Redesigning Protective Packaging Buffers from the Failure Modes Derived from Crack Characteristics

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Received 11 March 1998; accepted 31 July 1998

ABSTRACT: Protective packaging buffers are commonly used for the purpose of containment, protection, communication, and marketing of consumer products. Because the use of protective packaging is expected to increase markedly in the years ahead, it is imperative that their designs be cost-effective. Much of the known design heuristics have been encapsulated in design methodologies and procedures, except for one aspect, that is, the failure modes of the buffers upon impact with the ground after being dropped from a height. All packaging designs are subjected to a series of confirmatory impact tests, before design deficiencies are rectified through iterative cycles of redesign and retest. Because of the heuristic nature of packaging design, many cycles of redesign are necessary before a satisfactory design solution is found. This article discusses how, from the nature and severity of the cracks, the probable causes of failure and corrective redesign measures may be estimated. Based on the value of the crack ratio (i.e., the ratio of the depth of the crack to the buffer's bearing thickness), three distinct modes of failure can be identified: marginal, critical, and catastrophic. The variation of G-value with crack ratios was studied for varying drop heights. By comparing the measured G-value to the failure mode, the conditions contributing to the failure—*viz.* height of drop, direction of impact, the location of the centroid, the type of fit, and degree of contact between the buffer and the product—may be estimated. Redesign guidelines to avert catastrophic buffer failure are also discussed. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 72: 721–731, 1999

Key words: crack failure; protective packaging; heuristic design

INTRODUCTION

Packaging buffers protect commercial products against damage due to impact and vibration resulting from handling and transportation. Over the years, the consumption pattern of packaging materials has risen markedly, and this trend is expected to continue into the 21st century.[1] It is estimated that the world-wide packaging industry is worth about $300 billion annually (U.S. dollars).[2] The sizeable packaging market can be attributed to factors, such as growing consumerism, cheaper transportation and shipping costs, and better infrastructure and communication networks. Because of the sheer volume of material involved, it is imperative, then, that packaging designs be optimized both from the standpoint of costs and the level of protection afforded.

Protective packaging buffers can be made from various materials (e.g., plastic bubble sheets, corrugated paperboards, paper and paper products, foam blocking, and foam-in-place cushioning). Expandable polystyrene, being comparatively inexpensive and light in weight,[3] is a cost-effective solution for moderately heavy, fragile items such as artifacts, photographic equipment, audio and

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Journal of Applied Polymer Science, Vol. 72, 721–731 (1999)
 CCC 0021-8995/99/050721-11

video electronic products, and instruments. The design of expandable polystyrene cushioning buffers is fairly established,[4–10] centered mainly on the material's physical properties and other technical data published by the manufacturers of the expandable polystyrene. Notwithstanding this, there is not enough reliable design data, so many designers fall back on heuristic experience. The authors have attempted to encapsulate the expert knowledge of packaging designers into concepts and methodologies[11–13] and explicit procedures and rules using artificial intelligence techniques.[14–16] One of the few remaining aspects to be covered concerns the failure modes of expandable polystyrene buffers as a result of the impact of the product when dropped from a height.

All packaging designs are subjected to a series of confirmatory tests, especially impact, as soon as the first prototype of the product has been proven.[17,18] Design deficiencies are uncovered and rectified through iterative cycles of redesign and retest, until an acceptable solution is found. Because of the heuristic nature of packaging design, the number of cycles is not known *a priori,* even to the most experienced packaging designer, let alone the novice designer. The authors were therefore motivated to research into a heuristic diagnostic aid to shorten the redesign cycle.

THE DROP TEST

A packaged product, when dropped from a height, experiences considerable impulsive forces upon impact with a hard surface, such as the ground. The protective buffer undergoes considerable compression and, in the worst case, ruptures. As the material is compressed, the packaged product decelerates until it comes to a complete rest. If a is the deceleration of the packaged product and g is the acceleration due to gravity, then a G-factor may be defined as the ratio of the two: $\mathbf{G} = a/g$. This definition implies that the force acting on the packaged product is g times its weight. The G-factor therefore rates the susceptibility of the product to damage by impact shock. A product that can sustain a high G-value is less fragile than one that can only withstand a lower value. Although published G-values exist for different products, many companies are unable to determine the G-value of their products. This is because the assessment of the level of protection needed by a product is largely subjective and governed by several factors:

1. The likely drop height and the number of drops of the packaged product are dependent on whether Asian or European ergonomic data are applied. A methodology has been developed to predict the probability of the natural resting face of an object impacting a hard surface after free-falling from a height.[19,20]
2. Sometimes the components of a product that require protection against impact shock may not themselves fail, but may cause others to fail.
3. A trade-off between an adequate/reliable level of protection to the cost of packaging can often be established only with the benefit of experience.

Drop (impact) tests are usually conducted on a precision tester according to procedures set out in ASTM A5193[21] (i.e., the packaged product is dropped, in turn, from a designated height on each of its sides because the impact on one side may induce cracks on the adjacent sides). Figure 1 illustrates how a typical drop test is conducted. An accelerometer is mounted on a rigid face of the product near the center of gravity, and the G-values recorded and displayed on an oscillograph.

In this study, a 12 kg television set, encased by four edge cap protective buffers, each of 12 mm sectional (bearing) thickness, was packed in a cardboard carton and dropped in two stages. Figure 2 shows a typical edge buffer, whereas Figure 3 illustrates the common buffer parameters. The edge caps were designed according to standard design procedures[4–10] based on the product weight, density of the buffer material, and the anticipated G-value. In the first stage, the package was dropped on its top, right, and back sides, followed in the second stage by the bottom, left, and front sides. A total of 172 drops were performed. After each drop, the edge caps were inspected for deformations and cracks to ascertain the extent of the damage inflicted.

After the drop tests are completed, the buffer design is analyzed as follows:

1. The product is tested to confirm that it has not been damaged. In the absence of an understanding of the dynamics of impact among the various components and subassemblies of the product, a full functional test of the product is mandatory.
2. The G-values sustained by each of the sides are determined to ascertain if the

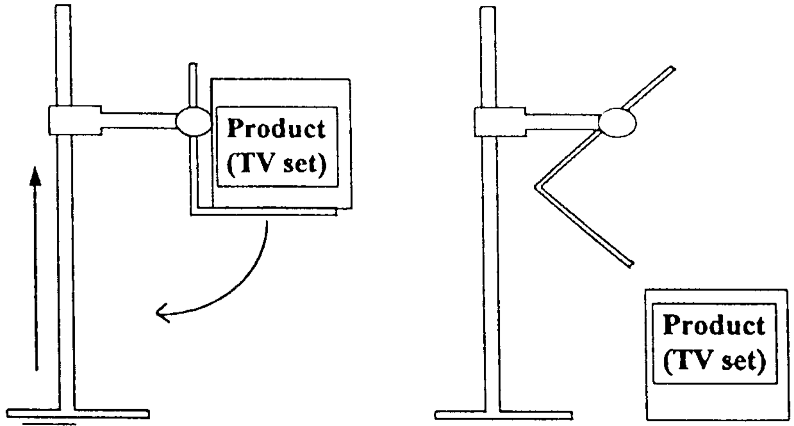

Figure 1 The way a drop test is conducted.

maximum allowable value has been violated. If so, the buffer failed to provide the desired degree of protection and would invariably be damaged. The protective buffer is then redesigned or, when this course of action is costly, the product itself may be redesigned.

Currently, the designer second-guesses the redesign of the buffer from an examination of the extent of damage to the buffer. In the absence of some definitive guide to the severity of the rupture of the buffer, only experienced designers are able to redesign the buffer with some confidence. In the ensuing sections, the authors discuss how the fracture characteristics of the buffer can be used as a guide to assess the severity of the impact and also to offer guidelines for the redesign of the buffer.

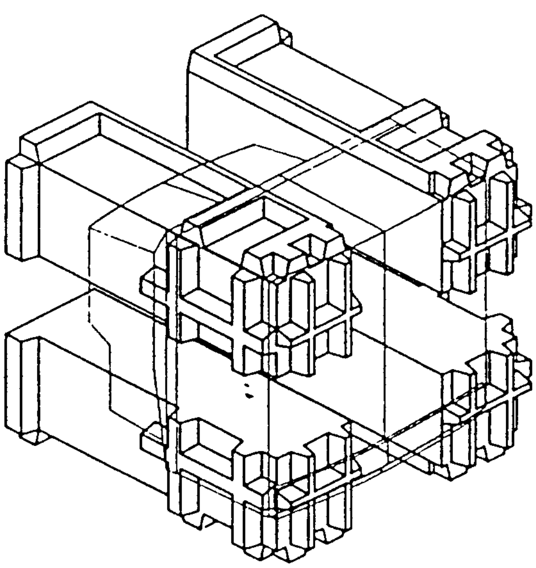

Figure 2 A typical edge buffer.

DIAGNOSIS OF EXTENT OF DAMAGE BY CRACK CHARACTERISTICS

Cracks are fissures or narrow lacerations sustained by the protective packaging buffer when the yield strength of the material is exceeded. As the buffer protects the product by absorbing the shock of the impact, the location and severity of the cracks is indicative of the magnitude of the G-values sustained by the buffer. The probable causes of failure may be inferred and corrective design measures recommended.

ESTIMATING FAILURE MODE FROM THE LENGTH AND DEPTH OF CRACK

To study the effect of repeated drops on the protective buffers, buffer designs shown in Figure 4 were fabricated from expandable polystyrene foam of 23.5 kg m^{-3} density. The buffers, of bearing thickness 12 mm, encased a 14-inch color TV weighing 8.5 kg. The protected TV set was dropped five times at each of four different drop heights of 15, 20, 35, and 60 cm. The depth and length of the cracks and the compressed buffer thickness were measured after each drop. The depth of the crack is the linear distance measured from the surface of the buffer through its bearing thickness, whereas the width is the gap of the crack on the surface (see Figure 5). The crack ratio is ratio of the depth of crack to the buffer

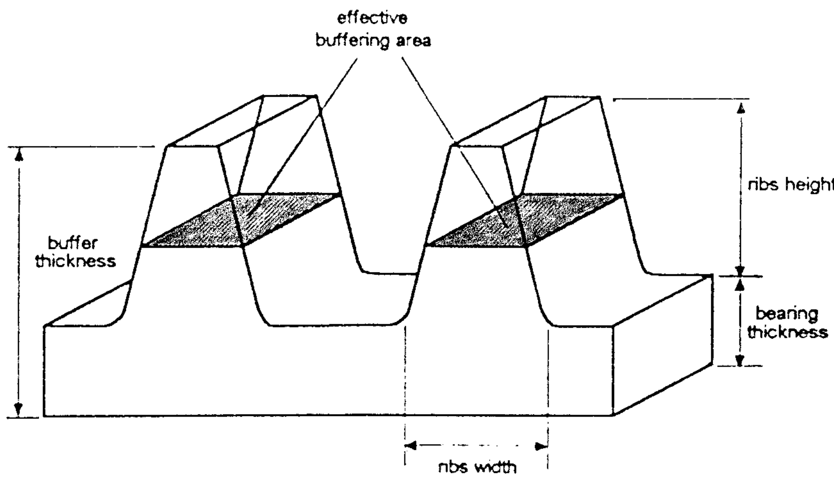

Figure 3 Common buffer design parameters.

bearing thickness. The average G-value, crack ratio, and % buffer compression were computed for each static stress value.

Figure 6 shows a plot of the G-value *vs.* static stress for varying h/d ratios, where h is the height of drop and d is the buffer thickness. It can be seen that for low h/d ratios, distinct minimum G-values for each curve are absent. Thus, for a given height of drop, h, the thicker the buffer, the better its cushioning effect over a wide range of static stresses. However, this design is uneconomic. Therefore, buffers should be designed for acceptable G-values over a reasonable working range of static stress.

When G-values are plotted against crack ratios for various drop heights, three distinct phases are evident, as shown in Figure 7. For low drop heights (<20 mm), the gradient decreases in the first phase, stays flat in the second, and rises markedly in the third. At drop heights exceeding 35 cm, only the 2nd and 3rd phases are evident. When the drop height exceeds 60 cm, the buffer disintegrates in catastrophic failure because it can no longer absorb the impact shock from repeated drops.

It is also meaningful to analyze the % compression of the buffer *vs.* the crack ratio. It can be seen from Figure 8 that, irrespective of the drop height, the % compression does not exceed 25% of the undeformed buffer thickness. The curves exhibit two stages. The first stage is very gradual; for low drop heights, this persists for up to crack ratios of 0.8. As expected, at greater drop heights, the compression is more severe and therefore the gradient is steeper. Sharp gradients typify all drop heights for crack ratios exceeding 0.9. These curves confirm the intuitive notion that buffers can sustain more repeated drops at lower drop heights.

Arising from the foregoing analyses, it is thus possible to map failure modes with respect to drop

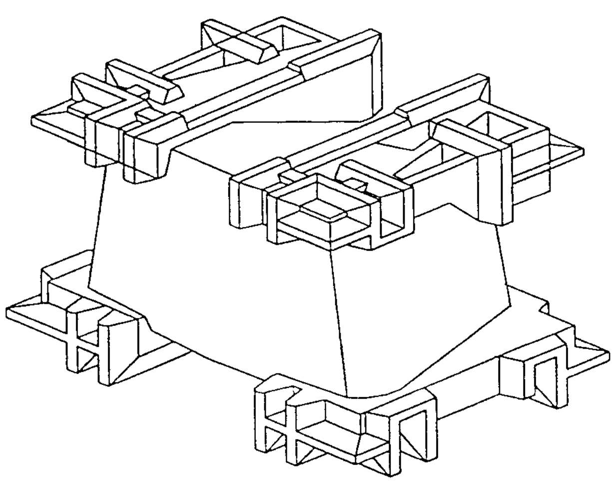

Figure 4 Buffers used in the drop tests.

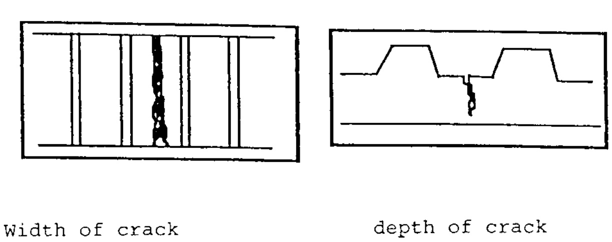

Figure 5 Crack parameters: width and depth.

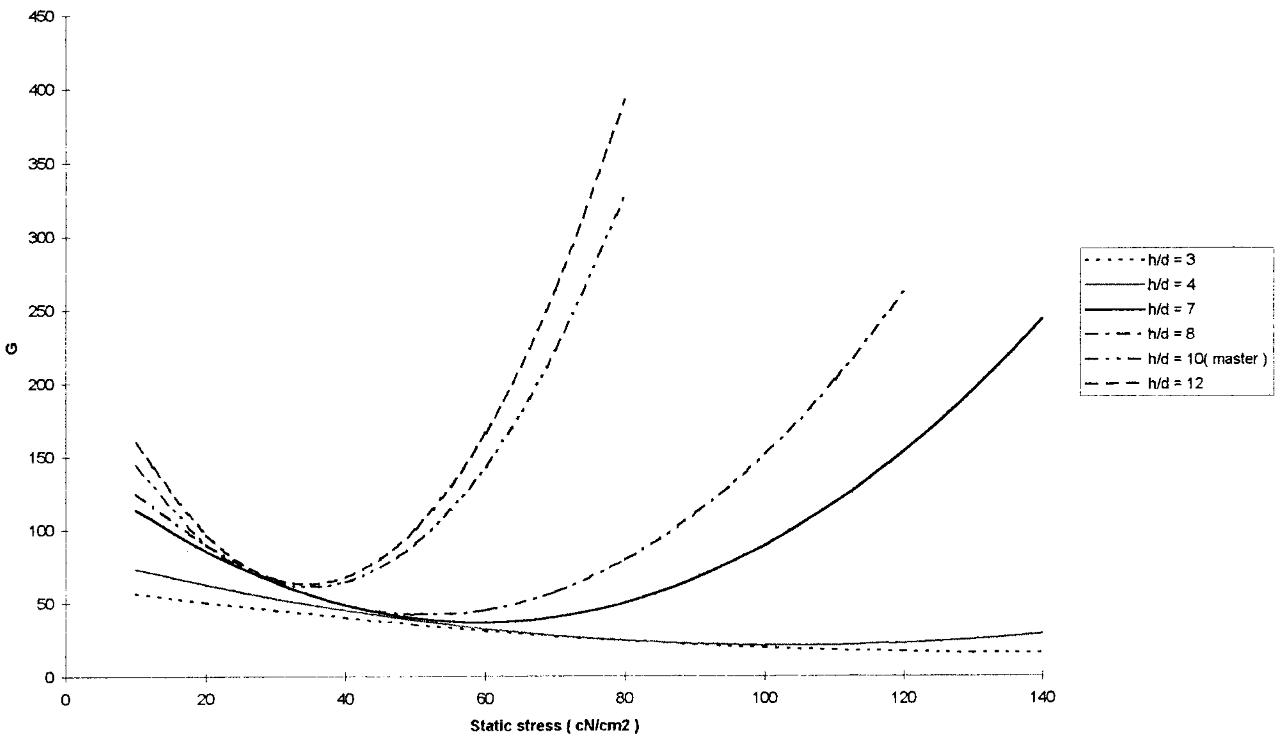

Figure 6 Cushion curves for EPS foam of density 23.5 kg m^{-3}.

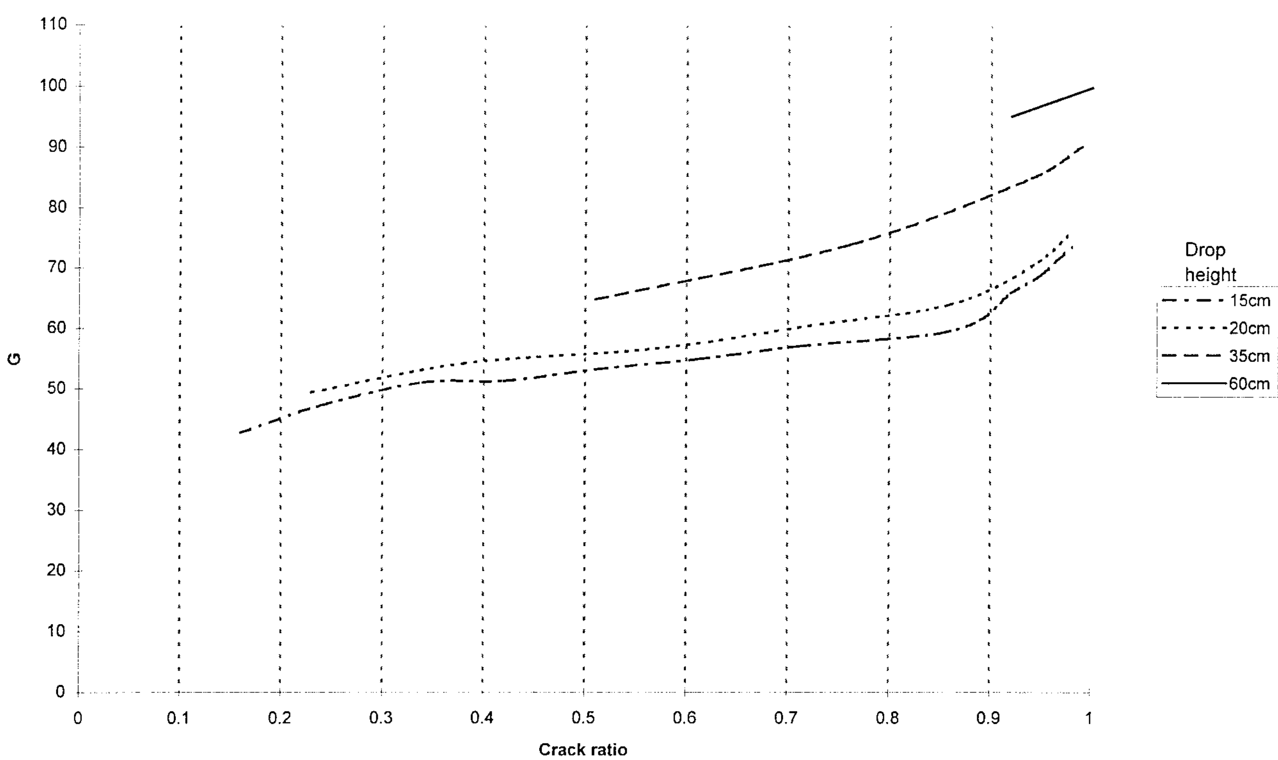

Figure 7 Plot of G-value versus crack ratio.

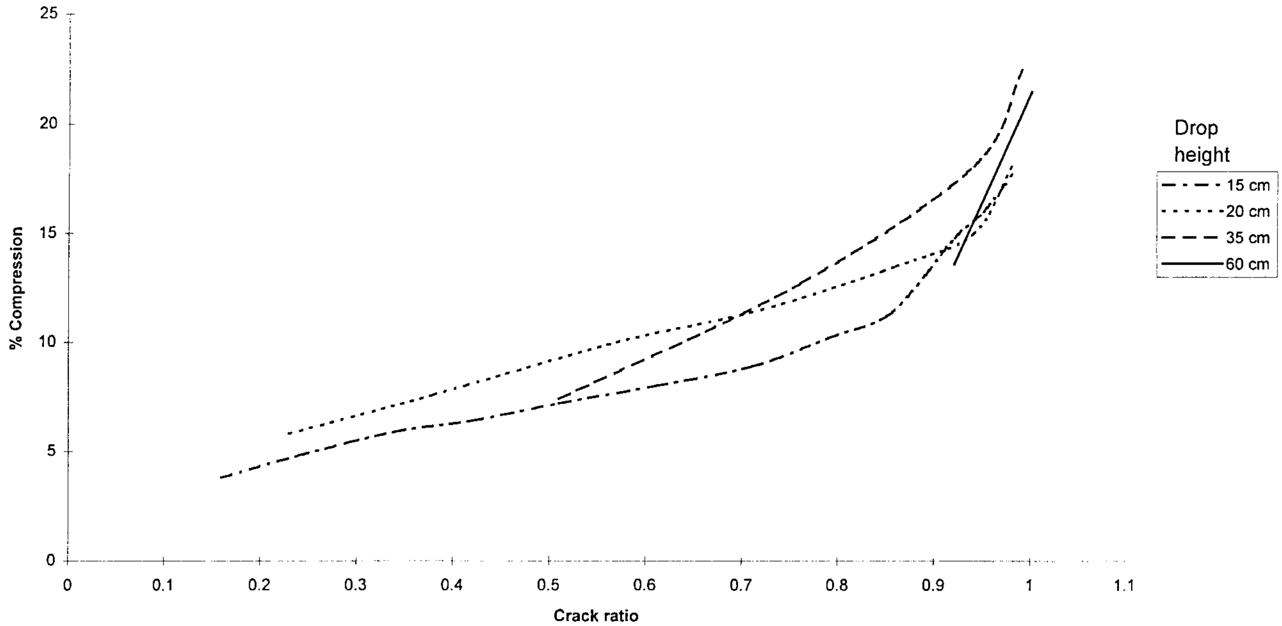

Figure 8 Plot of % buffer compression versus crack ratio.

height and crack ratio. The three distinct failure modes (marginal, critical, and catastrophic) may be denoted by the points of inflexion that can be seen in Figure 8: 0.35 and 0.9 for a drop height of 15 cm, and 0.4 and 0.85 for a drop height of 20 cm. Figure 9 shows distinct regions where specific failure modes predominate. The region denoted "infeasible" accounts for drop heights exceeding 60 cm, when the buffer experiences catastrophic failure. Thus, Figure 9 enables the failure mode to be estimated from the crack ratio computed.

Crack Parameters as an Indicator of the Severity of Impact

To corroborate the G-value with the type of crack, a series of experiments were conducted in which buffers were dropped a second time. The cracks that were found can be classified into three broad categories: *marginal, critical,* and *catastrophic.* Marginal cracks have a depth/bearing thickness ratio less than one-third. These cracks tend to be ~ 1–2 mm wide. Critical cracks are those with a depth/bearing thickness of between one-third to two-thirds, and are between 2–4 mm wide. Catastrophic cracks have a depth/bearing thickness ratio exceeding two-thirds, and a width exceeding 4 mm. Table I summarizes the three categories of cracks.

Results revealed that, on the second drop, the marginal cracks caused by the first drop worsened, but the G-value remained, by and large, unchanged. This is not unexpected, because marginal cracks do not distort the geometric shape of the buffer, which continues to function effectively. Buffers with critical cracks ruptured during the second drop, and the G-value registered exceeded the satisfactory range. As for buffers with catastrophic cracks, the second drop caused them to almost disintegrate, again lending support to the notion that buffers with catastrophic cracks are irreversibly damaged. Such buffers offer very little protection. It can therefore be inferred that buffers with critical cracks in a single drop are near optimal in design, with little scope for reduction in bearing thickness.

Tracing the Main Determinants of Buffer Failures

The severity of the cracks can be correlated with the measured G-value and the five design and drop conditions: drop height, direction of impact, location of the centroid, type of fit, and contact between the buffer and product (as shown in Table II).

Drop Height

Two trends can be observed. The first is that, when the measured G-values are much less than the designed G-values, marginal cracks are commonly detected. If catastrophic cracks are found,

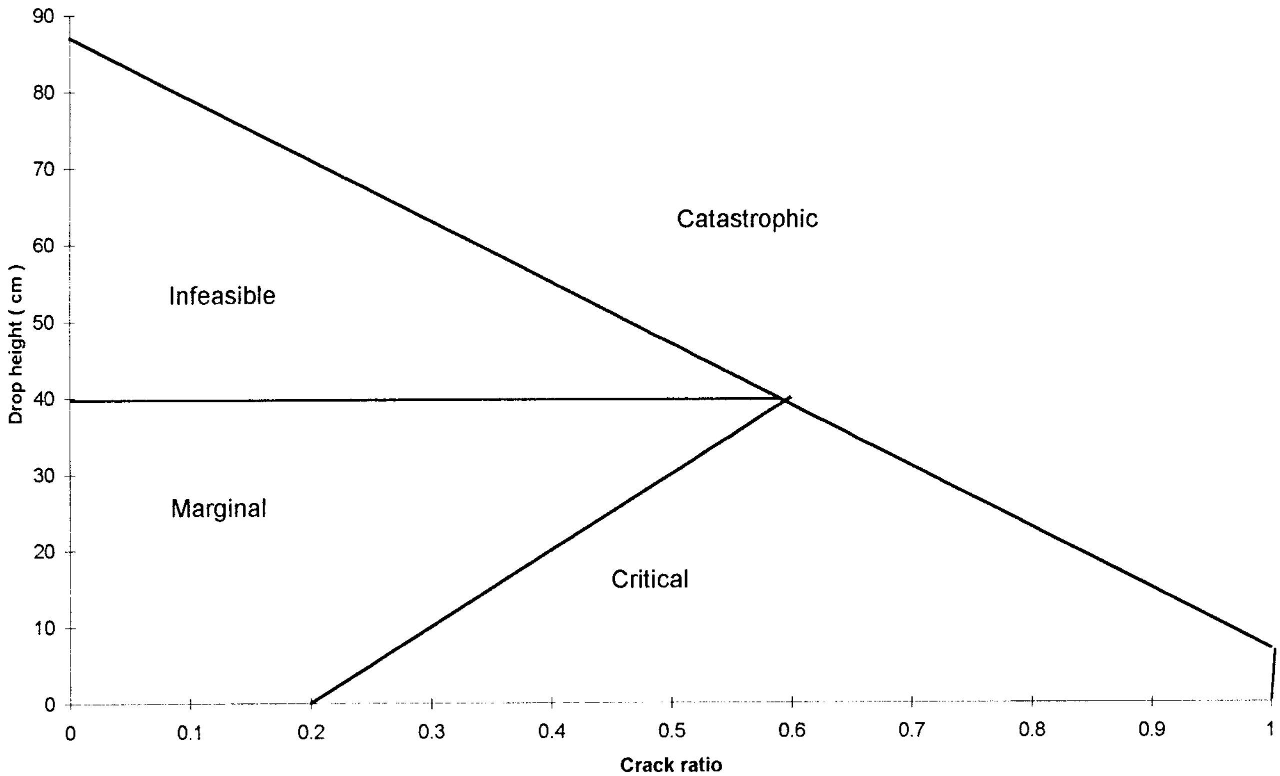

Figure 9 Classification of failure modes at various drop heights with respect to crack ratio.

the buffer has failed. This could be due to many reasons. For example, the inherent stress in the material where the cracks are found may be high, or the buffer design lacked support, or the drop height was too high. The second trend is attributable to the measured G-value being much greater than the designed value; if minor cracks are formed, the specified designed value may be too low. Thus, by observing the type of crack, the height from which the packaged product was dropped may be deduced. Whatever the trend, for a given buffer design and material characteristics, there is a critical drop height beyond which the buffer fails catastrophically. This critical drop height delimits the maximum capacity of the buffer to absorb the energy of impact.

Direction of Impact

During the drop test, the buffered product may experience forces as a result of direct and side impact as shown in Figure 7. Direct impact usually gives rise to more severe deformations of the buffer, because it absorbs much of the impact shock. Side impact is said to occur when the side of the packaged product impacts the ground following a direct impact. Hence, deformations resulting from the side impact can be expected to be

Table I Crack Parameters

Severity of Crack	Bearing Thickness (mm)	Crack Width (mm)	Crack Depth (mm)	Crack Ratio (=Crack Depth/Bearing Thickness)
Marginal	12	1–2	1–4	4/12 = 1/3
Critical	12	2–4	4–8	8/12 = 2/3
Catastrophic	12	> 4	8–11	11/12–1

Table II Crack Effects Versus *G*-Values

Type of Crack	Measured *G*-Value ≪ Designed *G*-Value	Measured *G*-Value = Designed *G*-Value	Measured *G*-Value ≫ Designed *G*-Value
Marginal or minor cracks	*Drop height*—The drop height is much lower than the critical allowable drop height. *Direction of impact*—Likely to be side impact. *C.G. position*—Quite a distance away from C.G. *Type of fit*—Snug press fit affording ideal protection. *Type of contact*—Smooth, like surface-to-surface contact.	An intermediate instance between the two extreme conditions, row-wise.	*Drop height*—The drop height is much lower than the critical allowable drop height. *Direction of impact*—Likely to be side impact. *C.G. position*—Quite a distance away from C.G. *Type of fit*—Loose fit *Type of contact*—Smooth, like surface-to-surface contact.
Critical cracks	An intermediate instance between the two extreme conditions, column-wise.	*Drop height*—Close to critical allowable drop height. *Direction of impact*—Likely to be direct impact. *C.G. position*—Near the C.G. position with adequate buffer protection. *Type of fit*—Can be anything between loose and press fit. Usually, the product is press fitted. *Type of Contact*—Can be anything between surface-to-surface and edge-to-surface. Normally, the product has a smooth surface-to-surface contact.	An intermediate instance between the two extreme conditions, column-wise.
Catastrophic cracks	*Drop height*—Drop height well exceeds the critical allowable drop height. *Direction of impact*—Likely to be direct impact. *C.G. position*—Very near the C.G., but level of protection is inadequate. *Type of fit*—Press fit. *Type of contact*—Sharp edges of product tears into the edge buffers.	An intermediate instance between the two extreme conditions, row-wise	*Drop height*—Drop height well exceeds the critical allowable drop height. *Direction of impact*—Likely to be direct impact. *C.G. position*—Very near the C.G., but level of protection is inadequate. *Type of fit*—Loose fit. *Type of Contact*—Sharp edges of product tear into the edge buffers.

C.G., center of gravity.

less severe than those resulting from a direct impact. Two observations emerged from a study of the direction of impact. The first is that, in the case of marginal cracks, when the measured *G*-value is much less than the designed *G*-values, the direction of impact is not predictable. Referring to Table II, it can be seen that, as the severity of the crack worsens (column-wise), a direct impact is most likely to be the case.

Type of Contact Between the Buffer and the Product

The damage sustained by the buffer depends on whether the edge or other protrusion of the product or its surface impacts the buffer (as illustrated in Figure 8). In the case of edge impact, severe cracks form because the entire weight of the product bears on the line of contact with the buffer, giving rise to extremely high, localized stresses. The full brunt of the impact force is borne by the buffer. On the other hand, because the impact load is distributed over a larger contact area, surface impacts result in less severe cracks. Thus, surface-to-surface contact generally give rise to marginal cracks, whereas product edge to buffer surface contacts invariably cause catastrophic failure.

Location of Centroid of Product

The location of the centroid of the product influences the location and severity of the crack. Components of the product near to the centroid experience a greater force than those further away. For this reason, and the fact that products are not always designed with their centroid coincident with their point of geometric symmetry, buffers should be designed with the location of the centroid in mind. Take, for instance, the 14-inch TV set. By virtue of the weight of its main component, the CRT, its centroid is near the front face (as illustrated in Figure 9). Thus, the edge buffers cushioning the front face of the TV set have to be designed to withstand greater impact forces than those protecting the rear. In fact, empirical results have shown the cracks in the buffers protecting the rear of the TV set to be marginal. One can therefore infer that, for the same buffer cushioning conditions, catastrophic cracks tend to appear near the centroid.

Degree of Fit Between the Edge Cap and the Product

Because of the inherent slack between the buffer and the product, it is possible for the TV set to be misaligned with the edge buffer inside the cardboard carton. The loose fit gives rise to severe damage that would otherwise be averted by the buffers. Drop tests conducted on a 14-inch TV set recorded G-values as high as 100 when the prescribed value is only 60. When the buffers are press fit against the TV set and then fit snugly into the cardboard carton (see Figure 10), no such anomaly was observed.

Redesign Measures Based on the Severity of Crack

The severity of crack can provide clues to the appropriate remedial measures to take. In the case of marginal cracks, redesign is not normally required. However, opportunities may arise to optimize the design by minimizing the volume of buffer material used. In the case of critical and especially catastrophic cracks, designers can opt for the following remedial measures in the regions where the cracks are found.

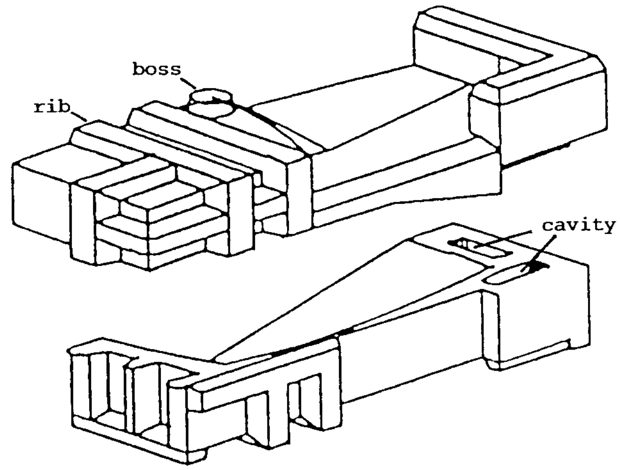

Figure 10 Example of a rib, boss, and cavity.

Increase the Bearing Thickness of the Buffer

Such action is recommended where there are many such cracks or when they occupy quite a large surface area of the buffer. The bearing thickness can be increased to improve the strength in that region. It can be seen from Table III that a 2% point reduction in the effective cushioning area can bring about a change of G-value.

Introduce Ribs

In such instances, a cushioning rib, as shown in Figure 10, can be introduced to absorb the excessive shock, rather than increase the bearing thickness that incurs a longer molding time and uses more material. However, the ribs have to be of the same height and evenly spaced out in order to be effective. Even if the ribs were suitably designed, sometimes the crack may be slanted and tapered.

Introduce Bosses

Bosses may be used in place of ribs (see Figure 10). These bosses should be distributed uniformly across the region of cracks to provide additional cushioning support. Small bosses should be designed for rigidity.

Fill Buffer Cavities

When the buffers fit the product loosely, critical and catastrophic cracks can be expected. Alterna-

Table III Effect of Buffer Thickness and Effective Cushioning Area on the *G*-Value

G-Value	Bearing Thickness	% Reduction of Buffer Thickness	Effective Cushioning Area	% Increase in Effective Cushioning Area
40	46.8		96.8	
45	42.1	10	108.9	12.5
50	37.4	11	121.0	11.0
55	34.3	8	133.7	10.5
60	31.2	9	145.2	8.6

tively, the cracks may be formed in weak regions, typically cavities in the buffer, such as those shown in Figure 10. Cavities are introduced to save material and to shorten the molding cycle. Therefore, the cavities should first be filled to increase the stiffness where the cracks are present, before the bearing thickness is increased.

Figure 11 summarizes the suggestions for redesign of the buffer based on the severity of the cracks.

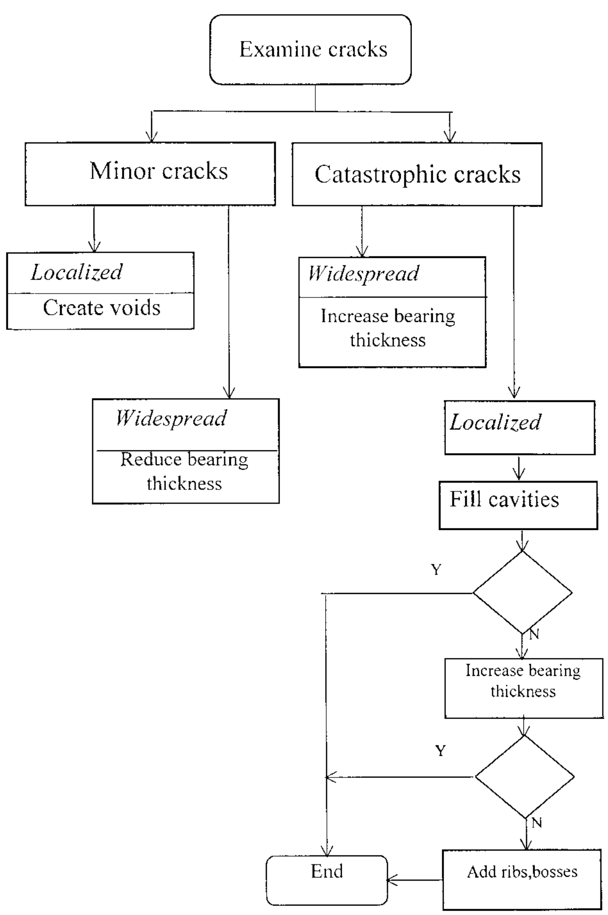

Figure 11 Buffer redesign suggestions based on the severity of cracks.

CONCLUSIONS

This article discusses how crack characteristics may be used to gauge the probable causes of failure of protective packaging buffer made from expanded polystyrene foam based on the severity of the shock and damage sustained, and to suggest corrective redesign measures.

Based on the value of the crack ratio (i.e., the ratio of the depth of the crack to the buffer's bearing thickness), three distinct modes of failure are identified: *marginal, critical,* and *catastrophic*. The onset of catastrophic buffer failure can be estimated from a family of curves showing the variation of *G*-value over a range of crack ratios. By comparing the measured *G*-value to the failure mode, it is possible to estimate the conditions contributing to the failure *viz* the height of drop, direction of impact, the location of the centroid, the type of fit and degree of contact between the buffer, and the product. The buffer thicknesses that can sustain acceptable *G*-values over a reasonable working range of static stress were determined.

Although marginal cracks require no remedial redesign of the buffer, catastrophic cracks can be averted by increasing the bearing thickness, by introducing ribs and buffers, or by filling up cavities and other voids in the buffer. It is good practice to fill up the cavities and other voids before increasing the buffer thickness.

The authors acknowledge with gratitude the assistance of Mr. H. F. Chong and Ms. P. H. Ngo in this project.

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