.88	0.59	3.13	1.15
0.8	1	28.35	28.89	30.96	32.07	33.81	31.43
	2	29.18	25.68	29.84	31.69	35.69	30.73
	3	22.98	27.84	30.31	32.49	37.46	32.03
	4	25.80	29.32	31.25	33.28	37.59	32.86
	5	19.07	23.37	25.39	27.79	30.45	26.75
	Average	25.08	27.02	29.55	31.46	35.00	30.76
	Stdev	4.14	2.48	2.39	2.14	2.97	2.37
1.0	1	33.25	37.32	42.56	44.31	44.67	42.22
	2	38.46	39.47	42.19	41.32	45.46	42.11
	3	35.47	40.12	43.28	45.36	47.24	44.00
	4	32.17	40.25	44.32	45.25	46.59	44.10
	5	35.69	37.31	39.46	44.89	45.55	41.80
	Average	35.01	38.89	42.36	44.23	45.90	42.85
	Stdev	2.44	1.47	1.81	1.68	1.01	1.11

Appendix A (continued)

Table A2. Peak accelerations for EPS at 30 inch drop height

Static Stress (psi)	Sample	1st	2nd	3rd	4th	5th	2-5th (ave)
0.5	1	47.26	68.45	71.46	78.69	78.45	74.26
	2	47.65	66.49	71.84	75.46	79.94	73.43
	3	44.25	66.83	72.59	76.20	77.19	73.20
	4	48.87	68.86	73.61	76.2	79.05	74.43
	5	45.57	70.46	74.62	77.46	77.42	74.99
	Average	46.72	68.22	72.82	76.80	78.41	74.06
	Stdev	1.82	1.61	1.30	1.28	1.14	0.74
0.8	1	49.92	66.45	69.15	73.92	73.68	70.80
	2	48.46	65.07	69.46	72.33	75.64	70.63
	3	51.78	66.54	70.49	72.79	78.95	72.19
	4	50.12	64.59	71.98	72.46	75.46	71.12
	5	48.34	66.59	70.46	72.79	77.79	71.91
	Average	49.72	65.85	70.31	72.86	76.30	71.33
	Stdev	1.41	0.95	1.11	0.63	2.08	0.69
1.0	Sample	1st	2nd	3rd	4th	5th	2-5th (ave)
	1	38.56	46.45	53.46	58.69	60.45	54.76
	2	35.40	47.83	51.84	55.46	62.35	54.37
	3	37.24	46.83	52.79	55.20	63.28	54.53
	4	40.11	48.46	53.71	59.8	62.19	56.04
	5	37.48	48.28	52.58	60.11	65.31	56.57
	Average	37.76	47.57	52.88	57.85	62.72	55.25
	Stdev	1.74	0.89	0.74	2.36	1.77	0.99

Appendix B

Table B1. Result of edge crush test and flat crush test

Sample	ECT (lb/in^2)	FCT (lb/in)
1	40.80	22.80
2	32.50	23.00
3	34.20	25.30
4	36.70	27.90
5	38.70	24.90
Average	36.58	24.78
Stdev	3.34	2.07

Appendix C

Table C1. G values for different number of layers of corrugated board cushion. (Drop height= 18")

Static stress	Sample No.	3 layers	4 layers	5 layers	6 layers	7 layers
0.325	1	45.02	38.51	40.24	33.62	37.57
	2	49.01	43.84	39.45	37.37	37.54
	3	50.84	43.14	45.62	35.99	42.38
	4	48.36	44.66	40.13	42.28	40.19
	5	51.32	38.67	38.57	32.35	38.76
	6	47.24	45.88	42.35	40.17	32.43
	Average	48.63	42.45	41.06	36.96	38.15
	Stdev	2.34	3.13	2.56	3.80	3.34
0.5	1	80.51	47.91	40.85	38.57	50.44
	2	79.14	52.61	45.16	39.57	49.66
	3	77.54	51.28	49.00	45.26	47.92
	4	79.24	49.27	52.36	52.07	45.43
	5	79.51	55.26	49.26	41.26	49.27
	6	78.36	47.73	50.16	49.28	47.28
	Average	79.05	50.68	47.80	44.34	48.33
	Stdev	1.01	2.95	4.13	5.49	1.83
0.8	1	137.96	137.10	55.55	37.21	32.22
	2	145.32	128.21	52.33	32.22	35.07
	3	136.42	127.70	58.32	35.39	39.25
	4	132.36	125.63	52.36	33.28	31.92
	5	138.25	130.25	55.93	39.25	30.25
	6	129.35	118.25	51.26	31.25	31.28
	Average	136.61	127.86	54.29	34.77	33.33
	Stdev	5.50	6.14	2.73	3.08	3.32

Appendix D

Table D1. G values for three different arrangements of layers.
(Drop height= 18", Static stress=0.2)

Arrangement	Sample No.	1st drop	2nd drop	3rd drop	4th drop	5th drop
Aligned flutes	1	45.56	52.29	60.48	142.72	179.46
	2	41.04	47.77	51.67	133.94	169.35
	3	40.90	47.42	60.10	144.68	170.36
	4	41.95	47.94	60.37	143.47	180.25
	5	45.89	53.57	62.46	146.25	169.42
	Average	43.07	49.80	59.02	142.21	173.77
	Stdev	2.46	2.90	4.21	4.81	5.58
Perpendicular flutes	1	40.59	41.42	67.39	136.25	182.35
	2	40.13	41.83	65.36	148.36	179.53
	3	42.36	45.36	63.47	142.36	186.63
	4	41.26	46.24	64.25	158.35	194.26
	5	40.28	48.00	60.42	147.53	177.36
	Average	40.92	44.57	64.18	146.57	184.03
	Stdev	0.91	2.86	2.57	8.17	6.69
Miss-aligned flute	1	38.28	43.65	63.23	139.46	186.82
	2	40.46	45.29	66.47	146.36	190.25
	3	37.47	47.25	69.36	138.25	184.25
	4	40.47	50.25	67.35	150.35	200.35
	5	40.59	51.58	65.36	142.36	189.25
	Average	39.45	47.60	66.35	143.36	190.18
	Stdev	1.47	3.31	2.28	5.00	6.14

Appendix D (continued)

Table D2. G values for three different arrangements of layers.
(Drop height= 18", Static stress=0.5 psi)

Arrangement	Sample No.	1	2	3	4	5
Aligned flutes	1	37.24	52.13	164.81	202.21	227.34
	2	40.04	47.04	154.40	204.31	240.24
	3	38.62	55.13	167.35	204.25	238.53
	4	38.70	53.23	165.33	203.24	245.33
	5	34.29	49.04	162.56	206.93	242.42
	Average	37.78	51.31	162.89	204.19	238.77
	Stdev	2.19	3.25	5.04	1.76	6.88
Perpendicular flutes	1	43.38	72.07	173.60	202.64	230.85
	2	44.93	60.96	199.80	210.07	235.38
	3	41.53	70.69	182.95	209.90	229.58
	4	42.62	66.22	188.30	208.54	232.56
	5	41.38	58.29	179.24	205.33	225.94
	Average	42.77	65.65	184.78	207.30	230.86
	Stdev	1.46	5.98	9.96	3.22	3.51
Miss-aligned flute	1	49.49	53.29	168.46	197.21	224.21
	2	39.21	63.48	171.46	196.32	203.46
	3	42.14	60.60	174.73	199.83	231.42
	4	46.99	70.00	171.24	193.12	223.28
	5	40.61	51.74	169.33	194.49	214.45
	Average	43.69	59.82	171.04	196.19	219.36
	Stdev	4.37	7.51	2.42	2.58	10.74

Appendix D (continued)

Table D3. G values for three different arrangements of layers.
(Drop height= 18", Static stress=0.8 psi)

Arrangement	Sample No.	1st drop	2nd drop	3rd drop	4th drop	5th drop
Aligned flutes	1	47.46	101.98	210.36	x	x
	2	48.38	103.73	207.36	x	x
	3	50.25	98.28	205.36	x	x
	4	47.80	103.47	225.36	x	x
	5	49.36	101.25	213.3o	x	x
	Average	48.65	101.74	212.11	x	x
	Stdev	1.15	2.19	9.07	x	x
Perpendicular flutes	1	35.89	107.47	224.47	x	x
	2	35.51	108.46	249.36	x	x
	3	34.07	106.36	215.36	x	x
	4	40.58	110.36	204.36	x	x
	5	36.49	108.24	212.35	x	x
	Average	36.51	108.18	221.18	x	x
	Stdev	2.44	1.47	17.32	x	x
Miss-aligned flute	1	29.33	121.80	220.35	x	x
	2	29.62	117.24	236.38	x	x
	3	30.21	125.25	259.3j	x	x
	4	29.60	129.25	221.36	x	x
	5	32.32	122.35	225.46	x	x
	Average	30.22	123.18	225.89	x	x
	Stdev	1.22	4.44	7.34	x	x

Appendix D (continued)

Table D5. Dynamic deflection for three different layer arrangements.
(drop height= 18", static stress= 0.5 psi)

Arrangement	Sample No.	1st drop	2nd drop	3rd drop	4th drop	5th drop	1st drop
Aligned flutes	1	1.26	1.17	1.065	0.95	0.94	1.32
	2	1.27	1.17	1.065	0.95	0.94	1.32
	3	1.26	1.15	1.067	0.96	0.92	1.32
	4	1.28	1.16	1.066	0.96	0.92	1.32
	5	1.26	1.16	1.063	0.95	0.93	1.32
	Average	1.27	1.16	1.07	0.95	0.93	1.32
	Stdev	0.01	0.01	0.00	0.01	0.01	0.00
Perpendicular flutes	1	1.275	1.125	1.05	0.94	0.92	1.32
	2	1.265	1.12	1.05	0.95	0.93	1.32
	3	1.26	1.13	1.06	0.93	0.92	1.32
	4	1.27	1.12	1.07	0.95	0.92	1.32
	5	1.26	1.13	1.05	0.94	0.92	1.32
	Average	1.27	1.13	1.06	0.94	0.92	1.32
	Stdev	0.01	0.00	0.01	0.01	0.00	0.00
Miss-aligned flute	1	1.25	1.125	1.04	0.95	0.91	1.32
	2	1.23	1.125	1.05	0.92	0.9	1.32
	3	1.24	1.122	1.05	0.92	0.91	1.32
	4	1.23	1.12	1.03	0.92	0.91	1.32
	5	1.21	1.12	1.03	0.92	0.91	1.32
	Average	1.23	1.12	1.04	0.93	0.91	1.32
	Stdev	0.01	0.00	0.01	0.01	0.00	0.00

Appendix D (continued)

Table D5. Dynamic deflection for three different layer arrangements.
(drop height= 18", static stress= 0.5 psi)

Arrangement	Sample No.	1st drop	2nd drop	3rd drop	4th drop	5th drop	1st drop
Aligned flutes	1	1.26	1.17	1.065	0.95	0.94	1.32
	2	1.27	1.17	1.065	0.95	0.94	1.32
	3	1.26	1.15	1.067	0.96	0.92	1.32
	4	1.28	1.16	1.066	0.96	0.92	1.32
	5	1.26	1.16	1.063	0.95	0.93	1.32
	Average	1.27	1.16	1.07	0.95	0.93	1.32
	Stdev	0.01	0.01	0.00	0.01	0.01	0.00
Perpendicular flutes	1	1.275	1.125	1.05	0.94	0.92	1.32
	2	1.265	1.12	1.05	0.95	0.93	1.32
	3	1.26	1.13	1.06	0.93	0.92	1.32
	4	1.27	1.12	1.07	0.95	0.92	1.32
	5	1.26	1.13	1.05	0.94	0.92	1.32
	Average	1.27	1.13	1.06	0.94	0.92	1.32
	Stdev	0.01	0.00	0.01	0.01	0.00	0.00
Miss-aligned flute	1	1.25	1.125	1.04	0.95	0.91	1.32
	2	1.23	1.125	1.05	0.92	0.9	1.32
	3	1.24	1.122	1.05	0.92	0.91	1.32
	4	1.23	1.12	1.03	0.92	0.91	1.32
	5	1.21	1.12	1.03	0.92	0.91	1.32
	Average	1.23	1.12	1.04	0.93	0.91	1.32
	Stdev	0.01	0.00	0.01	0.01	0.00	0.00

Appendix E

Table E1. G's for corrugate cushions in ECT mode

Static stress (psi)	Sample No.	Drop height	Peak G
0.325	1	16	210.19
	2	16	220.35
	3	16	238.82
	4	16	228.13
	5	16	212.17
	Average	16	221.93
0.325	1	18	210.34
	2	18	226.38
	3	18	210.8
	4	18	232.82
	5	18	222.13
	Average	18	220.49
1.0	1	18	163.40
	2	18	160.42
	3	18	159.83
	4	18	169.63
	5	18	168.55
	Average	18	164.37
2.0	1	18	160.42
	2	18	158.83
	3	18	159.36
	4	18	161.49
	5	18	158.83
	Average	18	159.78
2.0	1	32	218.49
	2	32	210.32
	3	32	199.46
	4	32	202.46
	5	32	180.46
	Average	32	202.24
4.0	1	18	92.45
	2	18	80.83
	3	18	92.46
	4	18	91.54
	5	18	86.46
	Average	18	88.75
5.0	1	18	43.00
	2	18	53.00
	3	18	62.00
	4	18	8.26
	5	18	1.45
	Average	18	52.67

Appendix E

Table E1. G's for corrugate cushions in ECT mode

Static stress (psi)	Sample No.	Drop height	Peak G
0.325	1	16	210.19
	2	16	220.35
	3	16	238.82
	4	16	228.13
	5	16	212.17
	Average	16	221.93
0.325	1	18	210.34
	2	18	226.38
	3	18	210.8
	4	18	232.82
	5	18	222.13
	Average	18	220.49
1.0	1	18	163.40
	2	18	160.42
	3	18	159.83
	4	18	169.63
	5	18	168.55
	Average	18	164.37
2.0	1	18	160.42
	2	18	158.83
	3	18	159.36
	4	18	161.49
	5	18	158.83
	Average	18	159.78
2.0	1	32	218.49
	2	32	210.32
	3	32	199.46
	4	32	202.46
	5	32	180.46
	Average	32	202.24
4.0	1	18	92.45
	2	18	80.83
	3	18	92.46
	4	18	91.54
	5	18	86.46
	Average	18	88.75
5.0	1	18	43.00
	2	18	53.00
	3	18	62.00
	4	18	8.26
	5	18	1.45
	Average	18	52.67

Appendix F

Table F1. Performance test results for EPS cushion, using EDR at 18 inches' height.

Event No.	Peak X	Peak Y	Peak Z	Peak R	Comment
1	35.63	7.353	93.223	100.377	Bottom
2	-4.496	23.613	132.71	135.541	
3	11.336	11.822	140.943	142.382	
4	19.323	19.503	136.359	139.882	
5	17.43	12.291	139.409	141.46	
6	34.637	-13.246	-95.27	100.678	Top
7	-24.46	19.335	-115.24	119.3834	
8	-14.738	20.003	-95.46	98.64046	
9	13.164	23.044	-125.34	128.1188	
10	-17.052	34.46	-107.89	114.5361	
11	-85.731	-11.112	17.476	87.203	Left
12	-89.385	-10.969	-13.778	91.056	
13	-87.848	-10.647	17.186	89.132	
14	-81.867	24.122	-23.353	83.349	
15	-78.348	10.399	14.037	79.649	
16	84.345	8.016	16.587	85.031	Right
17	82.413	8.948	-16.876	83.994	
18	85.038	-11.298	-15.445	86.454	
19	87.066	15.53	30.318	87.709	
20	88.036	8.007	18.194	89.36	
21	20.46	-89.46	-31.051	96.88069	Front
22	17.975	-88.293	-18.565	91.567	
23	-19.46	-97.89	31.356	104.6152	
24	-24.67	-94.61	33.772	103.4418	
25	17.64	-92.31	27.456	97.90882	
26	-16.661	99.072	-13.21	101.304	Back
27	-12.828	103.557	-15.225	105.189	
28	-16.328	104.482	21.434	106.428	
29	-18.859	104.815	-17.195	106.454	
30	-11.851	105.707	20.142	107.673	
31	33.703	-35.174	-26.905	53.798	Corner
32	34.407	-39.501	-25.881	56.549	
33	39.158	-39.614	37.368	60.371	
34	-34.039	31.633	-30.214	53.597	
35	-42.931	38.704	-29.989	62.637	

Appendix F (continued)

Table F2. Performance test results for EPS cushion, using EDR at 30 inches' height.

Event No.	Peak X	Peak Y	Peak Z	Peak R	Comment
1	12.815	-25.758	141.887	145.214	Bottom
2	23.299	15.725	142.625	146.912	
3	14.485	25.629	139.004	143.251	
4	-15.147	-21.333	136.314	139.884	
5	16.845	22.442	144.801	148.737	
6	-20.342	-27.161	-101.956	108.089	Top
7	16.538	37.452	-136.562	143.682	
8	-22.572	-32.467	-125.879	133.173	
9	32.915	27.738	-135.895	144.828	
10	-30.039	-30.771	-113.959	122.363	
11	-73.336	9.310	10.913	74.933	Left
12	-65.952	14.631	13.242	68.692	
13	-73.368	-15.564	23.343	76.149	
14	-67.834	-13.083	22.271	70.457	
15	-77.019	-9.502	20.054	78.948	
16	-77.487	-14.412	19.987	79.380	
17	70.618	9.406	27.287	72.367	Right
18	69.277	7.684	-22.033	73.184	
19	77.976	11.526	23.198	78.741	
20	66.618	13.789	-15.508	67.514	
21	80.114	17.43	-11.838	81.938	
22	12.021	103.132	29.131	107.734	Front
23	12.792	109.755	31.992	115.666	
24	10.438	111.576	28.236	115.92	
25	10.383	100.657	24.524	104.237	
26	10.696	105.312	-28.175	108.620	
27	21.078	-84.649	27.542	88.691	Back
28	17.272	-90.887	30.866	93.503	
29	17.328	-84.021	25.219	87.048	
30	17.886	-84.615	25.637	88.496	
31	9.124	-85.872	-4.231	86.795	
32	26.619	-33.305	-34.683	42.586	Corner
33	-31.227	-33.685	-28.550	45.800	
34	-34.817	-39.438	31.206	52.240	
35	-23.615	27.542	-31.501	40.440	
36	23.466	32.765	-25.082	40.402	

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