DESIGN PARAMETERS FOR

DEFORMABLE CUSHION SYSTEMS

PREPARED FOR:

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I. INTRODUCTION

De-formable cushion systems are those that wrinkle or crumple in response to a dynamic load such as would occur during a package impact. This is differentiated from a traditional cushion material that compresses during the same impact.

In both cases, the effect should be approximately the same. Namely, the package system will deflect or deform in response to a dynamic input, thereby lowering the peak acceleration and extending the duration resulting a more acceptable shock load for the product.

The use of crushable cushion systems is certainly not new. Exhibit the pulp egg carton and the length of time that it has been on the market. The primary difficulty in the introduction of new cushion systems of this type is not the availability of the materials or processes, but rather a good design protocol that would allow the engineer to design and test a reasonable package system in a competitive period of time. This paper attempts to review some design parameters that may be helpful in this regard and to offer a case history of a modern printer product that utilized a thermoformed plastic clamshell with de-formable cushion members.

De-formable cushion systems have several distinct advantages that make them desirable for protective packaging consideration. Among these include the following:
1. Space efficiency - Because the empty systems nest, they are very space efficient prior to utilization in a package.

2. Their shape and geometry often facilitates the use of recycled materials, including recycled plastics, molded paper pulp, and similar.

3. The cost of recycled and de-formable cushion systems can be a distinct advantage.

4. Unique marketing advantages are available based largely on the ability to mold-in product descriptions, brand identification, and similar.

5. Low coefficient of restitution values typical of these designs can give them good first impact shock characteristics.

As with most other things in life, there are both advantages and disadvantages. The disadvantages of de-formable cushion systems include the following.

1. Because they deflect and crumple in response to an implied shock load, these cushion systems are effective for a very limited number of impacts, typically one.

2. Vibration response characteristics are difficult to control or modify and can be terrible in designs based solely on shock parameters.

3. In designs based on thermoformed plastic materials, these structures can be highly temperature dependent in their response characteristics. Polyethylene film is known to behave in this fashion.

4. The materials used in these designs can lend themselves to dusting problems such as the generation of particulate in the case of molded pulp, or in undesirable electro-static attraction of dust in the case of thermoformed plastic materials.
II. THEORY OF SPRING COMPRESSION

All cushion systems can be analyzed as mechanical springs; that is, they compress in response to an applied load. The rate of compression is a function of the load and is referred to as the *spring rate* of the system.

If the compression of the spring is uniform as a function of load, the spring is referred to as *linear*. That is to say, doubling of the load will result in a doubling of the compression of the spring. Some springs display a condition referred to as *softening*. That is, the applied load decreases as the deflection increases. Conversely, other springs display a *hardening* characteristic wherein the force necessary to continue deflection increases as the deflection of the spring increases.

![Spring Compression F vs. d](image)

Spring Compression F vs. d
LINEAR SPRINGS

When a spring is compressed, the difference that occurs in the length is the deflection ($d$) and the force which causes the deflection is ($F$) (Hook’s Law). The rate between force and deflection (the slope of the linear portion of the curve) is defined as the “stiffness” of the spring.

**Spring Stiffness Model**

**Linear Spring Characteristics:** For a linear spring, we are able to write:

\[ \text{Force} = k \times d \]

Where:
- $F$ = force applied, lb.
- $k$ = stiffness or spring constant (lb./in)
- $d$ = deflection, in, corresponding to the applied force
HARDENING SPRINGS

Hardening Spring (vertical tangent elasticity) - Some springs are non-linear with a hardening characteristic; that is, the slope of the curve representing force vs. deflection increases with increasing deflection. Rubber in compression exhibits this behavior. An equation representing the initial slope of a hardening spring, force vs. deflection curve, is the following:

\[
\text{SPRING FORCE} = \frac{2kd}{\pi} \tan \left( \frac{\pi (\text{def})}{2d} \right)
\]

Note that for small deflections, the linear and the hardening spring may be characterized in similar fashions.

SOFTENING SPRINGS

Softening Spring (Hyperbolic tangent elasticity) - A non-linear spring may also have a softening characteristic. That is, the slope representing the force vs. deflection decreases within increasing deflection. This characteristic is rarely observed in real systems.

\[
\text{SPRING FORCE} = kd \tanh \left( \frac{\text{def}}{d} \right)
\]
Most springs used in packaging applications (cushions) are actually non-linear in that they display characteristics of all three spring types at some point in their deflection cycles. Normally, these cushions show a softening characteristic early in the deflection cycle where increasing force results in greater and greater deflection of the spring. As the cushion approaches its normal working range, a linear spring rate is often displayed. As the cushion nears the end of its working range and begins to bottom, a hardening spring characteristic is often seen.

These characteristics are well understood and mapped out for traditional cushions consisting of plastic foams and other right rectangular prisms. Unfortunately, these characteristics are not well understood for de-formable shapes such as thermoformed clamshells, molded pulp trays, and similar devices.

It is likely that the reason for this lack of clear understanding of the characteristics of these cushions is that their performance is highly dependant on the basic material characteristics and, even more so, on the shape of the cushion design which will vary in almost every application.
III. UNUSUAL CHARACTERISTICS OF CRUSHABLE SHAPE CUSHION SYSTEMS

COLUMN BUCKLING

In addition to analyzing crushable shapes as mechanical springs, it is also helpful to analyze them in terms of a column buckling model. Consider for example a column consisting of a flat panel or wall section with no bends or turns. This structure will deflect readily in response to an applied load because of the phenomenon of buckling. The same length of panel, however, formed into one 90° section will support many times the load because of the stability afforded by the vertical edge in the structure. Thus, the concept and study of a vertical edge is very important and, in fact, crucial to the understanding of how crushable shape cushion systems work.

It’s also instructive to study how a column of various shapes will react once buckling has initiated. The flat panel described above will have very little resistance to buckling once the compression cycle has been initiated. The material characteristics and the thickness of the material will be the predominant factors in the resistance to buckling of a flat panel once it has started to bend.

A structure with vertical edges, however, will have far greater resistance to the bending as it is necessary for the force to buckle the column at many places along its vertical edge rather than at one place only. Thus, the flat panel would resemble a softening spring once the buckling had initiated wherein sections with vertical edges could be considered linear or even hardening springs once a similar compression had begun.

Vertical edges with small or sharp radii are difficult to produce and are generally not strong. This is because of the thinning of material that is normally inherent in thermoforming or other formation processes for de-formed shapes. In addition, a sharp radius edge will buckle more readily in response to an applied load as opposed to the same configuration with a more generous radius.
DRAFT
Another common characteristic of de-formable shaped cushions is the draft angle used in the formation of the part. These parts are almost always formed by means of a male or female press or die (or in some cases both). Therefore, the part must be able to be removed from the die and, therefore, draft angles are necessary. These range from $1^\circ$ up to $10^\circ$ or more depending on the process and the materials used.

These draft angles can be very useful in the initiation of the crushing or buckling of a de-formable shaped cushion. When used as opposing sets, these draft angles will almost always dictate the direction in which buckling will occur and often will dictate where on the vertical column the buckling initiates.

For parts manufactured from thermoformed plastic sheets, generous draft angles are also desirable because they assist in the uniform distribution of the plastic material throughout the part. On the other hand, severe draft angles tend to lead to thinning of the material and, therefore, weakening of the structure.

Finally, these draft angles provide for stackability of the empty (unused) parts which is one of their primary advantages. This nestability results in tremendous space savings over traditional cushion designs that cannot nest or interlock.

In general, the following guidelines will apply for most crushable cushion systems.

1. A flat panel should be no longer than it is tall without the inclusion of vertical supporting edges.

2. Supporting ribs should have a width of at least 20% of the total height of the crushable member.

3. The radius on vertical edges should be approximately 10 to 20 times the thickness of the material.
4. For thermoformed parts, the depth of the rib should not exceed the distance from the nearest rib. That is to say, a rib 2" deep should be approximately 2" from its nearest rib member.

5. Draft angles of 10% to 15% seem to work fairly well for most thermoformed plastic parts.

6. The area of the cushion in contact with the product should be greater than the area of the cushion in contact with the outside container. This will result in deflection that occurs on the outside of the part because that is the point of highest loading. Thus, any permanent deflection will occur between the interface of the cushion and the box. This is generally much more desirable from an integrity standpoint. It is also much easier to predict the actual performance of a cushion designed in this manner.
Closure and/or locking tabs tend to be very desirable but should not be counted on to hold two halves of a part together. There should always be a supplemental means of holding parts together so that the dynamics of an impact will not cause a catastrophic failure in the package system.
IV. ANALYZING THE DYNAMICS OF DEFLECTION

Using the above guidelines and the principles of formation necessary for various types of structures, a prototype can be fabricated and analyzed for its dynamic properties.

For impact performance, traditional package drop testing is normally employed. If the product to be protected is acceleration sensitive, then it would be necessary to monitor the product with accelerometers in order to determine the transmitted deceleration upon impact.

**EXAMPLE 1: RPETG THERMOFORMED PRINTER CLAMSHELL**
1. **Stress/Strain Analysis** – The purpose of this test was to determine the flexural and load supporting characteristics of the ribs within the thermoformed package at various levels of compression of the container system. To conduct the test, the printer placed within its cavity was subjected to a compressive load at a constant rate of .5 in/min. The force versus deflection characteristics of the package were plotted. In addition, observations were made regarding the deflection patterns of various ribs and which ribs supported the loads at which point in the compression cycle. This information is potentially very useful when rib redesign is considered.
2. **Dynamic Impact Test** – Next, the printer product was subjected to a series of package freefall impact tests from drop heights of 18” and 24”. Accelerometers were mounted on the product in order to determine the level of shock transmitted through the cushion and into the product. All flat orientations were tested.

The acceleration versus time signals from each of the major axes in the drop test was then subjected to a double integration analysis. This process should reveal the actual deflection of the product from the onset of a shock pulse generated by the drop testing. **Note:** great care must exercised when using this analysis. Any translational motion of the product during the impact (a common occurrence) will cause potentially large distortions in the reported deflection of the cushion system (spring).
3. **Data Analysis** – The stress/strain data was first analyzed to determine the rib deflection at which sufficient force was generated to absorb the energy of a 24" freefall impact. This can be determined using the mass of the product and Newton’s Second Law; \( F = MA \). The data was then compared to the acceleration data generated from the freefall drop testing along with the resulting deflection data from the double integration of the waveforms.

A combination of these two analyses shows which rib patterns are supporting the required load, which are too stiff, and which are too soft in response to a dynamic input.

It was determined that the sides and top of the current design appear to be adequate. The base, front, and back direction, however, showed problems.
4. **Package Redesign** – The analysis mentioned above led to an increasing of rib area in the base of the part. This consisted primarily of increasing the amount of contact between the base of the product and the ribs that contacted the product. Because of the thermoform process, this has the affect of reducing the amount of contact between the container and the outside of the thermoform itself. This will generally result in deflection at the interface of thermoform and the container, which is desirable.
There are always cases where “the rules don’t work” and designing crushable cushion systems is no exception. In those instances, it’s essential to have “Plan B’s” in your hip pocket. One of those sometimes used on these systems is a supplemental cushion or add-in columns designed to add support or to resist bottoming when nothing else works. The photo below shows foam cushion “plugs” and separate thermoform elements that may spell the difference between a workable system and failure to meet the design parameters.
EXAMPLE 2: HDPE THERMOFORMED END CAPS

Some de-formable package cushions take advantage of material characteristics such as high density polyethylene to form a bellows type of cushion design. These designs can be very effective in terms of cushioning properties and are somewhat more predictable than buckling designs.

However, they are somewhat more limited in terms of their adaptability because the design tends to lend itself to a side or end cap configuration. In addition, the design is somewhat limited in its weight holding ability.

The design shown here is patented under the trade name “Geospring”. It is widely used for single shipments of Winchester disk drives and similar type products.

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