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Theoretical Predictions and Observations of Peak Deceleration Levels for Perfect Edge and Corner Drops

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THEORETICAL PREDICTIONS AND OBSERVATIONS OF PEAK DECELERATION LEVELS FOR PERFECT EDGE AND CORNER DROPS

By

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ABSTRACT

THEORETICAL PREDICTIONS AND OBSERVATIONS OF PEAK DECELERATION LEVELS FOR PERFECT EDGE AND CORNER DROPS

By

John Dominic Jackson

Statistically, combinations of edge, corner and flat drops occur in the distribution environment as opposed to that of flat drops alone. To date, little work has been done to study peak deceleration levels of either condition. This reason is two-fold; firstly, it is difficult to identify the "true" impact geometry of either condition, and secondly, because it is assumed that passing the flat drop test (which produces the highest G's) provides a built-in protection factor against all other impacts.

This study examines the performance of 2 pcf LDPE foam inside a corrugated box, under simulated perfect edge and corner drop conditions. The experiments followed ASTM procedures using five repeated drops from two drop heights of 24 and 36 inches. Two package weights of approximately 20 and 40 lbs per box were used. A similar study was conducted, however, the drop heights ranged from 18", 24", 30", 36" and 42". Unlike ASTM standards, 8-10 minute intervals were given between each drop for maximum cushion recovery.

A theoretical equation showed a very close correlation between the "predicted" and "actual" G levels to within ± 10%. Shock pulse data suggests that the first impact is absorbed by the corrugated board box, while the 2-5 impacts were absorbed mainly by the cushion.as the box gradually softens. The model confirmed that theoretical G levels can also be calculated for varying edge lengths. Two lengths of 4.5 and 9 inches were compared.

DEDICATIONS

To my mother

A woman who looked after me well and never discouraged me from doing anything I wanted too.

Most of the time !

In loving memory of my uncle: Thomas Doyle, Esquire.

Living proof that Santa Claus did exist. Start the show and take it easy!

To Dr. Stuart and Dr. Jodi Jackson

For all of their spiritual, emotional and (on occasion) financial support.

To my wonderful remaining family:

Dr. and Mrs. Mark and Joanne Jackson

Colette, Graham, Michael, Martin, Jamie and Daniel

Chris, Lynne, Jessica and Fiona

Mr. Frank 'Rocket Man' Owens

To the 'late' Catherine Richards.

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And finally to Dhruti. What can I say about this person without making her blush.

This is me signing off. Till next time.

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(1) Genius!

(2) Simplicity!

(3) Patience (alot of it)!

(4) Humor!

And other twisted and bizarre things also come to mind, however, I don't think we should mention this stuff here (HA,HA)!

I would also like to thank my remaining committee members: Dr. S. Paul Singh & Dr. Brian (he's that nice 'chaos' guy) Feeny. I would also like to thank Jason Chaneske and Stephane Fayoux for their friendship and advice and patience during my program and research.

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TABLE OF CONTENTS

TABLE OF CONTENTS - CONTINUED

TABLE OF CONTENTS - CONTINUED

LIST OF TABLES

LIST OF TABLES - CONTINUED

LIST OF TABLES - CONTINUED

Appendix D

Appendix E

Appendix F

LIST OF TABLES - CONTINUED

Appendix F

LIST OF FIGURES

LIST OF FIGURES - CONTINUED

Appendix C (Figure 16-20)

Appendix D (Figure 21-26)

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Background

In packaging, there is the option to either intentionally under or over package products. Traditionally, companies have tended to underpackage a product in order to reduce packaging costs at the expense of increasing product damage. This runs the risk of damaging consumer loyalty and in the long run may result in much higher packaging costs. Eventually these costs are passed onto the consumer. The other option is to overpackage a product in order to reduce damage levels considerably, but at the expense of increasing packaging costs. At some point this will affect the consumer as they are faced with the added costs of shipping and unnecessary excess packaging.

It has been estimated that damage to consumer products is as high as 10 billion dollars per year in the U.S. alone (1). This amount implies that products <u>are</u> generally underpackaged, despite views within the shock and vibration world that products are on the contrary, overpackaged (this will be discussed later in the chapter). At some point there has to be some kind of trade-off between damage and packaging, but at what cost? Another question that should be asked is whether manufacturers are willing to accept a certain amount of damage and live with the resulting financial loss versus the costs saved from underpackaging.

The packaging industry, as a whole, fails to realize that in a real distribution environment, much lower G's are experienced by a package compared to those encountered in testing laboratories. Tests used for designing and assessing packaging performance are ASTMD-4169: Standard Practice for Performing of Shipping Containers and Systems (2), the Hazmat / UN DoT and International Safe Transit Association (ISTA) standards. All of these tests use worst case scenario flat drop situations, in spite of the observed handling environments shown in Table (1).

Table (1), tells the designer/engineer how to define the expected drop height and environment. Based on certain parameters such as the package weight and given dimensions, you should generally expect to encounter the drop heights shown, impacting in a certain direction and as a result of being handled in a certain way. " It is generally agreed that, regardless of the transportation mode, the severest shocks likely to be encountered in shipping result from handling operations" (3). These shocks can occur as a result of dropping the package onto a floor, dock or platform. The information in Table (1) suggests that conditions experienced in the 'real' distribution environment are not like those recreated in the test lab. If a more realistic situation combines side, corner and even edge impacts, then the question we need to ask ourselves is why is this not accounted for in lab simulations?

To date, little attempt has been made to observe or characterize the physical behavior and the peak G deceleration levels that occur in the less severe, but more frequent edge or corner impacts under dynamic extremes. The ASTM-D 1596 standard: Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material has not yet accounted for these types of

Table 1. Handling Environments

Package Weight (lbs)	Greatest Dimension (inches)	Expected Drop Height (inches)	Type of drop	Form of handling
<20	48	42	Any side or corner	One man throw
20-50	36	36	Any side or corner	One man carry
50-100	48	24	Any side or corner	One man carry
100-150	60	21	Any side or corner	One man carry
50-200	60	18	Any side or corner	One man carry
200-600	72	21	Rotating, either end, roll or tip	Mechanical
600-3000	Unlimited	18	Rotating, either end, roll or tip	Mechanical
>3000	Unlimited	12	Rotating, either end, roll or tip	Mechanical

scenarios. This reason is two-fold: firstly, it is difficult to identify the true impact geometry in an edge and a corner and secondly, because it is assumed that passing the flat drop test (which produce the highest G's) provides a package with a built-in protection factor against all combinations of impacts.

It is considered a more rigorous test of the cushioning to consider primarily flat drops, as the greatest shock deceleration reaches the product when dropped only on the flat surface, when compared to a drop on an edge or corner. It is usually the case that perfect flat drops cause the most internal damage to the product. Based on the results of the flat drop test, it will be important to select the correct primary package or secondary package and an appropriate cushion with particular characteristic(s) that will prevent these high deceleration G levels being transmitted directly to the product.

Packages that 'pass' the flat surface test are very likely to pass edge, corner or combination surface drops. When the package design passes the flat drop test and package materials meet specifications, shipping shock damage of a product is rarely a legitimate issue. It is for this reason that the established procedure for cushion curve design is to protect against flat drops. However, "we never see perfect flat drops in a real distribution environment" (3). Packages are rarely dropped precisely on one flat surface, except in the test lab (with a shock machine). Another point worth noting is that of the differences in drop heights conducted by test facilities and those encountered in the 'real' environment. "Currently, test drop heights are considerably more stringent than general transportation standards" (4).

In all distribution environments, non-perfect flat drops occur much more frequently than perfect flat drops. This is because in a drop situation, the base experiences an initial impact followed by a combination of secondary impacts either over an edge and flat surface or a corner and flat surface. Rather than compressing the cushion, a large portion of the impact energy is dissipated through rotation of the whole package. This is also due to both normal and frictional surface forces acting on the product which prevents maximum deceleration being transmitted directly to the product.

The American Society of Testing and Materials test method: ASTM D-4169 has three assurance levels. All three specify the level of test intensity - one of which must be specified for your particular product /package system prior to testing. Choosing which test depends on several factors such as product value, knowledge of the shipping environment, the number of units being shipped and the desired level of damage that can be anticipated and tolerated. Choosing an "assurance level" of three provides the least severe test, while assurance 'level one' provides the most severe test. The 'level two' test is a medium intensity level test that is generally specified unless any of the above criteria suggest otherwise.

In terms of the aesthetics of a package, there are also two types of acceptance criterion used in ASTM D-4169. 'Criterion 1' specifies that the product is damage-free, while 'criterion 2' specifies that the package is intact (as well as the product). Under 'criterion 2', the effect of edge and corner drops would be the most harmful and influential as they tend to 'beat up' the outside of the package. Under this test, such impacts would classify a package as a 'failure'. These types of damage also cause severe crushing of the package and possible damage to the contained product. In a situation were package physical stability is required (especially in a palletized stack situation) edge and/or corner damage would increase the chances of damage. This would not only affect the product, but could also greatly increase the risk of collapse of the palletized stack and further damage to the products not directly inside the affected area.

Organizations such as the American Society for Testing and Materials (ASTM), the International Safe Transit Association (ISTA) and those involved in the development of UN/DoT and HazMat regulations are heavily involved in the development of testing standards for industry practice (5). It is known that these organizations/committees have spent a great deal of time developing these procedures and are used as a guideline. Several test methods such as ASTM D-1596 :<u>Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material</u> and <u>ASTM D-4169: Standard Practice for Performing of Shipping Containers and Systems</u> were developed for the sole purpose of developing better package designs that would be able to withstand the hazards of the distribution environment. Test procedures for hazardous materials fall under the HAZMAT or UN Deparment of Transport regulations. It is in these tests that under testing is being conducted on most packaging. Corner drop tests in particular, should be conducted much more than the currently specified one drop on the corner of the manufacturers joint. Edge drops are not as much of a concern in comparison as the impact area is much larger than that of a corner" (6). It is not known from my sources/findings whether this is a procedure carried out by other facilities, but there are recommendations that more severe testing should be placed on corner impacts for specific product and package combinations.

Today, many companies in the US conduct tests primarily in the flat orientation, than onto edges and corners. The test standard requires that only the top, bottom, one long side, one short side and one corner be tested (on the corner of the manufacturers joint). Considering that a typical rectangular shipper has 26 independent impact orientations to consider (12 edges, 8 corners, and only 6 flat surfaces) it seems unusual that such a limited number of tests are being conducted. However, there is no fixed method for testing a product / package system on a specific orientation. As a rule, either of these tests are followed with modification, depending on the nature of the item being packaged and its final destination. From this point a test can be quickly developed unique to this application given a specific set of goals.

The basic goal of ISTA testing is to get a certification label on a box signifying that a package has passed all aspects of ISTA laboratory testing procedure. As a result, any damage that the package experiences in distribution should be the fault of the carrier. Many people within the shock and vibration testing world believe that certain companies in the industry seem to be making a point of exploiting this fact. "Considering the minimal amount of testing that is generally being conducted on the edges and corners of a package - It has been found that certain companies still take advantage of the ISTA specified test conditions. This involves designing the packaging purposely so that it passes the test - even though in the real distribution environment it may fail. This way, extra packaging costs can be avoided and if the package passes the ISTA and is damaged during distribution then the carrier will suffer the consequences of having to pay for lost shipment" (6).

In light of this information, it would be possible to speculate that it is a more opportunistic and inexpensive option to underpackage a product by 'boosting' the structure of the test packages in certain areas expected for testing in that particular orientation. As a result, if only these 'boosted' areas pass the test and guarantee ISTA certification, then money has been saved. Any other type of damage to the package and product not accounted for in the test will be covered by the carrier. Based on these experiences and practices, one well known testing laboratory has begun to adopt their own tests on all of the orientations not specified in the test - in addition to those that are specified (6).

In general, testing for most heavy containers under the UN and Hazardous materials regulations produce failure on either the shortest or the top side of the package (6). The first is due to the largest pressure distributed over the smallest area (next to a corner area). The latter is because the product inside the package may tend to leak after conducting a flat drop on the top side - which causes failure; not only of the bottle but also the corrugated box. The other area of damage is at the corner of the manufacturers joint. Effective packaging involves many other consideratons such as the shape of the packaged object (important because it influences load transfer during impact); the capacity of the foam to dissipate the energy (which controls rebound); and the time for which the packaged object can tolerate the given deceleration (which influences the choice of foam thickness and density).

There are four major criticisms with ASTM standard D-1596, firstly, that the G levels predicted for the cushion curves are too high and secondly the tests are conducted for perfect flat drops only. The third factor, as previously mentioned, is that simulated tests use more stringent drop heights. The final factor is that conventional cushion curves are constructed using free standing cushions blocks, and in no way take into account the contribution of the corrugated box. All of these factors induce erroneous results that lead to over-specification and over-packaging. With the first example, the time interval between drops onto the cushion are too short as only one minute of recovery time is allowed for the cushion to regain as much of its original thickness as possible before conducting the following drop. This short time interval between drops does not allow the foam to recover.

1.2 Literature Review

Testing cushions for the development of cushion curves involves repeated impacts on a particular type of cushion. This and the time factor have a profound influence on cushion stiffness, and as a result, increases G levels. Over a period of time this will eventually lead to a premature breakdown of the material due to rupturing of the cells, which again results in an increase in peak deceleration G level. In the light of these facts, the experiments in this thesis will allow approximately 10 minutes between drops.

One way to handle edge and corner drop predictions is to equate the situation to an ‘equivalent flat drop’. If the ‘true bearing area’ were to be found, then it would be possible to deduce edge and corner drop G levels from standard cushion curves. If this was possible, then the results of this work could be further adapted with the research conducted by Granthan (7) who developed a method for predicting the shock transmission characteristics for ribbed polypropylene cushioning material. This work was also based on the calculation of bearing areas but looked at converting the ribbed cushion into an equivalent flat plank cushions to determine G level using standard cushion curves.

Kuang-nan Taw (7) has developed an empirical model that observes the isolated compression region of blocks of foam alone in a 45 degree edge drop. This procedure, like that of the conventional cushion curves, does not consider the role that corrugated board plays in deformation behavior and its effect on G level. The work of Chen looked at predicting peak deceleration levels for ribbed and flat EPS cushion(8). The results suggested that at low drop heights and static stresses, the peak deceleration levels were quite similar. However, at higher drop heights and static stresses the G levels were significantly different. Apart from looking at drop heights and static stresses, consideration must also be given to cushion density.

This research will develop a theoretical model for predicting G levels for perfect edge and corner drops for various thicknesses of cushion. However, the biggest problem in a non-flat drop situation is that cushion curves for the material cannot be used because unlike flat drop impacts, it is difficult to identify the true static loading. Given similar relationships of weight and drop height, the main question that this thesis will attempt to answer is what are the differences in G levels when comparing edge and corner impacts? What are the reasons for these differences (or similarities)? Which drop angle and material gives the greatest protection? Based on these G values will these experimental results highlight the importance of each material used in the making of the package? If we find that one material plays more of a significant role than another then it may be possible to increase or reduce the amount of material(s) used, reduce shipping costs and still provide sufficient protection?

1.3 Choosing The Right Cushioning Material

As well as defining the drop height the designer must define the product fragility. This can be easily determined using the shock table to develop a Damage Boundary Curve (DBC). Choosing the largest expected drop height and type of handling environments will help select a cushion that will lower the products critical deceleration and move the shock experienced by the product out of the "damage region" of the DBC (10). Choosing the highest drop height would also lead to over-specification of material as the drop height is largely dependent on the product weight. It is generally considered that the lighter the package - the greater the drop height from which it is likely to be dropped from (11).

An innapropriate choice of cushioning may give a scenario were the cushioned product would be damaged in a situation were, normally, the uncushioned product would not see any damage. Protection against certain shocks will lower the natural frequencies of the product and package, possibly forcing them into one of the main forcing frequencies that causes resonance and ultimately, vibration damage (12). Therefore, choosing the most economical cushion that guarantees the most adequate protection for both shock and vibration is important.

1.3.1 Implications of Choosing Foam Types

"The essence of any cushioning material and any type of packaging is its ability to absorb the kinetic energy of the packaged object while keep the peak force (acceleration or deceleration) on the packaged object below the limit which will cause damage or injury" (13). The 'ideal' foam must be able to absorb energy at constant deceleration. Cellular materials like foams, are especially good at this as they often generate a lower peak force. In order to achieve good cushion performance, it is important to understand how cellular materials behave. The properties of cellular foam can be characterized by analysing the properties of the chosen material itself. The second and most important property of the material, above all else, is its relative density (or porosity). Choosing the correct density is difficult because there are many factors involved.

Selection of the correct cell wall material must be chosen for the foam, which is relatively simple. Choosing the foam depends on whether the packaging material will carry repeated loading or whether it will be subjected to severe environmental conditions such as high temperatures. For example, an elastomeric cell wall material is needed for packaging which will be subjected to repeated loading. If the protection is needed only once, a plastic or brittle material is better because such cellular materials are more efficient.

Packaging sytems employing cellular materials are traditonally designed with an experimental database, requiring a large number of impacts (14). The "stress vs energy table" used in combination with existing cushion curves will allow empiricism to be combined with physical modelling (13). If used properly, the number of experiments needed in the design process can be significantly reduced. The data will be used for both rough calculations of embodiment design and detailed calculations, where it may be necessary to conduct a few selected experiments.

Another characteristic to consider is whether the material is an open or closed cell structure and the dimensions of the corresponding mean cell diameter (15). An open cell structure consists of a three dimensional network of linked cells. On impact, energy is absorbed by the cushion by allowing the air to move freely through and out of the cushion. In order to predict perfect edge and corner drop G's, a mathematical equation will be developed that will in some way have to account for these characteristics of the material. A high degree of consistency is required when accounting for material behavior and using an open-cell structure may not be appropriate for predicting G levels as the degree of confinement in the package alters the air flow and will cause unpredictability in the results.

Based on these facts, the choice of material in this experiment is the very popular and commercially available 2 pcf closed-cell Low Density Polyethylene (LDPE). The primary reason for using this material is not only is it one of most recognized foams on the market, but it is probably one of the most used for product protection. A closed-cell foam consists of individual pockets of air or gas trapped inside a thin unbroken plastic membrane. The choice of gases are either carbon dioxide or nitrogen, depending on the type of manufacturing process of the foam. The fact that closed cell foam has gas is trapped within the cells makes it ideal for predicting material behavior as the conditions are somewhat consistent. The fact consistency is accounted for compared to open-cell makes closed-cell the most appropriate choice. Additional to this is that closed-cell foam is much stiffer than open-cell and more suitable for heavier products.

Despite this, there is also the added uncertainty in the actual amount of contact bearing area and foam volume involved in the dynamic compression process for both edge and corner drop situations. The process of calculating this type of behavior is more complex than the methods used for flat drop analysis.

In addition to this the corrugated outer case also adds further complications to the calculation.

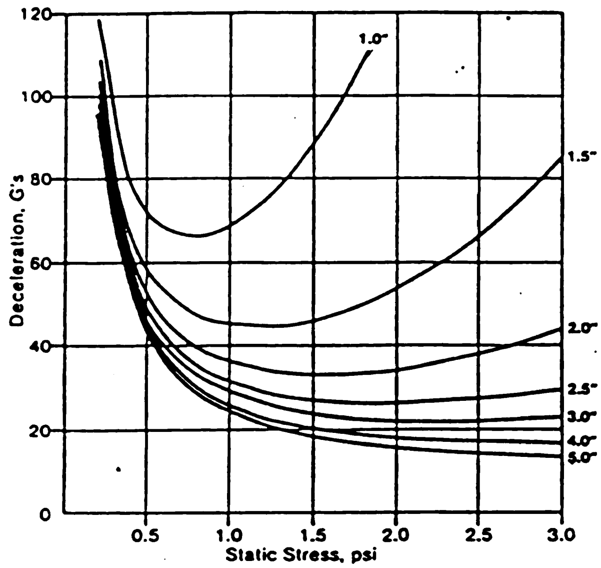
Almost all man-made and natural foams such as coral, stalks, leaves and many woods, are not isotropic (not regular) as their cells vary in shape and length, however, the structure can be thought of as one of regular units (15). However, no matter how anistropic (irregular) a foam cushioning material can be tailored in terms of refinement of the manufacturing process; few are completely isotropic. This is because their structure is completely damaged by the initial impact, which results in the progressive increase in the maximum deceleration levels recorded at each successive drop. Polyethylene is a good example of this and is one the reasons why deceleration G levels found in cushion curves are so high.

Another important consideration when comparing foams of different densities and types is 'compressive creep resistance': the ability of a material to resist progressive and permanent thickness loss over time under a static load. As density decreases, so does creep resistance (11). Although most varieties of resilient materials vary considerably, it is generally considered that many suffer little from thickness loss given sufficient recovery time and fatigue resistance is good. Thickness loss usually decreases logarithmically with time. "In practice, thickness loss due to creep will probably be smaller than the estimate derived from such curves" (11, 16).

Looking at Table (2), we can see the properties of many materials used in consumer and industrial packaging applications. Looking at the main characteristics of expanded polyethylene, we can see that the cushion factor is

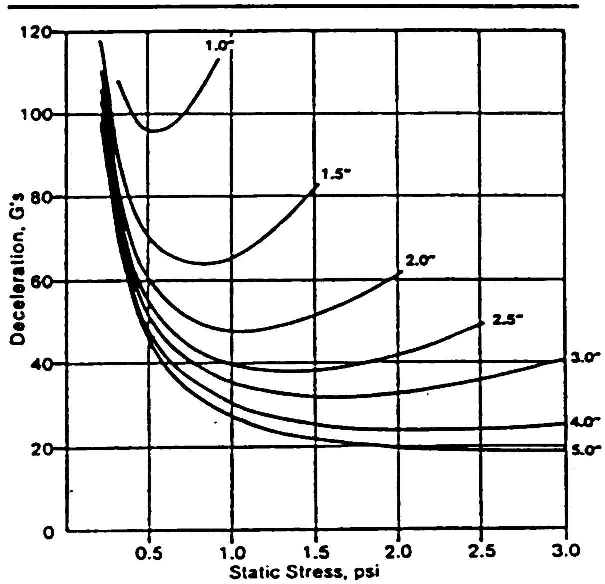
24" DROP

figure 5
24" Drop, 1st Impact Density = 2.0 PCF



24" DROP

figure 6
24" Drop, 2-5 Impact Density = 2.0 PCF



Set of Typical Cushion Curves for a 24 Inch Drop First and Second Through Fifth Impacts

moderately good. This number refers to the efficiency of a cushioning material. The lower the cushion factor, the higher the efficiency. Thickness recovery is also good and given sufficient recovery time - thickness can be maintained for a sufficient amount of time. However, foams (especially at higher densities) cannot gain back their initial thickness. As the amount of impacts increase, this produces a stiffer cushion which will inevitably increases G level. This becomes more of a problem for the product the more the cushion is subjected to further impacts.

Creep resistance is also good. The only drawback of polyethylene is the fact that its fatigue resistance is poor (lack of structural resilience). Temperature limits are reasonable, although below -20 degrees celsius the material can become brittle and cause potential failure given a severe enough impact. Above + 60 degrees celsius; the material can become to soft and not provide sufficient shock absorbancy. In both cases, G levels under safe conditions can be magnified significantly under these conditions. Water absorption is usually small in closed cell materials as compared to open structures. Corrosive and mold resistance also is not a problem in closed cell materials. The effects of dust on polyethylene is also not a major factor.

In terms of cost, a lower density material contains less total raw plastic resin than a higher density, therefore, it would seem logical that it would cost less to make. However, this is not necessarily true as the manufacturing rate, cost of blowing agent, the amount and price of the base resin all influence the cost (16).

An important factor affecting the performance of any closed cell cushioning material is a change in the manufacturing process. This will result in variations in terms of its eventual cell size, structure, or composition of the polymer that forms the cell walls, in which case could change the cushion's density and the results of the cushion curves significantly and the entire test procedure would have to be repeated (17,15). It is therefore necessary to assign grades of a particular foam material based on overall density, which is a function of cell size, basis weights used and percent resin impregnation (8). Models for these properties concern themselves with the microscopic struts and plates that make up the cell edges and faces, and the way they respond to load, or transmit heat, or dissipate energy (15).

1.3.2 Modelling Cushion Behavior

Several models have been developed for predicting the behavior of polymeric cushions. "Burgess (18) derived a model based on his study of the thermodynamic processes involved in closed cell cushions when partially trapped air is compressed rapidly in an elastic network of interconnected membranes. It was determined that the net effect of heat transfer is to dissipate energy continuously over the duration of the impact. "Throne and Progelhof" (19), have also researched the static and dynamic stress vs. strain behavior of closed cell foams and also a similar study for dynamic loading of a cushion. In the latter study, they determined that there is an energy balance between the maximum potential energy available in the drop is converted into energy stored in the foam at maximum cushion compression. At maximum compression, they determined that the energy stored per unit volume of material is the area under the static stress-strain curve, while the potential energy is simply the weight of the object times the drop height. None of these methods however are immediately applicable to edge or corner drops.

One study was undertaken were a mathematical model was developed for a 45 degree edge drop in order to predict the dynamic behavior of a low density closed-cell polyethylene foam. This was predicted by observing the stress-strain behavior of an edge of a cushion under static compression and identifying an isolated compression region (8). The predictions of the research were in error by as much as 50% of the actual value, thus making it impossible to accurately predict behavior theoretically.

Granthen (7), successfully predicted peak G levels by calculating the "true bearing area" of cushions in a flat drop situation. Using this area to calculate the static stress, he determined that ribbed cushions could be used with existing cushion curves meant for flat plank cushions. In both cases the studies have not investigated the influence of the box in either impact situation. This is an important factor to consider as the box has an extreme affect on the package behavior during an impact.

To date, little research has really attempted to study the prediction of G levels for perfect edge and corner drops. ASTM D-1596 has never made any attempt to specify tests for either edge and corner impacts or assess their contributions in terms of G levels. No work has been conducted that incorporates edge and corner drop G levels for use in combination with cushion curves. No attempt has been to develop new cushion curves specifically for these conditions. The reason for this is threefold. The first, because the 'true' bearing area of edge and corner impact geometry cannot be determined. This makes prediction of peak deceleration levels difficult. The second reason is because cushion curve data already exists for flat drop data. The final and most accepted reason for using flat drop data is that in terms of the greatest G levels;

both edge and corner impacts are less severe. This is because most of the impact goes into rotating the package which causes dissipation of energy.

1.3.3 Pilot Study

A pilot study was first conducted looking at cushion performance in flat drop situations. Traditionally, it is assumed that the cushion area should be based on the dimensions of the product area. In the case of products that do make full contact with the cushion, this is true. If the cushion does not make full contact then how can we determine the 'true bearing area' involved in cushion deformation of closed-cell Low Density Polyethylene cushions. The hypothesis was that using four arrangements (each representative of a product base) with the same weights and drop heights while sharing similar dimensional relationships (but spread out), would we get the same resultant G levels for each situation and if so, why? This is likely to be absorbing the force would be that directly underneath the impacting object. If the values were similar, then the distribution would not affect Peak G.

The study was split into two parts. In each part looked at two block legs with similar relationships. The relationship was similar in that they all comprised of a block with a fixed edge length of 9". Each block was individual in that the width dimension 'x' was divided into either one, two or three parts (x/2 or x/3), while still occupying the same dimensions. Four weights and three drop heights were conducted on each arrangement and dropped onto a cushion measuring 9"x 9" x 2". This gave a total of forty-eight drops. The G level data for both studies was compared.

It was assumed that the area likely to be absorbing the force would be that directly underneath the impacting object. The effect of cushion "drawdown" in closed-cell foam suggests that contrary to belief, the area of cushion deflection would be much greater than the area directly underneath the product base. The results, however, showed that in some cases, there was a significant difference between certain arrangements, but this was minimal. Roughly 90% of the results had G levels within ± 1-4 G within each others range, proving that there is no real correlation between the width of product base area, G level and the corresponding area of cushion collapse. From here, it was decided that "drawdown" was not as significant as expected, therefore eliminating the need to do further work.

1.3.4 Relation Between Edge and Flat Drops

Technology is available that on impact will record three individual shock pulses for the x, y, and z direction over a period of time. Individually, these pulses are present in no particular relationship. All three waveforms can be combined into a single shock pulse, which assumes that the "resultant" shock, which occurs in the vertical direction. This can be done by calculating the'resultant' G at every instant, using the equation:

$$G = \sqrt{Gx^2 + Gy^2 + Gz^2}$$

Using this combined 'resultant' G in combination with the individual x, y, and z pulses, we can calculate the impact angles of each pulse over a given duration. If the values on each pulse show a change over time, then it is possible to determine that the package is rotating. Therefore, it is apparent that a non-perfect edge or corner drop is taking place. Using this 'vector' relationship it is possible to determine the actual G associated with an oblique shock. The conclusion is that a vertical G on an edge or corner is always equivalent to two (or even three) simultaneous, but much less intense G levels expected on the sides of a package (see Figure 1). Therefore, designing for protection against edge drops by performing only flat drops requires that shocks on two or three faces be applied simultaneously, which is difficult to do. A shock to only one face such as in a perfect flat drop, does not guarantee that components will respond the same way. The downside of this is that over-packaging happens because of this fact.

It is envisioned that if it is possible to predict peak deceleration G values for perfect edge and corner drops, then the method should in some way have applications for use by the packaging engineer, in a similar procedure to that used by ASTM in the use of their cushion curves. It may be possible to predict the response of the first impact, and collect the average G response for 2-5 drops using the same procedure.

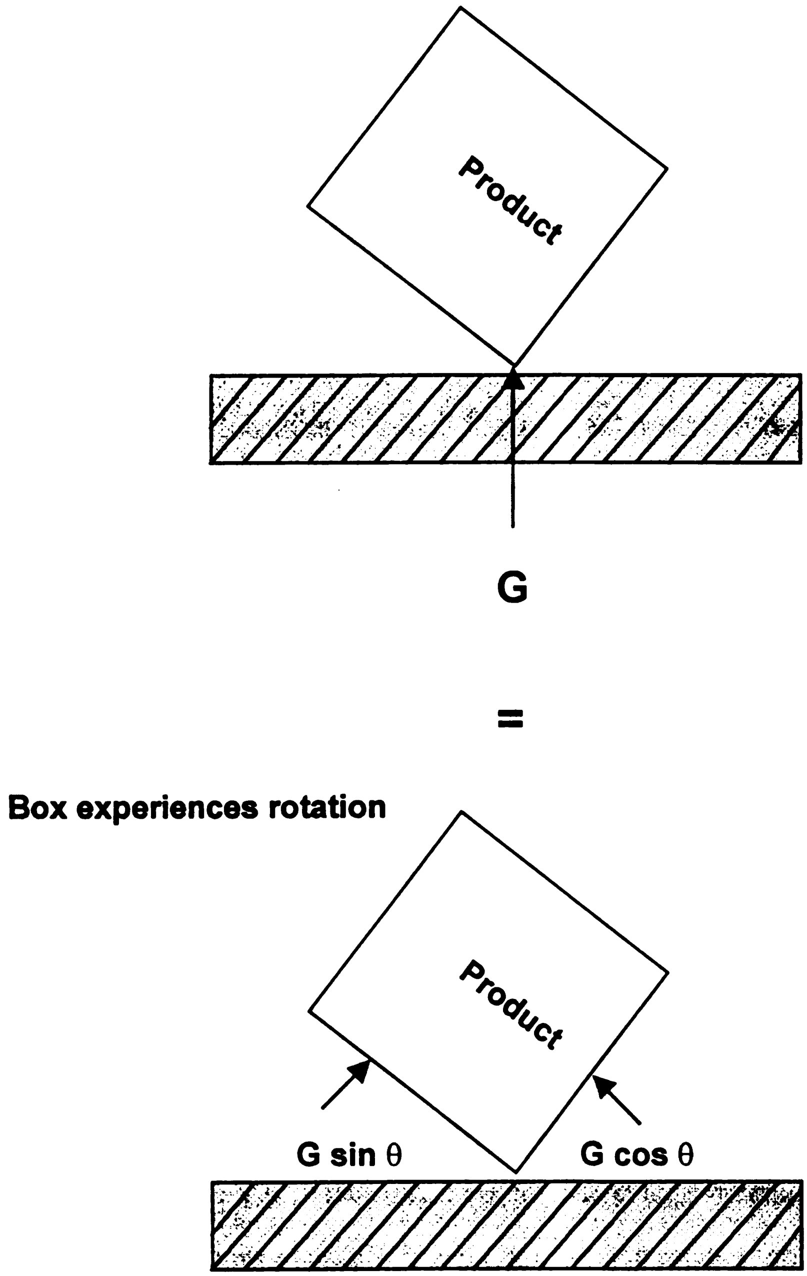


Figure 1. 'Vector' Relationship Associated With Oblique Shocks

CHAPTER 2

EXPERIMENTAL DESIGN FOR EDGE AND CORNER DROPS

2.1 Test Setup

As mentioned in the introductory section, the original pilot study suggested that there was no relationship between the distibution of product area, the contact area under deformation and the corresponding G level. Further investigation looked at situations in which the contact area involved in an impact was smaller than that of flat drops: edge and corner drops. The behavior of foam cushioning material and corresponding G levels in the corner drop mode has never been conducted. Work has been done on edge drop impacts, but like corner drops, the influence of the corrugated board and foam together has never been studied. In both situations, it is impossible to determine the actual bearing area. In this mode, the cushion encompasses greater and greater bearing area as the cushion continues to deform on impact.

A specially constructed jig was built with the facilty to attach the edge and corner block arrangements (each representative of the base edge or corner of a product). This was then clamped to the cushion tester which would be dropped onto a base measuring 9"x 9". The edge cushion/box system had fixed edge lengths of 4.5 " and 9" respectively. The choice of cushioning material used in this experiment was the commercially available low density polyethylene foam with a density of 2 pcf made by Dow Chemical. In Figure (2), the test setup utilizes the basic cushion tester. In Figures (3) and (4), we can see that two jigs were developed for both edge and corner drop tests, respectively.

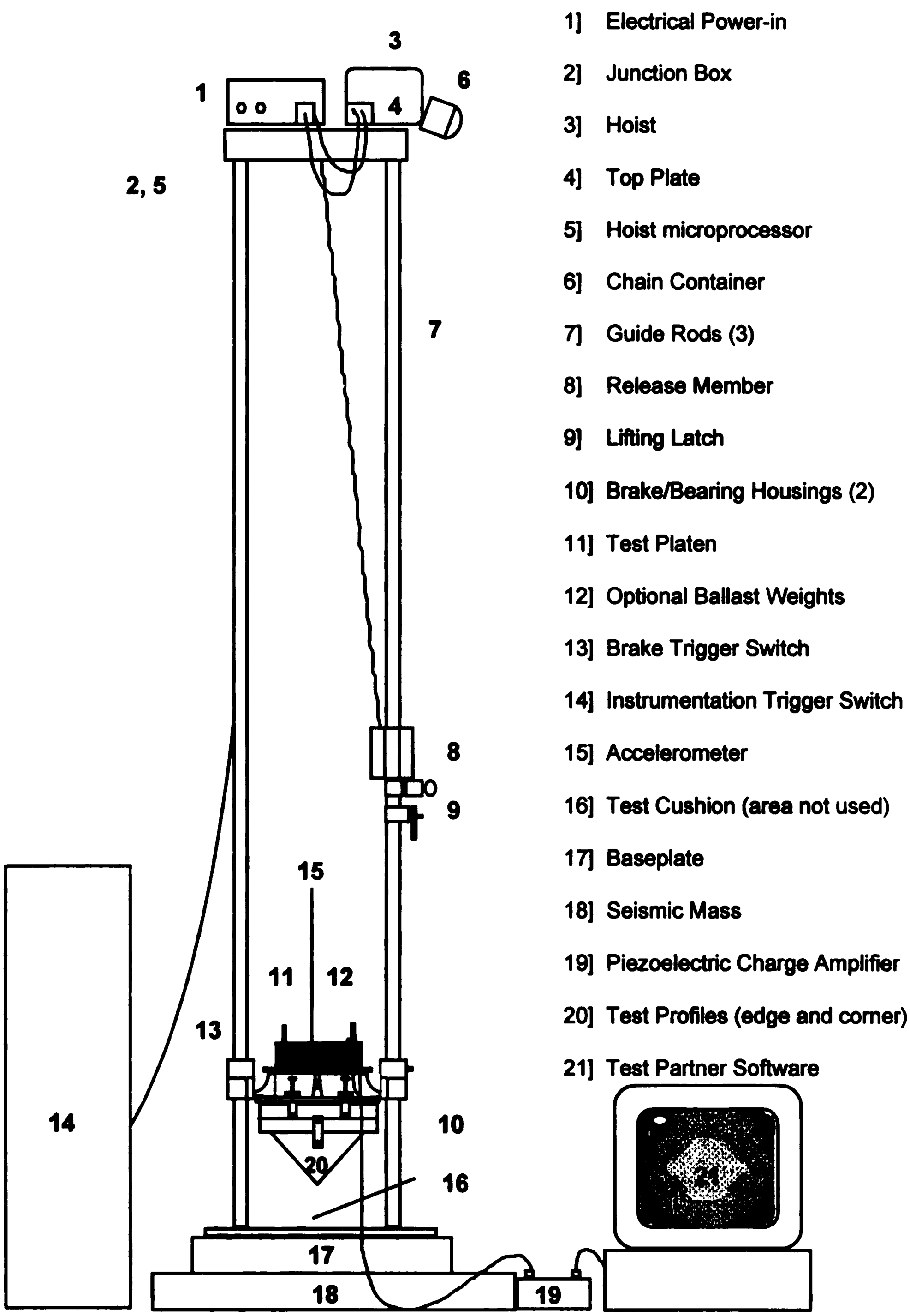
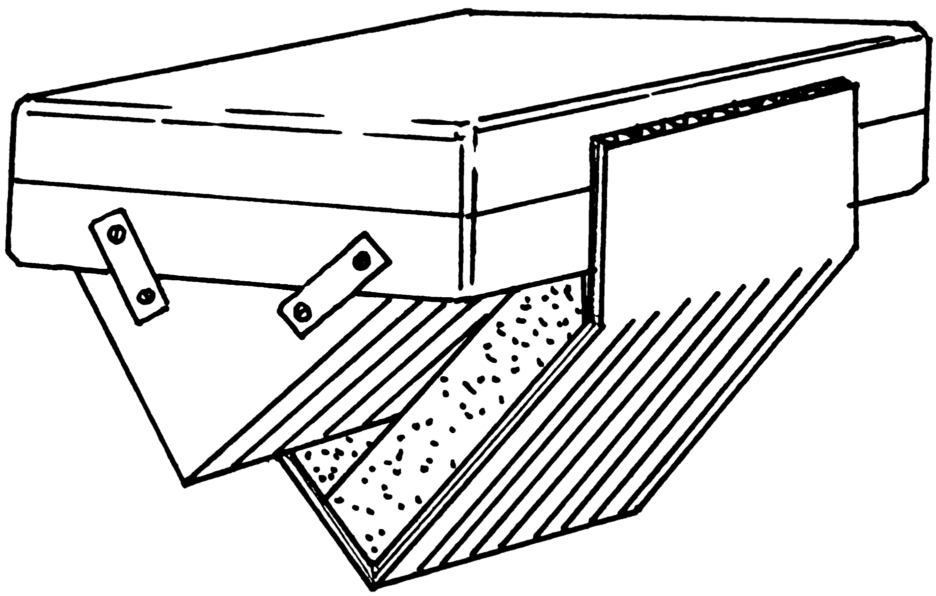


Figure 2. Cushion Tester with Test Apparatus (not to scale)

4.5 inch Edge Length with 2 inch Cushion Thickness.



9.0 inch Edge Lengths at 2 and 3 inch Cushion Thickness.

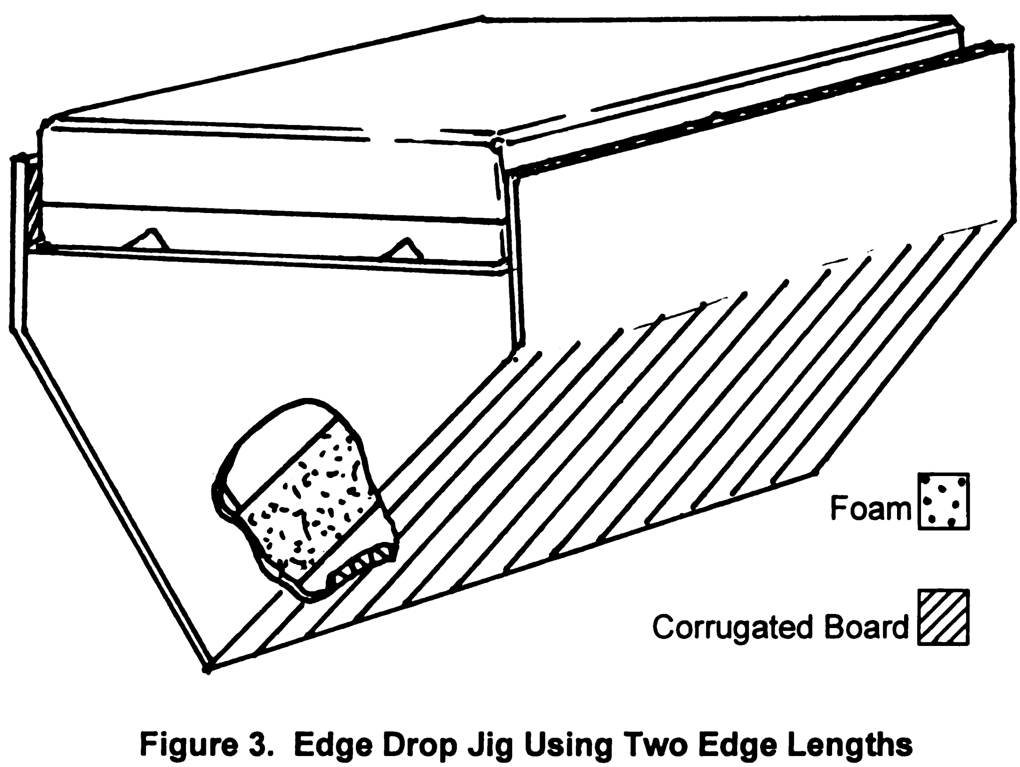


Figure 3. Edge Drop Jig Using Two Edge Lengths

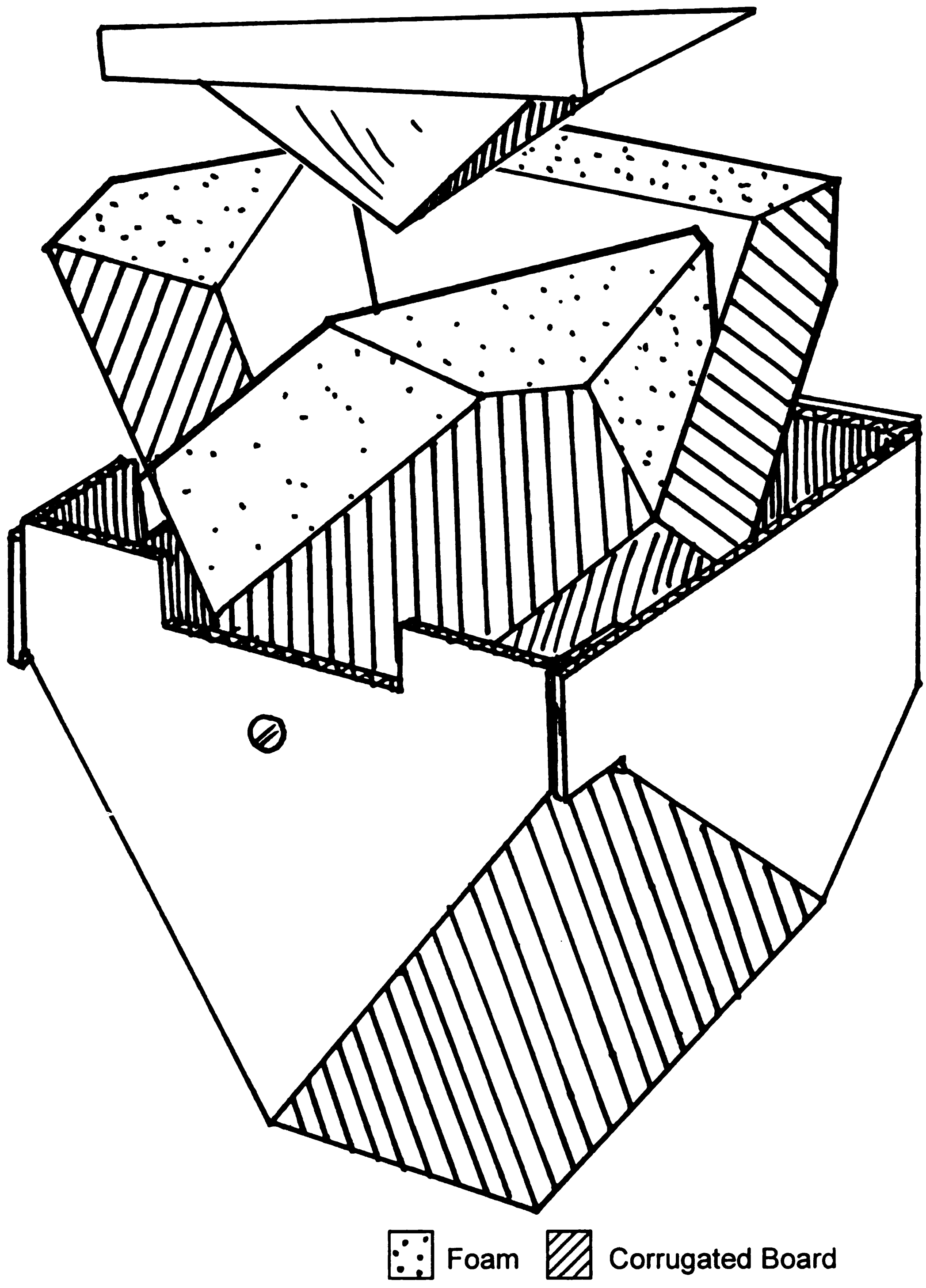


Figure 4. Corner Drop Jig With Undefined Impact Geometry

This would hold the box/cushion combination in the correct orientation for these drops. The experiment looked at two conditions for both perfect edge and corner drops. A third condition was be studied for edge drops only.

2.1.1 Test Condition 1:

This was the main area of investigation for the thesis and involved dropping the jig, with cushions measuring 2" and 3" in thickness and covered with C-flute corrugated to simulate in-the-box performance. The system was dropped from two heights of 24" and 36" using two weights at approximately 20.4 and 40.4 lbs (for 2"cushion) and 20.6 and 40.6 lbs for (3" cushion). This was done for both edge and corner drops. The length of the edge in the edge drop tests was 9" in order to fit inside the cushion tester. Five repeated drops were conducted for each phase. This was considered a more representative model of what happens to a package system over a period of time and repitition as specified in ASTM D-1596: Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material (20). Each box had the same weight, but was dropped from the five heights repeatedly. The extra weight of the three inch cushion had no significant affect on the peak deceleration values.

The reason for using the aforementioned weights is that based on the values in Table (1) we can see that the types of drops on the sides or corners of a package usually occur for packages weighing between 20 and 150 pounds. Weights of around 20 and 40 pounds were chosen because they are known to be dropped from greater heights. The drop heights chosen did not coincide with the values of greatest box dimension as there was no dimension in either condition that was near to these values. For this reason it was decided that two randomly picked drop heights of 24 and 36 inches were more representative for the lighter packages.

2.1.2 Test Condition 2:

This is a second experiment that involved dropping the jig, cushion and box system using the same two cushion thicknesses of 2 and 3 inches. The same two drop heights and weights were also used in this study (dependent on whether an edge or corner impact). The variation here is that five incremental drop heights of 18, 24, 30, 36 and 42 inches will be conducted for each phase. This would possibly show some unusual findings in terms of shock pulse shape and their associated G levels. Although this type of test is not conducted in any of the test standards, it was useful to study the behaviour of the product, cushion and box system over greater drop heights. This is possibly a more realistic situation compared to that of the conditions specified in ASTM D-4169: Standard Practice for Performing of Shipping Containers and Systems. This test also covers most of the drop heights typically encountered in the distribution environment (see Table 1). However, this cannot be proven. It was decided that one box should be used for each weight and dropped from the five consecutively increasing drop height measurements.

2.1.3 Test Condition 3:

In the case of the edge drop tests only, a third test was done which involved dropping the jig, cushion (2 inch thickness only) and box system, but this time using an edge length of 4.5 inches (see Figure 3), and again dropped from the same two drop heights and two weights (due to the size of the system). As in condition 1- five repeated drops were conducted for each phase.

The reason for this was to see if the model would predict theoretical peak deceleration levels for varying edge lengths. This would provide useful information for the packaging designer when predicting G values for prototype package development.

Fewer drops were conducted for both conditions compared to the amount in the flat drop phase. This is because, in the case of corner impacts - too much weight would possibly damage the accelerometer on the cushion tester. Relationships can also be derived with a minimal amount of information.

2.2 Edge Drop Test

The first experiment looked at establishing a correlation between predicted and actual G's for perfect edge drops. A perfect edge drop is where the box sides make 45 degree angles with the ground. The study will attempt to successfully predict G levels. The variables are the cushion thickness, weight, drop height and edge length. Again, the drops would be conducted using the experimental setup in Figure (3). The test involved measuring the peak G levels associated with dropping the jig, fabricated cushion (LDPE Arcel 512) and a corrugated outer box. A total of four boxes was used. The shock pulses generated from the cushion tester were captured after filtered over a series of drop height and weight conditions for the jig, cushion and box using the two cushion thicknesses of 2 and 3 inches. As already mentioned, edge lengths of 9 inches and 4.5 inches were used to test varying edge lengths.

2.3 Corner Drop Test

The same procedure as used for the edge drops was used for the corner drops in terms of weights and drop heights over both drop sequences. Edge length and material behavior are no longer variables but the drop height and weight will vary. The same method of capturing the shock pulses generated from the cushion tester and filtered, for each of the conditions of jig, cushion and corrugated box using the same two cushion thicknesses (2 and 3 inches) was used.

Shock pulses were collected both before filtering and after filtering for both edge and corner drops. Through dropping each test box repeatedly from the same height, it was expected that the shape of the shock pulse (at specific points in the sequence), would show different contribution of both materials to the overall shock absorbtion during the entire duration of the test. The box for example is likely to absorb most of the impact energy in the first drop because it is fresh. Over time, the box gradually gets beat up with repeated impact and so the cushion is likely to to take over absorbing most of the impact energy as drops go on. At the same point there may be equal contributions from both materials. At what point and time in the sequence of tests this will happen will be difficult to determine. And since drop height and weight are likely to affect the relative contributions it would not be possible to assume whether the box or the cushion in particular dominates another in an impact situation.

ASTM D1596-91: Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material, will be used as a guideline in this experiment. Some modification of the established ASTM D -1596 test procedure was necessary, but in general, testing was conducted similar to the standard in that five pieces of data were obtained. The theoretical model would then predict peak G values for the first and second through fifth drops. If the theoretical predictions are consistent and valid, then it may be possible to develop this data in the form of a series of cushion curves like that seen for flat plank cushion curves (see Figure 5), using the appropriate curve fitting/graphing software.

2.4 Equipment

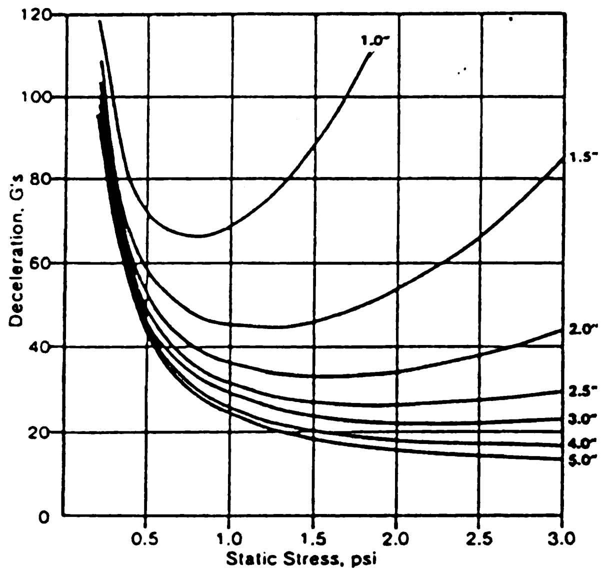
The Lansmont Corporation Model 23 cushion tester with a flat dropping platen head (see Figure 2) was used. Weights were added to the dropping platen at different intervals. A Dytran piezolectric accelerometer having a sensitivity of 10mV/g was mounted onto a free falling platen. A Dytran Model 4110 AC piezotron charge amplifier was also used to magnify the accelerometer output. Hardware filtering frequency was approximately 5000Hz.

A Lansmont Corporation Test Partner Version #2 data acquisition software system was used to record shock pulse waveforms from the accelerometer mounted on the cushion testers's platen as it impacted the base. The weighted platen was instrumented with a piezoelectric accelerometer and linked to Test Partner software. The complete history of the shock pulse was recorded and later filtered and later analyzed (discussed later).

The waveforms were filtered at some specific frequency in order to remove the high frequency components associated with the ringing of the test fixture becoming superimposed onto the underlying shock pulses. A trigger level of 20 G's has been specified in order to prevent small accelerations not originating from the actual impact from being recorded. Lubricant was applied in order to minimize frictional forces between the guide rods and the falling platen during testing. Unfortunately, these forces cannot be completely eliminated.

24" DROP

figure 5
24" Drop, 1st Impact Density = 2.0 PCF



24" DROP

figure 6
24" Drop, 2-5 Impact Density = 2.0 PCF

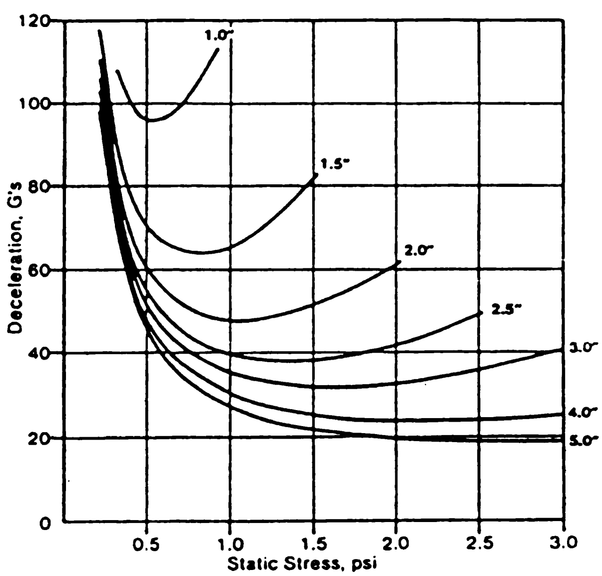


Figure 5. Set of Typical Cushion Curves for a 24 Inch Drop First and Second Through Fifth Impacts

CHAPTER 3

RESULTS AND THEORETICAL DEVELOPMENT

3.1 Results

This research combined physical testing and the development of a mathematical model that attempted to accurately predict peak deceleration levels in a dynamic situation. The first phase of this thesis was to develop a theoretical model that identifies the 'key' variables used to predict G levels for impacts that have non-defined dimensions absorbing most of the impact (edge and corner drops). In a corner drop, the impact geometry is not is not really known. It is assumed that if a 2 or 3 inch thickness cushion is specified, this does not necessarily mean that the whole thickness is absorbing the shock. A more realistic assumption is that only a portion of the corner edge is contributing to shock absorbtion. In Tables (3–16), respectively, we can see the results for all the actual peak G's obtained for edge and corner drop tests over all three conditions. The "theoretical" G's in these tables were obtained in the following.

3.2 Theoretical Development

3.2.1 Perfect Edge Drop Situation

In a perfect edge drop, there are four variables which control the G level in an impact. They are drop height, package weight, edge length and cushion thickness. Of course, the type of foam and corrugated board making up the box also play significant roles, but these are assumed fixed in the experiment. This then means that the results of the curve fit will be valid only for this foam and box arrangement. There is a good reason to believe that the fit will be reasonably

Table 3. 24" and 36" Edge Drop Results for 2" Cushion Thickness - 1st Impact Box Edge Length = 4.5 Inches

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)					
2"	19.8	24	23.65	23.64	-0.04	Outstanding	a =	-0.36
Refer to Table 29							b =	0.20
							Z =	36.80
2"	39.8	24	18.36	18.37	0.04	Outstanding		
2"	19.8	36	25.63	25.64	0.04	Outstanding		
Refer to Table 30								
2"	39.8	36	19.93	19.92	-0.04	Outstanding		

Table 4. 24"and 36" Edge Drop Results for 2" Cushion Thickness - 2-5 Impacts Box Edge Length = 4.5 Inches

Cushion	Weight (lbs) (a)	Drop Height (inches) (b)	Actual G (Z)	Average 2-5 Impacts	Theoretical G	% Difference	Agreement
2"							
Refer to Table 29	19.8	24	27.53		31.30	13.70	Good
	19.8	24	29.85		31.30	4.87	Outstanding
	19.8	24	32.86		31.30	-4.74	Outstanding
	19.8	24	33.68	31.0	31.30	-7.06	Very Good
2"							
	39.8	24	27.12		30.27	11.61	Good
	39.8	24	28.66		30.27	5.62	Very Good
	39.8	24	31.6		30.27	-4.21	Outstanding
	39.8	24	32.33	29.9	30.27	-6.37	Very Good
2"							
Refer to Table 30	19.8	36	33.2		35.59	7.20	Very Good
	19.8	36	35.86		35.59	-0.75	Outstanding
	19.8	36	38.45		35.59	-7.44	Very Good
	19.8	36	37	36.1	35.59	-3.81	Outstanding
2"							
	39.8	36	31.05		34.42	10.84	Good
	39.8	36	33.12		34.42	3.91	Outstanding
	39.8	36	35.24		34.42	-2.34	Outstanding
	39.8	36	36.67	34.0	34.42	-6.15	Very Good

Exponential Values	
a =	-0.05
b =	0.32
Z =	13.21

Table 5. 24" Edge Drop Results for 2" and 3" Cushion Thickness - 1st Impact Box Edge Length = 9. Inches

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)					
2"	20.4	24	26.09	22.45	-13.96	Good	a =	-0.22
Refer to Table 31							b =	0.16
							Z =	26.23
2"	40.4	24	21.05	19.28	-8.41	Very Good		
3"	20.6	24	19.22	22.40	16.55	Bad		
Refer to Table 32								
3"	40.6	24	17.69	19.26	8.87	Very Good		

**Table 6. 24" Edge Drop Results for 2" and 3" Cushion Thickness - 2-5 Impacts
Box Edge Length = 9. Inches**

Cushion	Weight (lbs) (a)	Drop Height (inches) (b)	Actual G (Z)	Average 2-5 Impacts	Theoretical G	% Difference	Agreement	Exponential Values	
2"								a =	-0.32
Refer to Table 31	20.4	24	38.07		33.27	-12.61	Good	b =	0.65
	20.4	24	32.15		33.27	3.48	Outstanding	Z =	10.96
	20.4	24	32.51		33.27	2.33	Outstanding		
	20.4	24	34.03	34.2	33.27	-2.24	Outstanding		
2"									
	40.4	24	29.58		26.78	-9.47	Very Good		
	40.4	24	32.69		26.78	-18.08	Bad		
	40.4	24	33.28		26.78	-19.53	Bad		
	40.4	24	33.7	32.3	26.78	-20.53	Bad		
3"									
Refer to Table 32	20.6	24	28.24		33.17	17.44	Bad		
	20.6	24	35.34		33.17	-6.15	Very Good		
	20.6	24	34.88		33.17	-4.92	Outstanding		
	20.6	24	31.25	32.4	33.17	6.13	Very Good		
3"									
	40.6	24	18.48		26.74	44.69	Bad		
	40.6	24	23.87		26.74	12.02	Good		
	40.6	24	24.37		26.74	9.72	Very Good		
	40.6	24	25.06	22.9	26.74	6.70	Very Good		

Table 7. 36" Edge Drop Results for 2" and 3" Cushion Thickness - 1st Impact Box Edge Length = 9. Inches

Cushion	Weight (lbs) (a)	Drop Height (inches) (b)	Actual G (Z)	Theoretical G	% Difference	Agreement	Exponential Values	
2"	20.4	36	28.56	26.49	-7.24	Very Good	a =	-0.38
Refer to Table 33							b =	0.23
							Z =	37.04
2"	40.4	36	21.19	20.41	-3.70	Outstanding		
3"	20.6	36	24.45	26.39	7.95	Very Good		
Refer to Table 34								
3"	40.6	36	19.64	20.37	3.70	Outstanding		

**Table 8. 36" Edge Drop Results for 2" and 3" Cushion Thickness - 2-5 Impacts
Box Edge Length = 9. Inches**

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Average 2-5 Impacts	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)						
2"								a =	-0.24
Refer to Table 33	20.4	36	35.43		36.05	1.74	Outstanding	b =	0.55
	20.4	36	39.23		36.05	-8.12	Very Good	Z =	10.14
	20.4	36	41.2		36.05	-12.51	Good		
	20.4	36	40.52	39.1	36.05	-11.04	Good		
2"									
	40.4	36	34.88		30.62	-12.22	Good		
	40.4	36	35.61		30.62	-14.02	Good		
	40.4	36	39.17		30.62	-21.84	Bad		
	40.4	36	39.09	37.2	30.62	-21.68	Bad		
3"									
Refer to Table 34	20.6	36	35.05		35.96	2.60	Outstanding		
	20.6	36	34.22		35.96	5.09	Very Good		
	20.6	36	30.93		35.96	16.27	Bad		
	20.6	36	32.5	33.2	35.96	10.65	Good		
3"									
	40.6	36	23.21		30.58	31.76	Bad		
	40.6	36	25.84		30.58	18.35	Bad		
	40.6	36	27.54		30.58	11.04	Good		
	40.6	36	28.13	26.2	30.58	8.71	Very Good		

Table 9. 18" Edge Drop Results for 2" and 3" Cushion Thickness - 1st Impact Box Edge Length = 9. Inches

Cushion	Weight (lbs) (a)	Drop Height (inches) (b)	Actual G (Z)	Theoretical G	% Difference	Agreement	Exponential Values	
2"	20.4	18	20.5	18.08	-11.78	Good	a =	-0.50
Refer to Table 35							b =	0.39
							Z =	26.66
2"	40.4	18	16.39	12.87	-21.50	Bad		
3"	20.6	18	15.82	18.00	13.76	Good		
Refer to Table 36								
3"	40.6	18	10.11	12.83	26.94	Bad		

Table 10. 24", 30", 36", and 42" Edge Drop Results for 2" and 3" Cushion Thickness - 2-5 Impacts - Box Edge Length = 9. Inches

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Average 2-5	Theoretical G	Average 2-5	% Difference	Agreement
	(a)	(b)	(Z)					
2"								
Refer to Table 35	20.4	24	30.04		24.42		-18.70	Bad
	20.4	30	33.19		30.90		-6.89	Very Good
	20.4	36	39.92		37.46		-6.17	Very Good
	20.4	42	44.41	36.9	44.07	34.2	-0.76	Outstanding
2"								
	40.4	24	26.65		20.99		-21.24	Bad
	40.4	30	32.42		26.56		-18.08	Bad
	40.4	36	42.51		32.19		-24.28	Bad
	40.4	42	53.61	38.8	37.87	29.4	-29.35	Bad
3"								
Refer to Table 36	20.6	24	28.49		24.37		-14.46	Good
	20.6	30	29.26		30.84		5.39	Very Good
	20.6	36	30.64		37.38		21.98	Bad
	20.6	42	33.71	30.5	43.98	34.1	30.45	Bad
3"								
	40.6	24	13.41		20.97		56.34	Bad
	40.6	30	24.58		26.53		7.93	Very Good
	40.6	36	27.69		32.16		16.13	Bad
	40.6	42	32.85	24.6	37.83	29.4	15.17	Good

Exponential Values	
a =	-0.22
b =	1.05
Z =	1.67

Table 11. 24" Corner Drop Results for 2" and 3" Cushion Thickness - 1st Impact

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)					
2"	20.4	24	19.66	18.44	-6.23	Good	a =	-0.31
Refer to Table 37							b =	0.08
							Z =	36.58
2"	40.4	24	17.27	14.89	-13.79	Good		
3"	20.6	24	17.2	18.38	6.86	Good		
Refer to Table 38								
3"	40.6	24	12.84	14.86	15.77	Good		

Table 12. 24" Corner Drop Results for 2" and 3" Cushion Thickness - 2-5 Impacts

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Average 2-5 Impacts	Theoretical G	% Difference	Agreement
	(a)	(b)	(Z)				
2"							
Refer to Table 37	20.4	24	24.67		26.28	6.52	Very Good
	20.4	24	30.15		26.28	-12.84	Good
	20.4	24	28.93		26.28	-9.16	Very Good
	20.4	24	29.58	28.33	26.28	-11.16	Good
2"							
	40.4	24	25.38		25.15	-0.90	Outstanding
	40.4	24	29.45		25.15	-14.59	Good
	40.4	24	31.18		25.15	-19.33	Bad
	40.4	24	30.78	29.20	25.15	-18.28	Bad
3"							
Refer to Table 38	20.6	24	22.68		26.26	15.80	Good
	20.6	24	26.48		26.26	-0.82	Outstanding
	20.6	24	24.08		26.26	9.06	Very Good
	20.6	24	24.44	24.42	26.26	7.46	Very Good
3"							
	40.6	24	19.92		25.14	26.23	Bad
	40.6	24	21.04		25.14	19.51	Bad
	40.6	24	22.25		25.14	13.01	Good
	40.6	24	24.12	21.83	25.14	4.25	Outstanding

Exponential Values	
a =	-0.06
b =	0.79
Z =	2.60

Table 13. 36" Corner Drop Results for 2" and 3" Cushion Thickness - 1st Impact

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)					
2"	20.4	36	22.22	19.38	-12.77	Good	a =	-0.29
Refer to Table 39							b =	0.62
							Z =	5.17
2"	40.4	36	16.85	15.85	-5.91	Good		
3"	20.6	36	16.82	19.33	14.91	Good		
Refer to Table 40								
2"	40.6	36	14.93	15.83	6.03	Good		

Table 14. 36" Corner Drop Results for 2" and 3" Cushion Thickness - 2-5 Impacts

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Average 2-5 Impacts	Theoretical G	% Difference	Agreement
	(a)	(b)	(Z)				
2"							
Refer to Table 39	20.4	36	31.35		31.01	-1.10	Outstanding
	20.4	36	35.42		31.01	-12.46	Good
	20.4	36	36.6		31.01	-15.29	Good
	20.4	36	36.81	35.05	31.01	-15.77	Good
2"							
	40.4	36	28.14		27.32	-2.93	Outstanding
	40.4	36	31.24		27.32	-12.56	Good
	40.4	36	32		27.32	-14.64	Good
	40.4	36	33.62	31.25	27.32	-18.75	Bad
3"							
Refer to Table 40	20.6	36	25.97		30.95	19.17	Bad
	20.6	36	27.52		30.95	12.46	Good
	20.6	36	28.51		30.95	8.56	Very Good
	20.6	36	27.52	27.38	30.95	12.46	Good
3"							
	40.6	36	23.39		27.29	16.68	Bad
	40.6	36	24.3		27.29	12.31	Good
	40.6	36	24.66		27.29	10.67	Good
	40.6	36	23.55	23.98	27.29	15.88	Good

Exponential Values	
a =	-0.19
b =	0.80
Z =	3.13

Table 15. 18" Corner Drop Results for 2" and 3" Cushion Thickness - 1st Impact

Cushion	Weight (lbs)	Drop Height (inches)	Actual G	Theoretical G	% Difference	Agreement	Exponential Values	
	(a)	(b)	(Z)					
2"	20.4	18	14.79	14.46	-2.24	Very good	a =	-0.46
Refer to Table 41							b =	0.30
							Z =	24.31
2"	40.4	18	11.41	10.58	-7.26	Good		
3"	20.6	18	14.06	14.39	2.38	Very good		
Refer to Table 42								
3"	40.6	18	9.8	10.56	7.73	Good		

Table 16. 24", 30", 36", and 42" Corner Drop Results for 2" and 3" Cushion Thickness 2-5 Impacts

Cushion	Weight (lbs) (a)	Drop Height (inches) (b)	Actual G (Z)	Average 2-5 Impacts	Theoretical G	Average 2-5 Impacts	% Difference	Agreement	Exponential Values	
2"									a =	0.08
Refer to Table 41	20.4	24	23.22		19.21		-17.27	Bad	b =	1.21
	20.4	30	25.1		25.18		0.34	Outstanding	Z =	0.32
	20.4	36	30.78		31.42		2.09	Outstanding		
	20.4	42	37.25	29.09	37.89	28.426	1.71	Outstanding		
2"										
	40.4	24	20.14		20.32		0.88	Outstanding		
	40.4	30	28.5		26.64		-6.54	Very Good		
	40.4	36	34.72		33.23		-4.28	Outstanding		
	40.4	42	44.72	32.02	40.07	30.065	-10.40	Good		
3"										
Refer to Table 42	20.6	24	21.86		19.23		-12.05	Good		
	20.6	30	25.34		25.21		-0.53	Outstanding		
	20.6	36	27.46		31.45		14.52	Good		
	20.6	42	32.62	26.82	37.92	28.449	16.24	Bad		
3"										
	40.6	24	17.77		20.33		14.39	Good		
	40.6	30	21.31		26.65		25.05	Bad		
	40.6	36	27.61		33.25		20.42	Bad		
	40.6	42	56.05	30.69	40.09	30.077	-28.48	Bad		

accurate for many types of foam for two reasons. First, most closed-cell foams are very similar in performance as the published cushion curves show and so changing over to a different foam should not drastically alter the results. Second, the foam only absorbs part of the energy: the box absorbs the rest. And since C-flute corrugated boxes make up the majority of board used, the contribution of the box to the G level is considered fixed.

The form of the curve fit to the experimental data was taken to be:

$$G = Z\, h^{a}\, W^{b}\, L^{c}\, t^{d} \tag{1}$$

where: h = drop height (inches) W = weight (lbs)

L = egde length (inches) t = cushion thickness (inches)

Z = unknown constant

a, b, c, d are unknown exponents

The choice of this form over any other fit such as a linear one ($G = a + bh + cW + dL + et$) for example, is motivated by the prediction for G using the linear spring mass model (21) in Figure (6),

$$G = \sqrt{\frac{2hEA}{Wt}} \tag{2}$$

where h is the drop height, W is the weight, A is the impact area, and t is the cushion thickness. The modulus of elasticity (E), depends on the type of foam, and so embodies the unknown Z in the fitted equation (1). If this linear model were to fit edge drop impacts, then the powers "a" and "c" in equation (1) would be 1/2. The powers of "b" and "d" would be -1/2.

$$G = \sqrt{\frac{2hk}{W}} = \sqrt{\frac{2hEA}{Wt}} \begin{array}{l} \sim Z(h)^b (L)^c (t)^d (W)^a \text{ (edge)} \\ \sim Z(h)^b (t)^d (W)^a \text{ (corner)} \end{array}$$

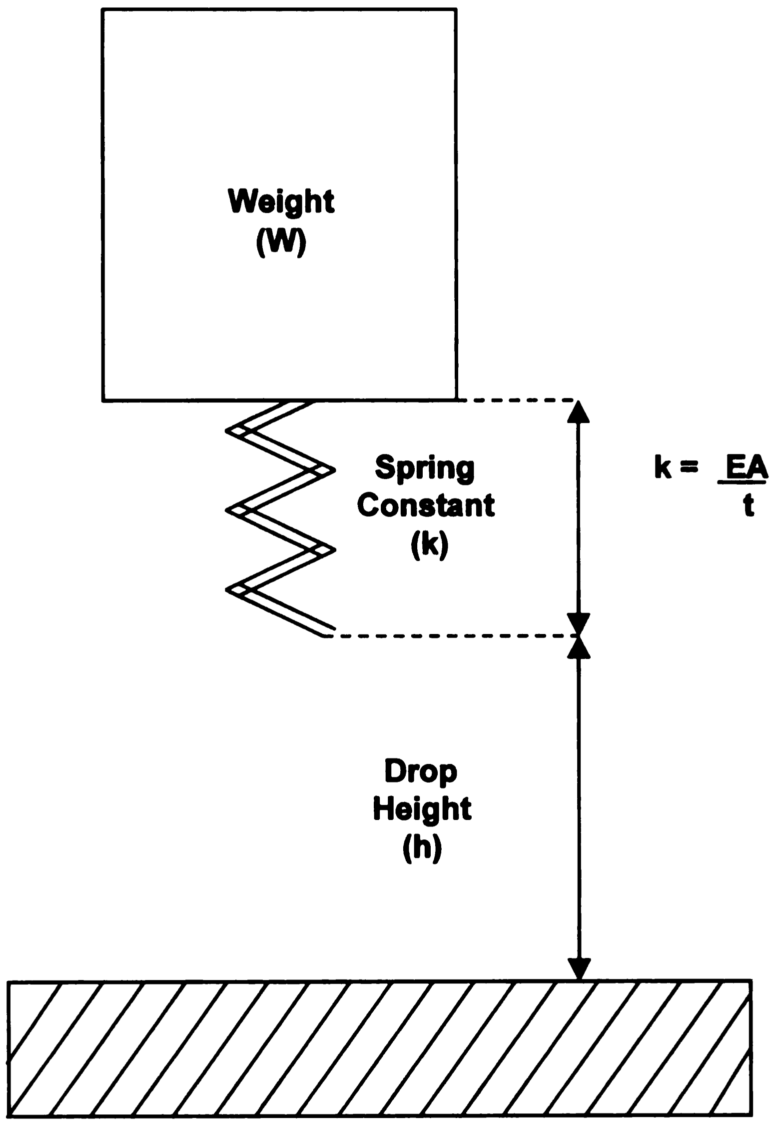


Figure 6. Model of a Linear Spring Mass System

The choice of fit in equation (1) is also motivated by the fact that if either W or h were zero, then G should be zero (and is in this formula). Only a 'product form' where the variables are multiplied by each other accomplishes this; a linear fit would still give a non-zero G even when h = 0 and therefore makes no sense. Based on the linear model and general observations on the cushion curves, it is expected that the powers "a" and "c" will be positive and less than one. Only the fit to the experimental data will confirm this.

3.2.2 Perfect Corner Drop Situation

In a perfect corner drop, we have a similar situation except there are only three variables which control the G level in an impact. They are drop height, package weight and cushion thickness. Remember, there are three radiating edges with no defined impact geometry, therefore, the same equation can be used without the "edge length" variable. The type of foam and corrugated box are again fixed, however, as mentioned previously the curve fit for this particular setup may also applicable for other varieties of cushioning materials used in combination with C-flute. The form of the curve fit in this situation looks slightly different in that the edge length is not included in the formula. The corner drop orientation does not have a defined edge length. Therefore:

$$G = Z\, h^{a}\, W^{b}\, t^{c} \qquad (3)$$

where: h = drop height W = weight

t = cushion thickness

Z = unknown constant

a, b, c, are unknown exponents.

3.3 Limitations of the Theoretical Model

For the remainder of the experiment, equations for both edge and corner drops will only be calculated for test conditions [1] and [3]. Using condition [2] for drop heights from 18", 24", 30", 36" and 42" will not be studied in any further detail. The fact that this is not the primary objective of the thesis adds to the fact that these results should not be included in the following analysis, as they might affect the outcome of the generated curve fitting information. Even if the incremental results fitted the spring mass model it would not be possible to construct a cushion curve in this form. The advantage of using these cushion curves is that hypothetical weights can be used for a given thickness and drop height.

3.4 Limitations of Curve Fit Software

Due to the limitations of commercial curve fitting software used, it was not possible to use the power fit equation. The alternative method was to use a polynomial fit equation. A slightly different method was used in which the logarithm was taken for each of the five variables. This gave two sets of "Z" and power values for "a" "b" "c" and "d" constants for both edges and corners dropped from 24 and 36 inches only. The polynomial equation is similar to the power fit equation except we take the logarithms of both equations (1) and (3). This gives us the the appropriate logarithmic equation in following form:

$$\ln(G) = \ln(Z) + a\ln(W) + b\ln(h) + c\ln(L) + d\ln(t) \qquad (4)$$

This generates our power values. Two equations for the first and second through fifth impacts, respectively for both edge and corner drop with the variables having their corresponding power coefficients. Below, we can see that calculating the power coefficient values (highlighted) for each of the variables based on equations 2 and 3 we find that each value lies in the region of ±1/2 (± 0.5) suggesting that the linear model does in fact apply to the behavior of edge and corner impacts also.

Final Edge Drop Equations

$$G^{1} = \mathbf{29.16}\ h^{+.25} L^{+.16} t^{-.44} W^{-.32} \tag{5}$$

$$G^{2\text{-}5} = \mathbf{27.33}\ h^{+.30} L^{+.13} t^{-.56} W^{-.19}$$

Final Corner Drop Equations

$$G^{1} = \mathbf{45.8}\ h^{+.14}\ t^{-.50}\ W^{-.30}$$

$$G^{2\text{-}5} = \mathbf{24.5}\ h^{+.31}\ t^{-.56}\ W^{-.12} \tag{6}$$

The predicitions from the "least squares fit " model were then entered into "Mathematica"® curve fitting software in order to generate an equivalent set of values for the "Z" and the power values for "a" "b" "c" and "d" constants (see above). Using these values, the software will also calculate the corresponding theoretical G values for both edge and corner drop conditions. The above results show that the negative and positive values assigned to each variable followed the prediction stated earlier in this chapter.

In Tables (3-16), we can see that in the "agreement" section of the spreadsheet, there are several comments that precede the percent difference value. Out of four possible comments anything over 16% error is considered "bad". A value of around 10% error (ASTM maximum percent error) is considered "good". Anything below 10% or 5% are considered "very good" or " outstanding", respectively. As already mentioned, the values of the experimental G are also in error by a certain percentage.

The results of the predicted and actual G's for both edge and corner drops are graphed in the form of cushion curves, using Microsoft Excel® software. The properties of each graph for both edge (see Appendix A (Figures 7-10)) and corner drops (see Appendix B (Figures 11-14)), will be similar to the cushion curves used for flat plank cushions in that the 'Y' axes will be the G level. The 'X' axis for edge drop cushion curves will be in the form of L^c / W^b. This was to make the curves analagous to standard cushion curves where static stress is used (weight/area) for flat drops. The fact that the corner area has no defined edge length, makes it impossible to calculate an equivalent static stress. Therefore, the 'X' axis will represent the product "weight", as this is the only remaining factor that G level is dependent upon.

A total of 25 "theoretical" data points were used to construct each cushion curve. Using the "new" equations - G levels were predicted for hypothetical product weights ranging from 2 - 50 pounds. This was applied to each condition of drop height, thickness and cushion length. This method was used due to the insufficient amount of experimental data necessary to construct each curve. The "experimental" datapoints for each condition were then superimposed over the "theoretical" cushion curves. In Tables 17-24 (edge drops) and 25-28 (corner drops), we can see that the percent difference between the predicted "theoretical" and "actual" values were within 2-10% for most conditions.

Table 17. Percent Differences Between Curve Fit and Experimental G Levels - 24" Edge Drop for 2" and 3" Cushion - 9" Edge Length - 1st Impacts

			Curve Fitted			
Drop	Theoretical	Actual	Theoretical	Experimental	%	
Height	Weight	Weight	G	G	Difference	Agreement
(inches)	(lbs)	(lbs)	(Dimensionless)	(Dimensionless)		
Cushion Thickness = 2" Edge Length = 9 inches						
24	20	20.4	25.7	26.09	-1.49	Very good
24	40	40.4	20.57	21.05	-2.28	Very good
Cushion Thickness = 3" Edge Length = 9 inches						
24	20	20.4	21.52	19.22	11.97	Good
24	40	40.4	17.22	17.69	-2.66	Very good

Table 18. Percent Differences Between Curve Fit and Experimental G Levels - 24" Edge Drop for 2" Cushion Comparing 4.5" and 9" Edge Length - 1st Impacts

			Curve Fitted			
Drop	Theoretical	Actual	Theoretical	Experimental	%	
Height	Weight	Weight	G	G	Difference	Agreement
(inches)	(lbs)	(lbs)	(Dimensionless)	(Dimensionless)		
Cushion Thickness = 2" Edge Length = 4.5 inches						
24	20	19.8	23.01	23.65	-2.71	Very good
24	40	39.8	18.41	18.36	0.27	Very good
Cushion Thickness = 2" Edge Length = 9 inches						
24	20	20.4	25.7	26.09	-1.49	Very good
24	40	40.4	20.57	21.05	-2.28	Very good

Table 19. Percent Difference Between Curve Fit and Experimental G Levels 36" Edge Drop for 2" and 3" Cushion - 9" Edge Length 1st Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	% Difference	Agreement
Cushion Thickness = 2" Edge Length = 9 inches						
36	20	20.4	28.43	28.56	-0.46	Very good
36	40	40.4	22.75	21.19	7.36	Good
Cushion Thickness = 3" Edge Length = 9 inches						
36	20	20.4	23.8	24.45	-2.66	Very good
36	40	40.4	19.05	19.64	-3.00	Very good

Table 20. Percent Difference Between Curve Fit and Experimental G Levels 36" Edge Drop for 2" Cushion - Comparing 4.5" and 9" Edge Length - 1st Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	% Difference	Agreement
Cushion Thickness = 2" Edge Length = 4.5 inches						
36	20	19.8	25.45	25.63	-0.70	Very good
36	40	39.8	20.37	19.93	2.21	Very good
Cushion Thickness = 2" Edge Length = 9 inches						
36	20	20.4	28.43	28.56	-0.46	Very good
36	40	40.4	22.75	21.19	7.36	Good

Table 21. Percent Differences Between Curve Fit and Experimental G Levels
24" Edge Drop for 2" and 3" Cushion - 9" Edge Length
2-5 Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2" Edge Length = 9 inches									
24	20	20.4	35.87	38.07	-5.78	Good			
24	20	20.4	35.87	32.15	11.57	Good			
24	20	20.4	35.87	32.51	10.34	Good			
24	20	20.4	35.87	34.03	5.41	Good	34.19	4.91	Very good
24	40	40.4	31.42	29.58	6.22	Good			
24	40	40.4	31.42	32.69	-3.88	Very good			
24	40	40.4	31.42	33.28	-5.59	Good			
24	40	40.4	31.42	33.27	-5.56	Good	32.21	-2.45	Very good
Cushion Thickness = 3" Edge Length = 9 inches									
24	20	20.6	28.53	28.24	1.03	Very good			
24	20	20.6	28.53	35.34	-19.27	Not good			
24	20	20.6	28.53	34.88	-18.21	Not good			
24	20	20.6	28.53	31.25	-8.70	Good	32.43	-12.03	Good
24	40	40.6	24.99	18.48	35.23	Bad			
24	40	40.6	24.99	23.87	4.69	Very good			
24	40	40.6	24.99	24.37	2.54	Very good			
24	40	40.6	24.99	25.06	-0.28	Very good	22.95	8.89	Good

Table 22. Percent Differences Between Curve Fit and Experimental G Levels 24" Edge Drop for 2" Cushion - Comparing 4.5" and 9" Edge Length 2-5 Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G Dimensionless	Experimental G Dimensionless	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2" Edge Length = 4.5 inches									
24	20	19.8	32.74	27.53	18.92	Not good			
24	20	19.8	32.74	29.85	9.68	Good			
24	20	19.8	32.74	32.86	-0.37	Very good			
24	20	19.8	32.74	33.68	-2.79	Very good	30.98	5.68	Good
24	40	39.8	28.68	27.12	5.75	Good			
24	40	39.8	28.68	28.66	0.07	Very good			
24	40	39.8	28.68	31.6	-9.24	Good			
24	40	39.8	28.68	32.33	-11.29	Good	29.93	-4.18	Very good
Cushion Thickness = 2" Edge Length = 9 inches									
24	20	20.4	35.87	38.07	-5.78	Good			
24	20	20.4	35.87	32.15	11.57	Good			
24	20	20.4	35.87	32.51	10.34	Good			
24	20	20.4	35.87	34.03	5.41	Good	34.19	4.91	Very good
24	40	40.4	31.42	29.58	6.22	Good			
24	40	40.4	31.42	32.69	-3.88	Very good			
24	40	40.4	31.42	33.28	-5.59	Good			
24	40	40.4	31.42	33.27	-5.56	Good	32.21	-2.45	Very good

Table 23. Percent Difference Between Curve Fit and Experimental G Levels 36" Edge Drop for 2" and 3" Cushion - 9" Edge Length 2-5 Impacts

			Curve Fitted						
Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Theoretical G Dimensionless	Experimental G Dimensionless	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2" Edge Length = 9 inches									
36	20	20.4	40.48	35.43	14.25	Good			
36	20	20.4	40.48	39.23	3.19	Very good			
36	20	20.4	40.48	41.2	-1.75	Very good			
36	20	20.4	40.48	40.52	-0.10	Very good	39.1	3.53	Very good
36	40	40.4	35.46	34.88	-7.71	Good			
36	40	40.4	35.46	35.61	-9.60	Good			
36	40	40.4	35.46	39.17	-17.82	Not good			
36	40	40.4	35.46	39.09	-17.65	Not good	37.19	-4.65	Very good
Cushion Thickness = 3" Edge Length = 9 inches									
36	20	20.6	32.19	35.05	-8.16	Good			
36	20	20.6	32.19	34.22	-5.93	Good			
36	20	20.6	32.19	30.93	4.07	Very good			
36	20	20.6	32.19	32.5	-0.95	Very good	33.18	-2.98	Very good
36	40	40.6	28.2	23.21	21.50	Bad			
36	40	40.6	28.2	25.84	9.13	Good			
36	40	40.6	28.2	27.54	2.40	Very good			
36	40	40.6	28.2	28.13	0.25	Very good	26.18	7.72	Good

Table 24. Percent Differences Between Curve Fit and Experimental G Levels 36" Edge Drop for 2" Cushion - Comparing 4.5" and 9" Edge Length 2-5 Impacts

			Curve Fitted						
Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Theoretical G (Dimensionless)	Experimental G (Dimensionless)	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2" Edge Length = 4.5 inches									
36	20	19.8	36.94	33.2	11.27	Good			
36	20	19.8	36.94	35.86	3.01	Very good			
36	20	19.8	36.94	38.45	-3.93	Very good			
36	20	19.8	36.94	37	-0.16	Very good	36.13	2.24	Very good
36	40	39.8	32.36	31.05	4.22	Very good			
36	40	39.8	32.36	33.12	-2.29	Very good			
36	40	39.8	32.36	35.24	-8.17	Good			
36	40	39.8	32.36	36.67	-11.75	Good	34.02	-4.88	Very good
Cushion Thickness = 2" Edge Length = 9 inches									
36	20	20.4	40.48	35.43	14.25	Good			
36	20	20.4	40.48	39.23	3.19	Very good			
36	20	20.4	40.48	41.2	-1.75	Very good			
36	20	20.4	40.48	40.52	-0.10	Very good	39.1	3.53	Very good
36	40	40.4	35.46	34.88	1.66	Very good			
36	40	40.4	35.46	35.61	-0.42	Very good			
36	40	40.4	35.46	39.17	-9.47	Good			
36	40	40.4	35.46	39.09	-9.29	Good	37.19	-4.65	Very good

Table 25. Percent Difference Between Curve Fit and Experimental G Levels 24" Corner Drop for 2" and 3" Cushion - No Edge Length 1st Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	% Difference	Agreement
Cushion Thickness = 2"						
24	20	20.4	20.46	19.66	4.07	Very good
24	40	40.4	16.62	17.27	-3.76	Very good
Cushion Thickness = 3"						
24	20	20.4	16.66	17.2	-3.14	Very good
24	40	40.4	13.53	12.84	5.37	Good

Table 26. Percent Difference Between Curve Fit and Experimental G Levels 36" Corner Drop for 2" Cushion only - No Edge Length 1st Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	% Difference	Agreement
Cushion Thickness = 2"						
36	20	20.4	21.65	22.22	-2.57	Very good
36	40	40.4	17.58	16.85	4.33	Very good
Cushion Thickness = 2"						
36	20	20.4	17.63	16.82	4.82	Very good
36	40	40.4	14.32	14.93	-4.09	Very good

Table 27. Percent Difference Between Curve Fit and Experimental G Levels 24" Corner Drop for 2" and 3" Cushion - No Edge Length 2-5 Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2"									
24	20	20.4	30.22	24.67	22.50	Bad			
24	20	20.4	30.22	30.15	0.23	Very good			
24	20	20.4	30.22	28.93	4.46	Very good			
24	20	20.4	30.22	29.58	2.16	Very good	28.33	6.67	Good
24	40	40.4	23.81	25.38	-6.19	Good			
24	40	40.4	23.81	29.45	-19.15	Not good			
24	40	40.4	23.81	31.18	-23.64	Bad			
24	40	40.4	23.81	30.78	-22.64	Bad	29.20	-18.46	Not good
Cushion Thickness = 3"									
24	20	20.6	27.71	22.68	22.18	Bad			
24	20	20.6	27.71	26.48	4.65	Very good			
24	20	20.6	27.71	24.08	15.07	Good			
24	20	20.6	27.71	24.44	13.38	Good	24.42	13.47	Good
24	40	40.6	21.83	19.92	9.59	Good			
24	40	40.6	21.83	20.04	8.93	Good			
24	40	40.6	21.83	22.25	-1.89	Very good			
24	40	40.6	21.83	24.12	-9.49	Good	21.58	1.16	Very good

Table 28. Percent Difference Between Curve Fit and Experimental G Levels 36" Corner Drop for 2" and 3" Cushion - No Edge Length 2-5 Impacts

Drop Height (inches)	Theoretical Weight (lbs)	Actual Weight (lbs)	Curve Fitted Theoretical G (Dimensionless)	Experimental G (Dimensionless)	Individual % Difference	Individual Agreement	Average Experimental G	Average % Difference	Average Agreement
Cushion Thickness = 2"									
36	20	20.4	34.3	31.35	9.41	Good			
36	20	20.4	34.3	35.42	-3.16	Very good			
36	20	20.4	34.3	36.6	-6.28	Good			
36	20	20.4	34.3	36.81	-6.82	Good	35.05	-2.14	Very good
36	40	40.4	31.44	28.14	11.73	Good			
36	40	40.4	31.44	31.24	0.64	Very good			
36	40	40.4	31.44	32	-1.75	Very good			
36	40	40.4	31.44	33.62	-6.48	Good	31.25	0.61	Very good
Cushion Thickness = 3"									
36	20	20.6	27.02	25.97	4.04	Very good			
36	20	20.6	27.02	27.52	-1.82	Very good			
36	20	20.6	27.02	28.51	-5.23	Good			
36	20	20.6	27.02	27.52	-1.82	Very good	27.38	-1.31	Very good
36	40	40.6	24.77	23.39	5.90	Good			
36	40	40.6	24.77	24.3	1.93	Very good			
36	40	40.6	24.77	24.66	0.45	Very good			
36	40	40.6	24.77	23.55	5.18	Good	23.98	3.29	Very good

CHAPTER 4

DISCUSSION / CONCLUSIONS

4.1 Discussion

The results confirmed a very close correlation between the predicted and actual G levels obtained in tests using a 'power law' equation. The model predicted values in the same way that the cushion curves are determined for flat planks in ASTM D-1596, in that the first drop will be predicted and the average of the second through fifth drops. The prediction of the theoretical G was very important in that if any of the results were in error of more than 10% of the actual G value, then the method of prediction was incorrect and a different approach should be taken. Fortunately, most of the theoretical predictions were within ± 2-10% of the actual G value given the parameters of weight and drop height and edge length (the latter applies to edge drops only). It should be noted that the actual values generated (experimentally) through Testpartner® will possibly be subject to error.

Although this theory is based on an ASTM test standard, I am unsure about using this approach as there can (and generally is) alot of deviation between these last four drops. Looking at the results in Table 4, 6, 8, 10, 12, 14 and 16, we can see that there is significant difference between the second and the third through fifth drops. The method of predicting theoretical G values for the second through fifth drops relies on an algorithm that produces a "Z" constant along with the appropriate number of power values. Having such a large deviation in the second drop produces a fixed theoretical G that is not representative of what is actually happening during the last four impacts. A modification of the spreadsheet would allow calculation of the first, second and third through fifth values. This would be a more accuarate and representative model.

4.2 The Affects of Weight and Cushion Thickness

The weight had an extreme influence on the G levels. The lighter weight conditions produced higher G levels. This is because there was not enough weight behind the impact to crush the box easily. This was more prevalent in the edge drop tests due to the resistance of the edge to deformation. In general, this results in a much higher peak stress and corresponding G level. The heavier box conditions, however, where generating lower G levels as the weight behind the cushion and box was sufficient enough to easily crumble the test boxes on impact, producing lower G's.

Comparing edge and corner drop conditions we also have to consider the contact area of each box/cushion system as both have different available compression boundaries. The corner drop, for example, has three radiating edges which provides a greater amount of material available for compression (especially with the 3 inch cushion). This is reflected in the results which show that corner impacts do absorb a greater amount of energy than an edge.

Although the G levels were not significantly different, in general, It was found that the three inch foam, being a softer and more flexible cushion, absorbed more energy than the two inch foam. Given the identical conditions of weight and drop height, the thicker foam undergoes smaller cell compression. As pointed out by Kuang (8), the thicker foam allows more cells to move and absorb the impact energy. The 3" foam accomodates a larger dynamic deflection compared to the 2" cushion under the same conditions because of the larger available compression boundary radius. Looking at equation 5 and 6, we see that the power values for thickness for both edge and corner drops are consistently high and do not change a great over time.

4.3 Edge Drop Results

For all three conditions - the first drop predictions were generally excellent. Out of the sixteen first drop predictions - only two showed 21.5 and 26.94% error. A third value showed 16.55% error, while the remainder showed less than 14% error. The 10% error values are in accordance with ASTM as the maximum acceptable limit for error precision. For the second through fifth data the results were in similar, if not better agreement with the first impacts. Looking at the drops from 24 and 36 inches for the 4.5 and 9 inch edge lengths 29 out of 48 were much less than 10% in error. The remaining 16 drops for the 18-42 inch incremental drops had values that were very inconsistent. The reliability of the theoretical model confirmed that theoretical deceleration levels can be calculated for a varying edge lengths. Two edge lengths of 9" and 4.5" were also compared. The results for the 4.5 inch edge length came out better than expected as all of the first impact values were less than 1% ; thirteen of the sixteen values for the 2-5 impacts were less than ± 8% of the experimental G. The fact that many of the high percent error values lay slightly above the ± 10% range is not a major concern as the actual results are also subject to some degree of error.

The theoretical comparisons for the 4.5 vs 9 inch edge lengths were very good and showed that reducing the edge length produces lower G levels. This would make sense as conventional wisdom suggests that the longer the a longer edge length the more material there is - which makes the cushion alot stiffer. As a result more impact energy can be absorbed - providing a bigger resistance that produces G levels that should be significantly higher too. However, looking at power values for edge length (equations 5 and 6), we should expect to see a power value that is very high (close to 0.5), yet the resultant value is very low. The value still show that as edge length increases-so does G level, but the difference is not really significant. This is because with a longer edge the material deforms non-uniformly. At maximum deformation, the cushion has not deformed as much expected producing a narrower contact area. The result is a trade -off between the stiffness aspects and the non-uniform deformation characteristics associated with longer edge lengths.

Despite the fact that we were getting higher G values for the edge drops compared to corner drop values, the G levels lacked consistency. This could be attributed to the box splitting which would allow the cushion to break free from the confines of the box. If this was the case then the cushion would be <u>allowed</u> to deform naturally. In both cases, the cushioned products center of gravity may have not been centered directly over an edge or a corner of a package assuming a perfect drop situation.

4.4 Corner Drop Results

For the corner tests only the first two conditions were tested. This is because a corner has three radiating edges and no defined dimensions. For both conditions - the first drop predictions were generally excellent and much more accurate than the edge values. Out of the 12 first drop predictions - two showed errors of 2.24% and 2.38%. One value borderlined at 15.77% error, while the remainder showed less than 15% error. Again the 10% error value is based on ASTM standard as the maximum acceptable limit for error (this will be discussed later). For the second through fifth data on average the results were similar in agreement with the second through fifth impacts as the edge drop test. Out of the sixty-four values, only twelve values were in error by more than 15%, nine values were less than 20% error and the remaining 43 values were less than 15% in error.

Lower G's were experienced than those in the edge drop phase. Also, the rate at which the G levels increased over the five drop sequences, was more progressive and consistent. This can be attributed to the fact that the impact area was not affected by susceptable areas (such as a manufacturers joint). In addition to this, although deformation was more contolled, it was also more severe as neither of the three radiating edges (of non-specific dimensions) would dominate during the entire duration of the impact which lead to a general lack of resistance. Also, the impact area involved in a corner drop was much smaller compared to the edge drop - making it an easier target. As the corners of the test boxes began to soften the cushion to dominate impact absorbtion, but less effectively than the corrugated board.

4.5 Comparison of Repeated Impacts vs Incremental Drop Tests

Comparing the theoretical model results with the 5 repeated drop conditions (Tables 9-10 and 15-16), we can see that the drops from 5 increasing heights showed few values that were close to the experimental G. Unlike the edge drops from repeated heights the power values for the corner impacts suggest the behavior in this condition to be representative of a non-linear spring mass system. The first impact values generate the correct power values, which suggest a linear spring mass model system and a s a result predict nicely. However, these numbers represent the box impacting against the ground. Looking at both 2-5 corner and edge impacts, the numbers suggest that the incremented drop heights are causing too much variation in the results. As a result the logarithms calculate power values that are not representative of a linear spring mass system. Like the drops from the repeated height; we see that the experimental values show that as weight increases, G level reduces. This is correct. Unfortunately, the theoretical predictions for the corner 2-5 impacts suggest the opposite.

4.6 Behavior of Shock Pulses During Impact

Looking at Figures (15), (16-20 (Appendix C)) and Figures (21-26 (Appendix D)) we see that, in general, the filtered shock pulses for both edge and corner drops behave in exactly the same way during the third through fifth drop. This indicates that no matter how you drop the box, it will always show a characteristic process of deformation. The first and second drops, however, vary depending on the weight, drop height and thickness. The shape of the pulse is a combination of either a very full half-sine wave or a short duration square wave each having some amount of surrounding noise. At this point the peak G is sometimes not clearly defined. In the case of the 3" cushion thickness -this is more significant as more energy is being absorbed over a longer duration.

Out of the five impacts conducted on each specimen the first and second drops (which are the most important), produced considerably less peak deceleration G values than those obtained on the 4-5th drops by as much as 50% in some cases. The first impact was absorbed by the corrugated board

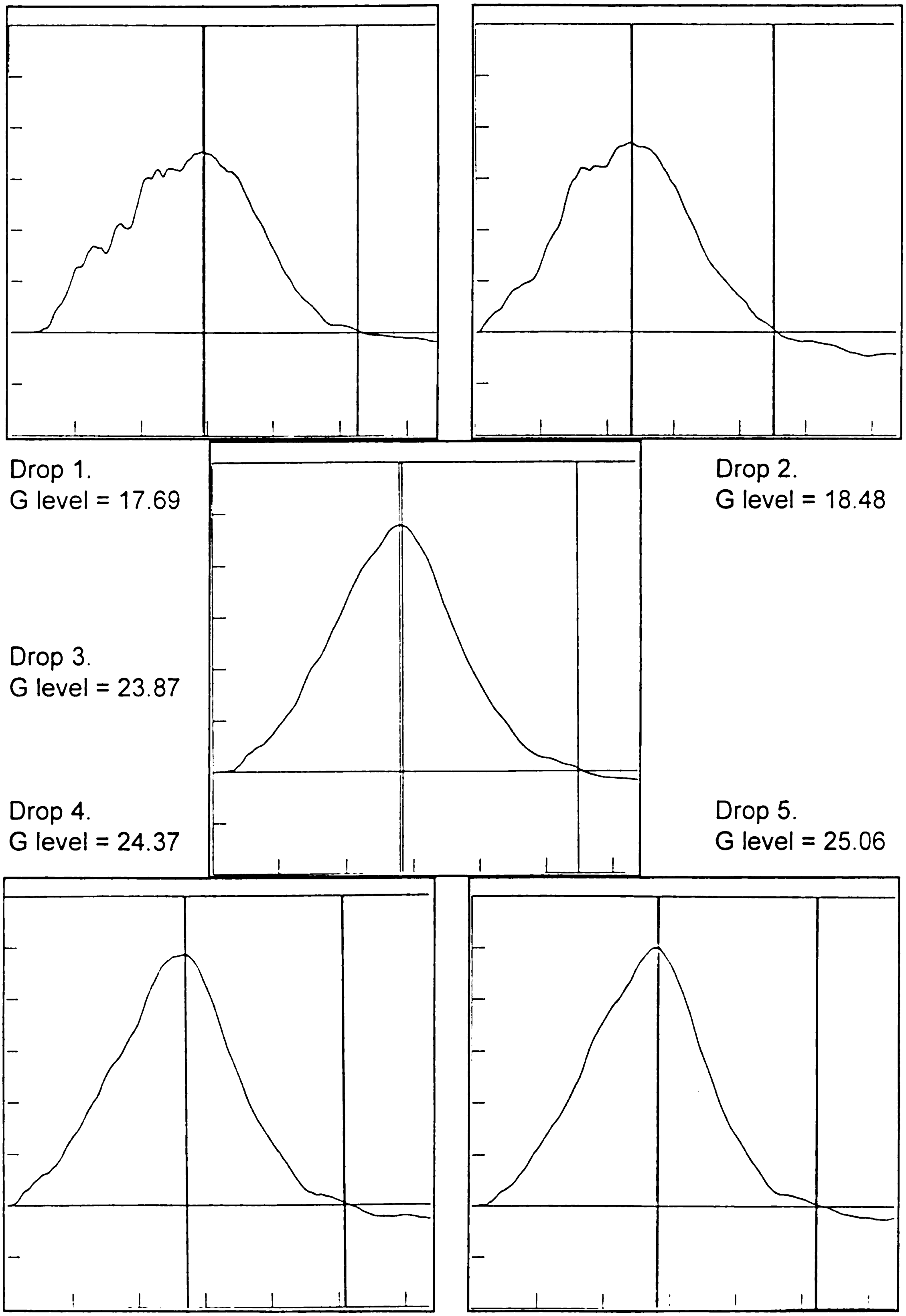


Figure 15. Shock Pulses For 24" Edge Drop Using 3" Cushion - 1st-5th Impacts

while the second through fifth impacts were absorbed mainly by the cushion as the box gradually softened. This showed that the box was, initially, the better absorber of shock than its foam counterpart. The strangest result in all of the tests was that, initially, the G level was low. By the third drop, the G level had peaked. The fourth and fifth drop would show a gradual reduction in G - even though the edges of the test boxes were softening and allowing the cushion to dominate absorbtion; we were experiencing fluctuations in values.

Looking at the first impact we can see that there are many pulses that contribute to this very full sine-wave/short duration square wave. Generally, the first pulse shows the impact of the box against the impacting surface. The second peak is the impact of the exterior plane of the cushion wall against the interior of the corrugated box. This happens naturally inside any box because the manufacturers joint prevents full contact between the cushion and the corrugated board. With the addition because extra folds are produced when gluing the half-box section together, an increased thickness contribution provides extra strength and rigidity. On impact, the box absorbed most of the impact while the cushion repositioned itself inside the box in order to eliminate this air space. As a result, it was found that the outer box edges absorbed the most severe part of the impact before the cushion began to absorb shock.

The shape of the shock pulse is now alot more reminiscent of a sine wave with either a sharp or rounded peak as both the outer box and cushion acting in unison. In some cases the peak G is clearly defined -while in other cases we find the opposite. As the drops progress, the shape of the pulse becomes narrower producing a more perfect half-sine wave with a very defined peak G. This is true whether we are dropping from repeated or incremental drop heights.

By the third drop, the box is now very flexible and is contributing less to the overall performance. As the number of drops are increased so did the G level. Additional to this we see that the edges and corners of the test boxes begin to soften -gradually contributing less and less to absorbing shock. It is at this point that the cushion starts to play a dominant role in absorbing the shocks and contribute to the overall cushioning performance. There was quite a steep increase in the G level. There was also a very large increase in G level as this transition progressed. You could also hear the differences in the impacts as the tests progress. The first drop on a solid edge produces a loud "thud" sound, whereas the third and fourth drops produce a softer sound more indicative of a soft cushion impact.

A dramatic transition in terms of the shock pulse shape demonstrated a shift from an initial square wave to a more concave half sine wave. If we look at Figure (15), we can see that the shape of the shock pulse for the last two drops indicates that the cushion is going through what is known as material "hardening". This is a result of repeated impacts which cause the material to compress until it starts to act more like a solid block. This makes sense if we pay more attention to the coeeficient values. If the coefficient value for any of the variables is less than ± 0.5, then the cushion undergoes material "softening", therefore, the spring/mass system (cushion) is deforming non-linearly. The shape of the shock pulse, resulting from this condition is also similar to that of a square wave. If the coefficient value is very close to ± 0.5, then the cushion is deforming exactly like a linear spring/mass model. On the other extreme, if any of the variable values are greater than ±0.5 (like that of the "thickness" variable for both edge and corner drops), then the cushion will undergo material "hardening" and we will see the shape of the shock pulse looking like a concave sine wave. This also produces a cushion that is deforming non-linearly.

It is not clear as to what degree the corrugated board influenced the behavior of both edge and corner drop conditions, however, from my observations of the experimental drops it was clearly a significant contribution. This behaviour further reinforces my opinion that the ASTM procedure for developing flat drop cushion curves is incorrect test method not only because it does not represent the 'real' distribution environment in terms of the oncorrect of impact, but it also does not take into account the effect of the corrugated board box.

4.7 Conclusions

Looking at the results in Tables (3-16), we see that out of the five tests conducted on each boxes, the first drop and second drops (the most crucial) produced considerably less peak deceleration G values compared to the third through fifth drop for that particular box under those certain test conditions. When comparing the actual G values we also notice that the corrugated board was a more effective material for absorbing the initial shock compared to the foam cushion. This is mainly because lower G values experienced during those crucial and most damaging first and second impacts (compared to the higher 3-5th values absorbed by the cushion). This is assuming that the box is subjected to a limited number of drops. The efficiency of the board will depend on the moisture content. However, this was not part of the experiment but it is expected that this will play a large role in predicting G values using this theoretical model.

Because of the large abundance and availability of corrugated board it is also very competitive with low density foams. It is also justifiable to say that more consideration should be given to its performance when designing transport packaging. It is usual for any packaging designer to place more emphasis on selection of the right type and thickness of foam rather than consider the contribution of the corrugated board. If more attention were given to corrugated material in package development along with the theoretical model defined in theis thesis - it is possible that cushioning can be reduced considerably along with material costs, without loss of protection.

4.8 Experimental Errors

4.8.1 Test Method

The experiment and the model predict values in accordance with ASTM D-1596 - in that the first drop and also the average of the second through fifth drops will be predicted for each condition. Because this is a standard test and I have experienced these fluctuations in G values - I am unsure about using this approach as there can be (and generally is) alot of deviation between these last four drops. Therefore, an average value should not be considered a value that is representative of what is actually going on during the last four impacts. Despite this fact, it is important that the results of these experiments have some application. Applications can be found for use in the testing laboratory and in the design of prototype packages. To correct this problem, I have adapted the original theoretical model to account for these large deviations. The model calculates three phases of a drop individually. This is because there are large deviations between the first, second and third to fifth impacts (see Tables 4, 6, 8, 10, 12, 14 and 16). Therefore, the new model can account for these differences by calculating and comparing the percent differences between all three phases.

The result is that the first value uses equation (4) divided by a percent error constant. The second drop is calculated using the standard equation (4), while the third through fifth drops use equation four multiplied by another percent error constant. The results are far more consistent.

4.8.2 Machine Error

Dropping the jig, cushion and box showed that for the first drop, very low G's were reported using the Test Partner software. The trigger level was 20 G's and anything below this the software could not detect. Using the oscilloscope was difficult because the reading of the shock pulses was not accurate enough (on a personal note), also, it was not possible to print out shock pulses. A more sensitive version of Test Partner was used (courtesy of Lansmont Corporation), which introduced its own set of problems. Although the machine was more sensitive to lower G levels, the difference in platen apparatus made it difficult to clamp the jig fixture as securely as that on the previous platen. This may have been the reason for the certain high frequency noise superimposed onto my shock pulses. It is one of the errors of the experiments that the Testpartner hardware inside both machines may have varying automatic filter frequencies.

A simple explanation of this is that once an impact transmits a voltage output through the amplifier converting it into a shock pulse; the Testpartner hardware puts this through an automatic filtering process to eliminate extraneous noise, before it is directed to the software for further manual filtering. It is at the point were the pulse reaches the software were the differences in the pulses are obviously different. From the differences in shock pulses, it would seem that the first Test Partner had a lower automatic frequency than the latter. This means that the lower the filtering frequency, the more noise is removed and the cleaner the shock pulse.

4.8.3 Foam Fabrication

The foam material was manually constructed around both jigs for the edge and corner test setup. Both involved sculptured fabrication and may have possibly recieved some damage in this process. This may have also introduced errors into the system.

4.8.4 Corrugated Board Fluting

There were many other possible errors involved in testing that may have affected the results. A major cause of variability would be the corrugated board itself. The box samples were made using 'C'-flute corrugated board sheets - many of which may have suffered from slight flute crushing or some other type of damaged. It is not known whether the fluting has been damaged internally in anyway, despite close inspection. The fluting will be positioned so that they will be vertically oriented like that of an actual box. This will play a vital role in the amount of contribution the cushion plays in an impact situation. If the fluting is in the vertical direction, then we could see a lot more contribution from the box because of the much stiffer nature of the board (still assuming that there is also air space between the box and cushion surface) rather than the cushion. This would assume that if the fluting was switched to horizontal, we would possibly see the cushion absorb more of the impact as a result of a greater amount of collapse from the corrugated medium because the material collapses easier in this direction.

During both the edge and corner drop studies it was found that the flute direction did play a vital role in absorbing the impact. The fluting in a regular box is always used in the vertical direction, then we saw a lot more contribution from the box (still assuming that there is also air space between the box and cushion surface) rather than the cushion. In the test positon for the corner drop, the fluting direction was switched to the horizontal plane.

On impact, the cushion absorbed more of energy as a result of easier and a greater amount of collapse from the corrugated medium. This was further complicated by the influence of temperature, relative humidity and resulting moisture content. These factors were never calculated during the experiment, however, on impact, it was obvious that certain boxes deformed and sounded differently in comparison to other test boxes. It is not known when the cushion begins to absorb the impact, but we can speculate that it would happen once the box has begun to crush and deform. Despite these factors, all box edges performed really well and stayed intact - during both conditions of repeated and increasing drop heights.

4.8.5 Corrugated Board: Box Assembly

The construction of the boxes was important because it was a represent one edge and one corner of a box and had to be as realistic a box construction as possible (given the confines of the 9"x 9" available space underneath the platen). It was obvious that the corrugated board did dominate the initial impact absorbtion more effectively than the cushion. However, the way in which the jig was constructed could have possibly influenced the behavior of the box slightly, in corner impacts especially as we will have extra-toughened corners. The half - split nature of the box meant that extra glue points were needed to keep it together. This provided extra reinforcement as gluing the corners and edges was necessary in order to keep it together.

Another source of error could have been the inconsistency in the amount of glue used. These factors could possibly influence the stiffness behaviour of the box slightly, but not a great deal. A contribution from a more stronger than usual edge or corner support in box form will have an extreme affect on the results (especially at the manufacturers joint). Their are differences in each situation as the G values for dropping on cushions only are slightly less than versus cushion in a box, because the cushion is allowed to compress/collapse in free form whereas with a cushion in a box, the cushion is restrained by the grip of the box walls and as a result tends to act a lot stiffer than if freestanding, therefore producing higher G values.

The most severe damage caused throughout the testing was from drops conducted on the edge. A more controlled resistance to deformation resulted but at the sake of 'bulging' the remaining areas of the test box. This was due to the two susceptable manufacturers joints some of which began to split as the drops increased. The nature of the test warranted a box design that needed two joints, which under certain extreme conditions would cause this to happen. However, this was generally a bigger problem for the incremented drop sequence. The differences in deforming naturally compared to simultaneous deformation may have also caused fluctuations in the response of the cushion. This only happened on certain boxes - so some type of cushion relaxation may also have been involved.

Although this sequence of tests were not the main thrust of the research, this type of damage was exhibited during the repeated drop sequences. In both cases, if the package and product's center of gravity was corrected maybe this 'splitting' could have been avoided.

4.8.6 Jig-Design

Affixing the box to the jig was difficult as we did not want the box to slip off the jig and yet we needed the snugness associated with a cushion tightly fitted inside a box. It was necessary to screw the box onto the jig in order to create the impression of a tight fit inside a closed box.

It was not known how both box types would deform. It is expected that when comparing both box/cushion systems, the edge length provides considerably more durability during both drop sequences. This seems obvious because the corner configuration has three radiating edges of non-specific dimensions (when talking about impact geometry) exposed to an impact and no one edge would dominate during an impact. The amount of deformation is not easy to predict in both situations, but it is clear that the corner will be more susceptable to more severe deformation.

There were many drawbacks associated with the method of attaching the cushion and box to the jig and maintaining a 'tight' connection. This was difficult as we did not want the box to slip off the jig and yet we needed the snugness associated with a cushion tightly fitted inside a box. It was also important not to fix the components together with a substrate that would act as a spring/mass system, i.e. velcro, tape, and adhesive pads, etc. The most reasonable choice was to screw the box onto the jig in order to create the impression of a 'tight' fit inside a closed box.

On impact, the box would tend to push itself up the side of the jig despite being screwed into position which caused the box to split. This could have slightly influenced G level as the jig, cushion and box are supposed to act as one body during freefall and impact rather than independent systems. but considering that the system was not completely in position under the platen like that of perfect flat drops - this was the most sensible method. It is possible that the screw fixture could have destoyed the box at the point were it made contact with the jig. This would possibly allow the cushion to loosen on its travel to the top of the platen before the next drop test.

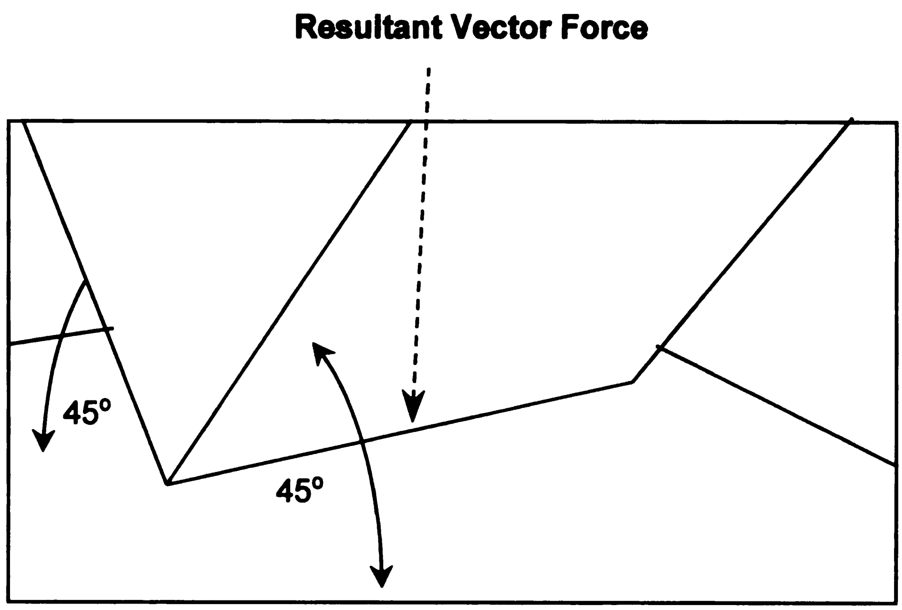
4.8.7 Perfect vs Non-Perfect Drops

There are many possible errors involved in testing both corrugated board and foam together under edge and corner drop conditions. The main area of concern is the unpredictability of the box material as this influences the behavior of peak deceleration by deadening the effect of the impact. In a distribution environment, this affect may be lost through rotation of the box. The fact that the cushion tester was recreating a 'perfect' drop situation, prevented the realistic compression of the edge or the corner through rotation of the package. Therefore, the energy will not be dissipated between the edge or the corner as well causing the G to be slightly higher in the test lab than compared to values obtained in a non-perfect edge or corner drop situation. We can therefore assume that producing an average value for G over several impacts would not be a true reflection of what is actually happening.

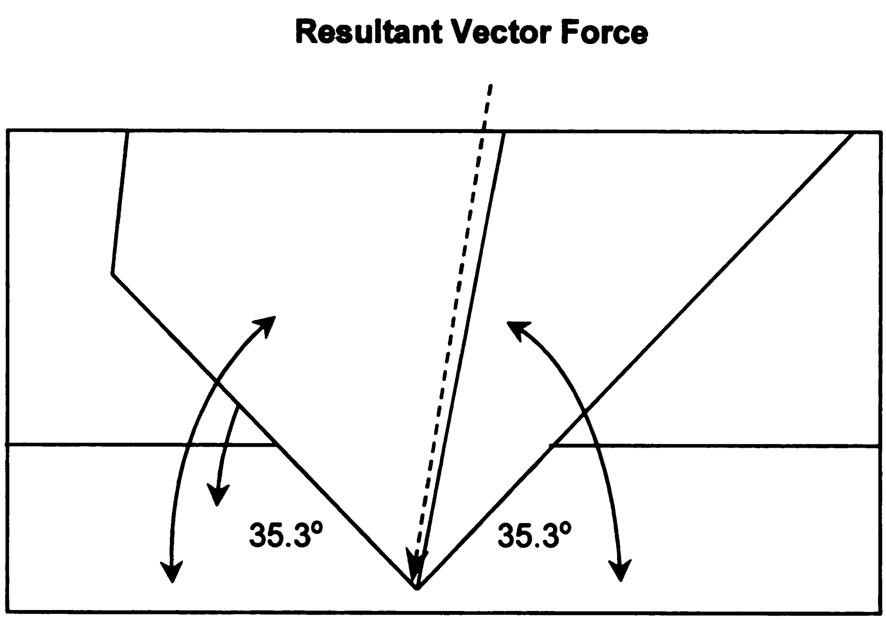
With both drop conditions the impact angles may not have been exact. In Figure (27), we see that in the case of the edge drops - any deviation from two of the 45 degree angles would have produced a non-perfect edge drop. In the corner drop situation - if one of the three angles were greater or less than 35.3 degrees, then this experiment would also be non-perfect. As a result both conditions would not give representative G levels. In the case of an edge impact, if the box is tilted down slightly, then the initial reported shock would be absorbed by one of the end points of the edge length before the other. We now know that the coefficient values in equations (5) and (6), suggest deformation that is non-linear. This probably resulted in a lower than expected G value , however, this is not conclusive. The influence of drop angle will be critical to the corresponding G level. However, the influence of weight shift/repositioning and its influence on box shifting was not a major factor in this theoretical model because it could not be entirely controlled. The major problem was that unlike perfect flat drops, the jig was not compressing the entire surface of the material. This meant that the box/cushion system would reposition itself slightly each time due to the initial change in direction of shifting.

4.8.8 Filtering

Filtering refers to the elimination of certain false information from a shock pulse. It is difficult to know how much should you filter before you lose vital information about the original underlying pulse. The lower the filter frequency, the less ripples in the shock pulse and the smoother it becomes, however, this can be a drawback as you could begin to lose the important characteristics of the shock pulse that identify the calculated values of peak G, drop height, coefficient of restitution, average G, RMS G, and faired G's.



Perfect edge drop with 2 angles at 45° to each other



Perfect corner drop with 3 angles at 35.3° to each other

Figure 27. Perfect Edge and Corner Drop Conditions

It is possible that a shock pulse can contain a large amount of noise superimposed on a smooth underlying pulse. This phenomena is known as "ringing" which refers to outside vibrational noise created from either the test equipment, the test speciman or from less conspicuous sources such as loose cable connections between the accelerometer and the coupler, electromagnetic interference or triboelectric charging. All of which can be working alongside the original shock pulse and superimpose themselves to produce false peaks and sometimes an unreconizable shock pulse. This leads to incorrect values being given in terms of peak G(affected most), duration and velocity change least (in that order).

The question several times during the filtering process was how much should I filter without losing vital information about the original pulse. Many say that you should use the very minimum frequency equal to that of the original unfiltered shock pulse, while others suggest an optimum filter frequency equal to three or five times that value. There was no correct method except for trial and error experimentation, however, consistency was required throughout the whole experiment. I decided to use the accepted industry standard of five times the original unfiltered shock pulse, as this was the most effective during trial runs.

Early on in the experiment the shock pulses produced through Test Partner contained a large proportion of "ringing" which could have come from either the test equipment, the test speciman or other sourecs mentioned in chapter 2 - Alot of false peaks were apparent early on. At one point it was necessary to change cushion testers because the machine at the school of packaging was not sensitive enough to pick up G levels lower than 20 G's. The oscilloscope was used to determine peak G levels, however, the machine was fairly primitive and tended to give results that were not as precise.

A second tester was used to finish the experiments because of this innaccuracy - courtesy of the Lansmont Corporation tesing laboratories. This machine was more sensitive in terms of picking up lower G levels, however a different in setup in the platen construction would not allow as much of a secure clamping of the jig as necessary, compared to the previous machine. This created a small space between the platen base and the top of the wooden jig. Unfortunately some of the shock pulses were quite noisy. On realizing this, I bridged the space with a small piece of LDPE foam in a hope that this would soften the impact. Despite this, alot of ringing was appearing on the shock pulses probably because of the jig impacting the platen. Although this may have been the case, this did not interfere with identifying the true peak G of the shock pulse. Seeking advice from certain parties experienced in this area considered that the noise on the shock pulses did not hinder the analysis of the impact performance.

In general, filtering these types of shock pulses were not as easy. When looking at a shock pulse it was evident that the second peak was more useful as that was the point at which the cushion impacted the interior surface of the box and was at this point a combination of both box and cushion acting as the shock absorbers. On most of the pulses the filtering and analysis of G level, velocity change, duration, drop height and coefficient of restitution was calculated using the latter of the two peaks fifth drop would result in the shock pulse acting more like a traditional half sign pulse.

It is possible that errors in predicting the filtering frequency may have also contributed to errors in filtering and determination of the true peak G. ASTM 3332-93 (10) specifies the duration to be the time width that corresponds to 10% of the peak acceleration. As a result, it was necessary to visually inspect each shock pulse to determine actual duration rather than to rely on Testpartner. This could also have resulted in incorrect filtering frequencies and peak G levels.

4.9 Recommendations and Future Work

Another area of investigation would be to determine a theoretical model for predicting G levels for a tumbling package. This will be useful information when you consider that in the real distribution environment we never see a perfect flat, edge or corner drop. What we actually see is a combination of all impact types. The results of this research suggest a way to predict with a good degree of certainty the type of G levels found in perfect drop situations. With this method of prediction in mind it would be beneficial if we could calculate predictions for any non- perfect drop situation.

This test method could be achieved by using the Environmental Data Recorder (EDR) and placing it inside a weighted box, and subjecting it to random non-perfect drop situations. This way it would be possible to obtain the triaxial shock pulses from the EDR memory and find a way of calcualting a predicting overall G contribution from each of the three given shock pulses. It would be feasible to estimate that you would get much lower G values than those obtained in perfect drop situations. This is mainly because a lot of the shock is lost in the rotation and tumbling of the box and not through the packaging material.

Using the same test conditions, but, varying the moisture content we can study the amount of contribution the box now has compared to the foam. We should see that the board has less impact on G level and the foam playing a more important role in absorbing impact forces. I found that this will be important in particularly for more severe environments.

APPENDICES

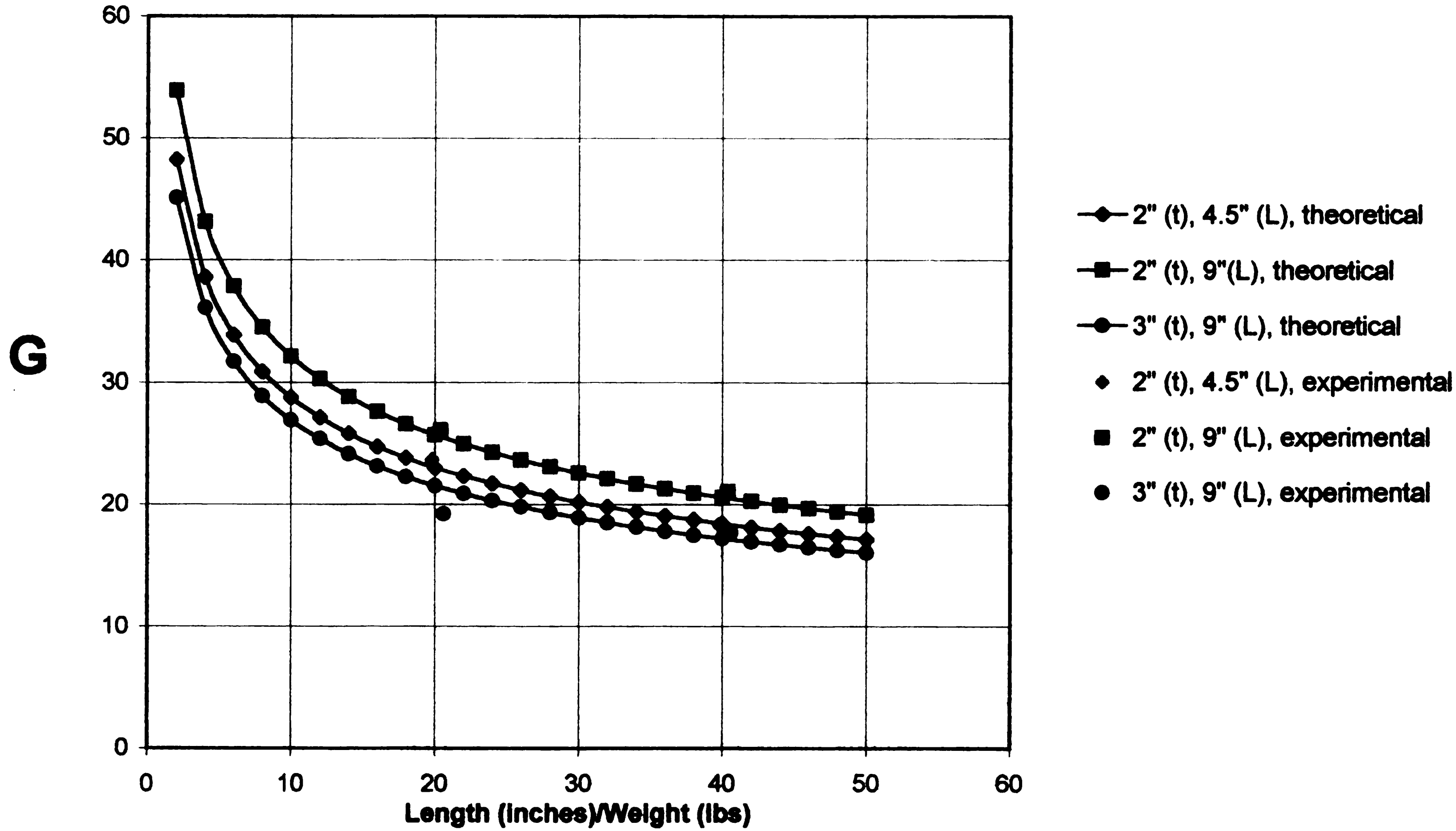
APPENDIX (A)

FIGURES (7-10)

EDGE DROP SHOCK PULSES
1- 5 IMPACTS

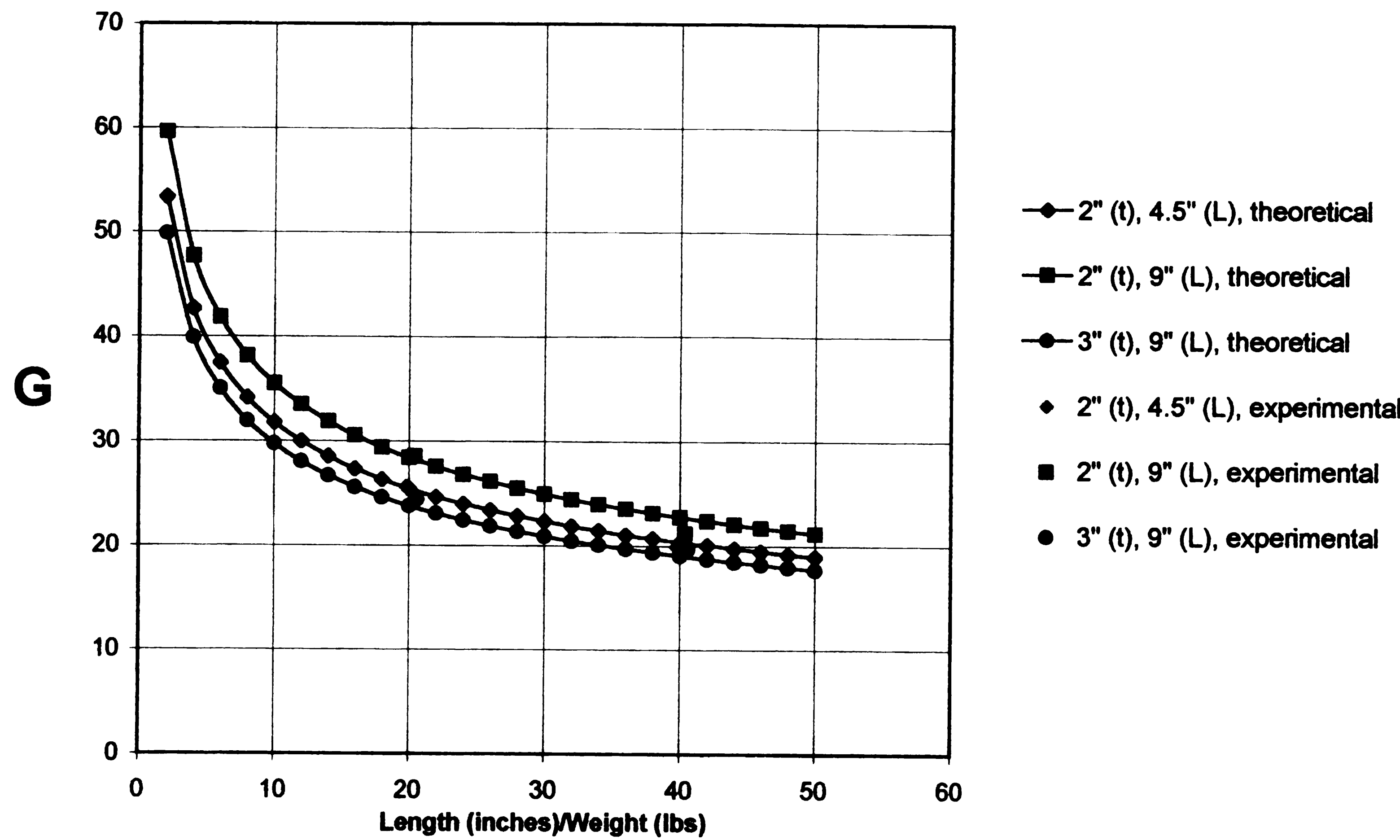
Appendix A

Figure 7. 24" Edge Drop onto 2" and 3" Cushion -1st Impact



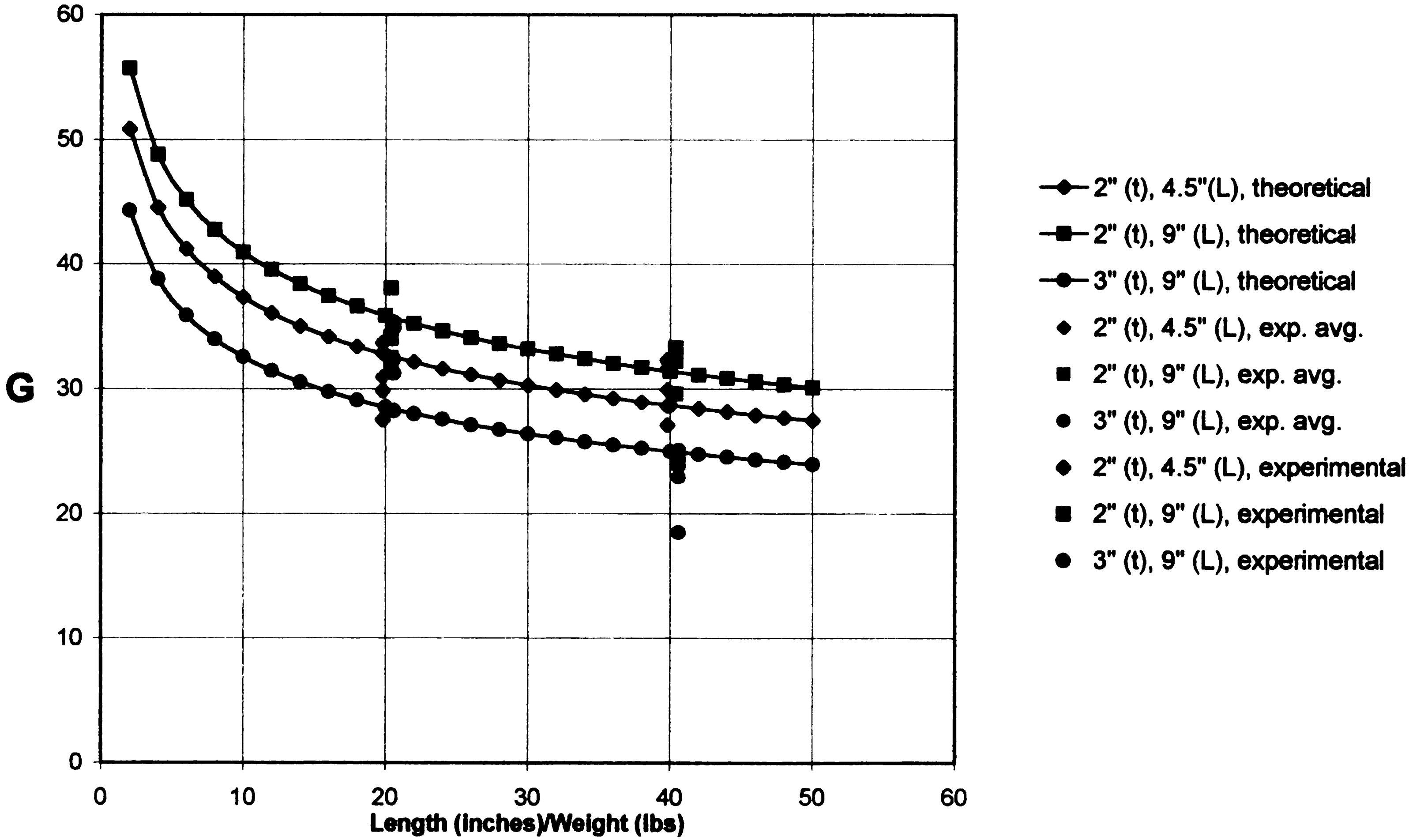
Appendix A

Figure 8. 36" Edge Drop onto 2" and 3" Cushion - 1st Impacts



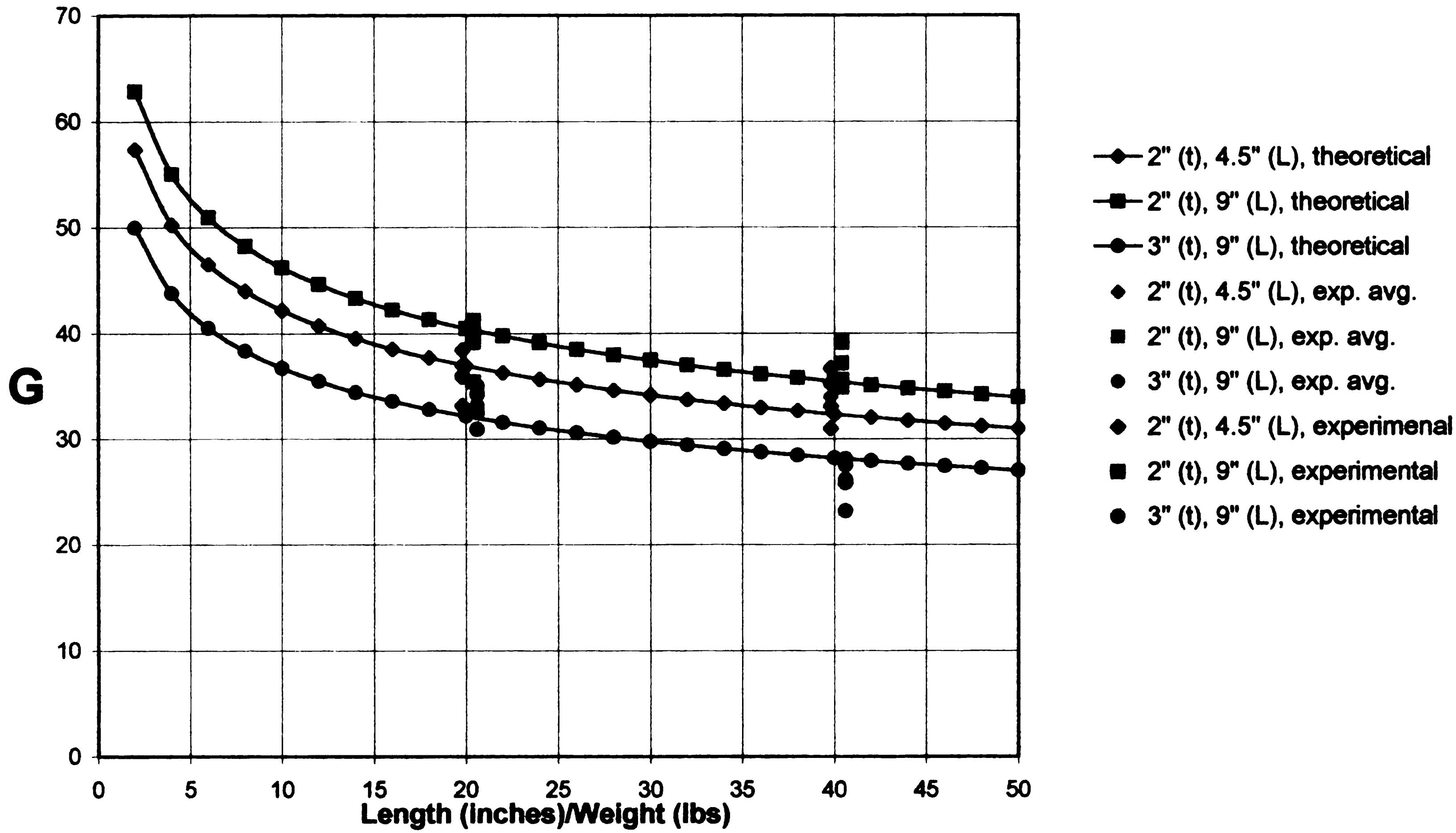
Appendix A

Figure 9. 24" Edge Drop onto 2" and 3" Cushion - 2-5 Impacts



Appendix A

Figure 10. 36" Edge Drop onto 2" and 3" Cushion - 2-5 Impacts



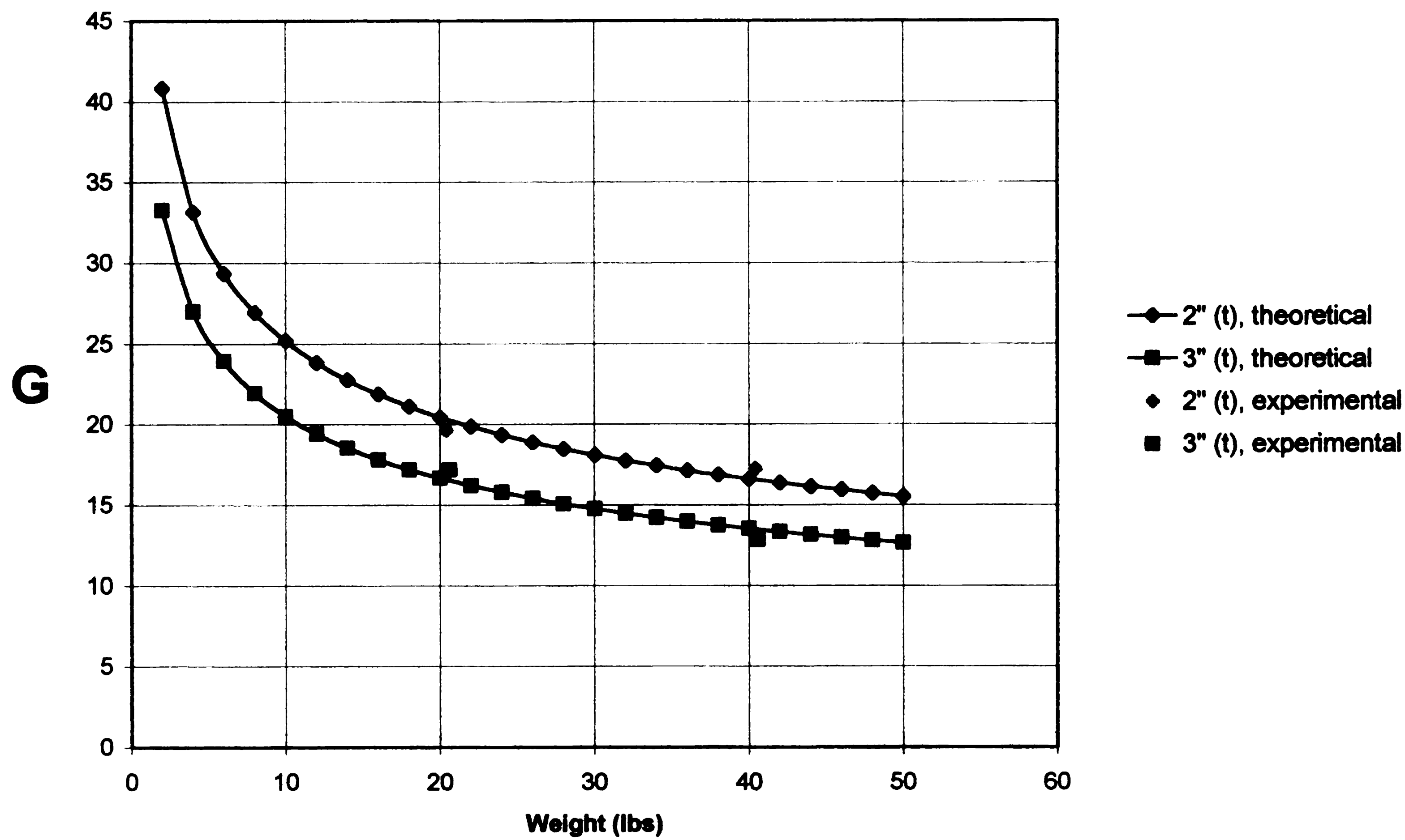
APPENDIX (B)

FIGURES (11-14)

CORNER DROP SHOCK PULSES
1- 5 IMPACTS

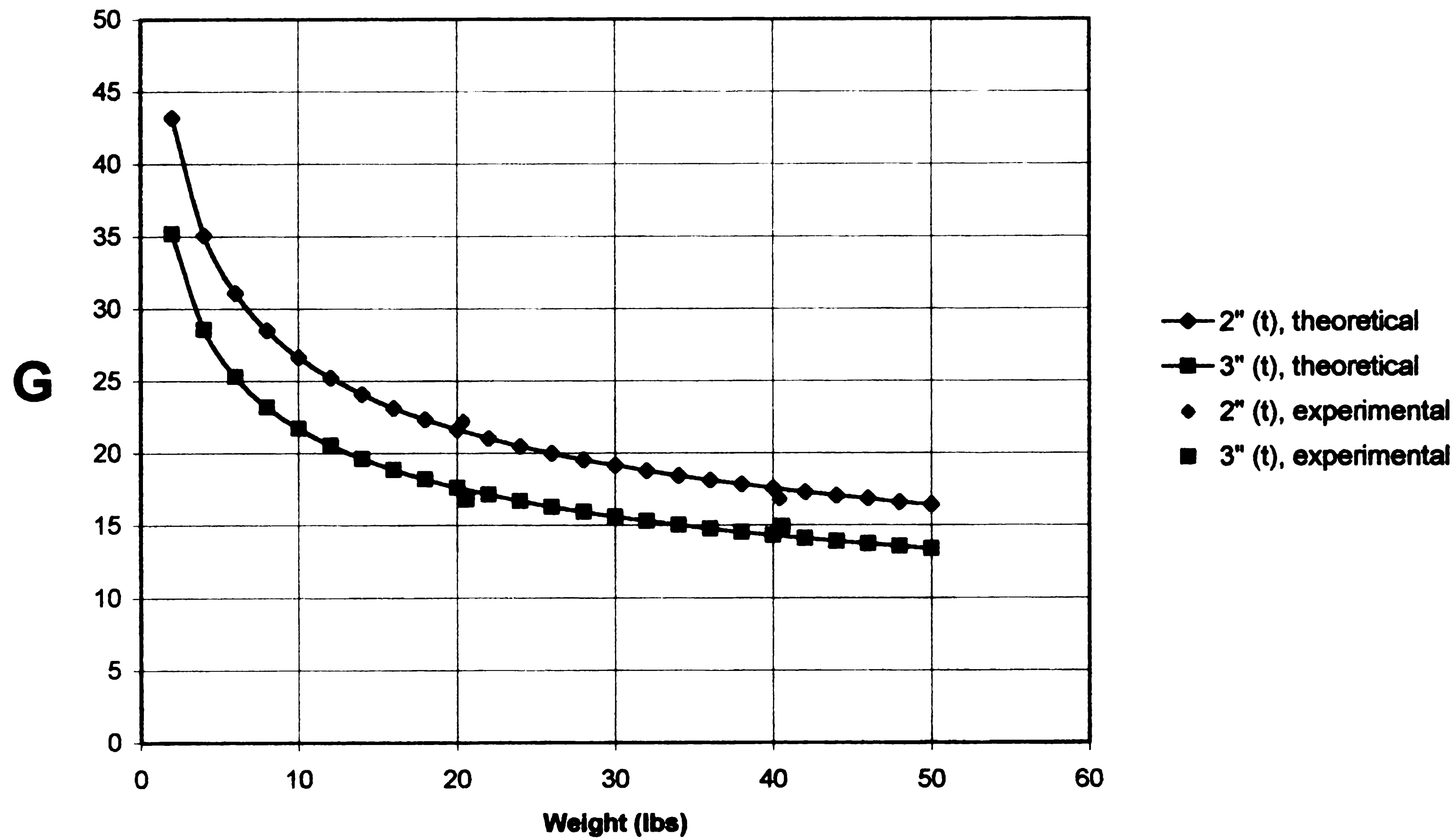
Appendix B

Figure 11. 24" Corner Drop onto 2" and 3" Cushion - 1st Impact



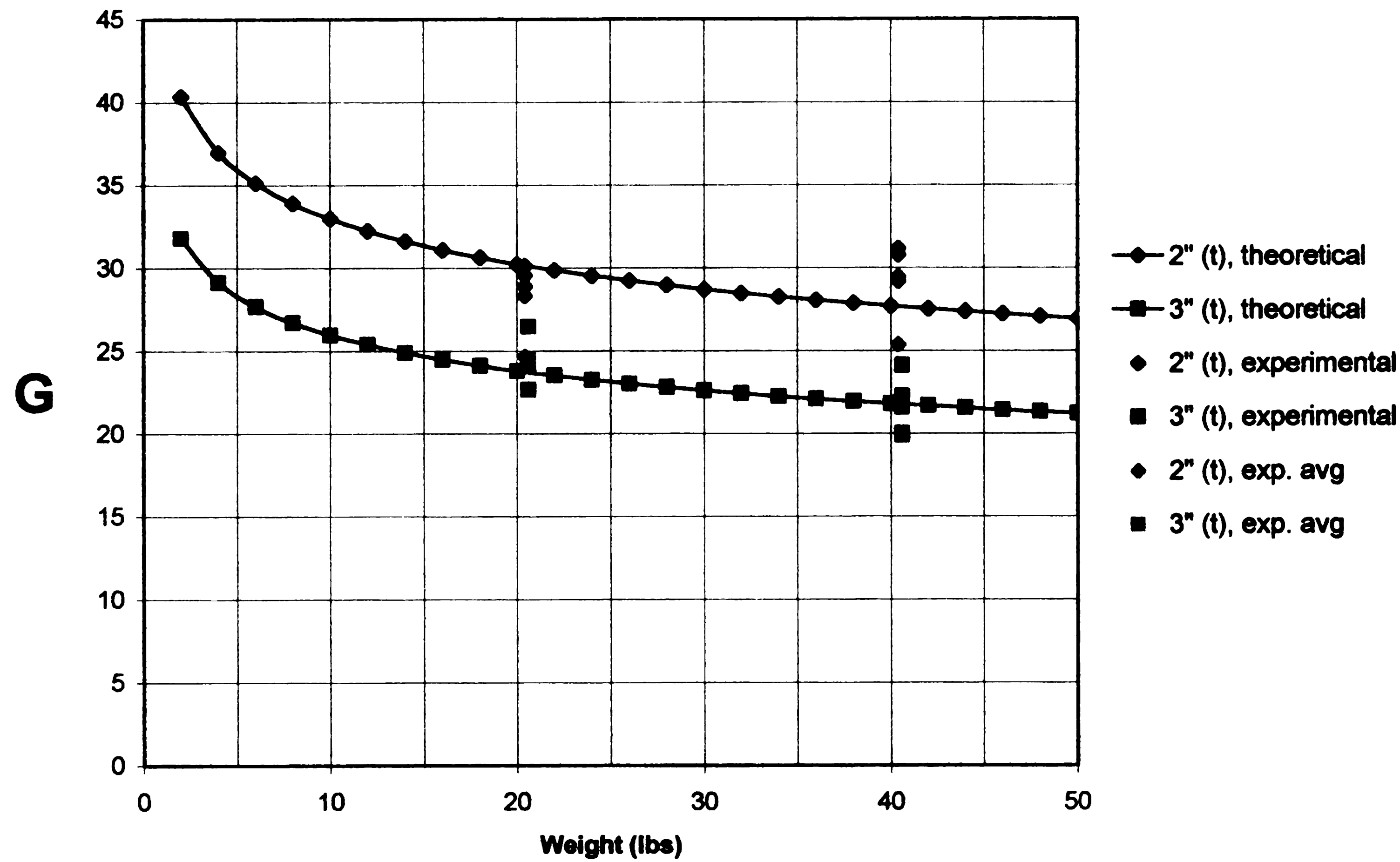
Appendix B

Figure 12. 36" Corner Drop onto 2" and 3" Cushion - 1st Impact



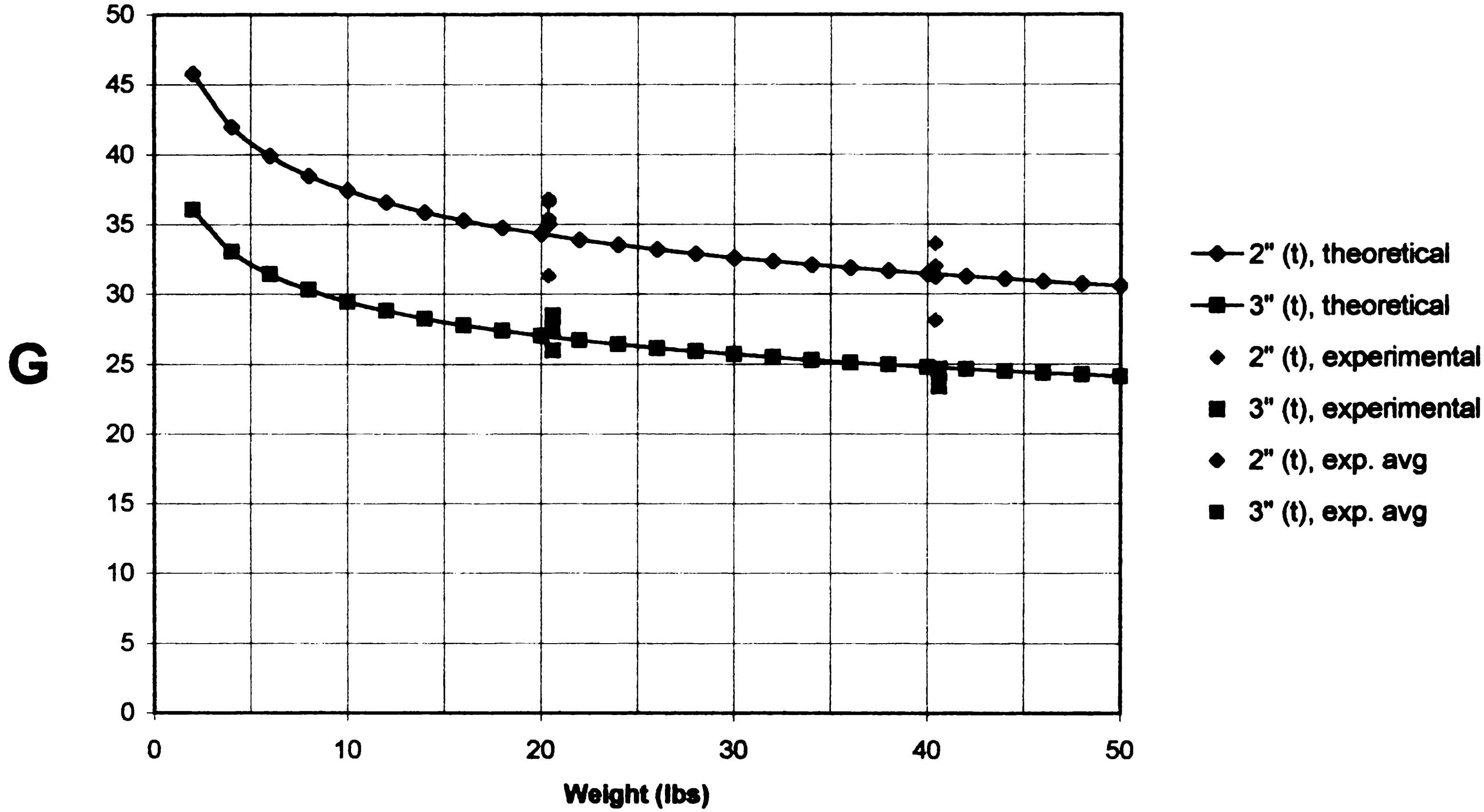
Appendix B

Figure 13. 24" Corner Drop onto 2" and 3" Cushion - 2-5 Impacts



Appendix B

Figure 14. 36" Drop onto 2" and 3" Cushion - 2-5 Impacts



APPENDIX (C)

FIGURES (16-20)

EDGE DROP SHOCK PULSES
1-5 IMPACTS

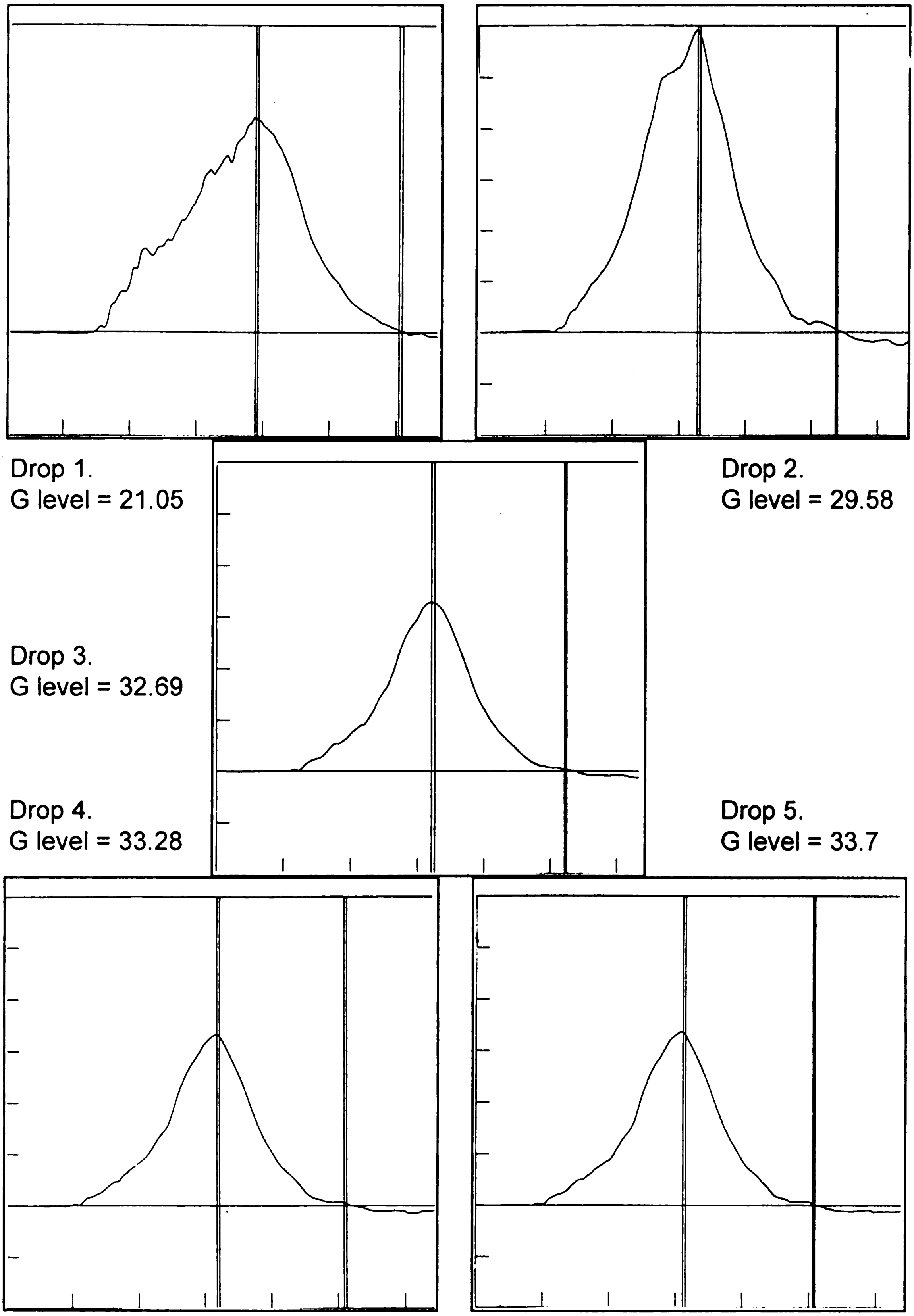
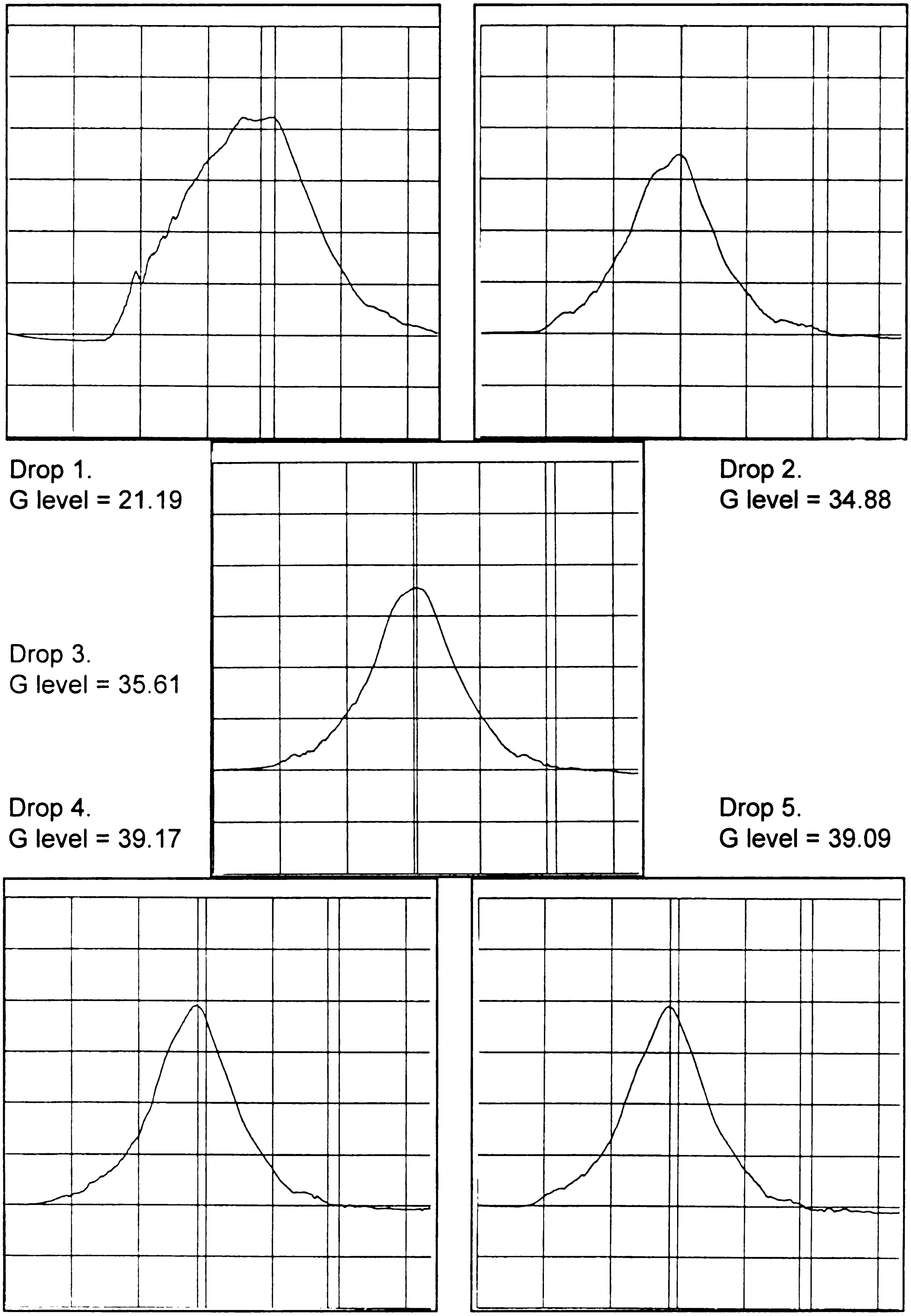


Figure 16. Shock Pulses For 24" Edge Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (C)

FIGURES (16-20)

EDGE DROP SHOCK PULSES
1-5 IMPACTS



Drop 1.
G level = 21.19

Drop 2.
G level = 34.88

Drop 3.
G level = 35.61

Drop 4.
G level = 39.17

Drop 5.
G level = 39.09

Figure 17. Shock Pulses For 36" Edge Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (C)

FIGURES (16-20)

EDGE DROP SHOCK PULSES
1-5 IMPACTS

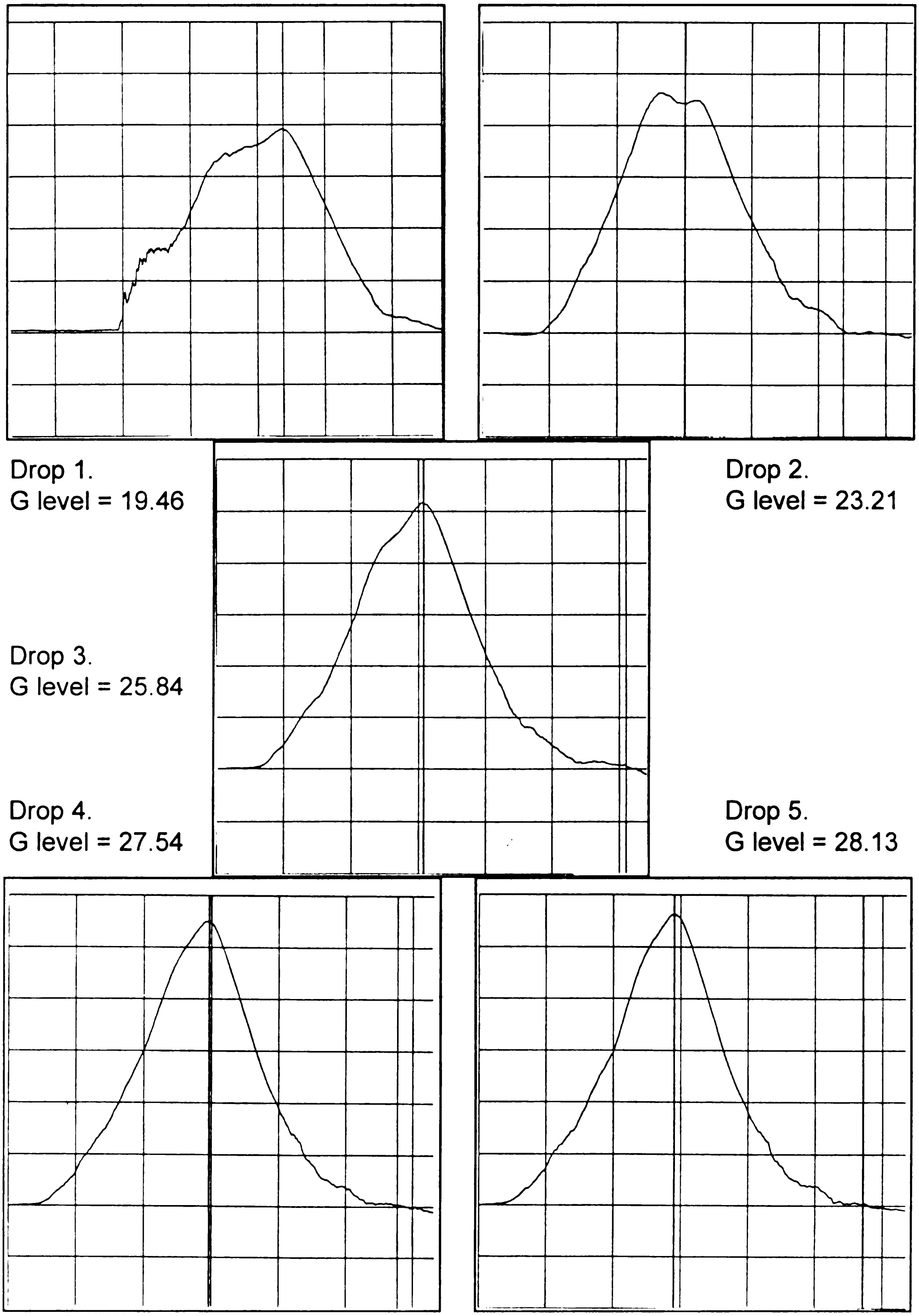


Figure 18. Shock Pulses For 36" Edge Drop Using 3" Cushion - 1st-5th Impacts

APPENDIX (C)

FIGURES (16-20)

EDGE DROP SHOCK PULSES
1-5 IMPACTS

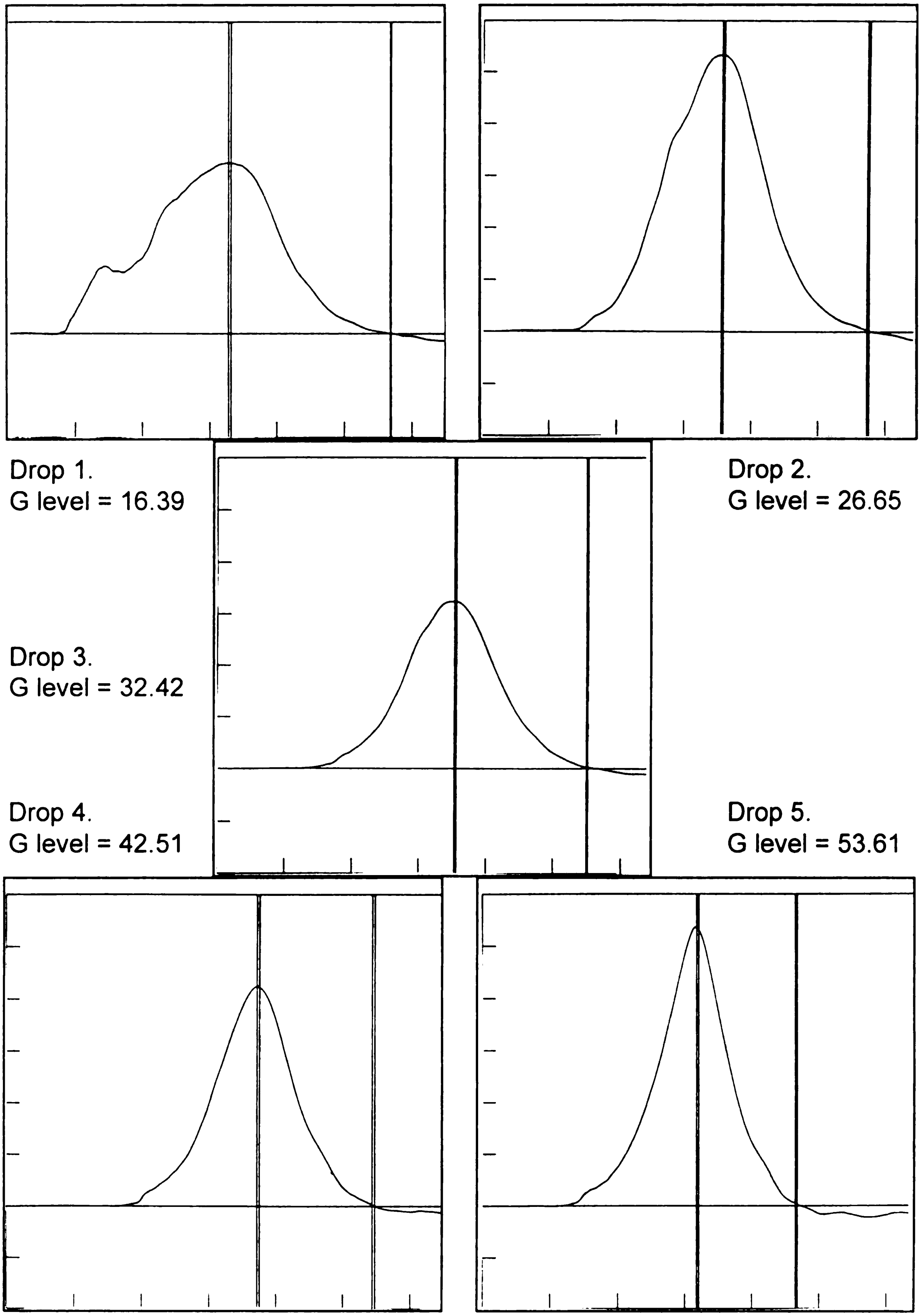


Figure 19. 18, 24, 30, 36, and 42" Edge Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (C)

FIGURES (16-20)

EDGE DROP SHOCK PULSES
1-5 IMPACTS

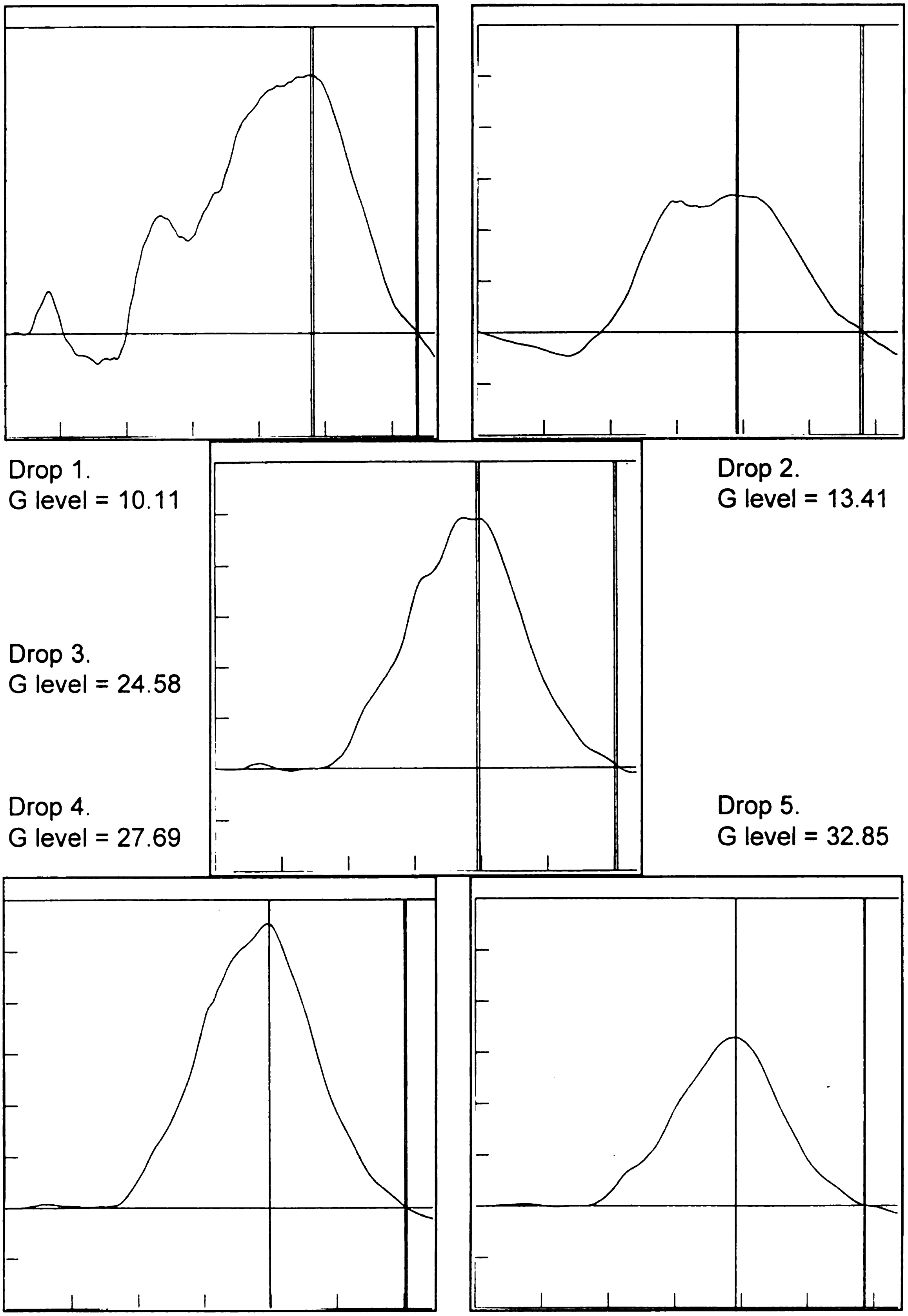


Figure 20. 18, 24, 30, 36, and 42" Edge Drop Using 3" Cushion - 1st-5th Impacts

APPENDIX (D)

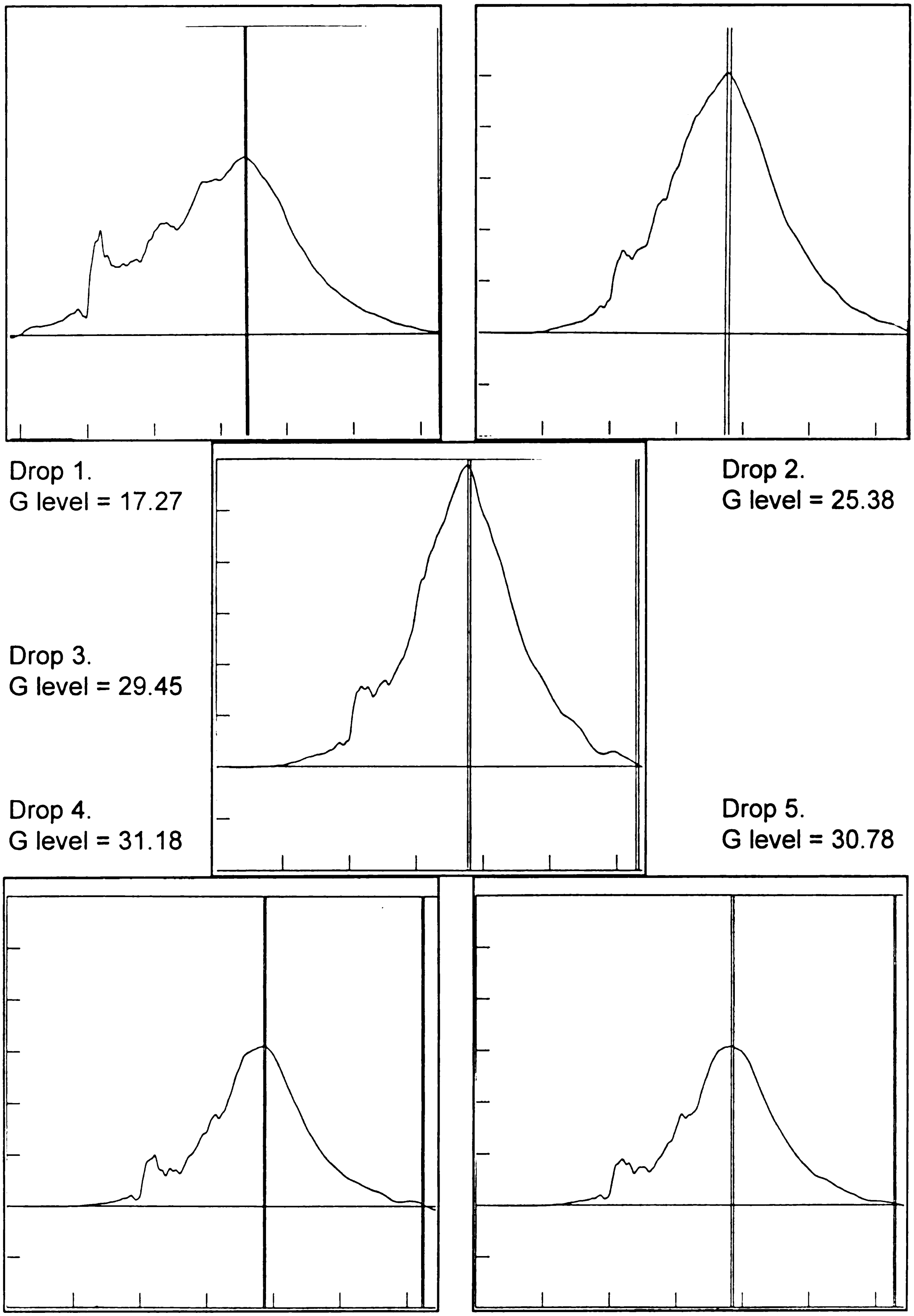


Figure 21. Shock Pulses For 24" Corner Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (D)

FIGURES (21-26)

CORNER DROP SHOCK PULSES
1-5 IMPACTS

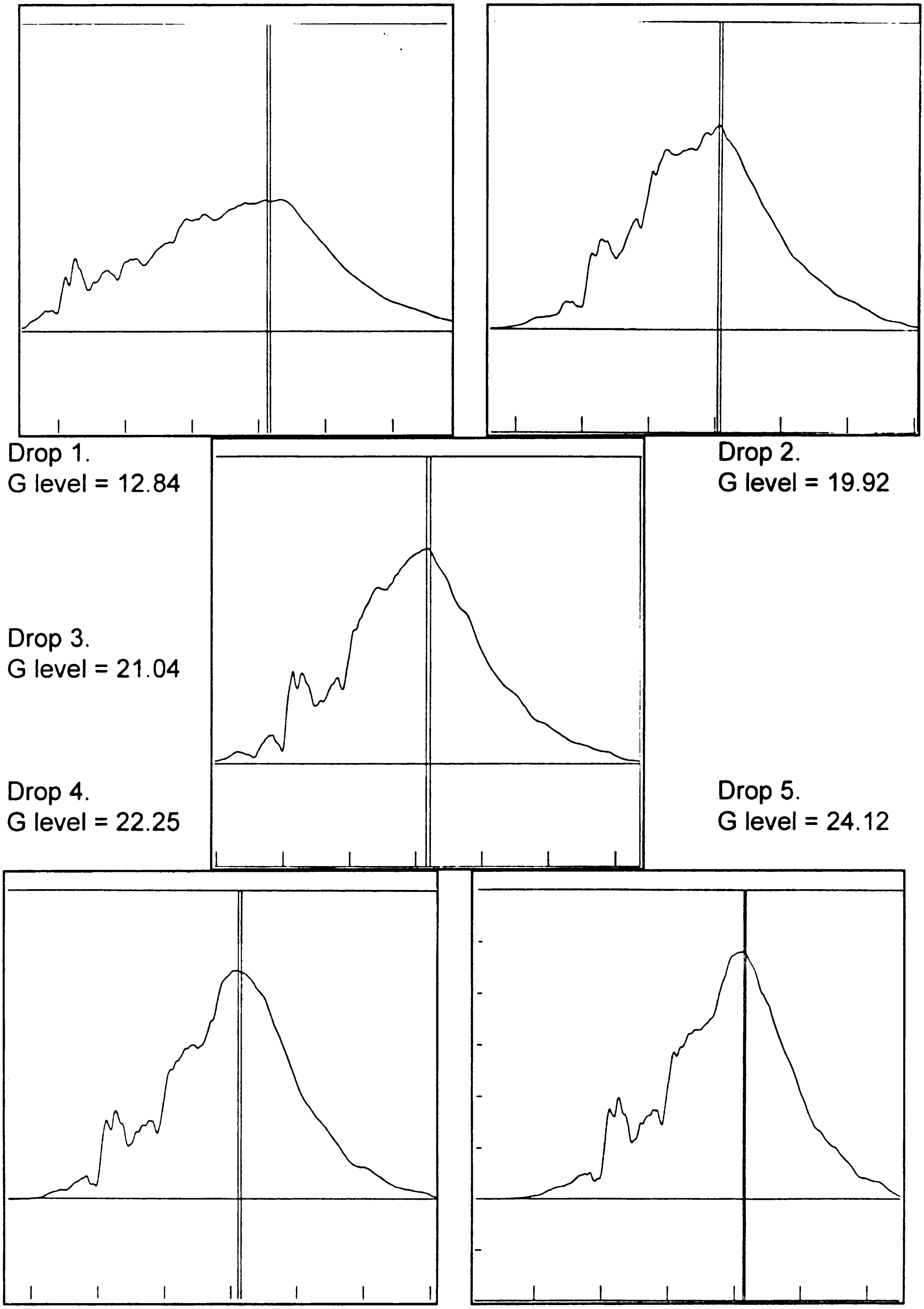
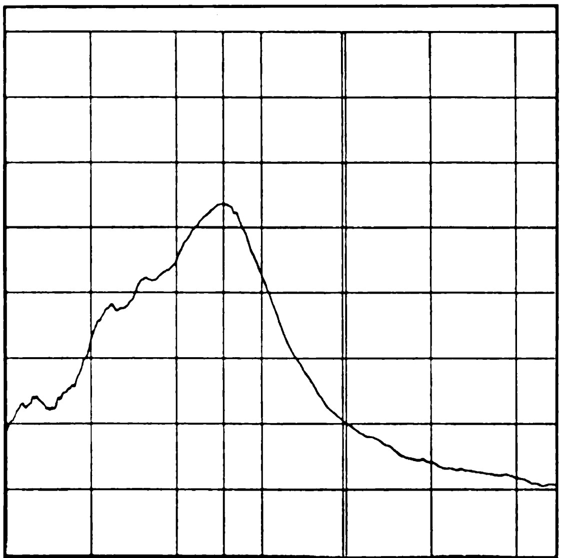


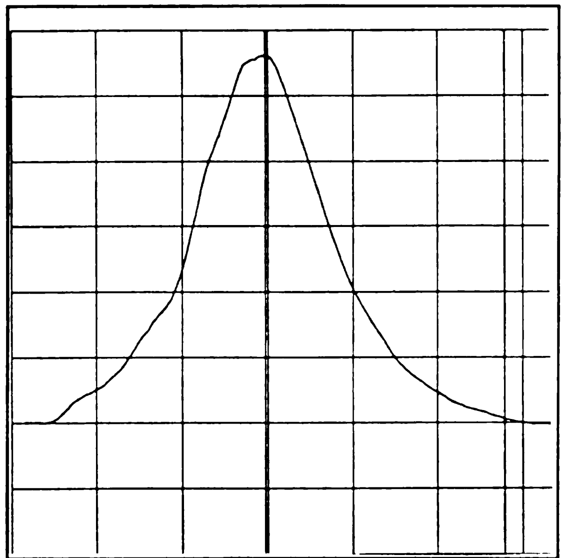
Figure 22. Shock Pulses For 24" Corner Drop Using 3" Cushion - 1st-5th Impacts

APPENDIX (D)

FIGURES (21-26)

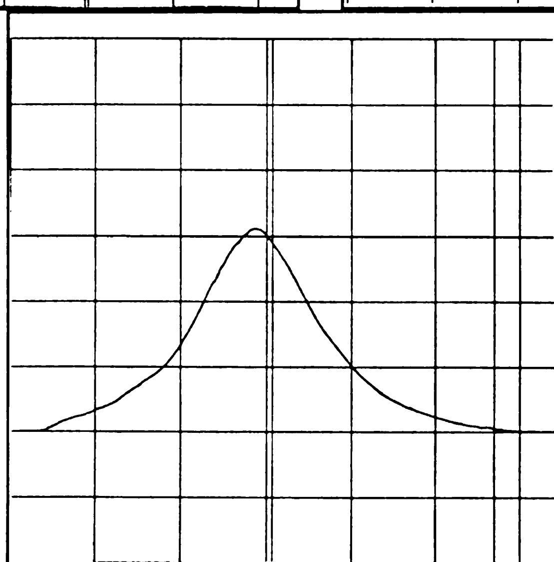
CORNER DROP SHOCK PULSES
1-5 IMPACTS





Drop 1.
G level = 16.85

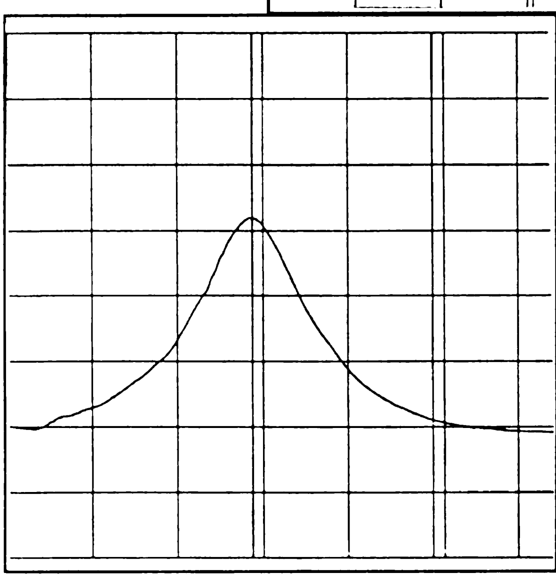
Drop 2.
G level = 28.14



Drop 3.
G level = 31.24

Drop 4.
G level = 32.00

Drop 5.
G level = 33.62



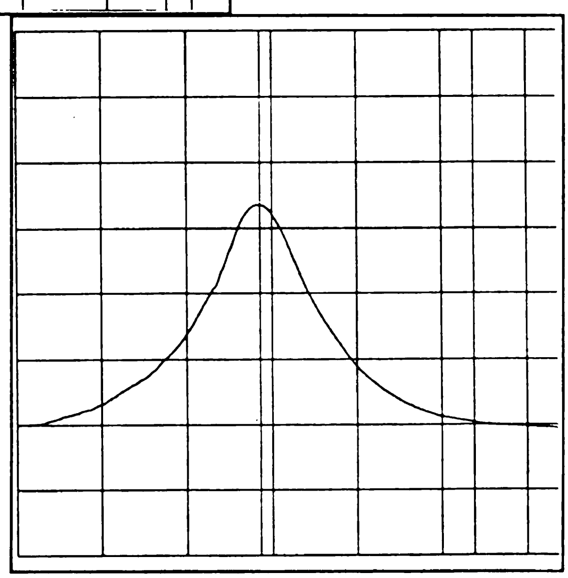


Figure 23. Shock Pulses For 36" Corner Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (D)

FIGURES (21-26)

CORNER DROP SHOCK PULSES
1-5 IMPACTS

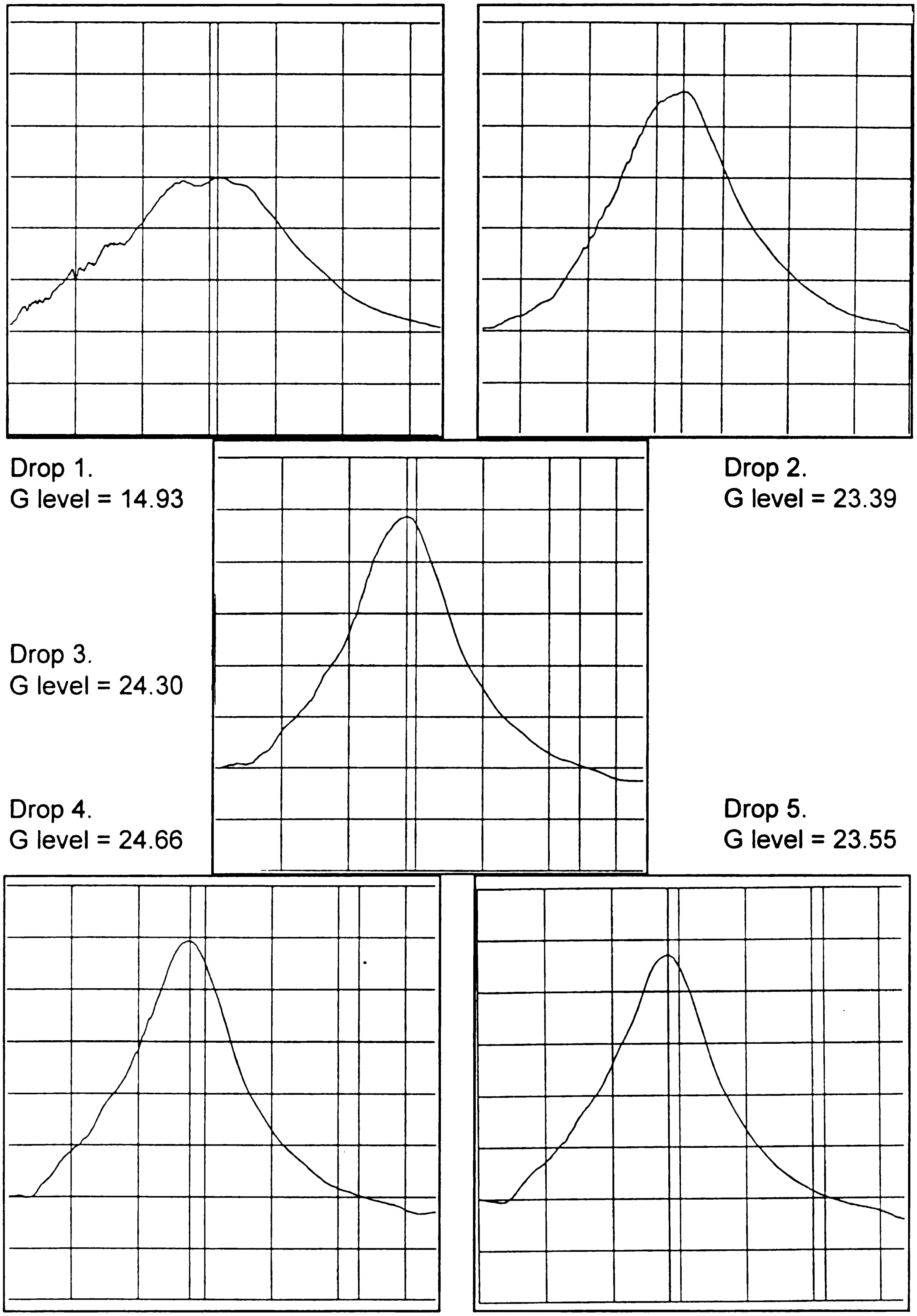


Figure 24. Shock Pulses For 36" Corner Drop Using 3" Cushion - 1st-5th Impacts

APPENDIX (D)

FIGURES (21-26)

CORNER DROP SHOCK PULSES
1-5 IMPACTS

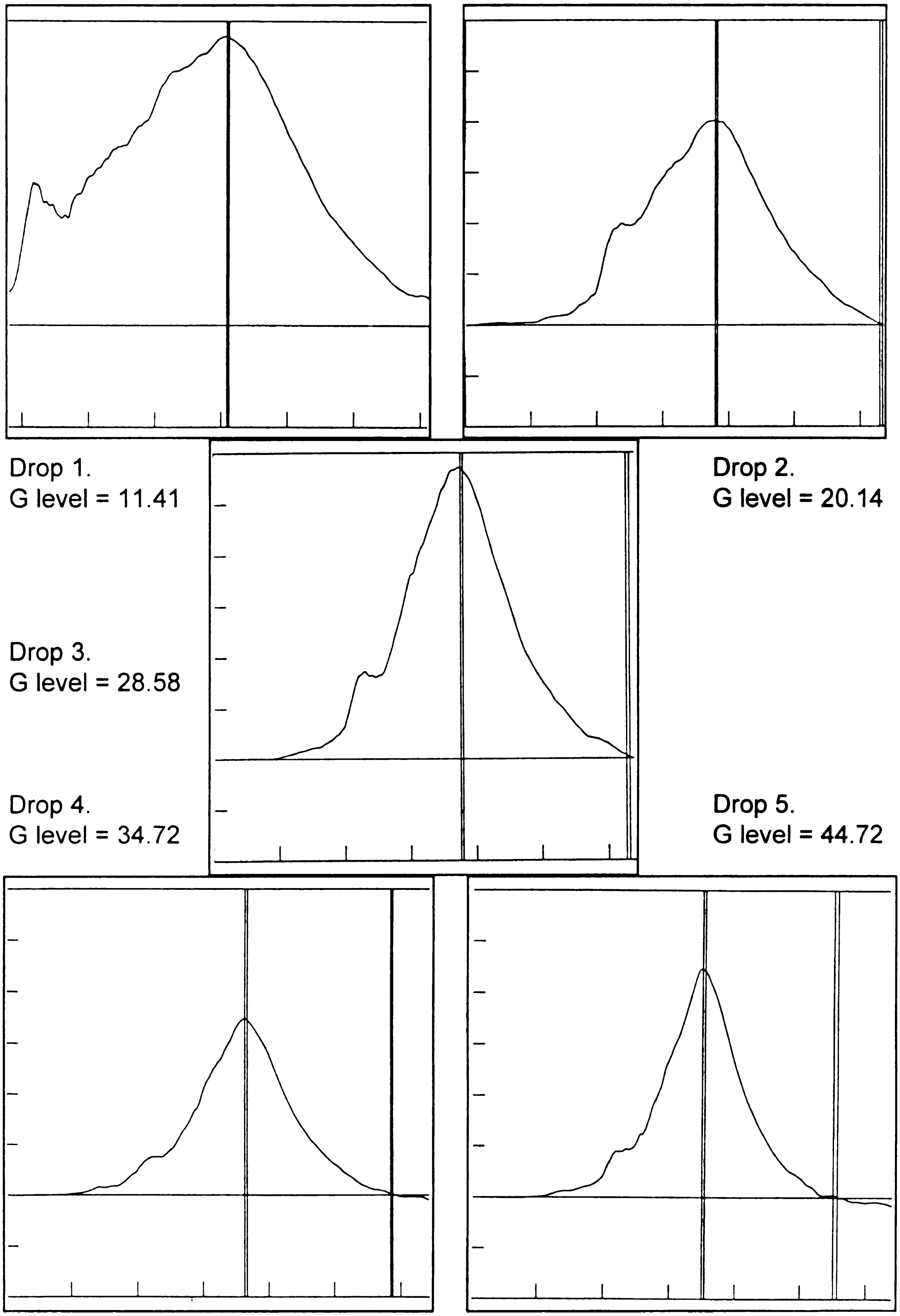


Figure 25. Shock Pulses For 18, 24, 30, 36, and 42" Corner Drop Using 2" Cushion - 1st-5th Impacts

APPENDIX (D)

FIGURES (21-26)

CORNER DROP SHOCK PULSES
1-5 IMPACTS

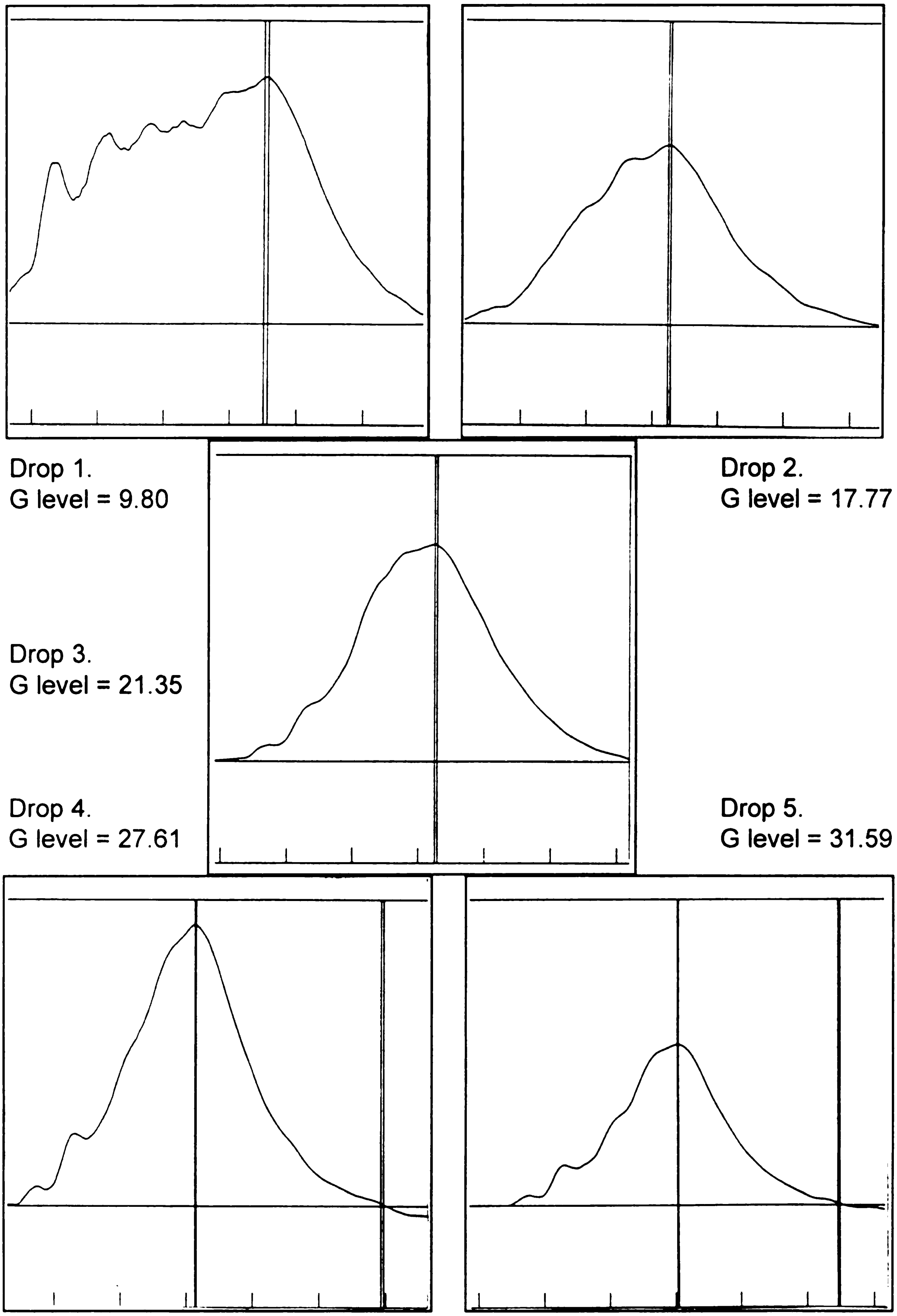


Figure 26. Shock Pulses For 18, 24, 30, 36, and 42 Corner Drop Using 3" Cushion - 1st-5th Impacts

APPENDIX (E)

TABLES (29-36)

EDGE DROP EXPERIMENTAL DATA

APPENDIX E

Table 29.
24 Inch Edge Drops on 2" Cushion With Box Edge Dimensions Measuring 4.5" Along Edge

Cushion Thickness (inches)	Drop Height (Inches)	Weight (lbs)	Filtered G	Argument (peak or halfway)
2	24	19.8	23.65	Peak
2	24	19.8	27.53	Peak
2	24	19.8	29.85	Peak
2	24	19.8	32.86	Peak
2	24	19.8	33.68	Peak
2	24	39.8	18.36	Peak
2	24	39.8	27.12	Peak
2	24	39.8	28.66	Peak
2	24	39.8	31.60	Peak
2	24	39.8	32.33	Peak

Table 30.
36 Inch Edge Drops on 2" Cushion With Box Edge Dimensions Measuring 4.5" Along Edge

Cushion Thickness (inches)	Drop Height (Inches)	Weight (lbs)	Filtered G	Argument (peak or halfway)
2	36	19.8	25.63	Peak
2	36	19.8	33.20	Peak
2	36	19.8	35.86	Peak
2	36	19.8	38.45	Peak
2	36	19.8	37.00	Peak
2	36	39.8	19.93	Peak
2	36	39.8	31.05	Peak
2	36	39.8	33.12	Peak
2	36	39.8	35.24	Peak
2	36	39.8	36.67	Peak

APPENDIX E

Table 31. 24 Inch Edge Drops on 2" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
24	20.4	27.11	28.3	600	88.33	26.09	30.7	272.73	16.90	148.81	13.8	0.55	p
24	20.4	46.96	23.8	600	105.04	38.07	30	241.57	13.50	199.87	15.7	0.83	p
24	20.4	37.97	30.6	600	81.69	32.15	35.7	255.31	16.30	192.17	19	0.75	p
24	20.4	34.73	31.6	600	79.11	32.51	32.9	261.74	15.40	192.90	17	0.74	p
24	20.4	36.23	30.10	600	83.06	34.03	32.8	259.51	16.30	205.61	16	0.79	p
24	40.4	24.12	40.3	600	62.03	21.05	44.1	252.43	23.10	181.08	21.1	0.72	p
24	40.4	32.08	33.6	600	74.4	29.58	41.8	288.76	20.90	195.15	20.5	0.68	p
24	40.4	36.11	33.6	600	74.4	32.69	39.2	272.48	19.40	236.90	19.6	0.87	p
24	40.4	34.92	32.9	600	75.99	33.28	39.2	280.17	19.80	220.32	18.7	0.79	p
24	40.4	35.80	33.1	600	75.53	33.7	39.8	286.75	20.20	217.55	19.1	0.76	p

APPENDIX E

Table 32. 24 Inch Edge Drops on 3" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
24	20.6	23.15	33.1	600	75.53	19.22	49	227	31.40	155.03	18.4	0.68	p
24	20.6	42.55	23.8	600	105.04	28.24	31.2	265.08	16.40	138.99	14.2	0.52	p
24	20.6	44.27	26	600	96.15	35.34	31.6	269.95	17.50	177.74	14.7	0.66	p
24	20.6	43.09	26.2	600	95.42	34.88	32	236.59	16.40	209.14	15.5	0.88	p
24	20.6	35.94	32.9	600	75.99	31.25	33.5	248.07	17.50	209.63	15.7	0.85	p
24	40.6	20.37	42.3	600	59.1	17.69	47.3	251.41	24.40	184.30	22.9	0.73	p
24	40.6	19.96	39.9	600	62.66	18.48	44	225.57	22.30	198.59	21.4	0.88	p
24	40.6	25.97	47.9	600	52.19	23.87	51.2	282.35	25.20	246.55	26.4	0.87	p
24	40.6	26.01	42.3	600	59.1	24.37	49.5	297.76	25.70	220.67	23.4	0.74	p
24	40.6	26.58	41.5	600	60.24	25.06	49.1	300.97	25.10	224.14	23.8	0.74	p

APPENDIX E

Table 33. 36 Inch Edge Drops on 2" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
36	20.4	30.29	31.4	398	79.61	28.56	34.3	119.8	16.6	68.13	17.8	0.57	p
36	20.4	39.22	31.4	446	79.61	35.43	35.9	113.04	15.2	89.14	19.5	0.79	p
36	20.4	44.95	29	498	86.21	39.23	36	117.5	15.7	93.29	20.2	0.79	p
36	20.4	46.92	31	444	80.65	41.2	35.6	111.71	16.3	102.5	19.4	0.92	p
36	20.4	47.99	34.4	426	72.67	40.54	36.2	110.13	16.3	104.55	19.5	0.95	p
36	40.4	23.81	47.6	331	52.52	21.19	48.7	110.11	22	82.59	26.8	0.75	p
36	40.4	37.19	35.8	413	69.83	34.88	44.2	126.61	21.8	91.79	22.1	0.72	p
36	40.4	38.41	39.5	410	63.29	35.61	46.2	122.01	25	104.35	20.9	0.86	p
36	40.4	44.01	37.9	418	65.97	39.17	43	123.44	23.4	103.86	19.5	0.84	p
36	40.4	43.07	35.5	429	70.42	39.09	40.1	118.67	20.3	105.76	19.5	0.89	p

APPENDIX E

Table 34. 36 Inch Edge Drops on 3" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
36	20.6	26.25	36.6	524	68.3	24.45	40.8	119.84	18.4	64.65	22.3	0.54	p
36	20.6	37.46	35.1	442	71.22	35.05	42	105.99	15.2	99.05	26.5	0.93	p
36	20.6	37.87	33.6	444	74.4	34.22	34	137.92	19	61.15	20.4	0.44	p
36	20.6	33.99	37.5	417	66.67	30.93	41.5	108.53	17.3	91.28	24.1	0.84	p
36	20.6	34.69	37.3	402	67.02	32.5	40.6	111.34	18.1	92.41	22.4	0.83	p
36	40.6	40.36	36.2	0	69.06	19.64	48.2	120.39	24.6	65.16	23.5	0.54	p
36	40.6	25.39	43.9	306	56.95	23.21	44.7	104.47	20.9	91.67	23.6	0.88	p
36	40.6	27.49	45.7	306	54.75	25.84	55.2	118.79	25	94.04	30.3	0.79	p
36	40.6	29.11	46.2	300	54.11	27.54	52.7	122.31	25.3	95.54	28	0.78	p
36	40.6	30.01	46.7	297	53.53	28.13	51.5	119.65	26.2	98.81	28.2	0.83	p

APPENDIX E

Table 35. 18, 24, 30, 36 and 42 Inch Edge Drops on 2" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
18	20.4	22.49	33.5	600	74.63	20.5	36.4	79.92	17.70	63.48	18.50	0.79	p
24	20.4	31.54	26.4	600	94.7	30.04	32.3	105.25	15.30	70.42	16.70	0.67	p
30	20.4	36.41	32.2	600	77.64	33.19	33.4	106.64	15.10	85.25	17.80	0.80	p
36	20.4	42.44	31.9	600	78.37	39.92	33	117.58	15.50	92.11	17.20	0.78	p
42	20.4	46.44	30.3	600	82.51	44.41	34.2	129.66	16.80	97.38	17.00	0.75	p
18	40.4	17.50	43.8	600	57.08	16.39	47.2	89.62	24.50	60.26	23.60	0.67	p
24	40.4	28.91	41.8	600	59.8	26.65	43.4	101.96	22.10	81.48	21.40	0.80	p
30	40.4	35.09	38.6	600	64.77	32.42	40.1	111.07	20.50	99.60	19.40	0.90	p
36	40.4	45.61	34.5	600	72.5	42.51	36.2	127.13	19.00	112.45	16.80	0.88	p
42	40.4	58.70	30.7	600	81.43	53.61	33.5	141.77	18.60	117.90	14.40	0.83	p

APPENDIX E

Table 36. 18, 24, 30, 36 and 42 Inch Edge Drops on 3" Cushion With Box. 9 Inch Edge Length

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
18	20.6	17.02	40.50	600	61.73	15.82	41.60	89.53	21.50	53.08	19.50	0.59	p
24	20.6	30.00	32.70	600	76.45	28.49	36.40	98.65	18.80	74.12	16.90	0.75	p
30	20.6	32.93	32.80	600	76.22	29.26	36.60	92.75	16.30	84.31	18.90	0.91	p
36	20.6	33.15	33.90	600	73.75	30.64	35.50	101.94	17.10	88.68	18.10	0.87	p
42	20.6	35.25	32.10	600	77.89	33.71	33.60	111.38	17.00	92.66	16.30	0.83	p
18	40.6	10.39	39.20	600	63.80	10.11	42.80	69.14	27.20	30.26	15.30	0.44	p
24	40.6	14.96	40.10	600	62.34	13.41	38.80	72.69	19.50	54.69	18.50	0.75	p
30	40.6	27.36	42.30	600	59.10	24.58	43.20	113.98	22.10	84.52	20.30	0.74	p
36	40.6	29.16	41.70	600	59.95	27.69	45.20	128.66	25.10	91.85	20.30	0.71	p
42	40.6	34.63	38.10	600	65.62	32.85	40.40	134.65	21.10	107.84	19.30	0.80	p

APPENDIX (F)

TABLES (37-42)

CORNER DROP EXPERIMENTAL DATA

APPENDIX F

Table 37. 24 Inch Corner Drops on 2" Cushion With Box

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
24	20.4	33.66	42.30	600	59.10	19.66	50.60	272.31	25.90	146.14	24.60	0.54	p
24	20.4	44.87	39.40	600	62.66	24.67	45.60	264.22	22.60	203.22	22.50	0.77	p
24	20.4	34.92	37.20	600	67.20	30.15	39.60	260.42	21.70	188.86	17.40	0.73	p
24	20.4	37.34	38.00	600	65.80	28.93	43.10	250.60	24.30	208.56	18.30	0.83	p
24	20.4	37.28	41.00	600	61.00	29.58	46.80	257.71	22.90	235.99	23.20	0.92	p
24	40.4	25.88	45.00	600	55.56	17.27	61.90	271.22	32.70	166.90	28.50	0.62	p
24	40.4	27.88	53.30	600	46.90	25.38	53.90	269.69	26.10	242.95	26.80	0.90	p
24	40.4	33.54	45.90	600	54.47	29.45	53.40	280.06	27.90	246.30	24.80	0.88	p
24	40.4	35.22	33.40	600	74.85	31.18	49.50	301.57	25.60	240.05	23.40	0.80	p
24	40.4	35.05	36.50	600	68.50	30.78	48.90	285.92	24.30	252.08	23.80	0.88	p

APPENDIX F

Table 38. 24 Inch Corner Drops on 3" Cushion With Box

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
24	20.6	30.67	43.9	600	56.95	17.2	52.9	223.48	25.9	185.82	26.1	0.83	p
24	20.6	30.62	40.3	600	62.03	22.68	44.5	218.06	24.4	186.93	19.5	0.86	p
24	20.6	31.95	36.2	600	69.06	26.48	43	239.85	22.5	216.53	19.4	0.90	p
24	20.6	26.39	43.5	600	57.5	24.08	48.3	250.11	23.6	229.9	24	0.92	p
24	20.6	27.50	43.4	600	57.6	24.44	48.2	296.52	26	191.17	21.2	0.64	p
24	40.6	23.32	68.5	600	36.5	12.84	78.3	272.81	43.6	167.34	34.1	0.61	p
24	40.6	27.04	55.2	600	45.3	19.92	81.3	279.01	31	206.06	29.6	0.74	p
24	40.6	28.14	48.4	600	51.65	21.04	64.1	285.08	31.8	224.08	31.4	0.79	p
24	40.6	27.88	43.8	600	57.08	22.25	58.6	263.01	29	236.57	29.3	0.90	p
24	40.6	27.83	36.8	600	67.93	24.12	55.4	291.18	31.7	208.69	23.7	0.72	p

APPENDIX F

Table 39. 36 Inch Corner Drops on 2" Cushion With Box

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
36	20.4	24.85	48.8	267	51.2	22.22	40.8	106.65	25.8	88.65	31.4	0.83	p
36	20.4	33.58	44	340	56.82	31.35	45.1	107.19	19.2	99.35	26.7	0.93	p
36	20.4	40.45	38.8	394	64.43	35.42	47	113.61	21.2	104.27	26.1	0.92	p
36	20.4	42.42	39.7	422	62.97	36.6	48.1	113.57	21.1	112.27	26.1	0.99	p
36	20.4	42.47	38.4	420	65.1	36.81	43.8	110.1	19.2	105.07	23.6	0.95	p
36	40.4	16.61	30.3	408	82.51	16.85	39.1	79.47	25.1	43.3	14.1	0.54	p
36	40.4	31.95	50.4	292	49.6	28.14	52.4	110.04	24.3	103.5	28.2	0.94	p
36	40.4	34.32	49.3	317	50.71	31.24	53.9	112.25	24.6	116.21	29.5	1.04	p
36	40.4	35.50	45.6	309	54.85	32	48	110.98	24.3	104.87	22.7	0.94	p
36	40.4	38.93	46.1	325	54.23	33.62	50.4	113.91	25.1	110.91	25.2	0.97	p

APPENDIX F

Table 40. 36 Inch Corner Drops on 3" Cushion With Box

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
36	20.6	18.29	51.5	223	48.5	16.82	54.3	91.82	24.4	86.99	30	0.95	p
36	20.6	29.13	45.5	351	54.94	25.97	47.3	100.23	21.4	92.49	25.9	0.92	p
36	20.6	29.47	44.7	314	55.93	27.52	45.8	107.87	21.2	92.3	25	0.86	p
36	20.6	32.20	42.5	312	58.82	28.51	48	105.07	22.3	93.92	25.8	0.89	p
36	20.6	31.08	47.7	312	52.41	27.52	50.2	104.44	23.4	93.62	26.7	0.90	p
36	40.6	25.70	51.6	0	48.45	14.93	68.3	102.91	32.9	84.04	34.4	0.82	p
36	40.6	25.63	60.7	260	41.19	23.39	64.2	113.84	30.1	102.41	34.2	0.90	p
36	40.6	25.90	49.5	292	50.5	24.3	52.8	99.85	26.6	88.89	26	0.89	p
36	40.6	26.62	43.4	280	57.6	24.66	48.2	99.22	23.1	86.74	25.4	0.87	p
36	40.6	25.96	45.1	267	55.43	23.55	46.5	95.43	23.3	80.37	23.5	0.84	p

APPENDIX F

Table 41. 18, 24, 30, 36 and 42 Inch Corner Drops on 2" Cushion With Box

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
18	20.4	16.57	47.5	600	52.63	14.79	53.6	209.13	27.2	135.46	25	0.65	p
24	20.4	25.72	43.5	600	57.47	23.22	48.2	228.43	20.9	200.16	26.7	0.88	p
30	20.4	28.75	40.6	600	61.58	25.1	42.6	240.26	18.2	235.95	23.8	0.98	p
36	20.4	33.96	41.3	600	60.53	30.78	44.2	276.8	21	230.53	22.4	0.83	p
42	20.4	40.32	36.2	600	69.1	37.25	40.7	308.84	18.4	267.7	22.2	0.87	p
18	40.4	12.52	72.8	600	34.34	11.41	83.4	237.44	41.9	164.85	40.9	0.69	p
24	40.4	22.62	51.7	600	48.35	20.14	54.8	252.07	30.1	204.89	24.7	0.81	p
30	40.4	32.71	49.8	600	50.2	28.5	52.4	290.01	27.1	259.66	24.7	0.90	p
36	40.4	39.96	43.8	600	57.07	34.72	47.3	301.17	25.1	281.65	21.8	0.94	p
42	40.4	53.24	41.2	600	60.68	44.72	43.9	328.09	23.7	308.67	19.7	0.94	p

APPENDIX F

Table 42. 18, 24, 30, 36 and 42 Inch Corner Drops on 3" Cushion With Box. No Defined Impact Geometry

Drop Height (Inches)	Weight (lbs)	Unfiltered G Dimensionless	Reported Duration (ms)	Filter Frequency (Hz)	New Filter Frequency (Hz)	Filtered G Dimensionless	Reported Duration (ms)	Impact Velocity (Vi)	Filtered Impact Duration (Ti)	Rebound Velocity (Vr)	Rebound Duration (Tr)	Coefficient of Restitution ('e')	Argument (peak or halfway)
18	20.6	15.69	51.10	600	48.92	14.06	55.30	85.39	26.80	66.11	28.10	0.77	p
24	20.6	23.45	47.50	600	54.70	21.86	49.10	98.51	24.20	78.65	24.50	0.80	p
30	20.6	27.50	46.40	600	53.88	25.34	47.50	104.86	23.20	93.57	23.90	0.89	p
36	20.6	29.31	45.40	600	55.06	27.46	46.70	116.78	23.20	96.67	23.30	0.83	p
42	20.6	34.62	42.40	600	58.96	32.62	45.00	130.02	22.70	107.74	22.10	0.83	p
18	40.6	11.49	62.10	600	40.26	9.80	78.30	105.34	49.00	41.37	28.20	0.39	p
24	40.6	19.70	61.10	600	40.92	17.77	64.30	107.54	31.80	79.35	31.90	0.74	p
30	40.6	23.00	59.80	600	41.81	21.31	60.60	118.23	29.40	93.26	29.00	0.79	p
36	40.6	29.64	52.60	600	47.53	27.61	54.60	126.20	26.50	105.06	27.80	0.83	p
42	40.6	34.21	44.60	600	56.05	31.59	49.20	135.95	24.90	110.37	24.10	0.81	p

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