THE PRACTICAL ASPECTS OF PROTECTIVE PACKAGE DESIGN

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I. INTRODUCTION

The purpose of this paper is to assist engineering, marketing and design personnel in the analysis of a customer's requirements for a package system. The basics of dynamic package design are present in a fashion useful to the packaging practitioner.

Certainly there are numerous sources that one can turn to for precise technical data on the behavior of products and materials in a dynamic environment. But how does one **use** this information? How does one determine what's important and what isn't in a particular customer interaction? How does one go about designing an optimum package system, or even recognizing when that system has been designed? Finally, how does one know whether the final numbers are believable or if significant question areas exist which would benefit from further analysis?

These and other areas will be investigated.

II. DETERMINE PACKAGE REQUIREMENTS

The primary functions performed by a package system are generally described in terms of protection, motivation and convenience which the package system affords. While important, the motivation and convenience functions of a package will not be dealt with here. The protection function of a package system refers to its ability to limit physical input to a level which is below the product's fragility (or maximum tolerable level). These inputs can be mechanical shock, vibration, temperature or humidity extremes, compression, static electric discharge, electro magnetic fields, etc. We will limit our remarks to the effects of shock and vibration.

The first step in the analysis of a dynamic packaging requirement is to establish whether or not there is a fragility related problem. While this may sound very basic, it is probably the cause of more headaches and wasteful overpackaging than any other single reason. Many engineers assume that because they're shipping a certain type of product they have to package to a "safe fragility level". For example, many manufacturers of computer systems think that the package must limit the acceleration to 30 G's or less. The simple fact is that most of today's computers (with Winchester disc drives) can safely withstand levels of 70 G's and more without product degradation. Examples include sophisticated (and expensive) personal computers.

Another common problem is that most engineers do not have a good intuitive feel for acceleration. When asked the fragility of a light bulb, most engineers will peg it at 20 G's or less, when in actuality, the normal light bulb has a fragility closer to 200 G's. Fragility levels of other common items are show in Table I.

Table I
TYPICAL FRAGILITY LEVELS

	G's
Biomedical Electronic gear, microwave tubes	25-30
Navigational equipment	30-40
Electromechanical equipment, printers, copiers	40-50
Computer processors, TVs, monitors, kitchen appliances	75-100
Electronic games, calculators, solid state electronic devices	70-150
Raw egg	above 200

In general, don't assume that fragility is known unless testing has been accomplished to provide exact numbers.

Remember that a simple relationship exists between the fragility (or ruggedness) of a product, the severity of the distribution environment, and the amount of protection (and cost) required of the package.

$$DE = PR + C$$

(Distribution Environment = Product Ruggedness + Cushion)

In other words, the product plus the protective package (cushion) must be equal to the bumps and shocks of the distribution environment. The more rugged the product, the lower the demands (and therefor the cost) of the protective package system for a given distribution environment. Since our ability to alter the distribution environment is very limited, product ruggedness becomes the major component of package cost.

III. METHODS FOR DETERMINING PRODUCT FRAGILITY

The term "product fragility" has an ominous and almost terminal sound to it. A broken ketchup bottle or exploded television set are typical mental pictures which come to mind. In reality, product fragility is simply another product characteristic just as size, weight and color are unique product characteristics. Fragility is normally a function of the strengths and interconnections of individual components within the product.

The classic way to determine fragility is with the Damage Boundary Test procedure described in ASTM D3332. Although this procedure is very accurate and has been around since 1976, it is not widely used in packaging, and it is generally still rare to encounter a product for which an accurate damage boundary test sequence has been run. The same is generally true for vibration sensitivity and vibration testing of products, even though Mil Spec testing has emphasized vibration characteristics for a good number of years.

Another method often seen is the "historical method" consisting of a large history of successful shipments in a certain package system. The response transmitted through that package is assumed to be the fragility of the product. In other cases, the fragility is an imposed number from a third party over which the package designer and his or her customer have little or no control.

In any case, the acceleration or “deceleration sensitivity” of the product must be clearly established prior to designing a package system. However, don't fall into the trap of assuming that any acceleration levels are do-able just because it's easier to design a package system than it is to accurately determine the product fragility. As Figure 1 indicates, there is a great deal of difference in cushion thickness (and overall cost) of a system designed to transmit 30 G's as opposed to 20 G's from a given drop height. In general the amount of cushion material increases exponentially as the fragility of a product decreases in a linear fashion. The result is a tremendous waste of material if an engineer decides to use 20 G's as the "assumed fragility" of the product just to be on the safe side, when the actual fragility of the product is 40 G's or more.

DEFLECTION CALCULATIONS

Given that a product will be handled in the prescribed manner and that a maximum transmitted deceleration level of 50 G's is assumed to be acceptable, the following equation describes the total cushion deflection required at impact. Note that this deflection does not indicate the overall thickness of the cushion material, only the deflection necessary to limit peak deceleration to 50 G's or less.

$$\Delta x = 2h / (G-2) = (2)\,(30\text{ in.}) / (50-2) = 1.25\text{ in.}$$

Figure I CUSHION DEFLECTION - INCHES

Theoretical deflection in inches necessary to achieve a given deceleration level a drop heights of 30 in . Assumes linear, undamped spring characteristics.

IV. ESTABLISH PACKAGE PERFORMANCE CRITERIA

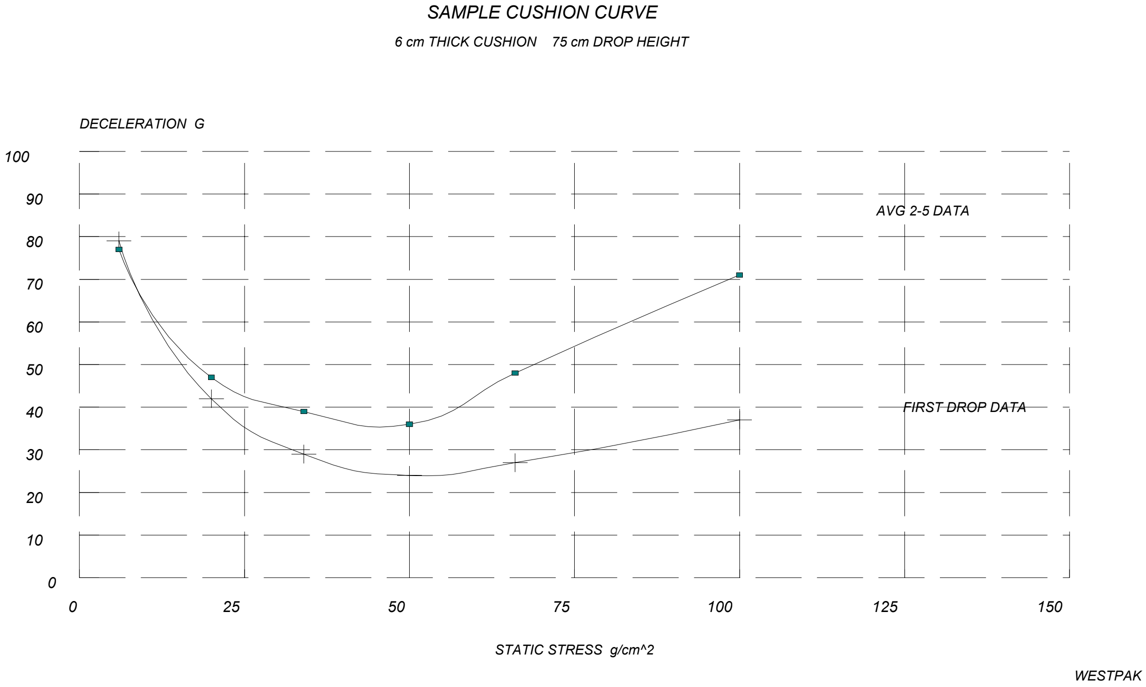
Before the package system is designed or tested, it is vital to establish the exact test procedure used to judge the performance characteristics of the package. This should include:

1) the design drop height
2) number and location of impacts
3) vibration test procedure

The reason for establishing the test procedure before the design process comes from the characteristic of some cushion materials whereby they transmit higher levels of acceleration with increasing drops (i.e., they take a set). For example, a close look at the cushion curve found in Figure 2 shows that the first drop from a given height and loading (static stress level) will result in lower transmitted deceleration than succeeding drops. This is especially true for semi-rigid and non-resilient cushion materials such as expanded polystyrene or molded pulp. The heavier loadings necessary to achieve lower deceleration levels will also have a negative effect on the cushion's ability to withstand repeated impacts. On the other hand, resilient materials such as expanded polyethylene generally show very little degradation with repeated impacts.

The bottom line is that if one were designing using EPS (Expanded Polystyrene or “styrofoam”) foam for a single impact verification test procedure, the static stress loading would be very different than if the test procedure required multiple impacts on the same face. However, if one were designing this for the same product using expanded polyethylene it would probably make little difference if the test procedure called for one impact on each face or multiple impacts.

Figure 2: Sample Cushion Curve



There is a subtle, though distinct difference between the **performance** and the **integrity** characteristics of a package system, both in terms of design criteria and the testing used to verify those criteria. The **performance** of a package system refers to its ability to mitigate shock and vibration input to a level which is below product fragility. This is distinguished from **integrity** which refers to the ability of a package system itself to withstand the normal forces involved in the distribution process. It is very possible to design a package which has the proper performance characteristics but will not withstand the bumps and jolts typical of shipment on common carrier truck.

Figure 3:

PERFORMANCE
VS.
INTEGRITY

- **Performance = ability to protect product by mitigating shock and vibration input. ASTM D-5276, D-999, D-4728**

- **Integrity = ability of the package to hold together, withstand normal bumps and jolts, UPS Gorilla, etc.**
  ISTA, ASTM D-4169, IEC 68-2

Package performance testing for shock normally involves a series of flat impacts with the deceleration transmitted through the cushion monitored by appropriate instrumentation. The shock integrity of a package system is generally verified by a series of corner and edge impacts typical of the ISTA (International Safe Transit Association) test procedure.

Vibration performance generally refers to the ability of a package system to attenuate vibration input at product natural (critical) frequencies. Vibration performance is tested by subjecting an instrumented package system to vibration input in a sinusoidal sweep or random vibration test like ASTM D999-B or ASTM D4728. The normal vibration integrity test involves one or more resonant dwells at the package critical frequencies. Random vibration testing is often used in place of resonant dwell tests.

It is interesting to note that **design performance** is something that is taught in school and can be verified by number crunching and analytical techniques. The **integrity of a design**, however, is something which normally must be learned by doing and is probably more art than science. It is indeed rare to find a person or a company which has successfully integrated both the performance and integrity requirements into package cushion designs.

V. DETERMINE CUSHION THICKNESS

The next step is to determine the thickness of the cushion material necessary to achieve the desired performance. For this exercise we assume the cushion material is a linear spring, undamped, and look solely at the total deflection necessary to achieve the required deceleration from the design drop height. This comes from the simple expression

$$\Delta X = 2h/(G-2)$$

where ΔX = cushion deflection (not cushion thickness),
h = design drop height, and
G = product ruggedness (fragility level)

Remember that this exercise gives us the theoretical **deflection** necessary, not the overall cushion thickness. In order to determine cushion thickness, you must consult a Stress/Strain Curve to find out at what deflection the material spring rate becomes nonlinear. In other words, when does it begin to "bottom out"?

In general, semi-rigid materials such as polystyrene and polyethylene will compress approximately 40 to 60% of their total thickness before bottoming starts to occur. More flexible materials such as polyurethane will compress approximately 80% of total thickness before beginning to bottom out. Data on other materials and systems are sketchy.

Design Example: Suppose a product has a fragility of 50 G's and a design drop height of 36". Calculate the deflection necessary and the resulting total cushion thickness for expanded polystyrene, polyethylene, and polyurethane foam cushions. The theoretical deflection can be determined from in the formula $\Delta X = 2h/(G-2)$. The resulting theoretical deflection is 1.5 inches. From this number the total cushion thickness necessary for the individual materials is as follows:

MATERIAL	OPTIMUM STRAIN %	TOTAL THICKNESS
EPS	40%	3.75 in.
PE	50%	3.00 in.
Polyurethane	70%	2.10 in.

these numbers can be modified somewhat through the use of ribs. However, these numbers do provide a good guideline for estimating cushion thickness. For example, if a customer wants to achieve a 50 G response from a 36" freefall, using a 2" thick EPS cushion, the numbers clearly show it is impossible.

VI. DETERMINE RIB CONFIGURATION

The next step in this process is to determine the pattern of the ribbing necessary for this cushion design. Before we do that, it is instructive to investigate why ribs are used in the first place.

The use of ribs will result in less cushion material in the overall design and therefore higher loading on the material which remains. Ribs will also change the nature of the stress/strain curve for a given material and can result in greater deflection for a given thickness of material.

There are no recognized procedures which would guide one to a certain configuration of ribs for a given design. Most of the work done in this area has been intuitive in nature with the ARCO Polymer Design Handbook being perhaps the best example. After reviewing the available literature, the following guidelines are offered for establishing rib configuration:

A. In general, the depth of a rib should be approximately one half to two thirds the total depth of the part cross section.

B. The cross sectional area of material at zero deflection should yield a static stress (loading) value of two or more times the optimum static stress obtained from a cushion curve for that material, thickness and drop height. For example: Using the 50 G response requirement from a 36" freefall, the optimum static stress loading for a material 3.75" thick would be approximately 0.75 psi. Using this guideline, the area of the top of the rib would yield a static stress loading of approximately 1.5 psi or greater.

C. The cross sectional area of the rib at 25% total deflection should be approximately equal to that which would give the optimum static stress loading for that thickness of material from a representative cushion curve. For the example listed above, the total cross sectional area at 25% deflection would equal 0.75 psi.

D. The cross sectional area at 50% total part compression should yield a static stress loading approximately one half that called for by the applicable cushion curve.

It is interesting to note that most rib designs are trapezoidal in cross section and most literature treats this as the "standard" shape for ribs in cushion designs. From a theoretical standpoint, the best rib design is a pyramidal cross section. A rib with a hemispherical cross section also is a good theoretical design. The reason is that at zero deflection the static stress loading is infinite and therefore deflection occurs very readily at the onset of a dynamic force input. As deflection continues in response to the force input, the loading decreases as the area of the cushion increases. Ideally this deflection and change in loading (area) will occur at a rate which is optimum for the shock performance of the cushion material.

Of greater significance is the fact that the vibration response characteristics of a cushion material can be altered drastically through the use of ribs. In particular, a high static loading at the peak of the rib will result in a low natural frequency for the package system which is generally the most desirable situation for vibration sensitive products. The force levels associated with vehicle vibration are relatively low and, therefore, the deflection of the cushion is correspondingly small. The majority of this deflection will occur at the point of maximum cushion loading and if this is the peak of the rib, that area will determine the vibration characteristics of the entire package system. If properly designed, it will effectively attenuate higher frequency vibration from reaching the product.

This is one of the most desirable characteristics of a molded cushion. Unfortunately it has been utilized infrequently by most molders. The same holds true for other moldable materials such as expanded polypropylene. It is unknown why we have fallen into the trap of using the trapezoidal rib so much, but its days may be numbered.

VII. PACKAGE DESIGN

Once the total thickness, static stress, and rib configurations are determined, the package must be designed using these parameters. This is where both the performance and the integrity requirements of the package system must come together. It is possible to use all the mathematical equations properly and still wind up with a package system that won't survive a drop test, especially in a corner or edge drop.

As mentioned earlier, the integrity characteristics of the package represent more art than science on the part of the designer. Numerous other material characteristics must come together in order to avoid problems inherent with a particular material. These problems are generally encountered and overcome on a one by one basis over a period of time. Therefore, an experienced designer should review all proposed configurations in the prototype stage before they are fabricated.

VIII. PACKAGE PROTOTYPE TESTING

Once the package design is complete and a prototype fabricated, it must be tested for performance and integrity.

For performance testing, flat drops are generally used with the deceleration transmitted through the cushion picked up by an accelerometer mounted on the product. The procedure should follow ASTM D5276 with care taken to insure flat impacts.

It is also important that the monitored location be as rigid as possible and ideally as close to the product/cushion interface as possible. The reason for this is that we are looking for the package input number, not the product response characteristics. In many cases these are difficult to separate. If the product were a solid mass of wood, it probably wouldn't make any difference where the accelerometer is located since the input from the cushion would be identical to the response of the block. However most products have suspended masses and other components which will be excited, or put into motion, by a shock input. The response of these various suspended components can cause things such as spiking, chattering or similar events on the response waveform. Oftentimes the peak of these responses are well above the input of the cushion. For example, a primary cushion response waveform may have a peak of 40 G's with spiking superimposed on top of it which may double that number. It is important to be able to separate these two by identifying the difference between package input and product response.

This is one of the most common problems in package response testing. There are several methods of dealing with this which should be helpful:

A. Learn to mount the response accelerometer in the proper location, avoiding flexible elements and locating the transducer as close as possible to the cushion material.

B. Understand the use of electronic filters and how they can be used to reduce the apparent effect of high frequency ringing superimposed on a primary response waveform. Use care to avoid overfiltering. (Refer to *To Filter Or Not To Filter, That Is The Question* available from Westpak.)

C. If possible, restrict flexible elements within the product in order to make it as homogeneous and rigid as possible. It is sometimes instructive to perform two drop tests; one with flexible elements unrestrained showing the high frequency response and the second with flexible elements restrained showing the difference this has on the package response characteristics.

Package integrity tests typically involve a series of corner and edge impacts such as those called out in ASTM D5276, ASTM D4169 and ISTA test procedures. The D4169 procedure is perhaps the most up-to-date method incorporating much of the environmental input studies published to date. This standard is highly recommended for package integrity testing. Recent improvements in the ISTA procedure also qualify for high recommendations.

The vibration performance and integrity characteristics of a package system can be tested using a random vibration test procedure called out in ASTM D4728. Random vibration procedures can be used to test both performance and integrity characteristics and are highly recommended for this reason.

Under no circumstances should the mechanical bounce test be construed as a vibration test procedure. This test method called out in the ISTA standard amounts to a series of repeated impacts with very short intervals between events. It may be referred to as a repeated impact test, a bounce test, a fatigue test or something else, but not as a vibration test.

IX. HELPFUL HINTS

The following generalizations and observations are offered to help identify key elements of a package design situation:

A. Remember the formula concerning total deflection necessary to achieve a given deceleration level from a certain drop height (page 9). This number is independent of material and assumes an undamped spring characteristic. Therefore, it may not give the exact number for a highly damped material or design such as polystyrene but it will give a good indication of whether or not a given thickness of material can be expected to achieve a certain performance level.

B. Learn to integrate shock pulses to see if the results are believable. The integral or area under an acceleration vs. time pulse can be thought of as the energy dissipated during that event. Energy is neither created nor destroyed, only changed in its format. Therefore, the total velocity change from a given drop test has to be within a certain range or the results are simply not believable.

To estimate the integral, multiply the peak acceleration in G's times the gravitational constant "g" times the duration of the pulse in seconds times .6 which is a factor to account for the shape of the waveform (generally something between a true half sine and a haversine). The formula is as follows:

$$\Delta V = A_p \times g \times \text{dur (sec)} \times .6$$

The resulting number, velocity change, should fall somewhere between the impact velocity and two times the impact velocity.

$$\sqrt{2gh} \leq \Delta v \leq 2\sqrt{2gh}$$

If it doesn't, there is something wrong with the test, and this should be investigated.

C. In general, the results obtained from a particular rib design cannot be accurately predicted prior to actual design and testing. However, the guidelines presented herein should form a good basis for optimum dynamic characteristics.

D. Designs which utilize <u>flectere</u> of a material instead of compression or multiple polymers used in series cannot be evaluated without undue amounts of trial and error. However, the same general guidelines given in Item B above apply to any type of material or design used in a dynamic response environment.

All cushions work in the same way, namely, they trade peak acceleration for duration. That is, they trade a high peak short duration shock pulse for a longer duration lower peak shock pulse. The longer duration is in response to defection. This deflection can be a result of compression, shear, tension or flexure of the material or design. But in any case the results are the same, namely the material or design must **give** in order to change the shape of the acceleration vs. time pulse delivered to the product.

E. Most importantly, one must remember that packaging dynamics is not a black art or anything of that sort. It is, on the contrary, a relatively simple, straightforward application of existing science, technology and experience. It is likely that this application will become more technical in the future, but that will simply involve adaptations of a few simple basic techniques explored herein. Learn to understand why and how cushions do their job and you will be able to design better overall packages.