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Predicting Shock Transmission Characteristics
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Using Standard Cushion Curves

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Manoch Srinangyam

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**PREDICTING SHOCK TRANSMISSION CHARACTERISTICS OF CONVOLUTED
POLYURETHANE ESTER CUSHIONS USING STANDARD CUSHION CURVES**

By

Manoch Srinangyam

A THESIS

**Submitted to
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1999

ABSTRACT

PREDICTING SHOCK TRANSMISSION CHARACTERISTICS OF CONVOLUTED POLYURETHANE ESTER CUSHIONS USING STANDARD CUSHION CURVES

By

MANOCH SRINANGYAM

The purpose of this study was to predict the peak acceleration G to falling weights onto 2 and 4 pcf convoluted polyurethane ester cushions. The prediction method was based on converting the convoluted cushion into the equivalent block cushion. The convoluted shape (fingers) act to reduce the effective drop height. Standard published cushion curves can be used to determine G level for the equivalent block cushion. Two densities of the convoluted cushion of 2 and 4 pcf, three different drop heights of 16, 22 and 28 inches, and three different loadings of 17.8, 22.8 and 27.8 lbs were tested. The results show that the predicted peak acceleration was only about 20% different from the experimental peak acceleration.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

One of the jobs of a packaging engineer is designing a package to protect products. The goal is to ensure that the consumer obtains an undamaged product. From the time the product is manufactured until it is carried and ultimately used, the product is subjected to some form of handling and transportation. During this process, the product can be subjected to many potential hazards. One of them is the damage caused by shocks (Baumdraher, 1995). In order to design a product/package system to protect the product, the peak acceleration or G force to the product that causes damage needs to be determined. In addition, it is sometimes necessary to determine the critical velocity change of the product as this also affects cushion design. The damage boundary curve contains this information and can be generated by following the American Society for Testing and Materials (ASTM) designation: D 3332-93, Standard Test Method for Mechanical-Shock Fragility of Products, Using Shock Machine. Once the product fragility is known, the cushion curves for selected cushion materials need to be consulted. For widely used cushion materials, the cushion curves are readily available. If not, standard cushion curves can be obtained by a standard test method as stated in ASTM D 1596-91, Standard Test Methods for Dynamic Shock Cushioning Characteristics of Packaging Material.

The purpose of this study was to predict the peak acceleration G delivered to a weight falling on convoluted polyurethane cushions under different static loadings.

The prediction method was based on converting the convoluted cushion into an equivalent block cushion. The finger part acts to reduce the effective drop height and standard published cushion curves can be used to predict the G level for the equivalent block cushion.

1.1 ASTM D 1596-91

This standard test method describes a procedure for obtaining dynamic shock cushioning characteristics of packaging materials. The data can be obtained by flat dropping a falling guided platen assembly onto motionless block-shaped cushion samples from different heights, static loadings and thickness of the cushion samples and recording the peak acceleration from an accelerometer attached to the platen. The data obtained may be used for producing dynamic cushion curves for the particular packaging material being tested. Inch-pound units are employed as the standard (ASTM D 1596-91, 1994) suggests.

1.2 Convoluted Cushions

Convoluted cushions shown in Figure 1 have been developed to conform to odd shaped products: for example, glassware, electronic components, and small appliances. The finger part will hold the product in place and may help to lower the peak acceleration.

Unlike block-shaped cushions, the convoluted cushion has two different thicknesses; the thickness of the finger tip and the block part. Therefore, standard

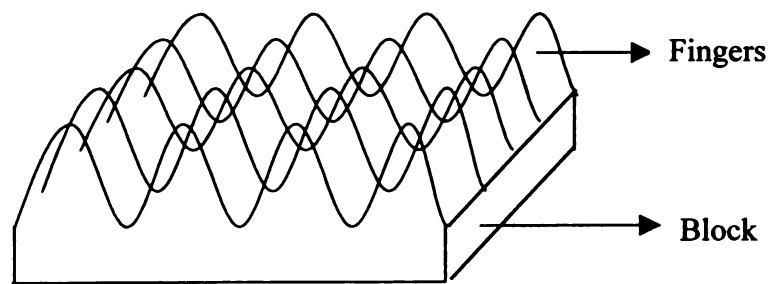


Figure 1. Convoluted cushion

cushion curves are not applicable for this cushion. This creates the need to develop a method to predict peak acceleration.

1.3 Manufacturing and Properties of Convuluted Polyurethane Ester Cushion

The manufacturing process for convoluted polyurethane cushions is shown in Figure 2. The continuous dispensing method is used heavily in the manufacture of flexible and rigid low-density foams. In continuous dispensing, the foam ingredients are rapidly mixed by machine and poured onto a moving belt. The foam rises and gels as it moves along the belt. The resulting foam slab, or bun, is sent through rollers and cut into two pieces of equal thickness. The finger parts of each piece are on the sides that face each other.

Polyurethane can range from very soft to very hard, from very flexible to very rigid, or from the hydrophilic type which soaks up water to types which repel water. Polyurethane falls mainly into two categories, esters and ethers. Esters are generally the tougher of the two but will eventually hydrolyze and degrade when exposed to water. Ethers do not hydrolyze or biodegrade even on prolonged exposure such as direct burial, but are not as tough and are less resistant to chemicals and oils (Markley and Gillis, 1994; Polyurethane Foam Association, 1991).

1.4 Damage Boundary Curve

A damage boundary curve (DBC) is a plot of the critical acceleration, G_p , on the ordinate (y-axis) and the critical velocity change, ΔV_p , on the abscissa (x-axis)

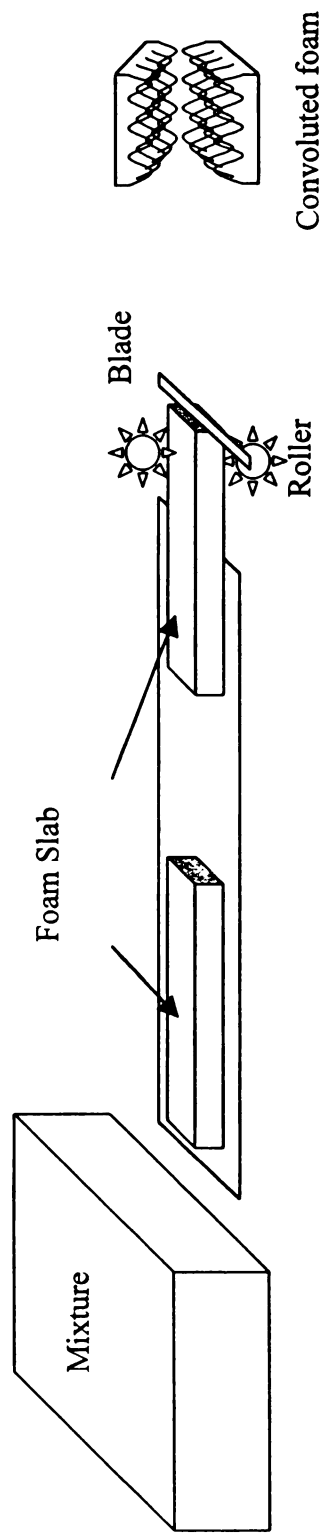


Figure 2. Manufacturing process for convoluted polyurethane cushions

of the input shock required to damage a product. The damage boundary curve is shown in Figure 3. The standard test procedure for determining the two fragility parameters is ASTM D3332-93.

The product is first mounted on a shock table and subjected to a series of drops using plastic programmers (high G, short duration shock) from higher and higher drop heights until the product breaks. The critical velocity change to the product is the area under the shock pulse just before the damage occurs. The product can tolerate any acceleration without damage as long as the velocity change to the product is less than this critical velocity change. When the velocity change is more than the critical velocity change to the product, the product may or may not be damaged depending on the peak acceleration to the product (Grantham, 1991).

To obtain the critical acceleration of the product, an identical new product in the same orientation is mounted on the shock machine and subjected to a series of drops using gas programmers (low G, long duration square wave). The table drop height of the shock machine was adjusted and fixed so that the velocity change is at least 1.57 times the critical velocity change of the product. The gas pressure is increased until the product breaks. The critical acceleration is the value measured just before damage occurs. The product can tolerate any velocity change, ΔV , or any long duration shocks without damage as long as the peak acceleration to the product is less than this critical acceleration.

It is important to note that the particular DBC is valid only for the specific product tested and for one orientation.

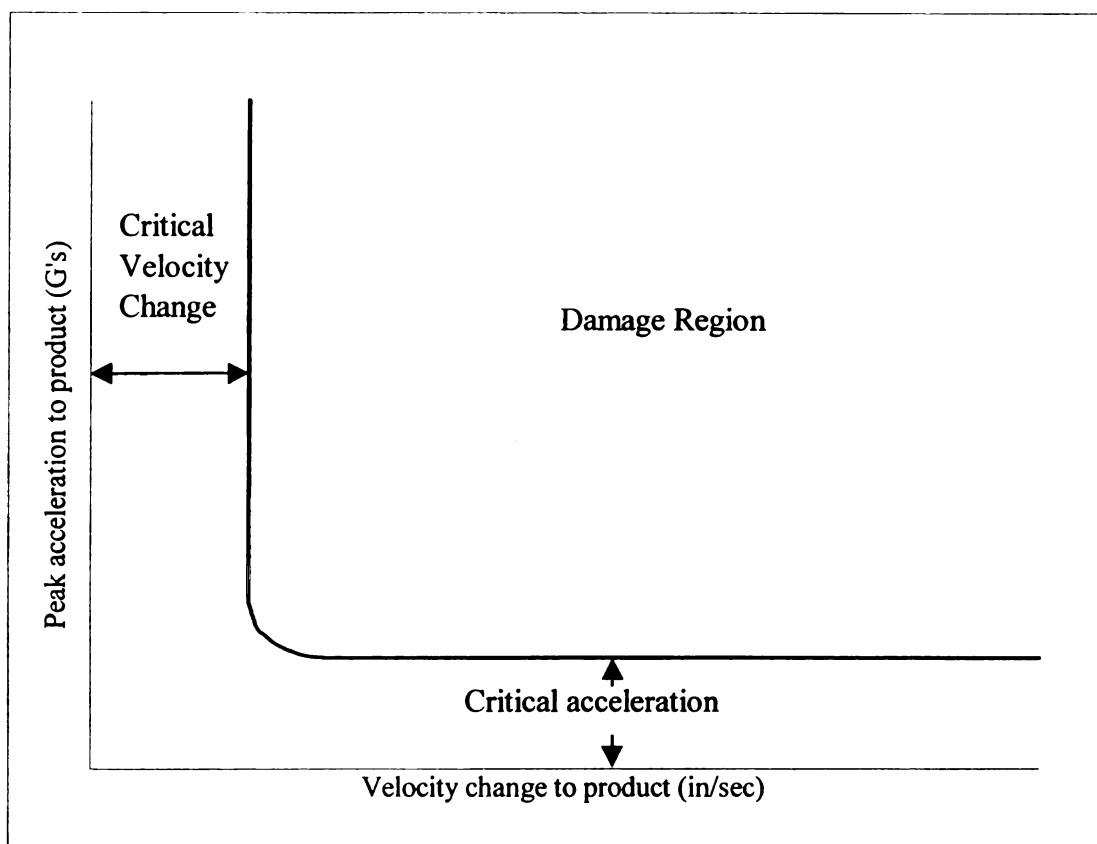


Figure 3. Damage boundary curve

1.5 Cushion Curves

A cushion curve is a plot of peak acceleration on the y-axis and static stress on the x-axis for a specific drop height and cushion thickness. It is valid only for the specific material tested as shown in Figure 4. It is important to mention that all standard published cushion curves are for block-shaped cushions which have uniform thickness. It should be noted that as static stress increases, the peak acceleration decreases until it reaches its lowest value and then starts to increase. The high peak acceleration at low static stress is due to the insufficient energy to compress the cushion while the high peak acceleration at high static stress is because the cushion bottoms out (Burgess, 1997).

There are many types of cushioning materials which are used in packaging. Cushions may be divided into two categories based on structure. These are open-cell and closed-cell foams. An open-cell foam is composed of a network of intercommunicating cells where air can flow between each cell and also out of the foam. Open-cell foam absorbs energy by letting the air escape from the foam. A closed-cell foam is composed of individual bubbles of air trapped and join together to form the cushion. The trapped air inside each cell absorbs energy from compression. Closed-cell foam is stiffer, stronger, and produces higher peak acceleration than open-cell foam.

In theory, a product will be damaged if both the peak acceleration and velocity change of the shock to it in a drop fall within the damage region of the DBC. Otherwise, the product will be fine and no cushion is needed. For instance, if the velocity change to the product is less than the critical velocity change, the product will have no damage, regardless of the peak acceleration. However, it is usually the case that the velocity change is more than the critical velocity change. To ensure that the product is not

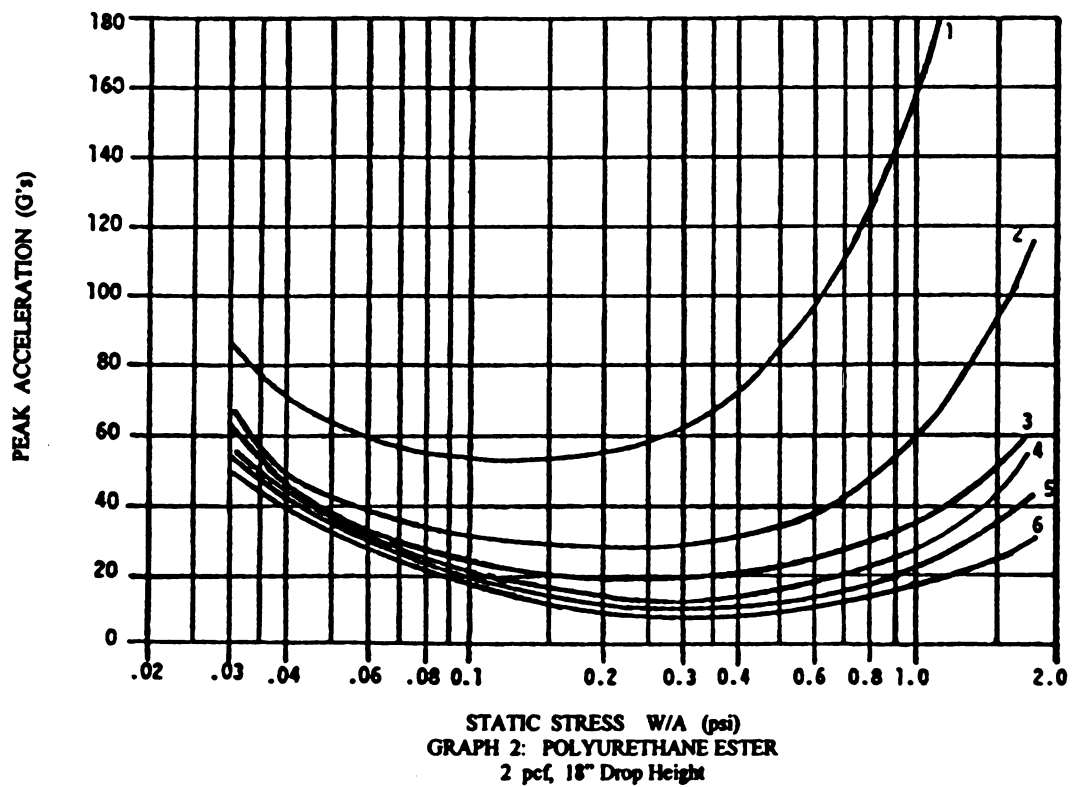
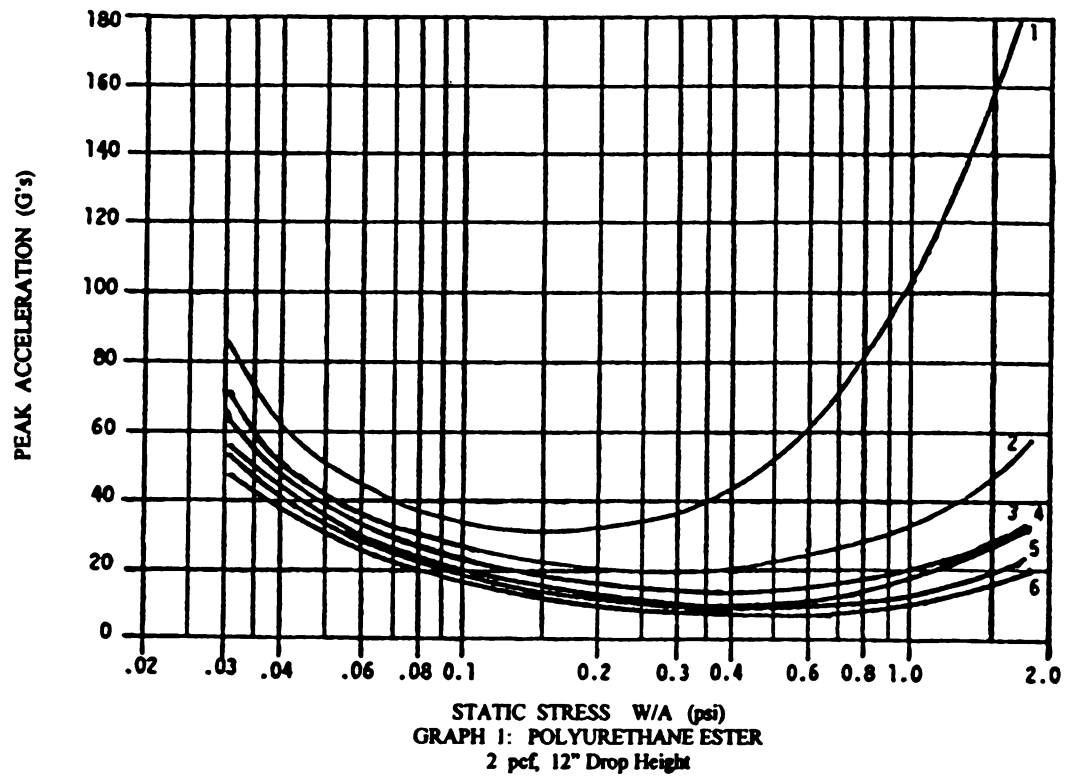


Figure 4. Cushion curves

damaged in this case, a cushion is needed to keep the peak acceleration lower than the critical acceleration.

There are many factors that need to be considered when selecting a cushion. They are type of material, density, shape, bearing area, and thickness. For irregular shapes like convoluted cushions, it is difficult to decide on the appropriate thickness to use on the cushion curves. If the thickness of only the block part is used when determining the peak acceleration from the cushion curve, the G level will be higher than actual because the fingers also provide cushioning. It will be over protection since the thickness of the finger part was ignored. On the other hand, if the thickness used to determine peak acceleration from the cushion curve includes the height of the fingers, the product might be damaged since it will receive a peak acceleration higher than what the cushion curves say. This is the reason why the predicted peak acceleration of a convoluted cushion needs to be developed.

To date, not much research has been done in the area of designing and predicting characteristics with convoluted cushions. Granthen (1991) studied the shock transmission characteristics of ribbed expanded polypropylene cushions using standard cushion curves for flat plank cushions. Three drop heights of 18", 30", and 42", three rib heights of 1.5", 2.0", and 2.5", three rib angles of 5°, 15°, and 25°, and three static loadings were tested. Granthen examined seven mathematical models to predict the G level. Each model is based on converting the ribbed cushion into an equivalent plank cushion so that published cushion curves can be employed to predict the peak acceleration. It was concluded that the "Equivalent Volume" model that weighs the

varying cross sectional areas of the ribbed cushion and the plank section of the cushion equally gave the best predicted peak acceleration.

CHAPTER 2

MATERIALS, EQUIPMENT AND TEST METHODS

2.1 Materials

The cushion material used in this research was convoluted polyurethane ester foam. The material is a low density open-cell structure, so that air can penetrate the intracellular spaces, made by Industrial Rubber & Supply Incorporated, Washington. Two different densities having the same shape were used in this research. They are designated as C-200 and C-400 meaning 2 and 4 pounds per cubic foot. The C-200 foam has a lighter color than C-400. The base dimensions of the convoluted cushion samples were 8 inch x 8 inch. The thickness is designated as 2¾ inch over 1¼ inch, meaning that the overall height is 2¾ and the block part (base) is 1¼ inch thick. Photos of the convoluted polyurethane ester cushion for 2 and 4 pounds per cubic foot are shown in Figure 5.

2.2 Cushion Testing

A Lansmont Model 23 Cushion Tester was used to perform all drop testing following ASTM D1596. As shown in Figures 6 and 7, a piezoelectric accelerometer was mounted on the platen of the cushion tester. The signal from the piezoelectric accelerometer was carried by a shielded cable to a Kistler piezotron charge amplifier and then to a twelve bit analog card on an IBM AT compatible 80286 computer. The software which was used by this computer to analyze the shock pulse was Test Partner

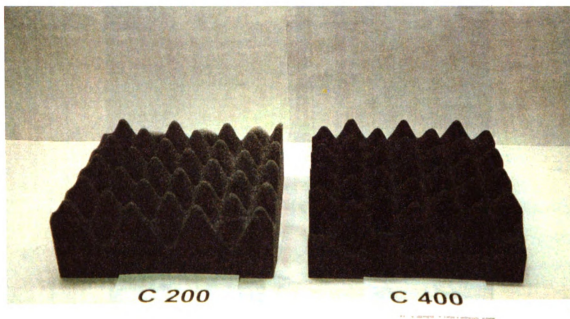


Figure 5. C-200 and C-400 convoluted polyurethane ester cushions



Figure 6. Photograph of cushion tester

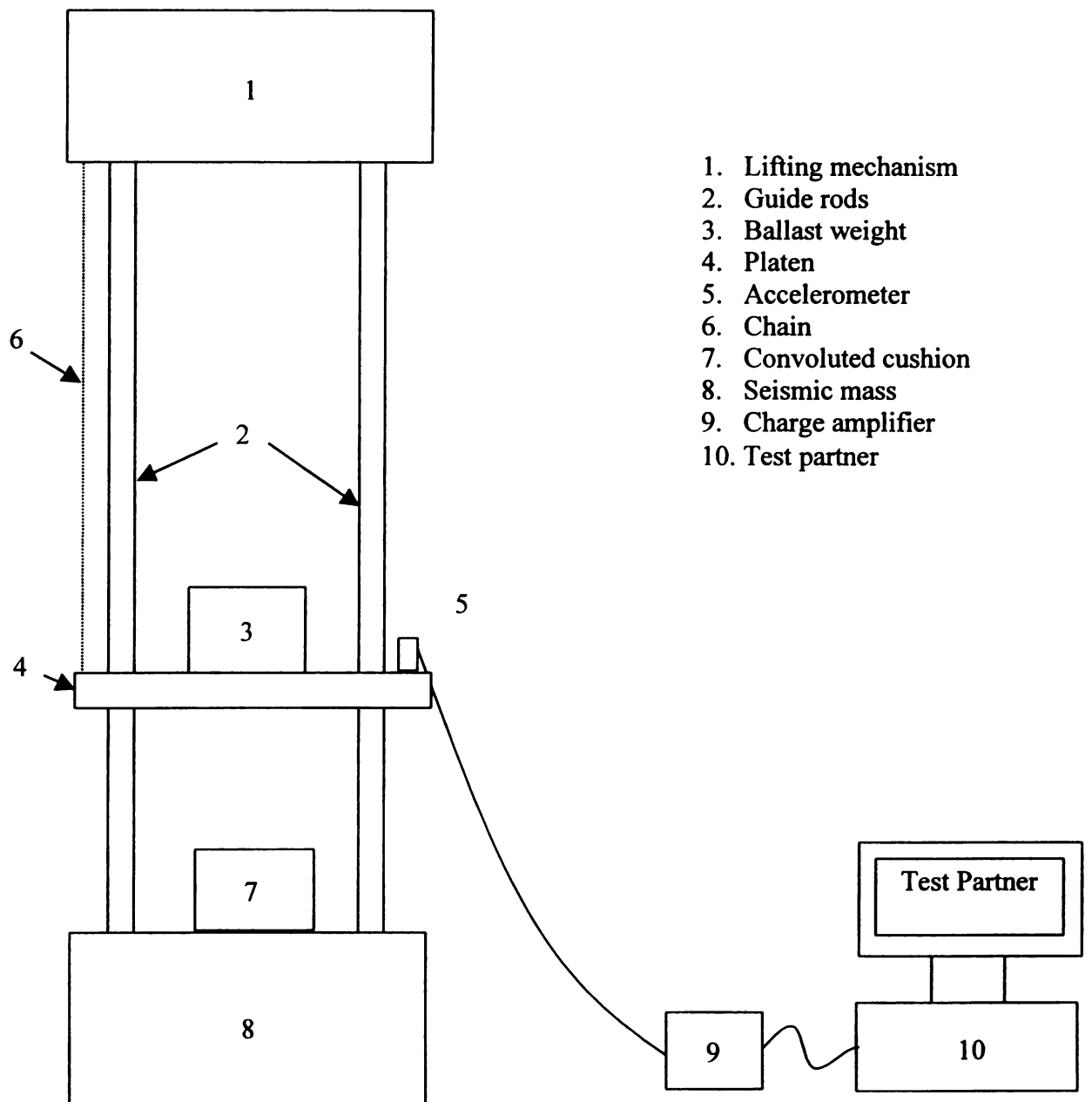


Figure 7. Schematic of cushion tester

version 2 from Lansmont Corporation. The shock pulses were displayed on a VGA computer monitor. A photograph and a schematic of the Lansmont Model 23 Cushion Tester are shown in Figure 6 and 7, respectively.

TEST PROCEDURE

The drop tests onto the convoluted polyurethane ester cushion samples were conducted as follows:

1. Mount the piezoelectric accelerometer on the platen and hook it up with the Kistler piezotron charge amplifier.
2. Turn on all switches which control the cushion tester, computer, and open the valve on nitrogen tank which supplies air brakes.
3. Set up the computer program to monitor and analyze the shock pulse.
4. Make sure that the guide rods are clean and have a thin film of lubrication. Friction between the guide rods and the platen will slow down the platen. Because of friction, the platen must be raised higher than the actual free fall drop height. The relationship between the actual free fall drop height and the height of platen will be explained later.
5. Insert a convoluted polyurethane ester cushion test sample underneath the platen.
6. Put a variety of ballast weights on the platen to get different static loadings.
7. Raise the platen and drop it onto the cushion sample.
8. After each drop, Test Partner will show the shock pulse on the monitor. A typical shock pulse from a convoluted cushion is shown in Figure 8.
9. Record the two peak acceleration values for the finger part and block part.
10. Repeat steps 3 through 9 for all drop heights, static loadings and types of cushions.

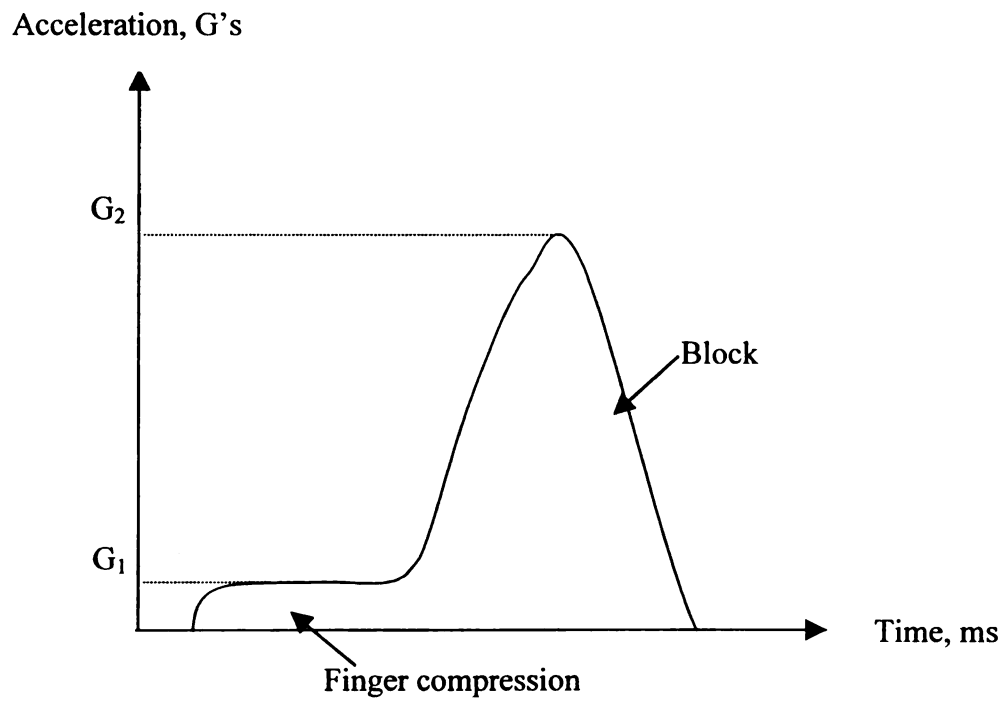


Figure 8. Typical shock pulse using convoluted cushion

ADJUSTING PLATEN DROP HEIGHT

According to step 4, due to friction between the guide rods and the platen, the platen must be raised higher than the desired free fall drop height as stated before. In the absence of any resistance, products, regardless of their size, weight, or composition, drop toward the ground with nearly constant acceleration (Resnick and Halliday, 1977). Since the free fall drop height of a packaged product is not too great, just 1-6 feet height, the acceleration can be assumed constant throughout the drop. Since impact velocity is what really matters, it can be calculated from drop height in a free fall where there is no resistance using

$$V^2 = 2gh \quad (1)$$

Where V is impact velocity

h is free fall drop height

g is acceleration due to gravity (386.4 in/sec²)

On the cushion tester, the platen falls with an acceleration less than g and so in order to obtain the same impact velocity V, the platen was raised and must be higher than the actual free fall drop height. In order to find the correct platen drop height, the platen was dropped onto an Ethafoam 220, closed-cell polyethylene foam, and the shock pulse was recorded. Test Partner software was used to calculate the impact velocity which is the area under shock pulse from the start of the shock pulse to its peak. This procedure was repeated by moving the platen up and down until the impact velocity corresponded to the desired free fall drop height as in equation (1). The average values of platen height

corresponding to the impact velocity and the actual free fall drop height are shown in Table 1.

Table 1. Actual free fall drop height, impact velocity, and platen height.

Actual free fall drop height (in)	Impact velocity (in/sec)	Platen height (in.)
16	111.2	25
22	130.4	36
28	147.1	44

DROP TESTS

Using the cushion tester, two different kinds of foams, C-200 and C-400, were dropped from three different drop heights, 16 in, 22 in and 28 in. At each drop height, three different loadings were tested: 17.8, 22.8 and 27.8 lbs. Ten replicates were performed for each loadings. After each drop, the G levels corresponding to finger compression and block compression from the shock pulse were recorded. The experimental design is shown in Figure 9.

The results of the drop tests on the convoluted polyurethane ester cushions are shown in Tables 3 through 5 in Appendix A. These experimental results are compared to predictions using mathematical modeling later.

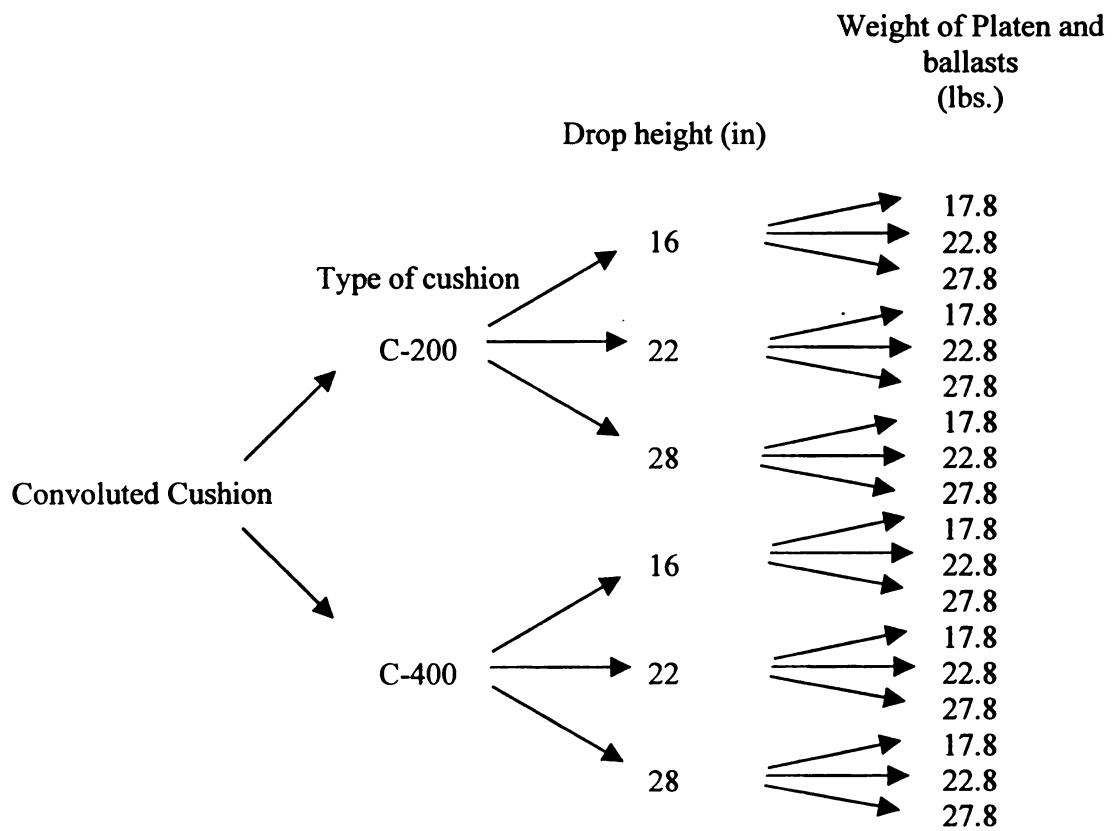


Figure 9. Experimental design

2.3 Compression Testing

The Lansmont Model 152-30TTC Compression Tester shown in Figure 10 was used to perform compression testing. The compression tester was used to measure the force and deflection required to compress the cushion in a static situation. This was done to evaluate the contribution of the fingers to overall cushion stiffness. As the cushion starts to compress, the force increases rapidly to a nearly constant level. During this time, only the fingers compress, not the block part. This is a small force compared to the force required to compress the block part. For purposes of modeling, this finger buckling force was assumed to be constant. Two samples of both convoluted cushions, C-200 and C-400, were compression tested. The buckling forces and deflections were then recorded and printed out as shown in Figures 14 through 17 in Appendix B. For each type of cushion, the average buckling force and deflection were then calculated as shown in Table 6 in Appendix B and used in mathematical modeling later.

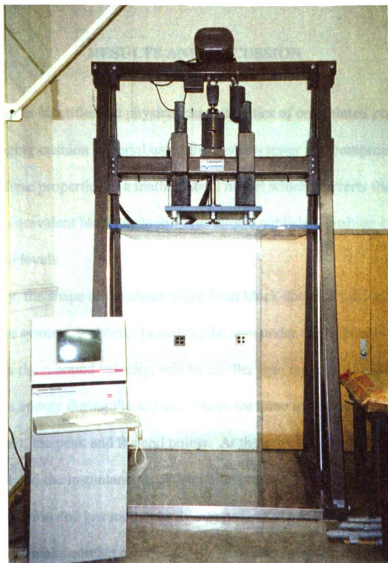


Figure 10. The compression tester

CHAPTER 3

RESULTS AND DISCUSSION

This chapter identifies the physical characteristics of convoluted polyurethane ester as a packaging cushion material using the cushion tester and compression tester results. It uses these properties in a mathematical model which converts the convoluted cushion into an equivalent block cushion. This allows published cushion curves to be used to predict G levels.

Typically, the shape of the shock pulse from block-shaped cushion looks like a half sine wave or symmetrical bell. In reality, the area under the right side of the bell, which represents the rebound velocity, will be smaller than the area of the left side since the product loses energy during the impact. There are three important points on the bell which are the start, the peak and the end points. At the start, the product makes contact with the cushion and the instantaneous acceleration is zero. The product will obtain the maximum acceleration and has momentarily stopped at the peak point. Finally, at the end point, the product breaks contact and the acceleration is zero again. Figure 11 imitates a typical shock pulse from a block cushion.

Unlike the block-shaped cushion, the convoluted cushion shock pulse is almost as same as the block shaped cushion but with a raised leading edge. Figure 8 imitates the shape of shock pulse from a convoluted polyurethane ester cushion. The shock pulse has two peak acceleration points. The first peak is much lower than the second peak and stays

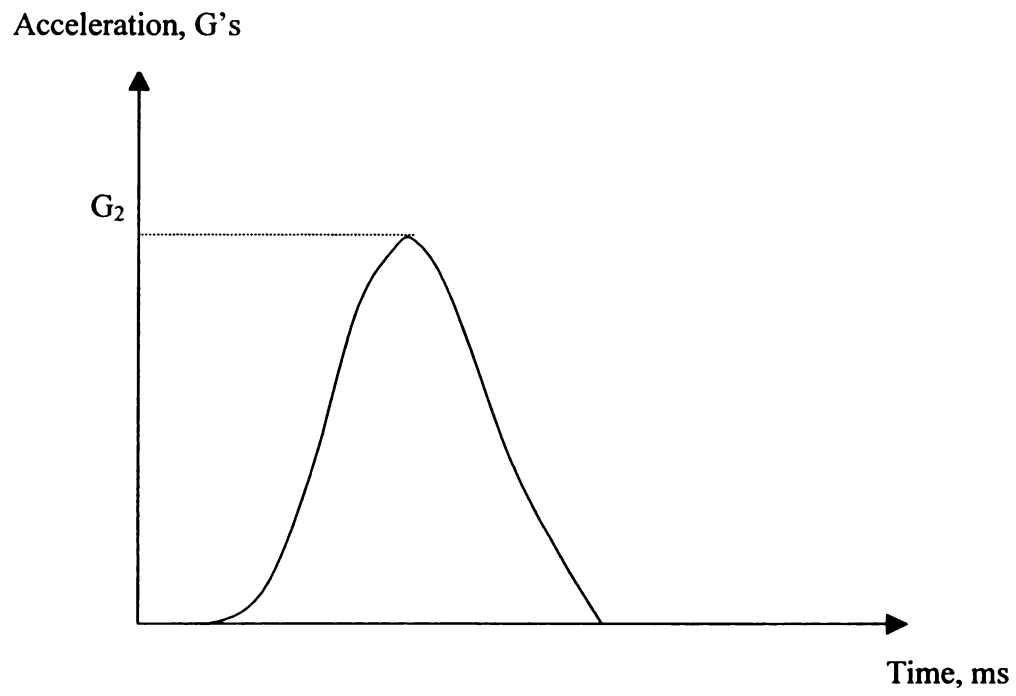


Figure 11. Typical shock using block cushion

constant for a short time before it rises. This short time happens while the falling weight compresses the fingers of the cushion. From the shock pulse in Figure 8, during compression of the fingers the acceleration stays constant and the block part stays uncompressed. The second peak is much higher than the first and the shock pulse drops immediately after it reaches the peak. This peak occurs because the block part of the cushion has been compressed.

To predict the peak acceleration which occurs during finger compression, Newton's second law was employed. Newton's second law states that a net force acting on a body gives it an acceleration which is in the direction of the force and has a magnitude inversely proportional to the mass of the body (Ohanian, 1985),

$$\bar{a} = \frac{\bar{F}}{m} \quad (2)$$

where $\bar{a}$ is acceleration

$\bar{F}$ is force acting on the body (lbs)

m is mass of the body

By applying the Newton's Second Law, equation (2) can be rewritten as

$$F = ma = mgG_1 = WG_1 \quad (3)$$

Where g is acceleration due to gravity

W is weight of the product (lbs)

G_1 is the acceleration as a multiple of gravity

From the shock pulse in Figure 8, G_1 is constant. Since W is also constant, the product of WG_1 , which is F , is constant as well. In other words, the compression force stays constant during finger compression. This makes sense because the mode of deformation of the fingers is buckling, and the buckling force is typically independent of

the amount of compression. To predict the acceleration G_1 , the compression tester was used to determine the buckling force and corresponding deflection of the fingers, as discussed earlier. The buckling force acts on the falling weight and produces the acceleration G_1 . Since the buckling force is proportional to the number of fingers and since the number of fingers is proportional to the base area of the convoluted cushion, the ratio of buckling force to base area should be a constant, independent of the size of the cushion. The buckling stress is defined as

$$BS = \frac{F}{A} \quad (4)$$

where BS is buckling stress

F is the buckling force

A is the base area of the cushion sample tested

The buckling stress is a constant value for the specific shape and density of the convoluted cushion. Therefore, equation (4) can be rewritten as

$$BS = \frac{WG_1}{A} \quad (5)$$

By definition, the static stress is the stress on the cushion created by the weight of the product resting on top of the cushion. The static stress or “static loading” as it is sometimes called on the cushion curves is defined as

$$SL = \frac{W}{A} \quad (6)$$

where SL is static loading

W is weight of the product

A is area of the cushion

Since the buckling stress is known and the static loading can be calculated, the acceleration G_1 can be predicted from equation (7) as

$$G_1 = \frac{BS}{SL} \quad (7)$$

The G_1 prediction from equation (7) will be compared with the experimental data later.

The principle of conservation of energy (Resnick and Halliday, 1977) states that

$$\Sigma W = \Delta E_k \quad (8)$$

where ΣW is the total work done on the product

ΔE_k is the change in kinetic energy

The situation at the end of finger compression (beginning of block compression) can be analyzed using equation (8),

$$mg(h_1 + f) - mgG_1f = \frac{1}{2}mv^2 \quad (9)$$

where m is the mass of product

g is acceleration due to gravity

h_1 is drop height

f is finger height

G_1 is the constant acceleration during finger compression

v is velocity of the product as the block part begins to compress

Equation (9) can be rewritten as

$$v^2 = 2g[h_1 - (G_1 - 1)f] \quad (10)$$

The fingers can now be viewed as having the net effect of slowing down the product before it starts to compress the block part of the cushion. The product therefore appears to have fallen from a reduced height. The reduced drop height, h_2 , can be calculated as

$$v^2 = 2gh_2 \quad (11)$$

where v is the same impact velocity
 g is acceleration due to gravity
 h_2 is the reduced drop height

Setting equation (10) equal to equation (11),

$$2gh_2 = 2g[h_1 - (G_1 - 1)f] \quad (12)$$

$$h_2 = h_1 - (G_1 - 1)f \quad (13)$$

Since the part of the shock pulse in Figure 8 corresponding to the compression of the block part of convoluted cushion is just like the kind of shocks appropriate to cushion curves, the convoluted cushion drop can be viewed as an equivalent block cushion drop from the reduced height h_2 . The published cushion curves can now be used to determine the peak acceleration of block part of the convoluted cushion which is called G_2 in Figure 8. The equivalent block cushion is the block (base) portion of the convoluted cushion. This equivalence is shown in Figure 12. This was done and the predicted peak acceleration was compared with the experimental data.

Since published cushion curves have discrete values for the thickness of the cushion, static stress and drop height, interpolation usually needs to be used for predicting G_2 . The percent error from the mathematical model can be obtained as

$$\% \text{ error} = \frac{(G_{\text{exp}} - G_{\text{pre}})}{G_{\text{exp}}} \times 100 \quad (14)$$

where G_{exp} is the peak acceleration from experiment

G_{pre} is the predicted peak acceleration

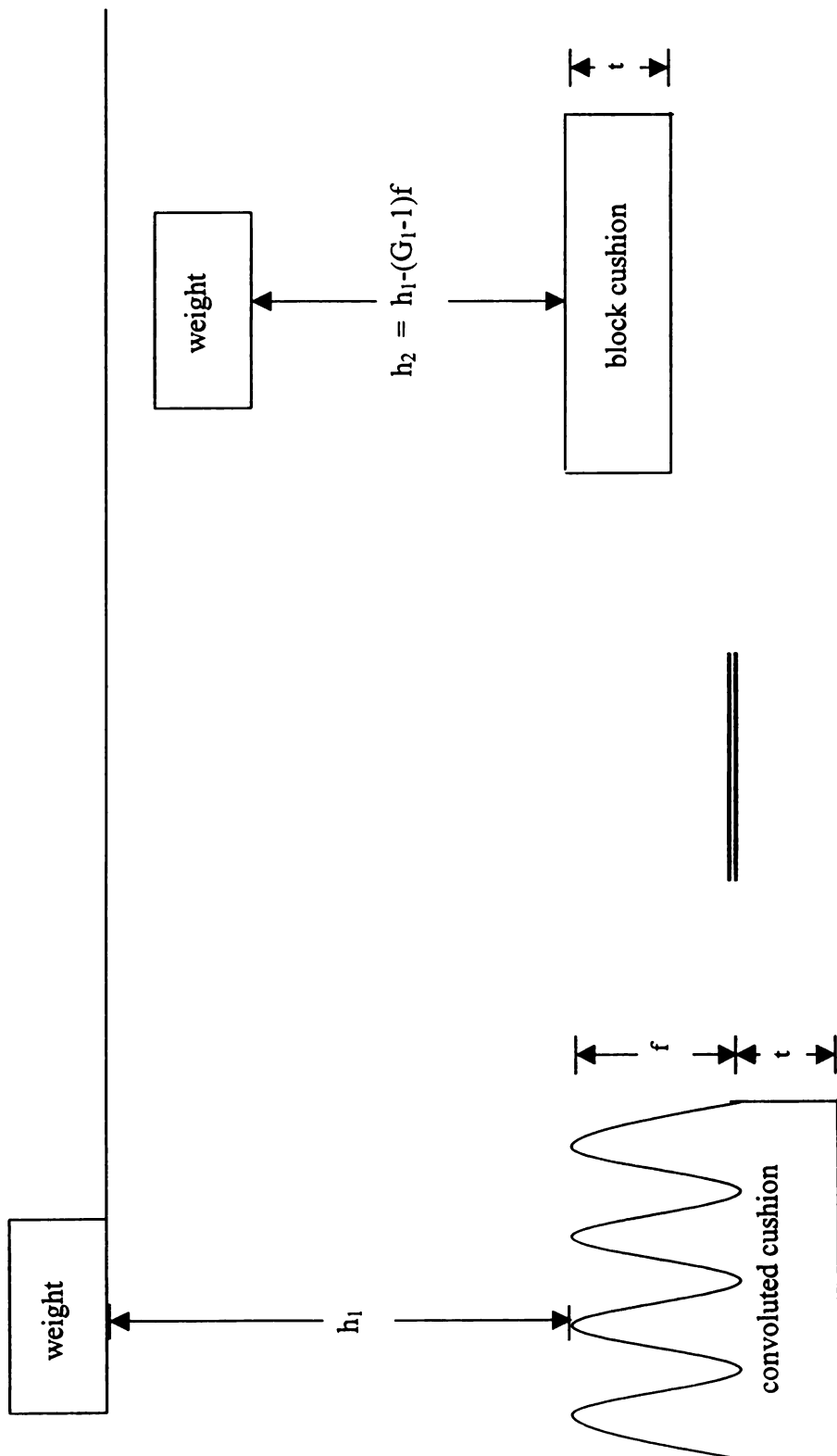


Figure 12. Equivalence between convoluted and block cushions

This equation can be applied for errors in both G_1 and G_2 . However, G_1 is typically very small, usually less than 5 G. This is comparable to the error associated with the kinds of accelerometers used to capture shock pulses. It is therefore likely that the percent errors on G_1 calculated using equation (14) will be falsely high. The acceleration of most interest, G_2 , is much larger and so errors are much more likely to be due to modeling than to instrument precision.

The comparison between experimental and predicted G_1 and G_2 is presented in Table 2. The detail of experimental and predicted values are shown in Appendixes.

Table 2. Comparison of experimental and predicted G_1 and G_2

Cushion	Drop height (in.)	Static stress (psi.)	G_1			G_2		
			Exp. ^{*1}	Pre. ^{*2}	% Error	Exp. ^{*1}	Pre. ^{*2}	% Error
C-200	16	0.28	2.82	3.75	-32.98	30.11	28.89	4.05
		0.36	2.74	2.94	-6.57	34.62	33.11	4.36
		0.43	2.47	2.44	1.21	41.00	38.41	6.32
	22	0.28	7.77	3.75	51.74	53.87	42.22	21.63
		0.36	5.93	2.92	50.76	61.67	51.14	17.07
		0.43	4.90	2.44	50.20	73.17	58.90	19.50
	28	0.28	6.76	3.75	44.53	68.37	66.67	2.49
		0.36	7.14	2.92	59.10	82.59	74.68	9.58
		0.43	5.46	2.44	55.31	99.86	87.52	12.36
C-400	16	0.28	4.30	4.86	-13.02	27.81	31.05	-11.65
		0.36	2.79	3.78	-35.48	32.15	33.80	-5.13
		0.43	1.76	3.16	-79.55	37.36	35.17	5.86
	22	0.28	9.30	4.86	47.74	49.41	39.04	20.99
		0.36	5.77	3.78	34.49	58.42	45.15	22.71
		0.43	4.04	3.16	21.78	69.12	54.33	21.40
	28	0.28	8.02	4.86	39.40	64.74	53.70	17.05
		0.36	7.06	3.78	46.46	78.37	61.33	21.74
		0.43	5.66	3.16	44.17	93.34	72.17	22.68

^{*1} Experimental

^{*2} Predicted

The calculated peak acceleration of the finger part, G_1 , are shown in Tables 7 through 9 in Appendix D and then compared with experimental values in Tables 10 through 12 in Appendix E. The calculated peak acceleration of the block part, G_2 , are also shown in Tables 7 through 9 in Appendix D and then compared with experimental values in Tables 13 through 15 in Appendix E.

CHAPTER 4

CONCLUSIONS

The goal of this thesis was to be able to predict the peak acceleration in dynamic loadings of convoluted polyurethane ester cushion using published information for block-shaped cushions made of the same material.

Suppose, for example, a 27.80 lb product was dropped onto a convoluted polyurethane ester C-200 cushion from a drop height of 16 inches as shown in Figure 13. The base dimensions of the convoluted cushion is 8 inches x 8 inches. The thickness is designated as 2¾ inches over 1¼ inches. From Appendix B, the buckling stress for the C-200 material is 1.05 psi. The static loading is $27.80/64 = 0.43$ psi. According to equation (7), the predicted G_1 is $1.05/0.43 = 2.44$. In the actual drop, the average experimental G_1 was 2.47 as shown in Table 3, Appendix A. In this case, the error between predicted and actual G_1 is $[(2.47-2.44)/2.47] \times 100 = 1.21 \%$.

To predict G_2 , the reduced drop height needs to be determined using equation (13). The reduced drop height is $16 - [(2.44-1) \times 1.50] = 13.84$ inches. Knowing the type and density of the cushion, the equivalent block cushion thickness of 1.25 inches, the static loading and drop height, the peak acceleration can be determined from published cushion curves. Since there are no published cushion curves for this material at the reduced drop height (13.84 inches), interpolation needs to be used. From graph 1 in Appendix C, for the C-200 cushion, drop height of 12 inches, static loading of 0.43 psi and cushion thickness of 1.25 inches, the peak acceleration is 33.28 G. From graph 2 in Appendix C, at drop height of 18 inches, static loading of 0.43 psi and cushion

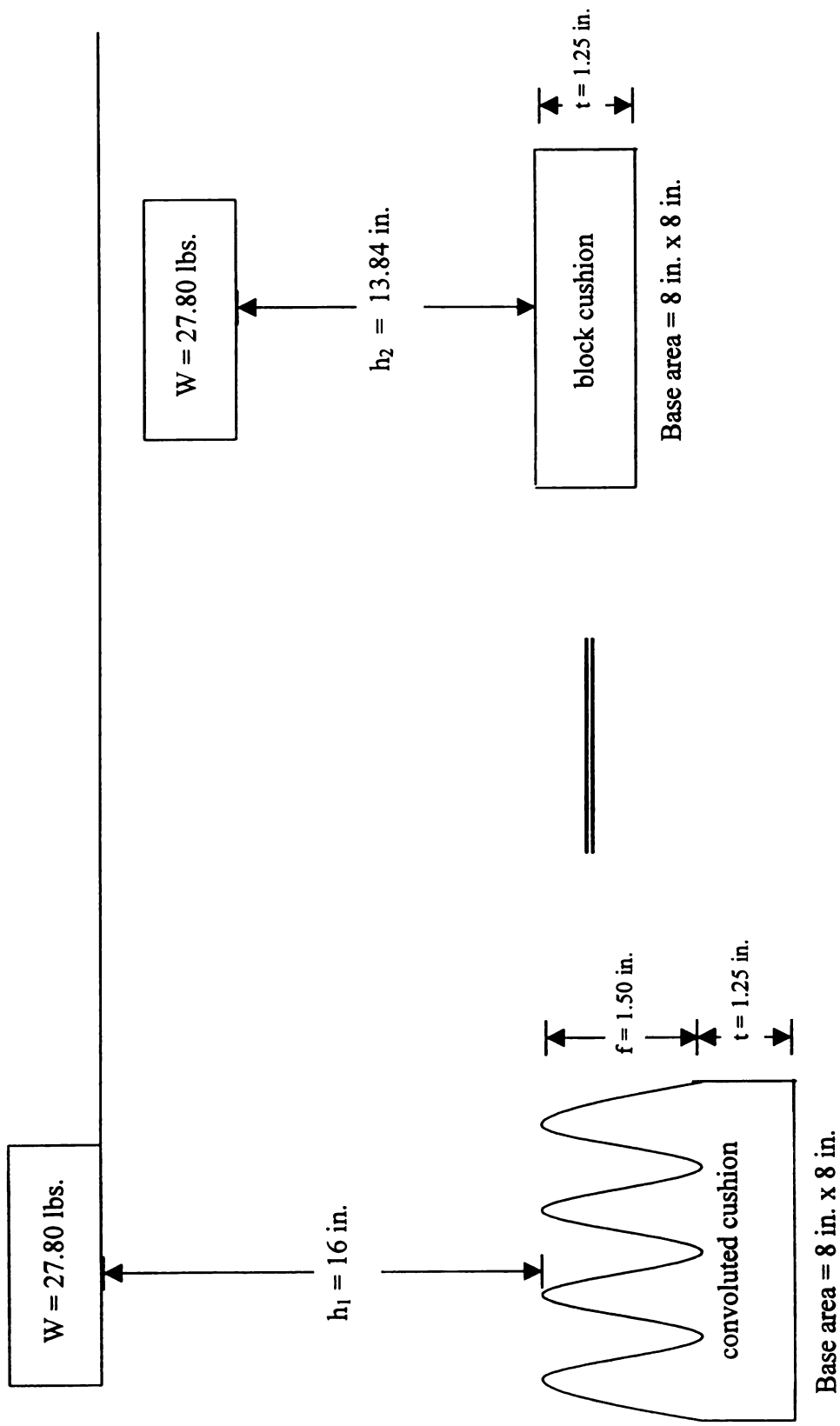


Figure 13. Particular example

thickness of 1.25 inches, the peak acceleration is 50 G. Therefore, the interpolated acceleration at a drop height of 13.84 inches is 38.41 G. This value is the predicted G_2 . The average experimental G_2 was 41.00 as shown in Table 3, Appendix A. In this case, the error between predicted and actual G_2 is $[(41.00-38.41)/41.00] \times 100 = 6.32\%$

OTHER PREDICTIONS

1. The buckling stress also represents the largest static stress that can be used to take advantage of the fingers ability to reduce the drop height. In general, if BS is larger than SL, $G_1 > 1$ and from equation (13), the reduced drop height will be less than the actual drop height. In the case that BS is equal to SL, $G_1 = 1$, and the reduced drop height will be equal to the actual drop height. To obtain an advantage using the convoluted cushion, packaging engineers need to make sure that the buckling stress is more than the static loading.

2. In the case where the actual drop height is not greater than $f(BS/SL-1)$ the product will compress only the fingers, not the base. Substituting $h_1 = f(BS/SL-1)$ into equation (13) gives $h_2 = 0$. The shock to the product consists of G_1 only, with $G_1 = (BS/SL)$. This will not likely damage a product because G_1 is usually about 5 G which is very small. In this case, even though the product is dropped on to the convoluted cushion, no compression of the block part occurs. This is one of the advantages of convoluted cushions.

3. A compression tester is not required to find the buckling stress BS. The buckling stress can be obtained from a recorded shock pulse by measuring G_1 and using equation (7) $BS = G_1 \times SL$.

ERRORS

Tables 10 through 12 in Appendix E show the predicted G_1 at each drop height and comparisons with experimental G_1 values. The results show that the percent errors between the experimental and predicted peak G_1 were very large, up to 80%. The reason of these large errors is partly due to the sensitivity of accelerometer, which was not reliable at low accelerations. Another source of error is the fact that the number and shape of the fingers per unit area varies from sample to sample. The predicted G_1 is in theory independent of the drop height since it came from buckling stress divided by static stress.

Tables 13 through 15 in Appendix E show the predicted G_2 at each drop height and comparisons with the experimental G_2 values. The results show that the percent error between the experimental and predicted G_2 was about 20%, which is good because published cushion curve are usually no more accurate than about $\pm 15\%$. At lower drop height like 16 inches, the predicted G_2 tended to be over estimated. On the other hand, at higher drop heights, 22 and 28 inches, the predicted G_2 tended to be under estimated.

APPENDIX A

CONVOLUTED CUSHION DROP TEST RESULTS

Table 3. Experimental G_1 and G_2 at actual free fall drop height 16 inches

Weight	G's											
	C-200						C-400					
	17.8 lbs		22.8 lbs		27.8 lbs		17.8 lbs		22.8 lbs		27.8 lbs	
	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2
1	2.49	26.71	2.13	33.73	2.15	40.14	5.10	30.11	2.80	29.00	2.76	36.46
2	3.09	27.31	2.58	34.13	2.79	40.81	5.33	27.49	3.01	35.46	1.83	32.70
3	2.91	27.88	2.87	33.83	2.32	39.46	4.21	24.98	2.89	30.30	1.80	43.05
4	2.01	35.97	3.13	34.85	3.32	41.34	4.81	31.04	2.98	29.50	1.85	36.77
5	2.69	27.90	2.94	35.00	3.11	41.39	3.43	26.39	3.09	37.29	1.17	33.58
6	2.91	27.08	3.17	34.69	2.26	41.60	3.93	25.96	2.46	31.19	1.59	41.96
7	2.99	36.09	2.19	34.79	2.19	40.80	3.74	30.64	2.56	29.86	1.54	37.11
8	2.86	27.82	2.47	35.17	1.92	41.78	3.24	25.78	2.76	35.92	1.77	34.13
9	2.96	27.77	2.87	34.83	2.20	40.61	4.23	25.58	2.32	31.23	1.72	42.70
10	3.30	36.54	3.09	35.15	2.46	42.08	5.00	30.15	3.04	31.75	1.57	35.16
Avg.	2.82	30.11	2.74	34.62	2.47	41.00	4.30	27.81	2.79	32.15	1.76	37.36
SD	0.36	4.22	0.38	0.53	0.45	0.80	0.73	2.40	0.26	2.97	0.41	3.87

Table 4. Experimental G_1 and G_2 at actual free fall drop height 22 inches

Weight	G's											
	C-200						C-400					
	17.8 lbs		22.8 lbs		27.8 lbs		17.8 lbs		22.8 lbs		27.8 lbs	
	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2
1	7.73	46.60	5.88	62.38	5.52	71.94	8.95	45.29	5.37	53.73	4.58	75.50
2	5.92	60.19	6.07	60.43	5.67	71.62	10.67	45.07	6.59	64.07	3.90	64.92
3	8.26	48.60	6.15	60.63	4.57	73.59	9.73	52.42	5.54	56.88	4.25	61.02
4	8.32	49.23	5.81	61.06	4.99	73.73	8.92	48.87	6.32	54.88	4.14	77.30
5	6.00	65.10	5.92	62.27	5.31	73.94	9.47	47.07	5.67	64.38	3.40	66.25
6	8.96	52.16	5.85	61.88	4.67	71.65	8.96	54.76	5.34	57.57	4.79	62.95
7	8.62	50.58	5.73	62.56	4.72	73.47	8.68	49.84	5.64	54.87	3.62	75.85
8	6.49	64.73	5.89	61.72	4.47	73.70	9.98	47.50	6.06	65.19	3.71	66.43
9	8.89	50.53	5.88	61.98	4.38	74.29	9.40	54.54	5.51	57.92	3.97	62.92
10	8.54	50.99	6.08	61.78	4.71	73.79	8.23	48.76	5.69	54.66	4.08	78.01
Avg.	7.77	53.87	5.93	61.67	4.90	73.17	9.30	49.41	5.77	58.42	4.04	69.12
SD	1.19	6.83	0.13	0.73	0.45	1.02	0.71	3.49	0.42	4.45	0.43	6.73

Table 5. Experimental G_1 and G_2 at actual free fall drop height 28 inches

Weight	G's											
	C-200						C-400					
	17.8 lbs		22.8 lbs		27.8 lbs		17.8 lbs		22.8 lbs		27.8 lbs	
	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2
1	6.49	69.06	6.61	86.95	6.42	97.76	8.85	56.85	6.53	87.21	6.45	101.15
2	6.90	67.83	8.95	82.74	4.94	100.05	8.22	62.25	6.56	72.43	5.37	86.22
3	7.00	69.17	7.86	81.88	5.29	98.39	8.31	71.73	7.78	76.71	6.67	101.32
4	6.81	68.18	7.17	83.41	6.25	99.86	8.50	62.19	7.06	88.09	5.05	84.61
5	6.64	67.97	7.00	81.57	5.64	98.71	7.64	65.80	7.82	73.81	5.19	89.73
6	6.94	68.14	6.73	81.95	4.52	99.34	7.86	72.48	7.58	75.89	6.55	104.60
7	7.19	70.04	7.33	83.82	4.59	100.23	8.24	63.16	6.68	73.36	4.39	87.45
8	6.97	68.31	6.55	84.89	5.03	102.10	7.26	63.55	7.45	75.78	5.03	102.82
9	6.20	66.66	6.43	79.05	5.69	101.65	8.02	63.82	6.46	86.23	6.09	84.64
10	6.50	68.29	6.75	79.64	6.22	100.55	7.33	65.54	6.72	74.21	5.76	90.86
Avg.	6.76	68.37	7.14	82.59	5.46	99.86	8.02	64.74	7.06	78.37	5.66	93.34
SD	0.30	0.91	0.77	2.35	0.69	1.38	0.51	4.60	0.54	6.22	0.77	8.15

APPENDIX B

CONVOLUTED CUSHION COMPRESSION TEST RESULTS

From the attached force versus compression curves, the following buckling forces have been identified.

The average buckling force for C-200 = $(70+64)/2 = 67$ lbs.

The average buckling force for C-400 = $(88+86)/2 = 87$ lbs.

Table 6. Buckling force and deflection for convoluted polyurethane ester cushions

Cushion	Average buckling force, lbs	Deflection of fingers, inches	Equivalent block thickness, inches
C-200	67	1.50	1.25
C-400	87	1.25	1.50

The buckling stresses for the two types of cushions based on Table 6 and a base area of 8 inches x 8 inches are:

$$BS = 67/64 = 1.05 \text{ psi for C-200}$$

$$BS = 87/64 = 1.36 \text{ psi for C-400}$$

The deflection of the fingers, the equivalent block thickness and buckling stress (BS) will be used to calculate h_2 , predict G_2 and G_1 , respectively, in Appendix D.

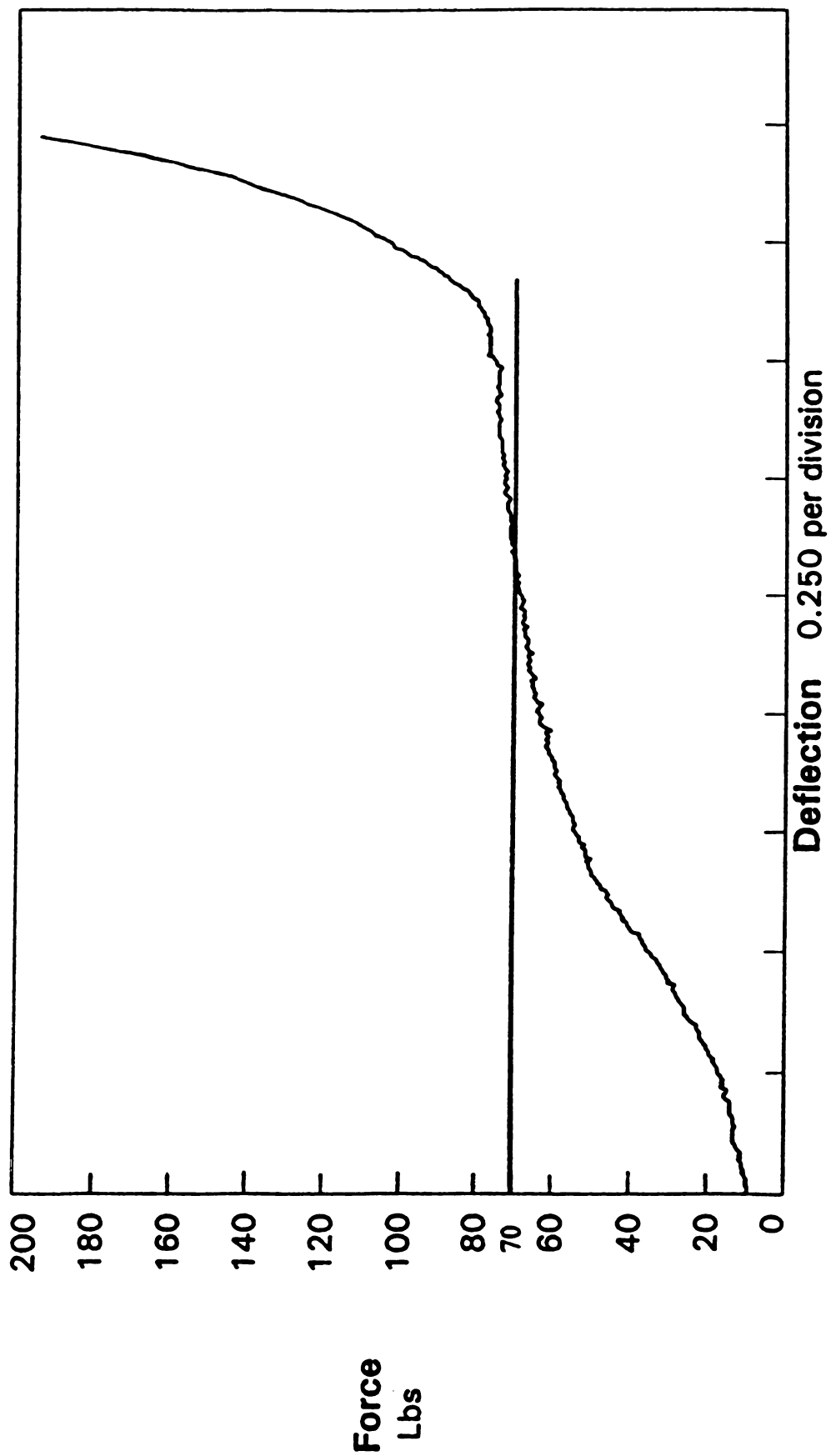


Figure 14. Force versus deflection for C-200, test 1

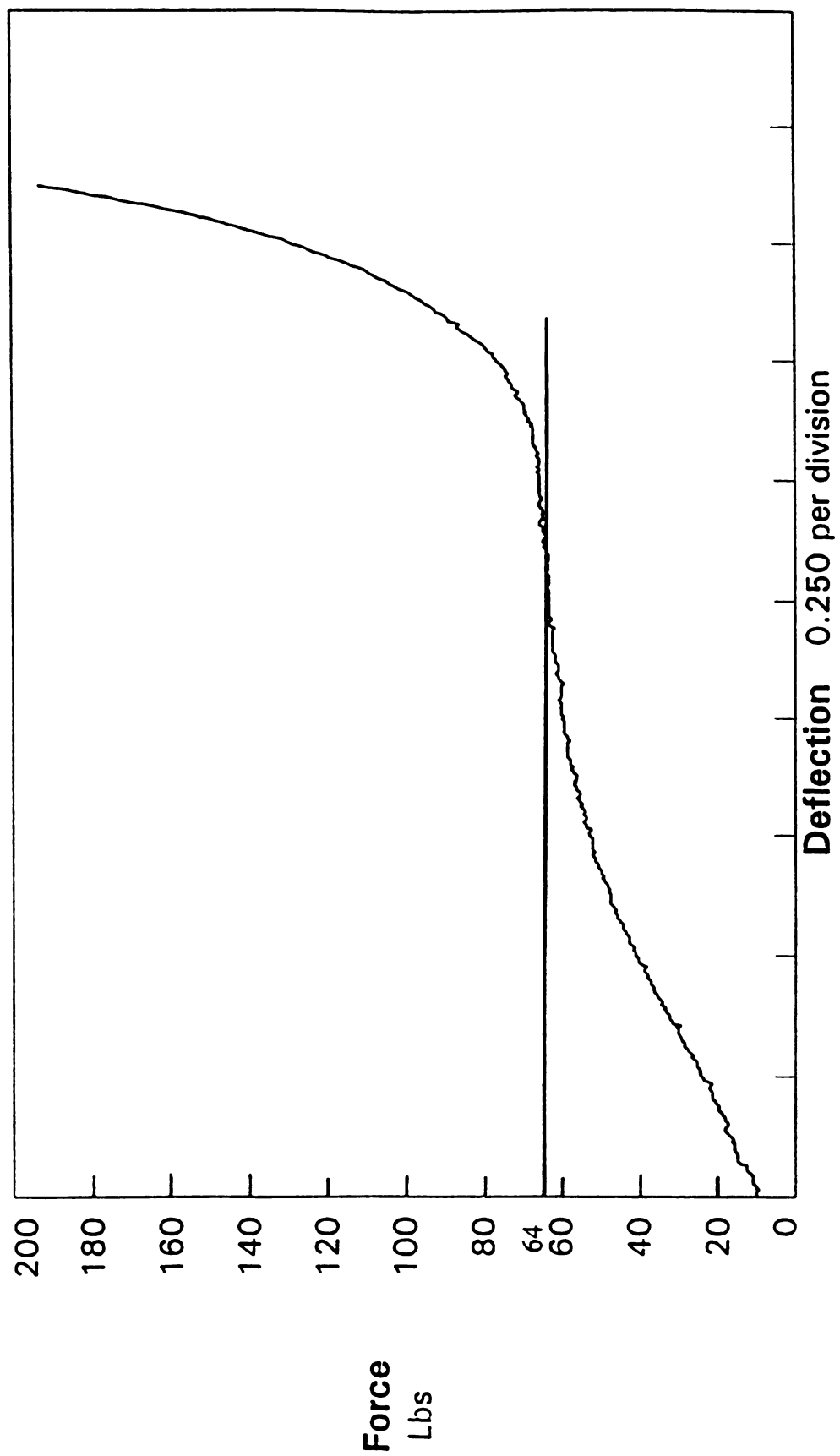


Figure 15. Force versus deflection for C-200, test 2

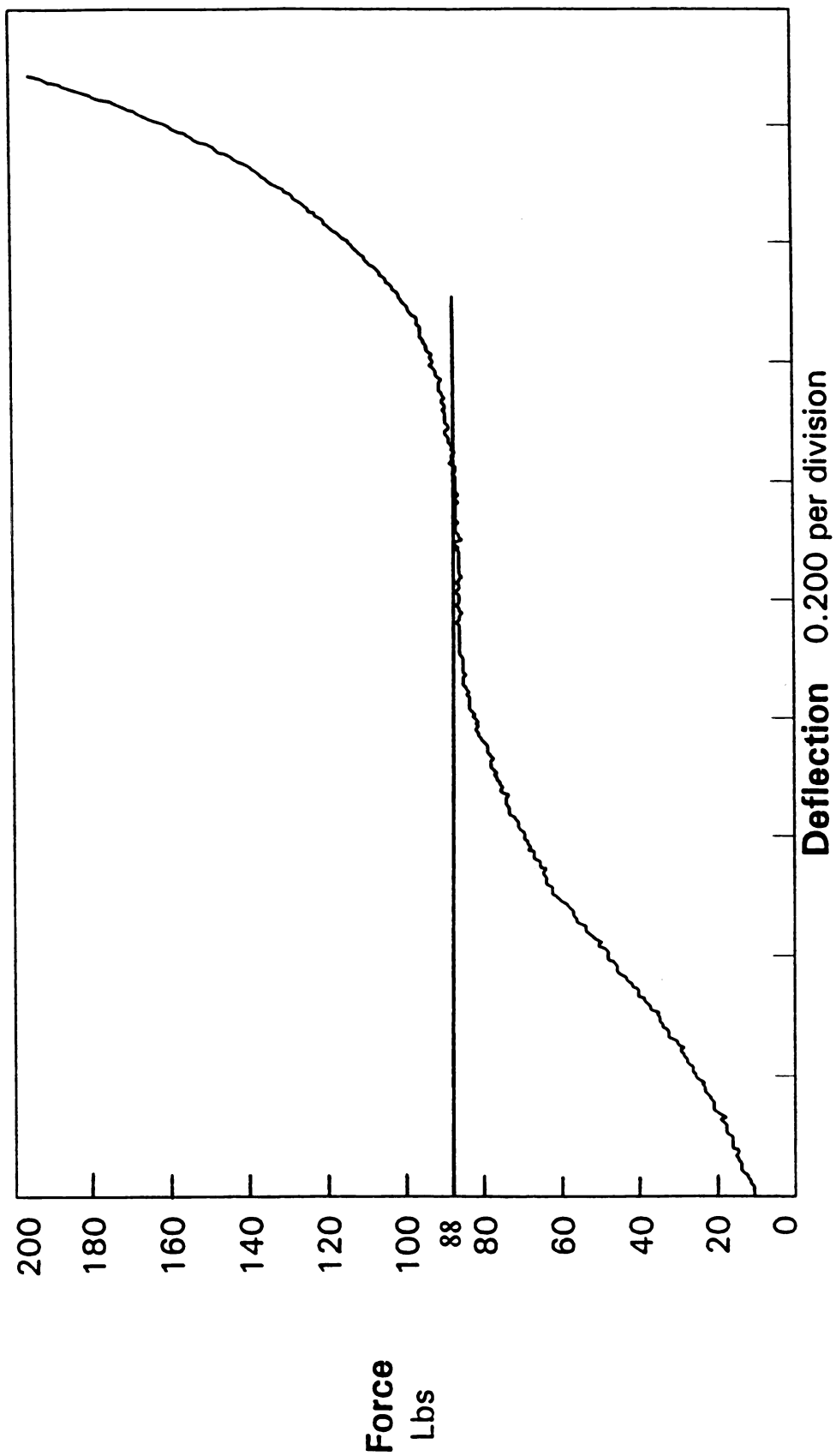


Figure 16. Force versus deflection for C-400, test 1

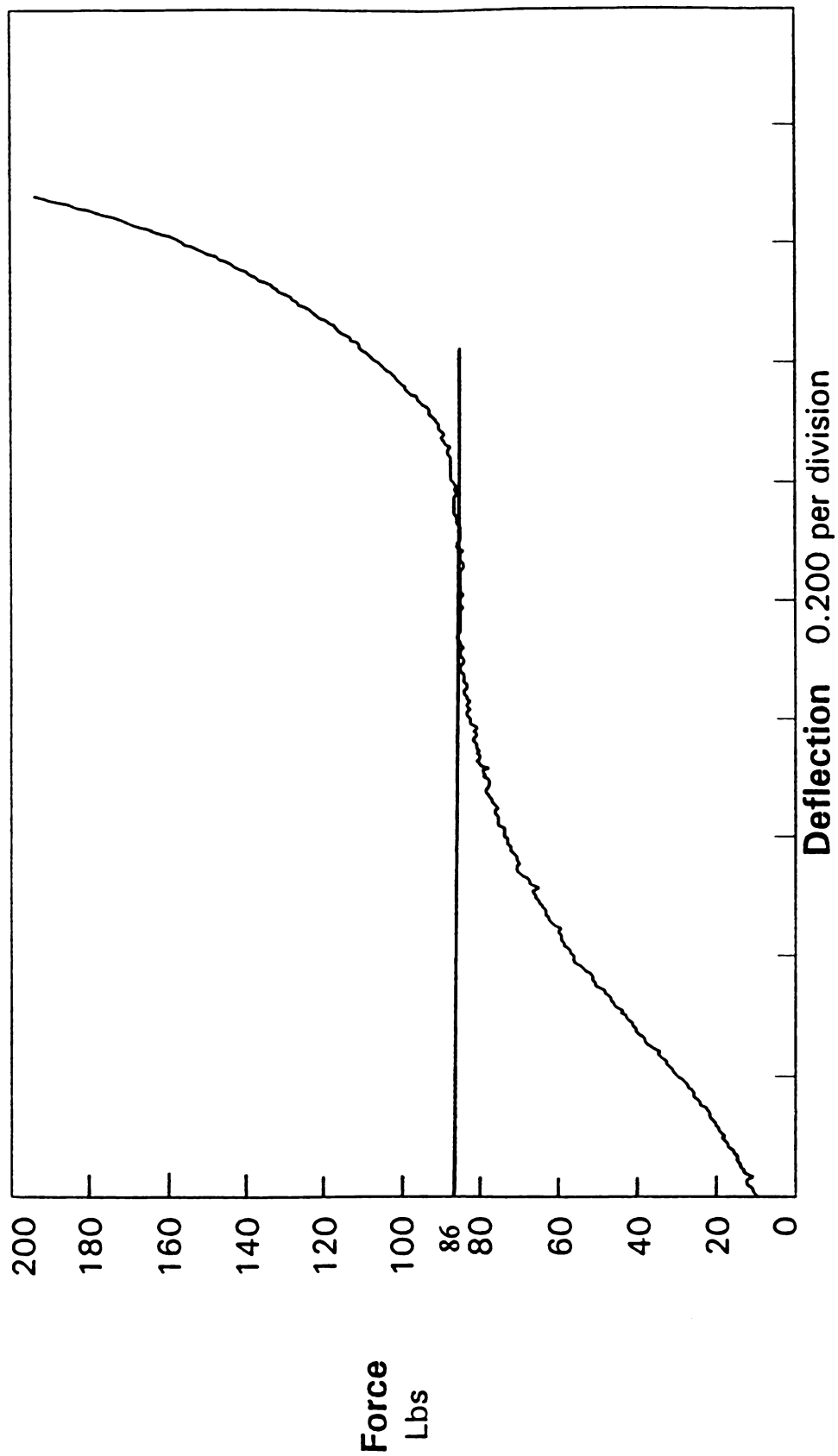
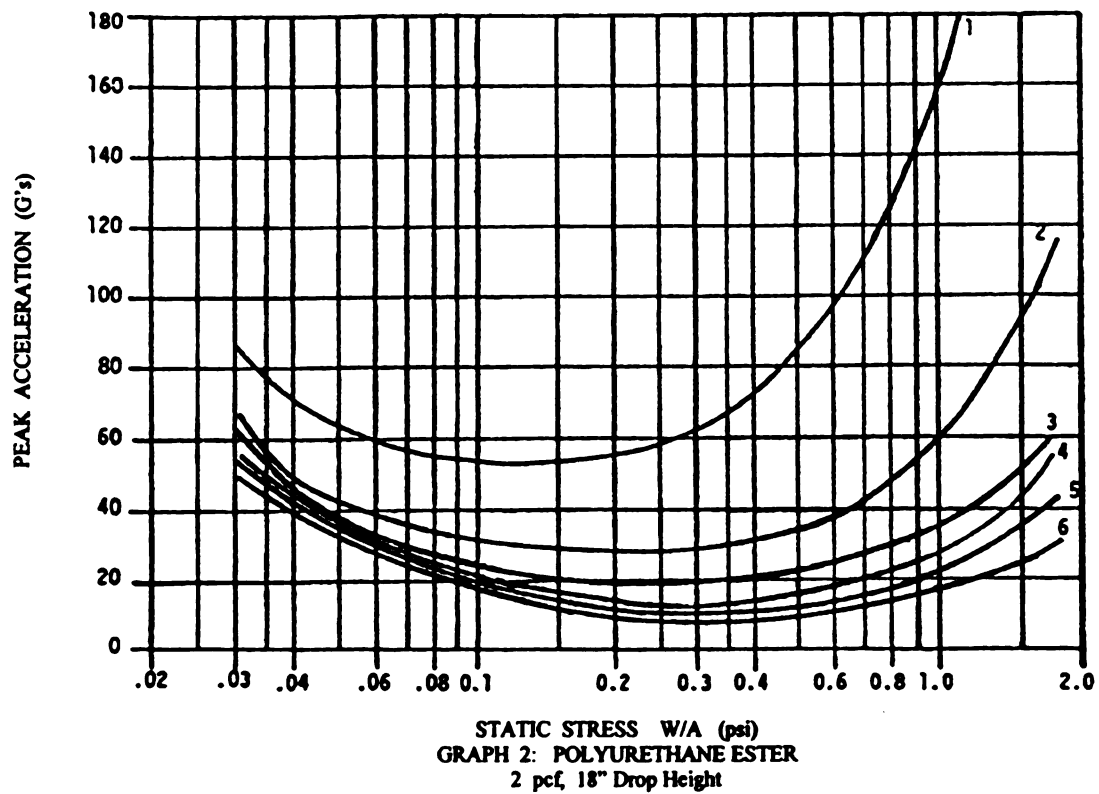
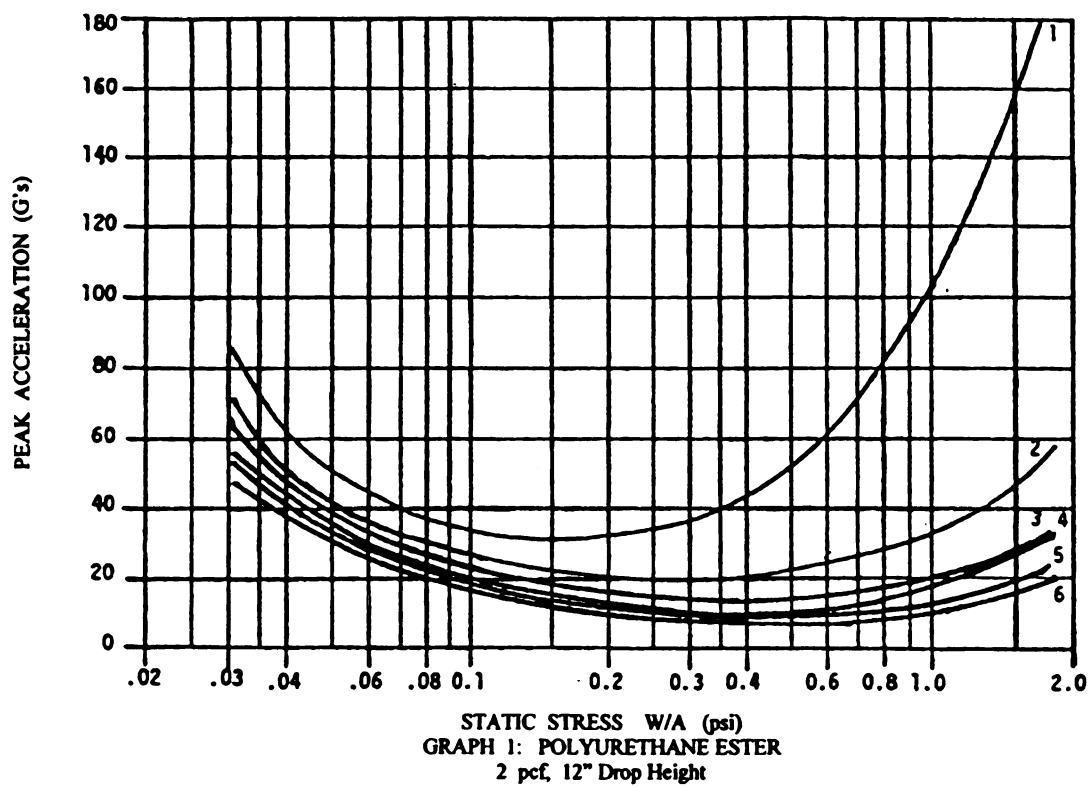


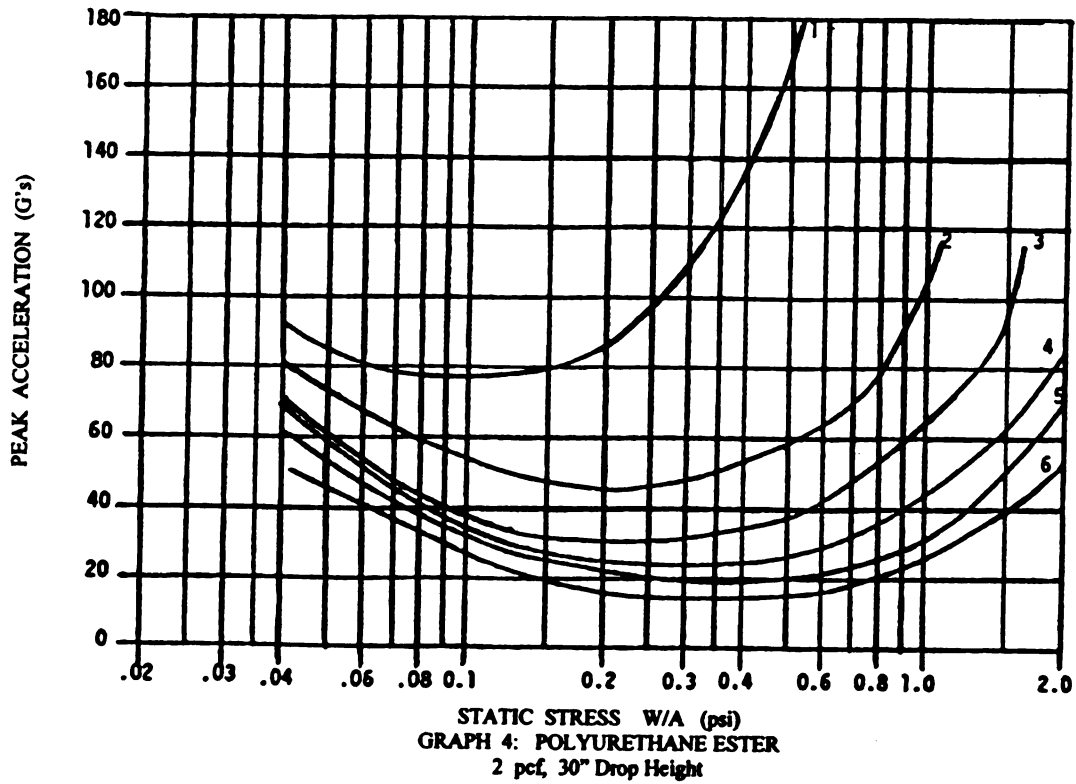
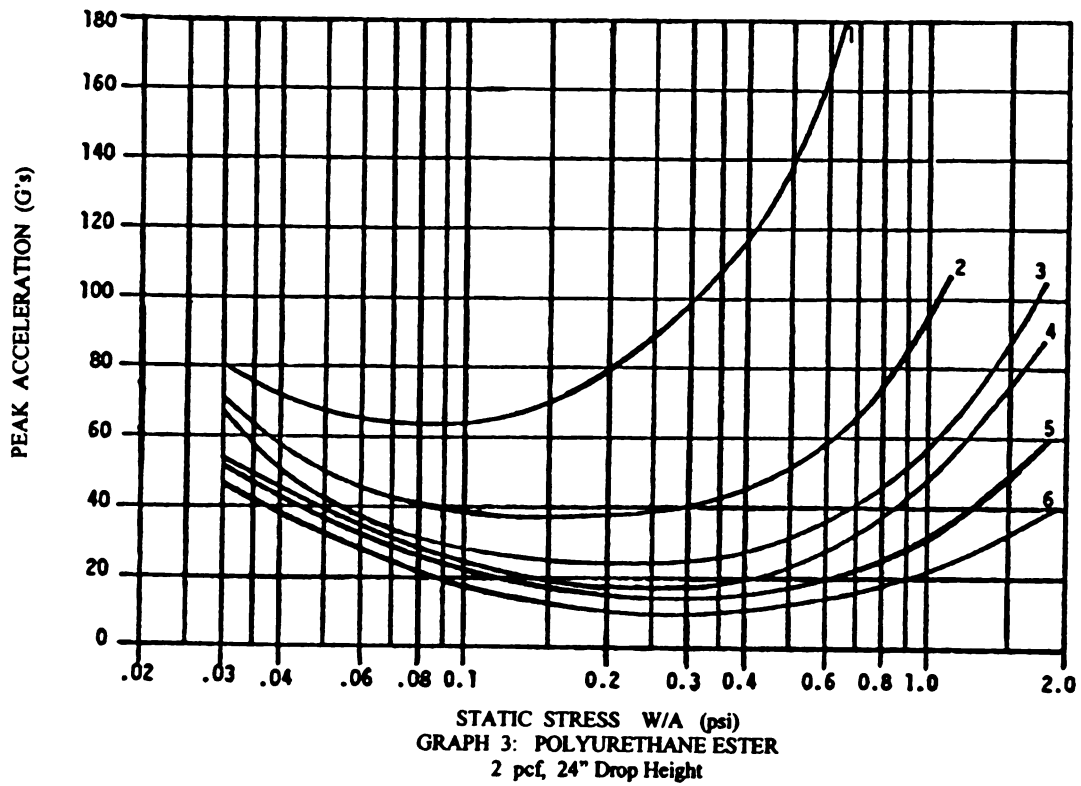
Figure 17. Force versus deflection for C-400, test 2

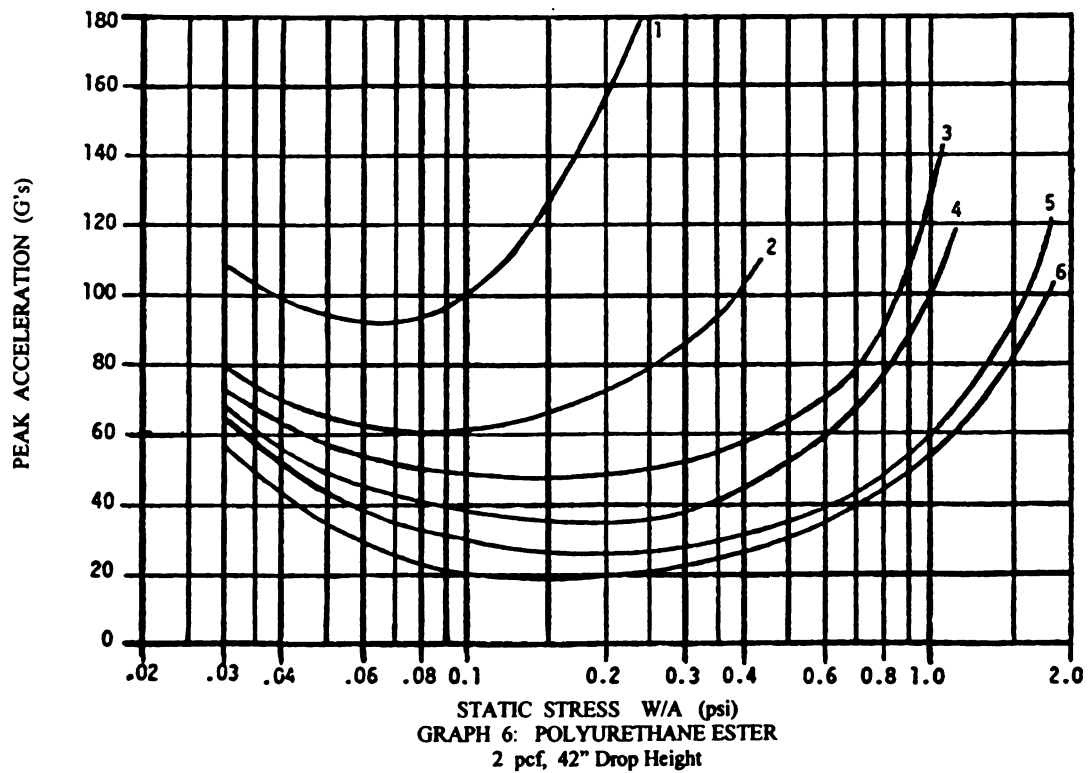
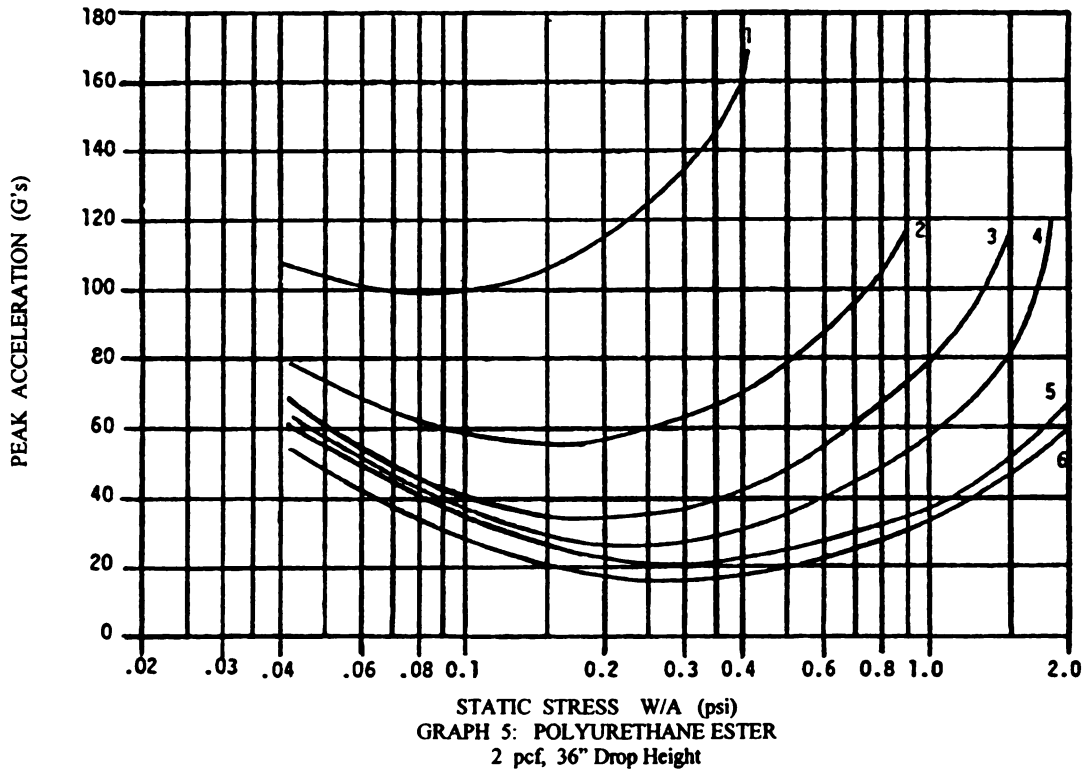
APPENDIX C

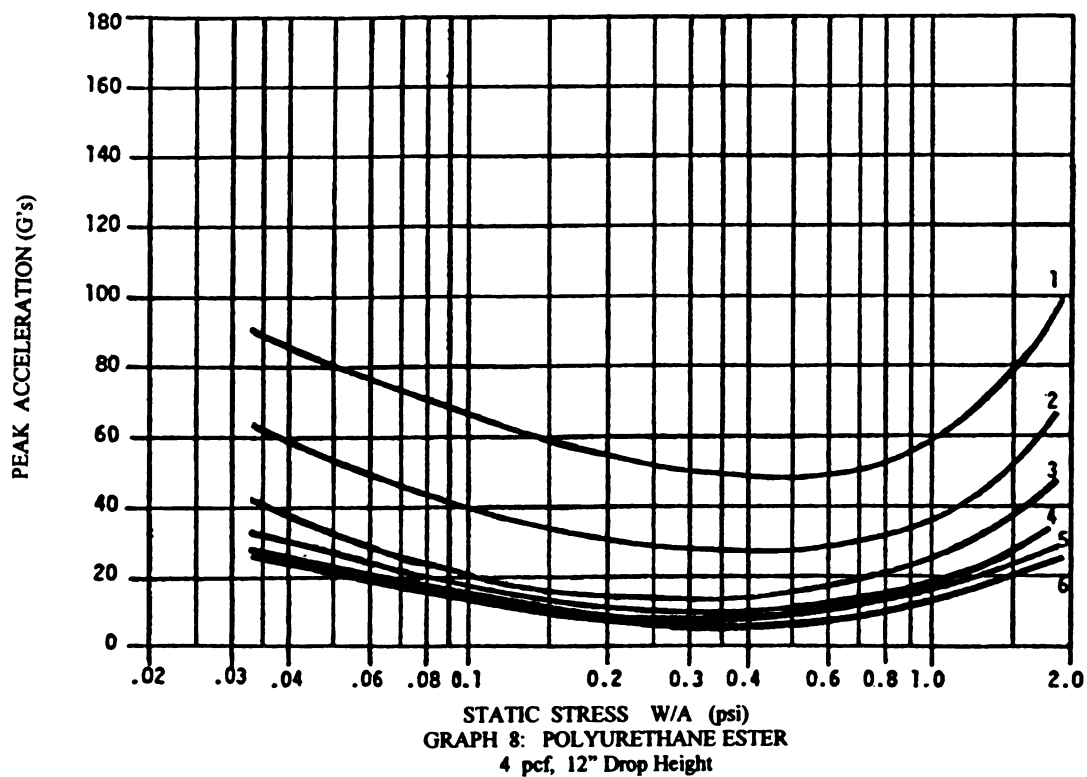
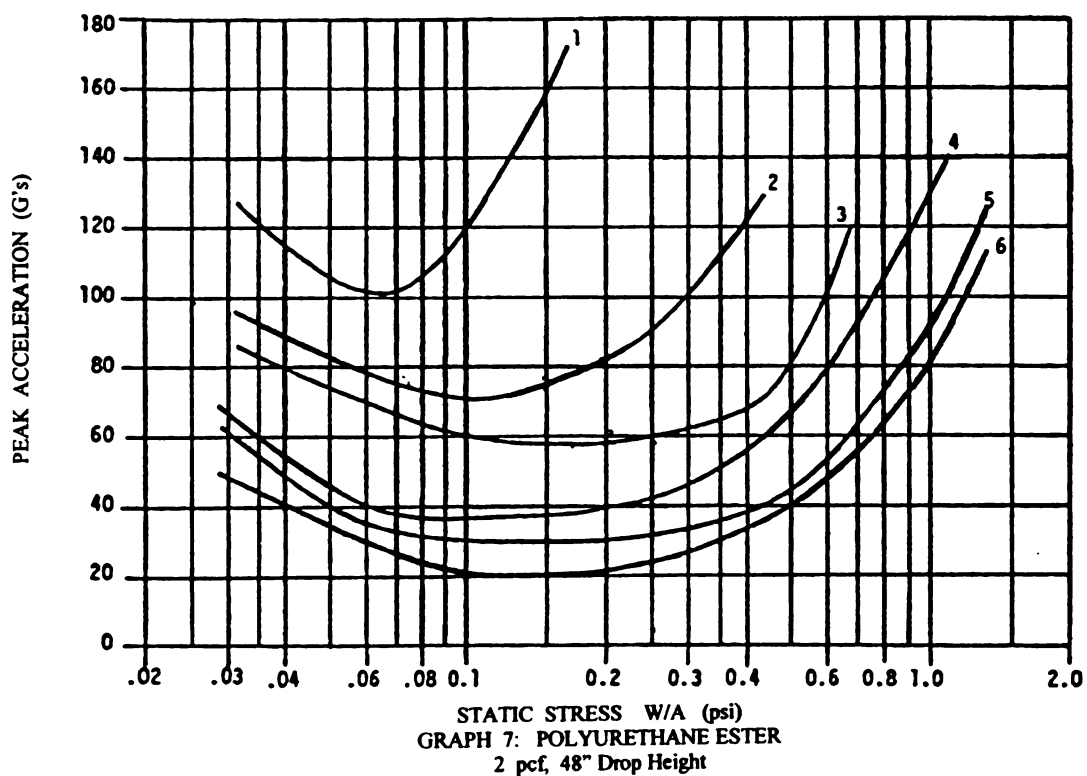
PUBLISHED CUSHION CURVES FOR POLYURETHANE ESTER

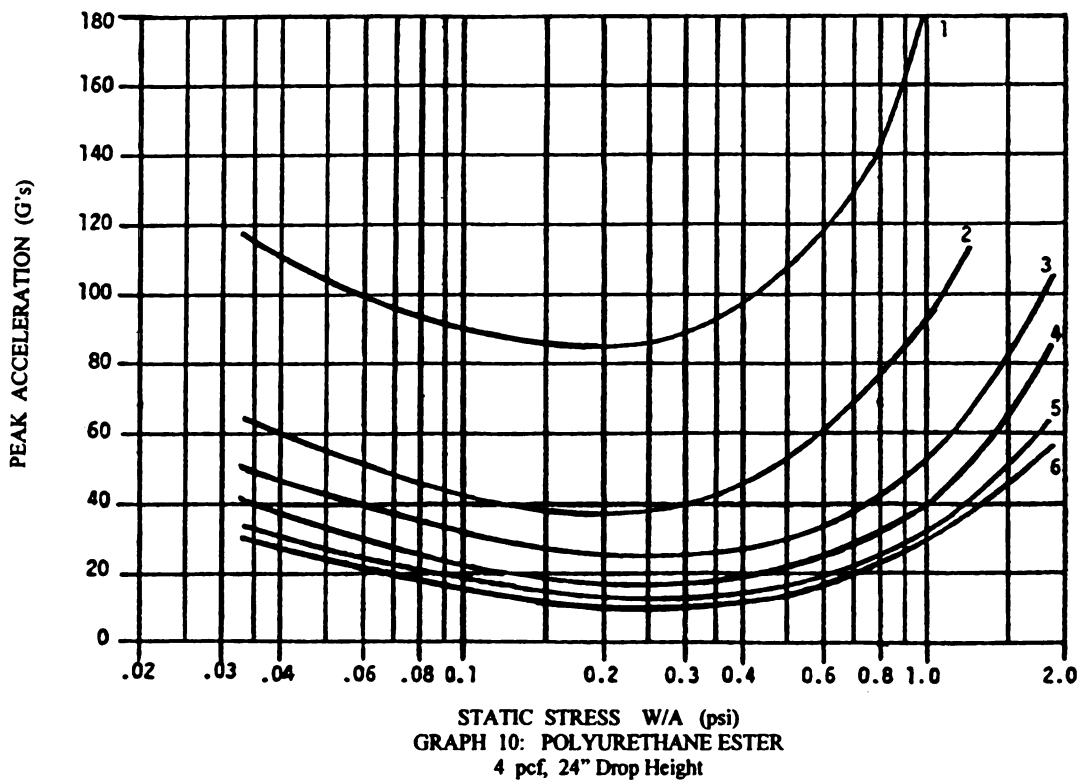
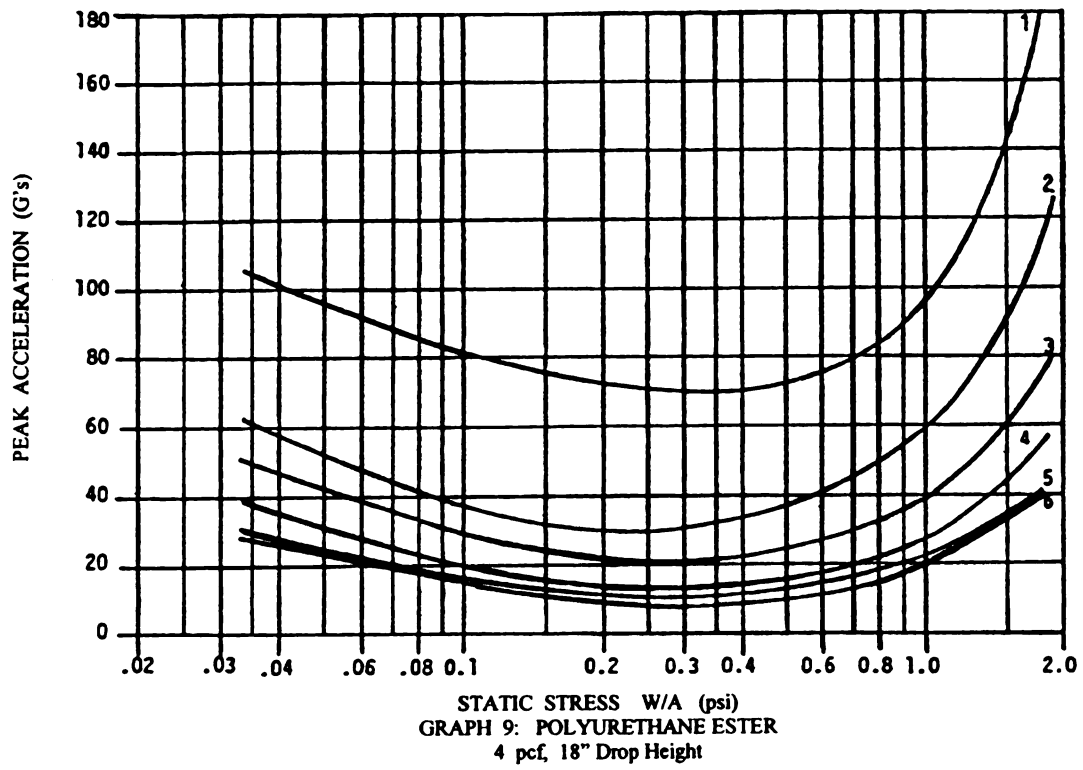
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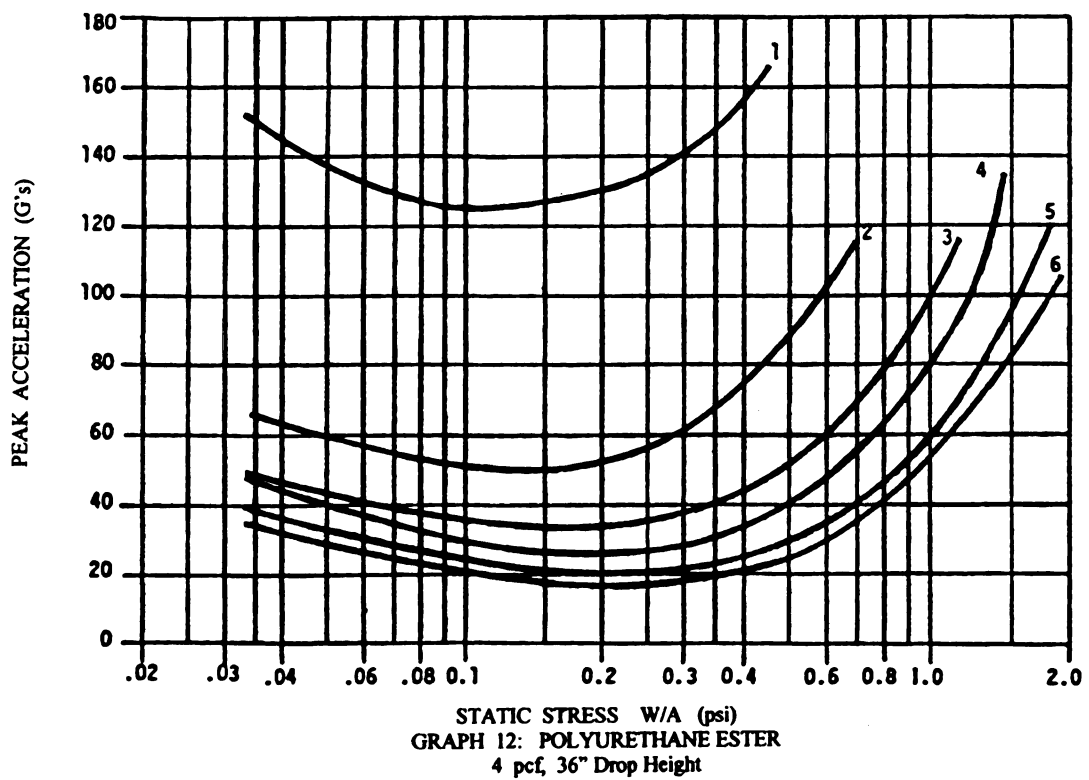
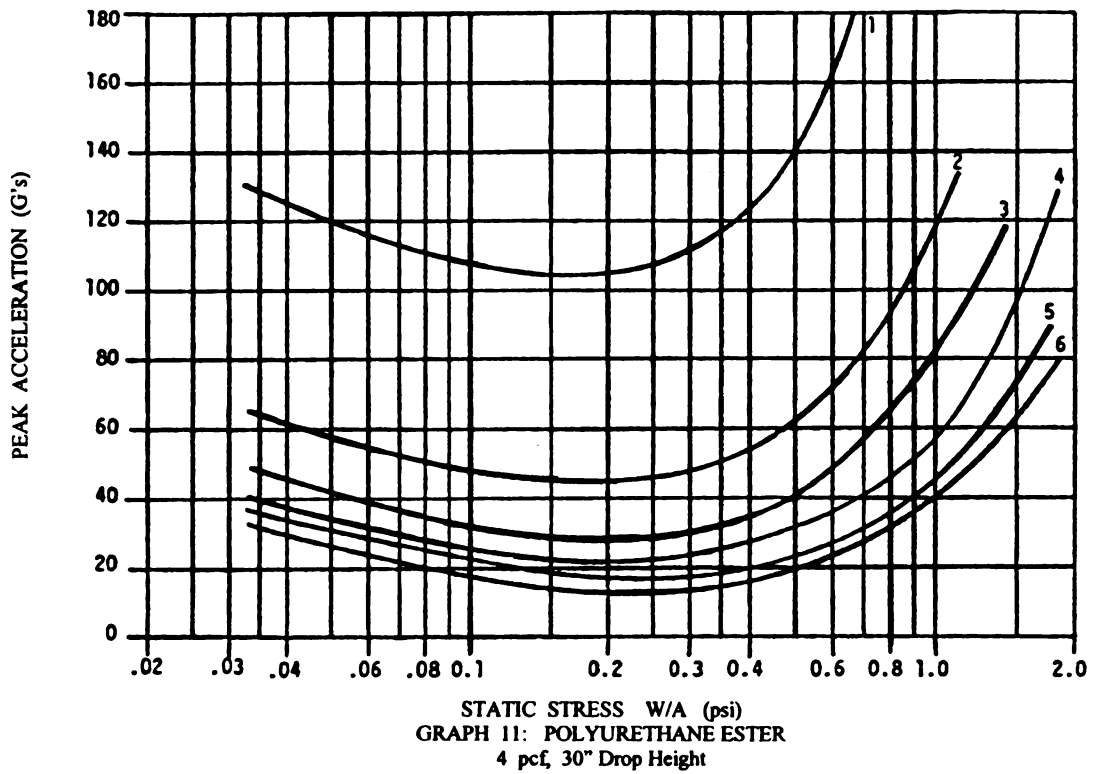


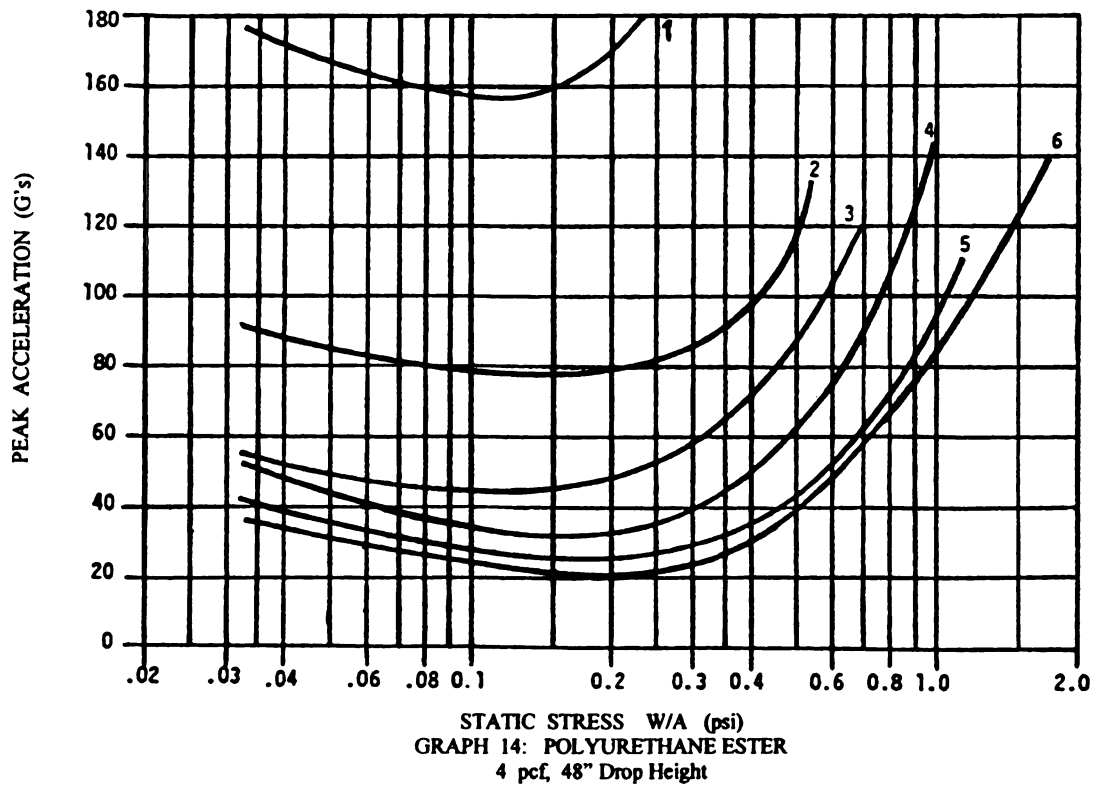
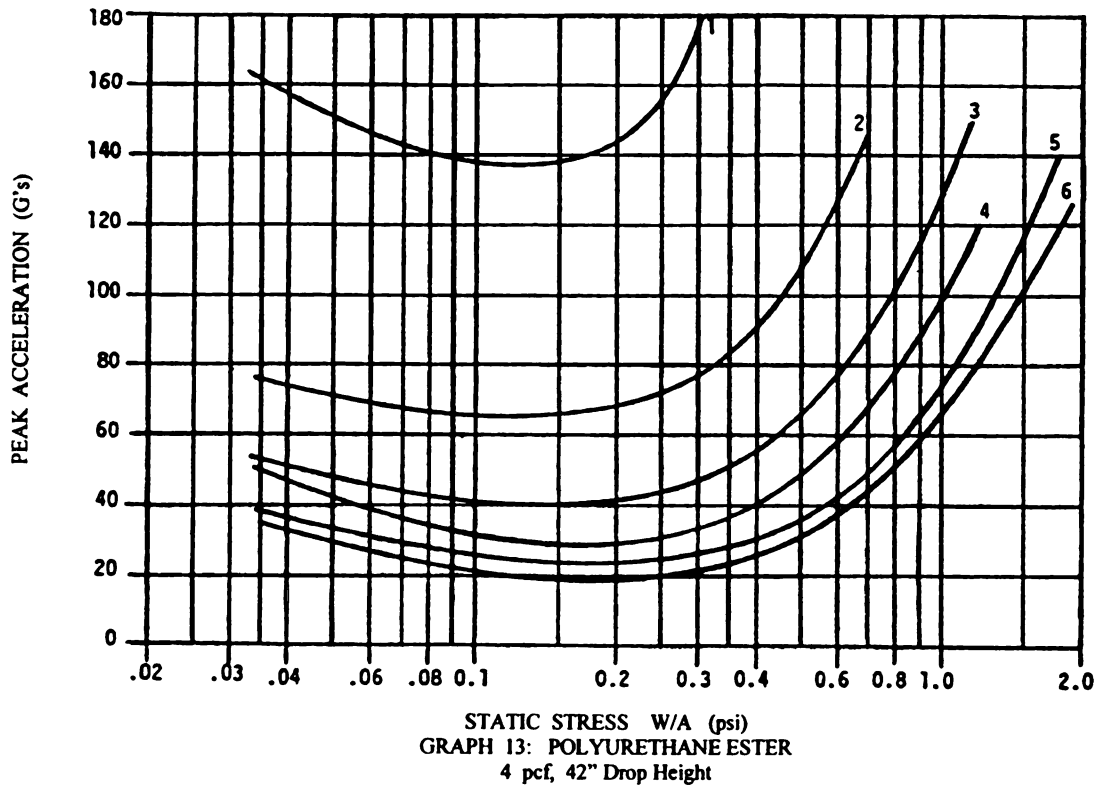












APPENDIX D

PREDICTED PEAK ACCELERATIONS

Table 7. Predicted G_1 and G_2 from actual free fall drop height of 16 inches for C-200 and C-400 convoluted cushions.

Cushion	Weight, lbs	BS, psi	SL, psi	G_1	h_2 , in.	G_2
C-200	17.80	1.05	0.28	3.75	11.88	28.89
	22.80	1.05	0.36	2.92	13.12	33.11
	27.80	1.05	0.43	2.44	13.84	38.41
C-400	17.80	1.36	0.28	4.86	11.18	31.05
	22.80	1.36	0.36	3.78	12.53	33.80
	27.80	1.36	0.43	3.16	13.30	35.17

where $SL = W/A$

$$G_1 = BS/SL$$

$$h_2 = h_1 - (G_1 - 1)f$$

G_2 was obtained from cushion curves for equivalent block cushion.

Table 8. Predicted G_1 and G_2 from actual free fall drop height of 22 inches for C-200 and C-400 convoluted cushions.

Cushion	Weight, lbs	BS, psi	SL, psi	G_1	h_2 , in.	G_2
C-200	17.80	1.05	0.28	3.75	17.88	42.22
	22.80	1.05	0.36	2.92	19.12	51.14
	27.80	1.05	0.43	2.44	19.84	58.90
C-400	17.80	1.36	0.28	4.86	17.18	39.04
	22.80	1.36	0.36	3.78	18.53	45.15
	27.80	1.36	0.43	3.16	19.30	54.33

Table 9. Predicted G_1 and G_2 from actual free fall drop height of 28 inches for C-200 and C-400 convoluted cushions.

Cushion	Weight, lbs	BS, psi	SL, psi	G_1	h_2 , in.	G_2
C-200	17.80	1.05	0.28	3.75	23.88	66.67
	22.80	1.05	0.36	2.92	25.12	74.68
	27.80	1.05	0.43	2.44	25.84	87.52
C-400	17.80	1.36	0.28	4.86	23.18	53.70
	22.80	1.36	0.36	3.78	24.53	61.33
	27.80	1.36	0.43	3.16	25.30	72.17

APPENDIX E

ERROR ANALYSIS

Table 10. Error between predicted and actual G_1 at free fall drop height of 16 inches.

Cushion	Static stress, psi	Experimental G_1	Predicted G_1	% Error
C-200	0.28	2.82	3.75	-32.98
	0.36	2.74	2.92	-6.57
	0.43	2.47	2.44	1.21
C-400	0.28	4.3	4.86	-13.02
	0.36	2.79	3.78	-35.48
	0.43	1.76	3.16	-79.55

Table 11. Error between predicted and actual G_1 at free fall drop height of 22 inches.

Cushion	Static stress, psi	Experimental G_1	Predicted G_1	% Error
C-200	0.28	7.77	3.75	51.74
	0.36	5.93	2.92	50.76
	0.43	4.90	2.44	50.20
C-400	0.28	9.30	4.86	47.74
	0.36	5.77	3.78	34.49
	0.43	4.04	3.16	21.78

Table 12. Error between predicted and actual G_1 at free fall drop height of 28 inches.

Cushion	Static stress, psi	Experimental G_1	Predicted G_1	% Error
C-200	0.28	6.76	3.75	44.53
	0.36	7.14	2.92	59.10
	0.43	5.46	2.44	55.31
C-400	0.28	8.02	4.86	39.40
	0.36	7.06	3.78	46.46
	0.43	5.66	3.16	44.17

Table 13. Error between predicted and actual G_2 at free fall drop height of 16 inches.

Cushion	Static stress, psi	Experimental G_2	Predicted G_2	% Error
C-200	0.28	30.11	28.89	4.05
	0.36	34.62	33.11	4.36
	0.43	41.00	38.41	6.32
C-400	0.28	27.81	31.05	-11.65
	0.36	32.15	33.80	-5.13
	0.43	37.36	35.17	5.86

Table 14. Error between predicted and actual G_2 at free fall drop height of 22 inches.

Cushion	Static stress, psi	Experimental G_2	Predicted G_2	% Error
C-200	0.28	53.87	42.22	21.63
	0.36	61.67	51.14	17.07
	0.43	73.17	58.90	19.50
C-400	0.28	49.41	39.04	20.99
	0.36	58.42	45.15	22.71
	0.43	69.12	54.33	21.40

Table 15. Error between predicted and actual G_2 at free fall drop height of 28 inches.

Cushion	Static stress, psi	Experimental G_2	Predicted G_2	% Error
C-200	0.28	68.37	66.67	2.49
	0.36	82.59	74.68	9.58
	0.43	99.86	87.52	12.36
C-400	0.28	64.74	53.70	17.05
	0.36	78.37	61.33	21.74
	0.43	93.34	72.17	22.68

REFERENCES

- ASTM D 1596-91. 1994. Standard Test Methods for Dynamic Shock Cushioning Characteristics of Packaging Material. Selected ASTM Standard on Packaging. 4th ed.
- ASTM D 3332-93. 1994. Standard Test Method for Mechanical-Shock Machines. Selected ASTM Standard on Packaging. 4th ed.
- Burgess G. 1997. Class Lecture Notes. Packaging 805, Advanced Packaging Dynamics. Michigan State University.
- Baumdraher DE. 1995. Shock Fragility Testing of Fatigue-Sensitive Products. M.S. Thesis. School of Packaging, Michigan State University.
- Grantham G. 1991. Predicting Shock Transmission Characteristics for Ribbed Expanded Polypropylene Cushions Using Standard Cushion Curves for Flat Plank Cushions. M.S. Thesis. School of Packaging, Michigan State University.
- Markley RL and Gillis HR. 1994. Modern Plastics Encyclopedia Handbook. McGraw-Hill, Inc.
- Ohanian HC. 1985. Physics, W.W. Norton & Company.
- Polyurethane Foam Association. 1991. Information on Flexible Polyurethane Foam. In-Touch Magazine. 1(5).
- Resnick R and Halliday D. 1977. Fundamental of Physics, Part 1 3rd ed. John Wiley & Sons, Inc.
- United State Department of Defense. 1978. Military Standardization Handbook, Mil-HDBK-304B. Packaging Cushion Design.