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Plastic Tote Distribution

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Abstract Plastic totes have been commonly used to transport healthcare products from a distribution center to a retail store. Damages often occur in partially-filled totes. This article reviews the research performed at the Healthcare Packaging Consortium, including problem validation, the use of a bubble wrap sheet at the bottom of a plastic tote to cut down potential damages, the use of air pillows at the top of the a tote to reduce immediate and subsequent impact accelerations, and equations developed to predict drop height and impact acceleration at the interior tote bottom based on peak accelerations logged from a shock recorder.
Keywords *Plastic Totes; Cushion; Impact Acceleration; Drop Height*

1. Introduction

Plastic totes are commonly used to distribute products from distribution centers (DC) to retail stores. Typically the distribution cycle is daily and within a few hundred mile radius from a DC. Partially-filled totes with an unorganized arrangement of contents are usually found to be the case (Figure 1). Damages (Figure 2) of contents occur to the product packaged in loosely packed totes. These damages include abrasion, dent, corner crushing, bending, scratch, and etc., which can negatively influence customers' decision when buying the products.

Figure 1: *Unorganized Partially-Filled Plastic Tote*

Figure 2: *Samples of Damages*

The Healthcare Packaging Consortium at Christian Brothers University studied this problem during 2010 to 2012 and published findings in the Proceedings of the 2011 International Transport Packaging Forum [1], the IoPP Journal of Packaging [2, 3], and the MAESC 2012 Conference Proceedings [4, 5], which was hosted by the consortium. This article provides a review of these findings so they can be archived in one article.

2. Materials and Methods

2.1. Problem Validation

The first part of the CBU tote study was to validate the problem [1]. Two partially-filled totes were shipped to a site about 150 miles away and returned via a commercial carrier. The first tote contained randomly placed healthcare products, similar to Figure 1. The second tote contained the same products. Its contents, however, were organized to reduce voids, as shown in Figure 3. The objective of this part of the study was to see the differences, if any, between the two tote content arrangements.

Figure 3: *Tote Contents Organized to Reduce Voids*

2.2. Weight Study

Thirty free-fall, flat-bottom drops were made for totes weighing at 7.36 lb, 9.36 lb, 12.36 lb, and 16.20 lb at different drop heights of 12”, 15”, 18”, 21”, and 24” [4]. Impact accelerations were recorded using a shock recorder (red instrument on the left side of Figure 4 labeled “A”). Due to the 100-g maximum limit of the recorder, it was placed on a thick layer of bubble wrap. A single-axis accelerometer was also used to measure the impact acceleration at the tote bottom in parallel to the shock recorder. However, data from the accelerometer was not used in this study due to its inconsistency. Part “B” of Figure 4 shows the tote placement on a free-fall drop tester. The objective of this part of the study was to see the effect that different weights had on impact acceleration.

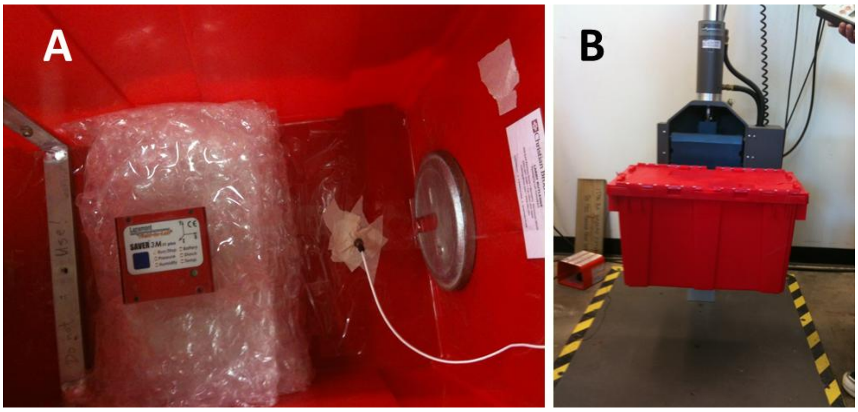


Figure 4: *Setup for Weight Study*

2.3. Cushioning at Tote Bottom and Top

An over-the-counter medication box was placed at the tote bottom with three different cushioning materials underneath: $^{3}/_{16}$” bubble wrap, $^{5}/_{16}$” bubble wrap, and ½” 1.3 lb/ft^{3} viscoelastic foam [2]. A single-axis accelerometer was attached to the top of the product package (“A” in Figure 5). Impact accelerations from the accelerometer were recorded through a data acquisition system as shown in "B," "D," and "E" of Figure 5. Drop heights were 12" to 24" with a 3" increment. The purpose of this part of the study was to see the effectiveness of shock absorption of the three different cushioning materials.

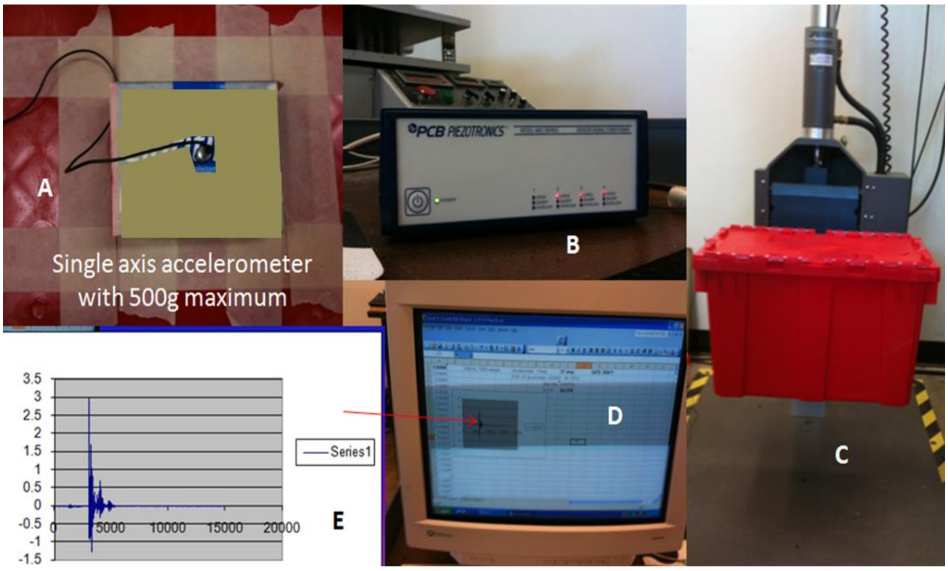


Figure 5: *Setup for Cushioning at the Tote Bottom*

Air pillows have been used to tighten up the empty space above products in a tote/box. A fixture was developed to simulate how a product moves in flexible air pillows as shown in Figure 6. The ball-bearing sleeve, labeled "B", moved in the vertical direction along the guide rod, labeled "A", then, into the air pillows or into the air when no air pillow was used. A single-axis accelerometer was mounted to the sleeve at position labeled "C." A flexible disc, shown as "D", was used as the platform to support the sleeve. A PVC pipe ("E") prevented the disc and sleeve from sliding downward. The purpose of this part of the study was to investigate the effect the air pillows had on impact acceleration.

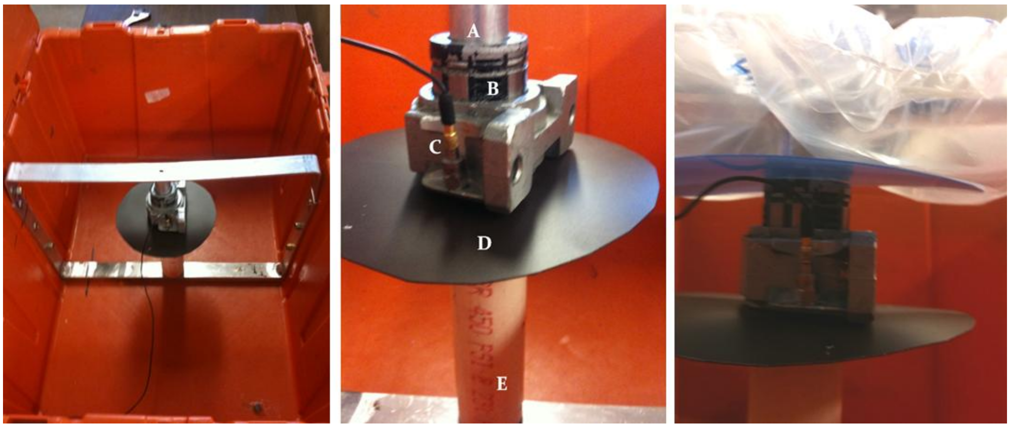


Figure 6: *Simulating Product Movement with Air Pillows on the Tote Top*

2.4. Drop Height and Impact Acceleration at Tote Bottom

A shock recorder or an accelerometer records impact acceleration. Often, it is desirable to know drop heights. Correlation of drop heights and impact acceleration was made using a shock recorder [3]. The shock recorder used in this work had a limit of 100g, thus, it was housed in a corrugated box with eight layers of $^{5}/_{16}$" bubble wrap underneath as shown in Figure 7. The box was secured in a plastic tote, which was dropped at 12" to 24" with a 3" increment. Later the experiment was extended to a 48" drop height.

Figure 7: *Shock Recorder Setup*

An attempt was made to measure impact acceleration at the tote bottom. However, due to the vibration of the thin plastic bottom of the tote, the data varied significantly. An indirect approach was used to determine the impact acceleration at tote bottom with one layer of $^{5}/_{16}$" bubble wrap from the data obtained from an experiment with multi-layers of the wrap [3].

3. Results and Discussion

3.1. Problem Validation

Damages to products, such as printed-carton abrasion and scuffing, folding-carton crushing, shrink wrap-film tares as shown in Figure 2, are numerous [1] in the randomly-placed, partially-filled tote. Organizing the products in a partially-filled plastic tote would prevent some damages. However, productivity would be reduced and training would be required. In addition, it would be hard to develop a rigid "how-to" manual/training on filling a tote appropriately due to the many product sizes, shapes, weights, as well as quantity of each product type in the tote. Only general rules based on common sense can be established.

3.2. Weight Study

Data from drop tests of different tote weights at different drop heights was compiled in Table 1 [4]. For each drop height, impact accelerations of different tote weights were comparable. Thus, the tote weight has no effect on impact acceleration. However, a heavier tote has more mass, thus, more impact force is created as determined from **F** = **ma**, where "**F**" is the impact force, "**m**" is the tote mass, and "**a**" is the impact acceleration.

Table 1: *Thirty-Drop Average of Impact Accelerations Obtained from Saver/Recorder*

Tote Weight (lbs)	12-inch Drop Height	15-inch Drop Height	18-inch Drop Height	21-inch Drop Height	24-inch Drop Height
7.36	37.90g	43.32g	49.08g	53.75g	59.32g
9.36	37.92g	43.35g	49.30g	54.56g	58.65g
12.36	37.38g	42.86g	49.12g	50.20g	54.26g
16.20	36.76g	41.76g	46.84g	52.41g	58.13g
Average =	37.49g	42.82g	48.59g	52.73g	57.59g

3.3. Cushioning at Tote Bottom and Top

Thirty-drop averages of tote with cushioning at tote bottom were summarized in Table 2 [2]. Bubble wrap placed at the tote bottom is very effective. The $^{3}/_{16}$" and $^{5}/_{16}$" wraps reduced the impact acceleration by 23% and 34%, respectively. The more expensive viscoelastic foam only reduced the impact acceleration by 9%.

Table 2: *Summary of Tote Bottom Cushioning Drop Tests*

Drop Height (in)	No Cushion	3/16" Bubble Wrap		5/16" Bubble Wrap		1/2" 1.3 lb/ft^3 Viscoelastic Foam	
	Impact Acceleration	Impact Acceleration	% Change from No Cushion	Impact Acceleration	% Change from No Cushion	Impact Acceleration	% Change from No Cushion
12	146.93g	120.09g	-18	110.03g	-25	134.45g	-8
15	200.09g	154.33g	-23	136.14g	-32	180.65g	-10
18	229.76g	179.94g	-22	151.38g	-34	209.75g	-9
21	264.25g	194.23g	-26	159.24g	-40	246.63g	-7
24	293.68g	219.18g	-25	183.65g	-37	257.99g	-12
			Avg = -23		Avg = -34		Avg = -9

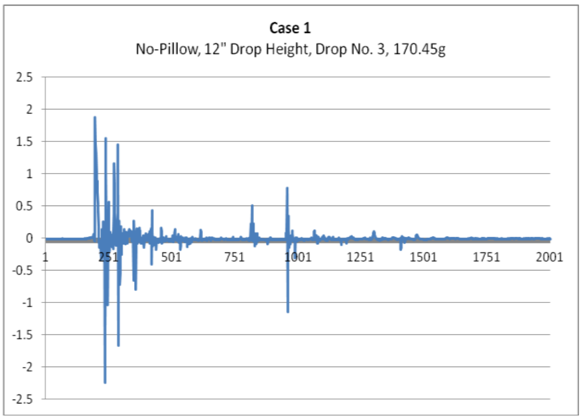
Thirty-drop averages of tote with air pillows at tote top were summarized in Table 3 [2]. On average, the impact acceleration was reduced by 15.33% by tightening up the tote contents using air pillows. In addition, air pillows reduced the subsequent impact accelerations [5] as shown in Table 4 and Figure 8, where impact acceleration versus time graphs of comparable peak impact accelerations were compared.

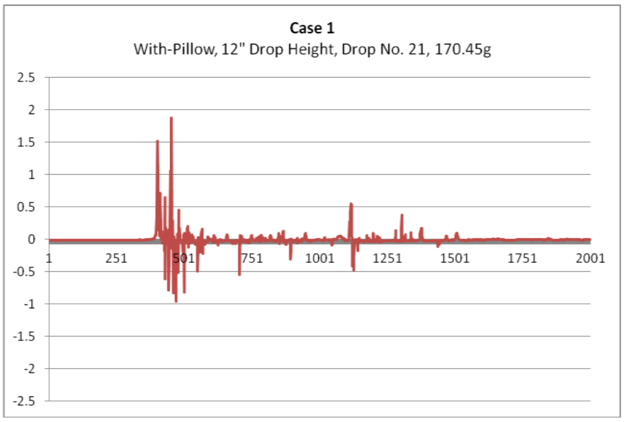
Table 3: *Summary of Tote Top Cushioning Drop Tests*

Drop Height	No Air Pillows	With Air Pillows	% Change by Adding Air Pillows
12 inches	220g	203g	-8
15 inches	252g	242g	-4
18 inches	326g	248g	-24
21 inches	347g	252g	-27
24 inches	315g	272g	-14
			Average = -15

Table 4: *Twelve Comparison Cases*

Case	Max Impact Acceleration (g)			Subsequent Impact Accelerations Reduced by Pillow?
	Drop Height (in)	No Air Pillow	With Air Pillow	
1	12	Drop No. 3 170.45	Drop No. 21 170.45	Yes
2	12	Drop No. 13 221.5	Drop No. 12 221.95	Yes
3	15	Drop No. 3 245.47	Drop No. 11 242.37	Yes
4	15	Drop No. 2 323.6	Drop No. 13 324.04	No
5	18	Drop No. 2 227.27	Drop No. 25 226.38	Yes
6	18	Drop No. 5 196.2	Drop No. 21 198.42	Yes
7	21	Drop No. 8 378.2	Drop No. 9 375.98	Yes
8	21	Drop No. 22 270.33	Drop No. 19 273.88	Yes
9	24	Drop No. 25 289.42	Drop No. 8 288.97	Yes
10	24	Drop No. 13 239.26	Drop No. 1 242.81	Yes
11	12/18	Drop No. 9 (12-in) 299.18	Drop No. 16 (18-in) 299.63	Yes
12	21/15	Drop No. 14 (21-in) 282.76	Drop No.16 (15-in) 280.54	No





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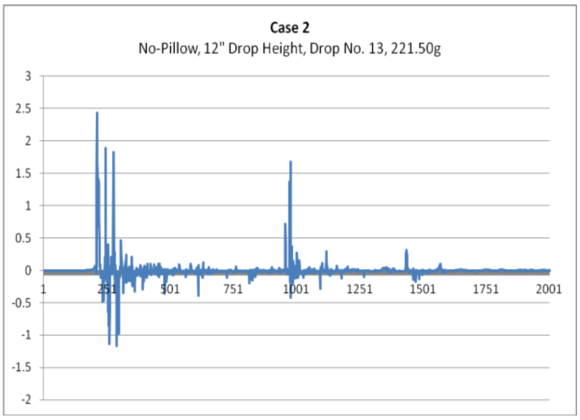

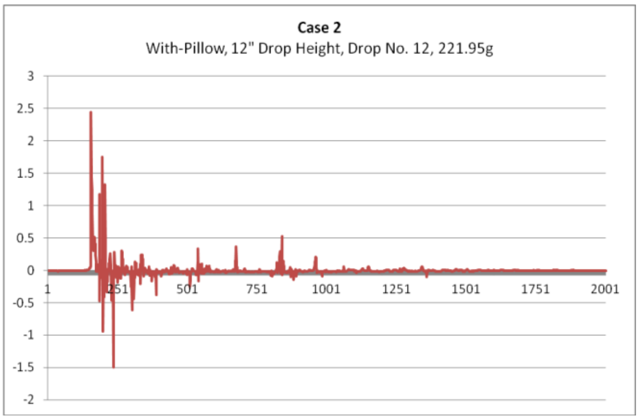

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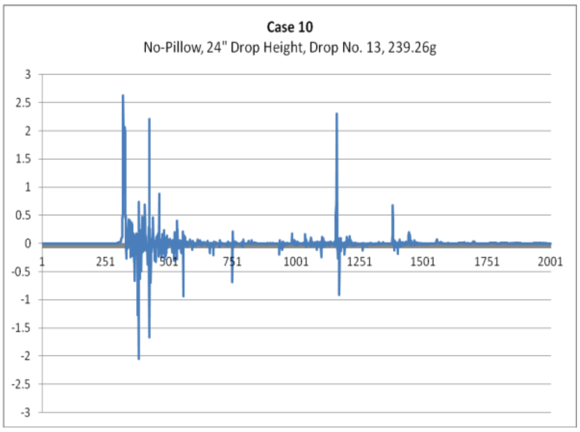

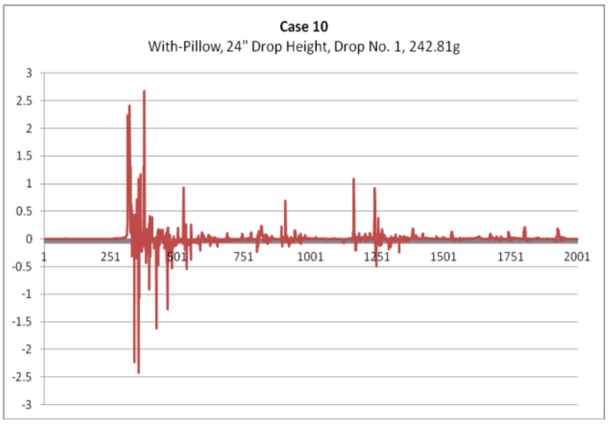

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Figure 8: *Effect of Air Pillows on Subsequence Impact Accelerations – Comparison Samples*

Validation of the effectiveness of using bubble wrap at tote bottom and/or air pillows at tote top was performed using vibration and drop tests. For each test, the four totes contained the same products randomly placed. However, the randomness was kept consistent among the four totes. The first tote used had no cushion, while the 2nd, 3rd, and 4th used $^{5}/_{16}$" bubble wrap at tote bottom, air pillows at tote top, and bubble wrap at tote bottom together with air pillows at tote top, respectively. Figure 9 shows a $^{5}/_{16}$" bubble wrap sheet and air pillows placed at tote bottom and top.

Figure 9: *Bubble Wrap Sheet (left) and Air Pillows (right)*

A one-hour vibration sequence was used per ISTA Procedures 1C, 1D, 1E, 1F, 1G, 1H, 2A, 2B, and 4G [6]. Flat-bottom, free-fall drops at a 24-inch drop height was used in the validation. Validation results are shown in Tables 5 and 6. Using both bubble wrap at tote bottom and air pillows at tote top were found to be most effective.

Table 5: *Vibration Validation Test Results*

Case	Damaged Items	Damage Type
No cushion	5 out of 18 items	Abrasion (1 item) Dent (1 item) Corner crushing (2 items) Bending (1 item)
Bubble wrap sheet at bottom	4 out of 18 items	Edge crushing (1 item) Bending (1 item) Scratch (1 item) Corner crushing (1 item)
Air pillows at top	2 out of 18 items	Abrasion (2 items)
Bubble wrap sheet at top and air pillows at bottom	0 out of 18 items	None

Table 6: *Drop Validation Test Results*

Case	Damaged Items	Damage Type
No cushion	6 out of 18 items	Edge crushing (3 items) Bending (2 items) Dent (1 tiem)
Bubble wrap sheet at bottom	3 out of 18 items	Edge crushing (3 items)
Air pillows at top	2 out of 18 items	Edge crushing (2 items)
Bubble wrap sheet at top and air pillows at bottom	1 out of 18 items	Edge crushing (1 item)

3.4. Drop Height and Impact Acceleration at Tote Bottom

Thirty-drop impact acceleration averages per drop height were summarized in Table 7 [3]. Initially, data from 12” to 24” drop heights was used to develop an equation to estimate a drop height for a given impact acceleration. Later the range was expanded from 12” to 48” drop heights. Thus, the following two equations were obtained, where y = estimated drop height (inches) and x = saver’s impact acceleration (g):

$y = 0.5243x – 3.4853$ (R^2=0.969) for drop heights from 12” to 24” … Eqn. (1)
$y = 0.5082x - 2.7711$ (R^2=0.9989) for drop heights from 12” to 48” … Eqn. (2)

Validation was made using 85 independent drop data (Figure 10). Both equations yield comparable results. Equation 1, though, yields slightly better results at higher drop heights. However, realistic drop heights are in the range of 12” to 24”.

Table 7: *Average Recorder’s Impact Acceleration from 30 Drops per Drop Height with 8 Layers of 5/16” Bubble Wrap underneath the Recorder*

Drop Height (in)	Average Recorder’s Impact Acceleration (g)
12	30.67
15	35.33
18	39.76
21	45.52
24	52.37
27	58.15
30	64.73
33	70.63
36	76.72
39	82.27
42	88.40
45	94.38
48	99.32

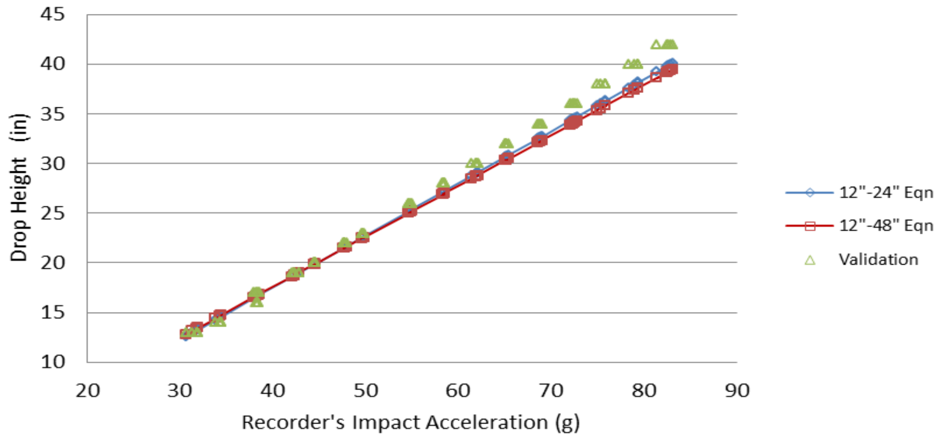

Figure 10: *Validation of Drop Heights Using 85 Drops*

To develop an equation to estimate the impact acceleration at the interior tote bottom, initially, direct measurement using an accelerometer was used. However, it was shown [3] that data collected was inconsistent with standard deviations in the range of 25% to 37% of average values. An indirect approach was then developed using 3 to 8 layers of $^5/_{16}$" bubble wrap. One and two layers of bubble wrap yielded unacceptable standard deviations. Data from 3 to 8 layer cases was used to predict the impact acceleration with one layer of $^5/_{16}$" bubble wrap. It should be noted that one layer of $^5/_{16}$" bubble wrap at tote bottom was recommended since it was shown to reduce impact acceleration by 34% in Table 2. These predicted impact accelerations were then correlated with drop heights to yield the following equation:

$$y = 4.1854x + 146.68 \qquad \text{… Eqn. 3}$$

Where x = drop height obtained from Equation 1 (inches) and y = impact acceleration at tote bottom with a layer of $^5/_{16}$" bubble wrap (g).

Validation was made using the 85 data points used earlier in drop height prediction. Three different trend lines were plotted in Figure 11; (1) direct approach (12" to 24" drop height range), (2) indirect approach (12" to 24" drop height range), and (3) indirect approach (12" to 42" drop height range). As can be seen, the two trend lines using indirect approach yielded much better results than that from direct approach. Also, the 12" to 24" range trend line was slightly better since it divided validation data points almost 50-50, i.e., 43 above and 42 below, while the 12" to 42" range trend line had 48 above and 37 below. It should be noted that the 85 data points for validation were obtained using direct measurement which yielded highly inconsistent data.

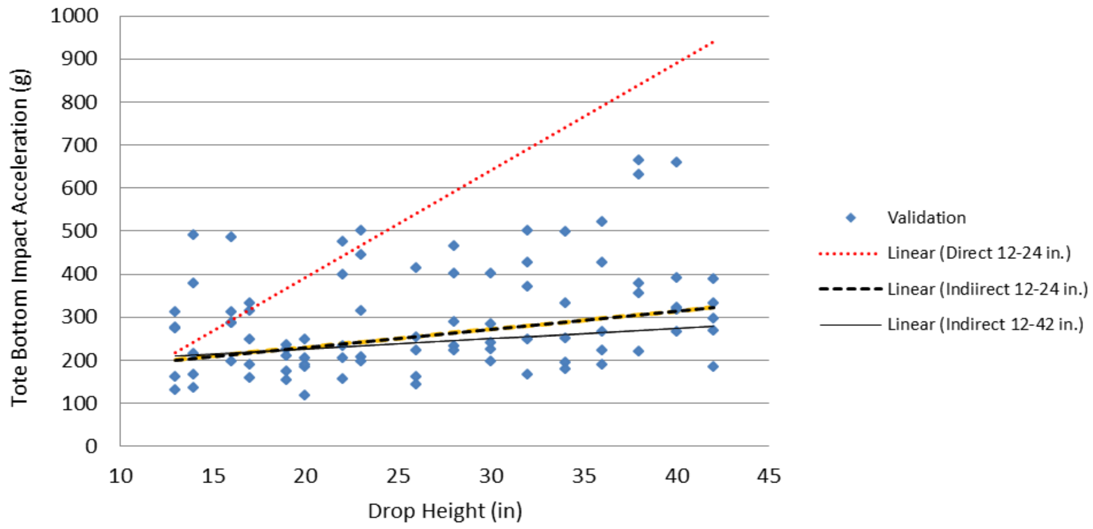

Figure 11: *Validation of Tote Bottom Impact Acceleration*

4. Conclusions

From the tote study at the Healthcare Packaging consortium, the following conclusions/ recommendations can be made:

- Randomly and partially filled plastic totes have high potential of product damages.
- Tote weight does not affect impact acceleration. However, heavier totes result in higher impact force.
- Providing a layer of $^{5}/_{16}$" bubble wrap sheet at the bottom of the tote interior could reduce impact acceleration by 34% while tighten up the space at the top using air pillows could reduce impact acceleration by 15%. Using both a bubble wrap sheet at tote bottom together with air pillows at tote top is the most effective way to reduce product damages.
- A drop height could be estimated accurately from an impact acceleration obtained from a shock recorder using Equation 1 given that the recorder is set the way described in this article.
- Impact acceleration at tote bottom is hard to predict. Equation 3 can provide an estimate, which could be off significantly from an actual single drop.
- All data presented was based on flat-bottom drops. Real-life drops could be on an edge or a corner, which would result in much higher impact accelerations.

Acknowledgement

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