Volume 5 • Number 3 • July 2011
ISSN: 1557-7244

Journal of APPLIED PACKAGING RESEARCH

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JOURNAL OF APPLIED PACKAGING RESEARCH—Published quarterly—January, April, July and October by DEStech Publications, Inc., 439 North Duke Street, Lancaster, PA 17602-4967.

This journal is recommended by The National Institute of Packaging Handling and Logistics Engineers (www.niphle.org).

Indexed by Chemical Abstracts Service.

Indexed and abstracted by Pira International.

Subscriptions: Annual $319 (Print), $319 (Electronic) and $344 (Print and Electronic). Single copy price $95.00. Foreign subscriptions add $45 per year for postage.

(ISSN 1557-7244)

DES*tech* Publications, Inc.
439 North Duke Street, Lancaster, PA 17602-4967, U.S.A.

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Effect of Horizontal Offset on Vertical Compression Strength of Stacked Corrugated Fiberboard Boxes

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ABSTRACT: The purpose of this study was to evaluate the effect of horizontal offset on the compression strength of stacked box configurations. Four different boxes of varying sizes and similar board combinations, made from similar flute but different manufacturers were studied. The single box compression strength for each type of box was determined to represent as the control for this study. The compression strength of control boxes were compared to overall strength of a three-high stack and in three different offset configurations. In addition, a set of perfectly aligned boxes stacked three high were compression tested for comparison with control and mis-aligned stacked boxes. The stack configurations were offset either in the length, width or diagonally (both length and width) with an offset distance of 12.7 mm, 25.4 mm or 38.1 mm (0.5, 1, and 1.5 inches).

1.0 INTRODUCTION

THE compression strength of a corrugated fiberboard shipping container is affected by various factors including but not limited to dimensions, flute size, basis weight of linerboards/medium, exposure to temperature and humidity, creep, stacking configuration, as well as shipping and handling. Some of these climatic and physical factors can contribute towards the natural variation and degradation in the fiberboard and box compression strength or the box's ability to stack and support other filled and loaded boxes during storage and shipping. Over the past four decades the industry has developed various methods to un-

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derstand the performance of a box after it is filled and supports a load to survive the various elements of the distribution environment [1–3]. The most common method to evaluate the strength of an "empty" box and then predict it's degradation due to each individual factor is to perform compression strength tests in the vertical orientation using a fixed rate compression tester. The information from this type of test helps package designers and engineers to predict performance and compensate for strength reducing factors that are associated with a given customer's distribution environment.

The test methods [4] that have been widely accepted and used globally to test empty box compression strength for over forty years is ASTM D642 "Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components and Unit Loads" or its International Standards Organization (ISO) equivalent ISO 12048 "Packaging-Complete, Filled Transport Packages-Compression and stacking test using a compression tester". For the last forty years paper fiberboard boxes are tested with no contents (empty) or filled with actual product. This information is used to compare their expected performance in actual conditions after they are filled and stacked in warehouses. The test method was originally developed by the paper industry through the Technical Association of Pulp and Paper Industries (TAPPI). TAPPI standard T804 was the original standard for "Compression Testing of Fiberboard Containers". The authors caution readers of this paper that while this has been the most used and internationally accepted test method to measure strength of a fiberboard box, testing of filled containers will have a significantly different performance. Bulk liquids and bulk granular products when filled in a fiberboard box will cause it to bulge and most likely reduce strength of the box, whereas semi-rigid and rigid contents will enhance overall package (combined box and contents) strength.

Box compression strength can be measured by either a floating platen or a fixed platen on a compression testing machine (ASTM D642) [4]. A research study [5] showed that there was no significant difference in box compression strength between the two methods, comparing several types of boxes. The conclusions found that there is more variation associated with the compression strength performance between identical boxes as opposed to the difference between fixed and floating platen methods [4]. However, both paper and corrugated fiberboard, and box manufacturing processes have improved considerably over the past few decades in order to reduce the natural variation in box compression strength, by increased refining and calendaring towards making mechanical properties of containerboard more uniform.

Additional studies have also shown that overall vertical compression strength of stacked boxes is lower than that of individually tested boxes [1]. Results show that in a three-high column stack of perfectly aligned boxes, strength reduction of 6–15% was observed in regular-slotted-container (RSC) style boxes, when compared to strength of a single box [1]. These effects are further magnified if the stack is misaligned [1,7]. A study performed previously investigated the reduction in box compression strength where a stack was deliberately offset by 12.7 mm, 25.4 mm or 38.1 mm (0.5, 1.0 and 1.5 inches) in the lateral and diagonally offset boxes [8]. The findings of this study show strength reductions of 59% in misaligned stacks as compared to individual box vertical compression strength [8]. Since, shipping containers are stacked on a pallet during transportation and warehousing, it is critical to minimize offsets during stacking to maintain a stable unitized load over long periods of storage.

Twede and Selke [9] have discussed the effects of humidity and creep on box performance based on earlier studies done by the Institute of Paper Chemistry. The study also cites factors for interlocking and column stacking of boxes on a pallet. The authors [9] state that column stacked aligned boxes on a pallet retain 85% of the box compression strength, whereas an interlock stack pattern that indicates an offset loading, will reduce strength of the stack by 50%.

During palletization of boxes on a pallet it is likely that misalignment among stacked layers may occur. Since, it has been established that vertical edges of a box contribute 2/3 (66.7%) of the total box compression strength [1], significant strength reductions in stacked boxes will occur if they get misaligned during stacking [7]. A study was performed to compare loss of strength in stacked boxes due to increase in relative humidity and misalignment [6]. It was found that misaligned stacks with lateral or diagonal offset showed greater reduction in compression strength than changes due to humidity [6]. Results showed that stacked boxes lost 24% of strength due to exposure to high humidity of 90%, whereas misalignment in lateral and diagonally offset stacks showed a 52% reduction. It was noted that the combined effect of both high humidity and misalignment of “tested” boxes was 64%. This study found a very interesting conclusion that combined effects of several factors (such as misalignment and humidity) do not show a cumulative effect based on the worse case of individual factors.

Table 1. Sample Box Specifications.

Box Type	ECT (Kgf/cm)	Length (m)	Width (m)	Height (m)	Fiberboard Box Supplier
Box 1	5.71	0.48	0.38	0.25	Coastal Container, MI
Box 2	5.71	0.48	0.33	0.15	Coastal Container, MI
Box 3	5.71	0.38	0.25	0.25	South Haven Packaging, MI
Box 4	5.71	0.41	0.30	0.25	Michcor Container, MI

2.0 MATERIALS AND METHODS

Four regular slotted fiber board boxes of varying dimensions made from same board grade with an ECT of 5.71 Kgf/cm were selected for this study (Table 1). The test samples were obtained from three different box suppliers in Michigan. These boxes were erected, hot glued, and pre-conditioned at 23°C (73°F) and 50% RH in accordance with "standard" conditions described in ASTM D4332 [10], for at least 72 hours prior to compression testing in accordance with ASTM D642 [4] (Figure 1). Thirty samples of each box type were tested for individual box compression strength using a compression tester (Lansmont Corporation, Monterey, CA). The vertical compression strength of individual

***Figure 1.** Boxes pre-conditioned at standard conditions for at least 72 hours.*

Figure 2. *Test set up for single box compression strength.*

boxes for each type as seen in Table 1 was represented as the "control" (Figure 2). Data measured with three-high stacking and misalignment was compared to these "control" strength values (Figure 2).

The second phase of this study compared the box compression strength of the three-high stack, with three different types of offsets (Length, Width and Diagonal or Both Side) as shown in Figure 2. The offset amounts used were 12.7, 25.4 and 38.1 mm (0.5, 1.0 and 1.5 inches). A set of perfectly aligned boxes stacked three-high were compression tested for comparison with control and a misaligned stack. Ten replicates of compression testing were performed for each test set up, and the experimental design is shown in Table 2. All tests were performed under "standard" conditions.

Table 2. Experimental Design for Different Test Treatments.

	Number of Replicates			
Stack Offset	**12.7 mm**	**25.4 mm**	**38.1 mm**	**Perfectly Aligned**
Length Panel	10	10	10	10
Width Panel	10	10	10	
Two Adjacent Panel	10	10	10	

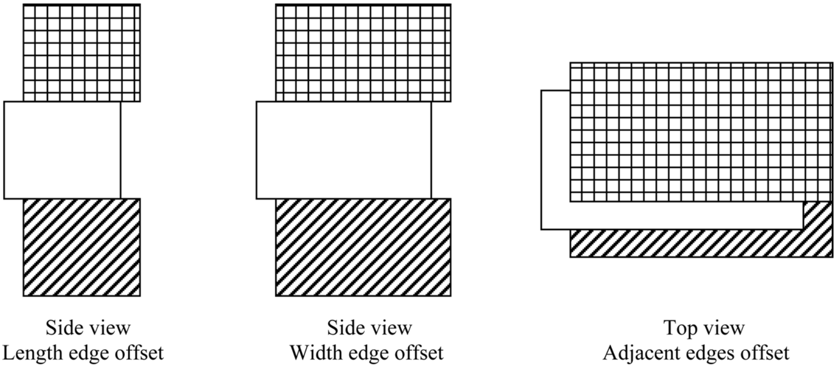

Figure 3. *Illustration of misaligned three-high stacks of boxes.*

3.0 RESULTS AND DISCUSSION

The data representing the average single box compression strength and that of a perfectly aligned three-high stack of boxes is shown in Table 3 and Table 4. The loss of strength in corrugated boxes as a function of lateral and diagonal offset was also studied (Figures 4–6). The average compression strength of three-high stack of boxes with the three different levels of misalignment was also measured and is shown in Table 5.

The single box measured compression strength was the highest for Box 2 followed by Box 1, Box 4 and Box 3 (Table 3). It was observed that the standard deviation in compression strength of identical boxes ranged between 6 to 8% for all types of boxes. A similar trend was observed for the box compression strength for perfectly aligned stack of boxes, where Box 2 was recorded to have the highest box compression strength followed by Box 1, Box 4 and Box 3. However, the standard deviation in compression strength of identically stacked boxes with no misalignment was between 4 to 10% for all types of boxes. This shows that the natural variation in single box compression strength further contributes to further variation in the stack of perfectly aligned boxes.

Table 3. Single Box Compression Strength.

Box Type	Compression Strength (lbs)	Max	Min
Box 1	227.7 ± 14.7	261.9	196.5
Box 2	280.8 ± 20.8	317.0	230.6
Box 3	138.1 ± 15.1	160.4	102.4
Box 4	191.2 ± 16.2	233.4	164.7

Table 4. Box Compression Strength of Aligned Stack.

Box Type	Compression Strength (Kg) Control
Box 1	212.9 ± 16.2
Box 2	227.5 ± 11.5
Box 3	127.0 ± 16.5
Box 4	176.4 ± 19.4

Data for this is shown Tables 3 and 4. The percent loss in compression strength of a perfectly aligned stack of boxes ranged from 6.5% to 19% (Table 6). This finding agrees with a study done earlier, where the percent reduction of compression strength of three-high stacked boxes ranged from 6–15% [3].

Similar trends were observed when comparing box compression strength of single boxes to the various misaligned stacks of boxes (Table 6). The percent loss in compression strength was observed to be the highest for misaligned stacks with an offset distance of 38.1 mm (1.5 in) followed by the 25.4 mm (1.0 in) and 12.7 mm (0.5 in) offset in the lateral directions along the length and the width (Table 7) for all four box types. However, the effect of offset direction on box compression strength was the highest when a stack of box was diagonally offset by

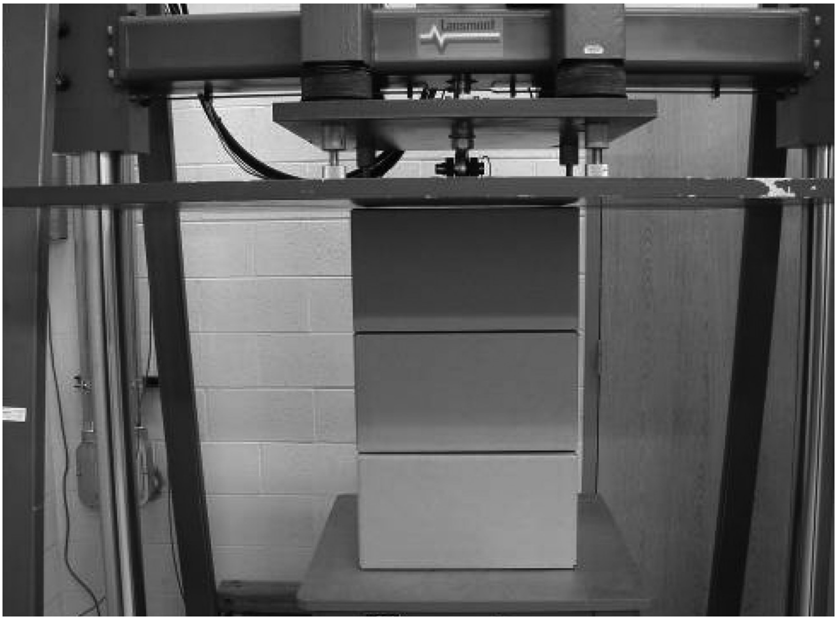

Figure 4. *Test setup for misaligned three-high stacks of boxes along the long edge.*

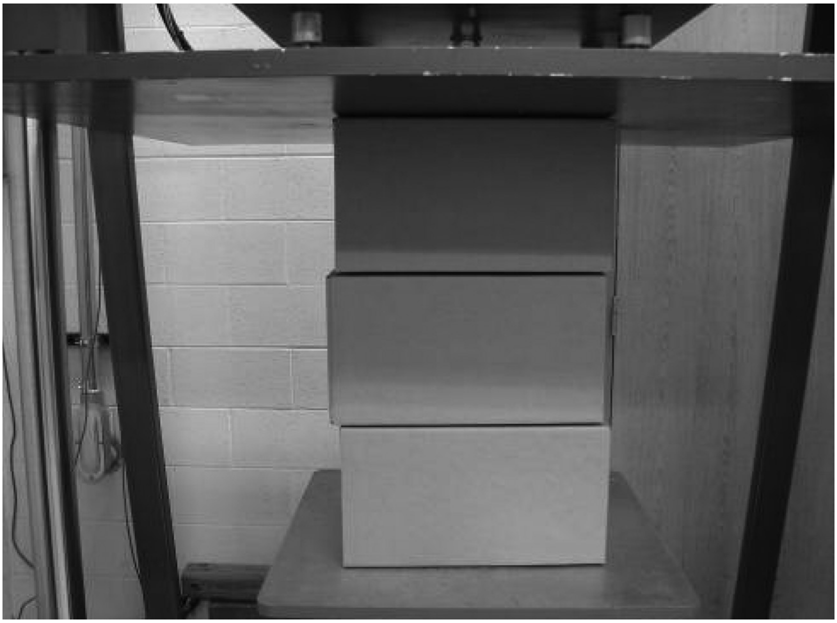

Figure 5. *Test setup for misaligned three-high stacks of boxes along the wide edge.*

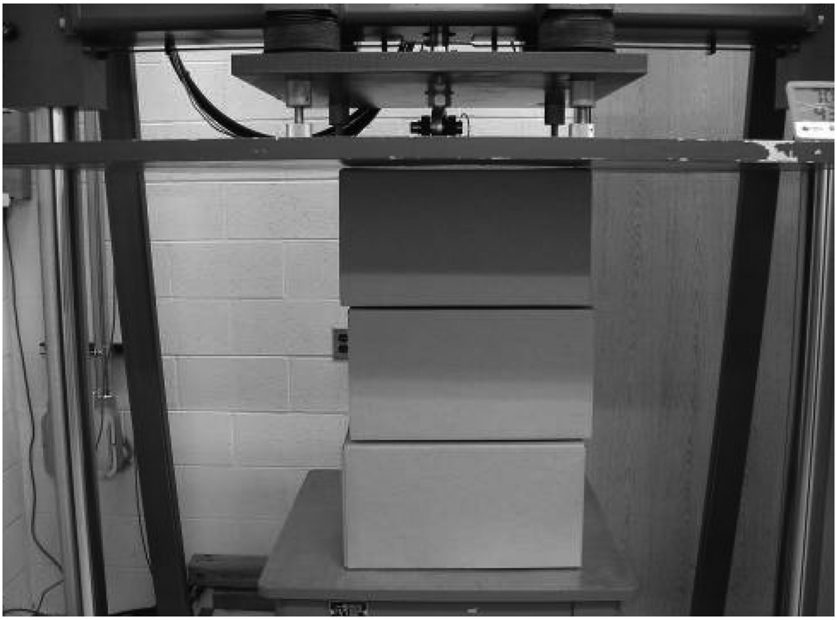

Figure 6. *Test setup for misaligned three-high stacks of boxes along the adjacent edges.*

Table 5. Box Compression Strength of Mis-aligned Stack.

	Compression Strength (Kg)		
Box Type	**Offset 12.7 mm**	**Offset 25.4 mm**	**Offset 38.1 mm**
		Length Panel	
Box 1	202.6 ± 8.3	154.7 ± 19.1	137.7 ± 35.6
Box 2	196.6 ± 11.8	168.6 ± 24.2	149.5 ± 12.1
Box 3	94.4 ± 4.7	84.3 ± 8.3	80.6 ± 6.5
Box 4	145.3 ± 8.6	113.7 ± 16.3	103.0 ± 9.7
		Width Panel	
Box 1	185.7 ± 10.9	169.6 ± 10.1	164.3 ± 9.7
Box 2	206.7 ± 16.1	193.0 ± 24.2	171.0 ± 13.8
Box 3	91.9 ± 11.1	80.6 ± 8.2	76.1 ± 6.5
Box 4	149.6 ± 14.4	130.7 ± 7.1	115.9 ± 14.2
		Adjacent Panels	
Box 1	186.2 ± 9.2	147.2 ± 5.2	109.1 ± 8.3
Box 2	188.2 ± 8.9	152.8 ± 5.3	113.3 ± 10.8
Box 3	95.7 ± 6.1	76.7 ± 5.4	54.5 ± 0.6
Box 4	136.8 ± 17.0	105.0 ± 13.2	89.1 ± 19.9

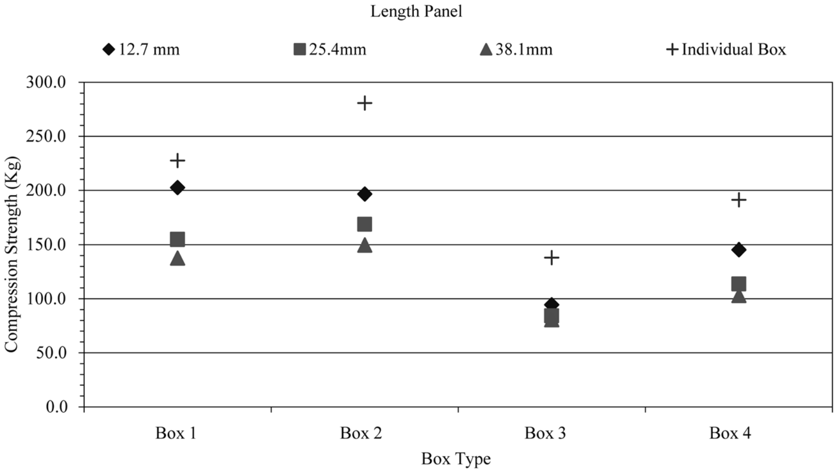

Figure 7. *Compression strength results as a function of offset on the long edge.*

Table 6. Percent Loss in Box Compression Strength of Aligned Stack.

Box Type	Percent Loss Compression Strength
Box 1	6.5%
Box 2	19.0%
Box 3	8.0%
Box 4	7.8%

38.1 mm (1.5 inches). Table 7 shows the data for boxes stacked with an offset. It is clear that even the smallest offset of 12.7 mm or 0.5 inch produces a large reduction in compression strength. This can be seen in Figures 7–12. Additional offset amounts continued to show additional reduction in strength.

4.0 CONCLUSIONS

The following conclusions were reached in this study:

1. A perfectly aligned stack of boxes shows a 6–15% reduction in compression strength when compared to the individual compression strength of a box, irrespective of the box specification.
2. Stack misalignment contributed towards the reduction of box compression strength.
3. Compression strength of stacked boxes with an offset of 12.7 in either of the 3 directions showed similar reduction in box compression strength for all sizes of tested for this study.

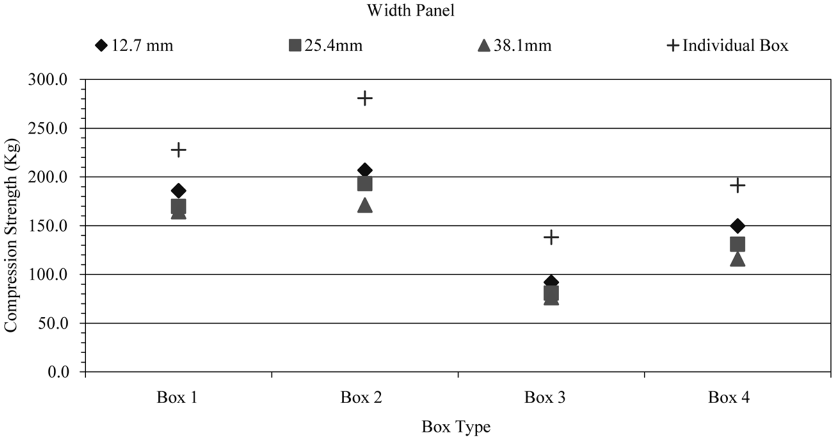

***Figure 8.** Compression strength results as a function of offset on the wide edge.*

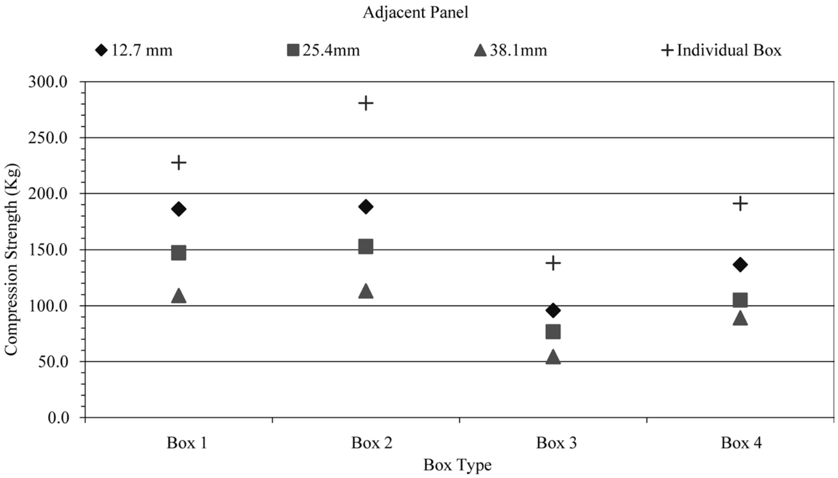

Figure 9. *Compression strength results as a function of offset on 2 adjacent edges.*

4. The reduction of box compression strength of a misaligned stack as an effect of offset distance and direction was more pronounced for 25.4 mm and 38.1 mm offset along the length, width and adjacent panels.
5. Reduction in box compression strength was the highest for stack offset along the adjacent panels followed by length and width panel.

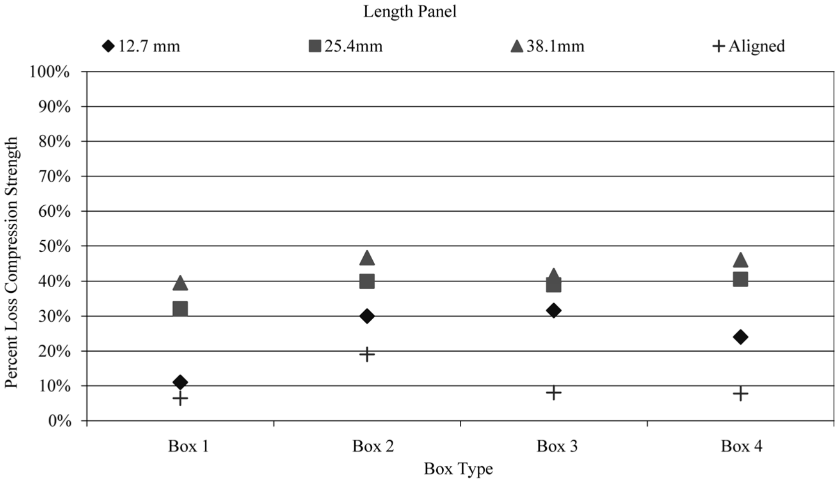

Figure 10. *Percent Loss in box compression strength of mis-aligned stack along the long edge.*

Table 7. Percent Loss in Box Compression Strength of Mis-aligned Stack of Corrugated Box.

	Percent Loss in Box Compression Strength		
Box Type	**Offset 12.7 mm**	**Offset 25.4 mm**	**Offset 38.1 mm**
		Length Panel	
Box 1	11%	32%	40%
Box 2	30%	40%	47%
Box 3	32%	39%	42%
Box 4	24%	41%	46%
		Width Panel	
Box 1	18%	26%	28%
Box 2	26%	31%	39%
Box 3	33%	42%	45%
Box 4	22%	32%	39%
		Adjacent Panels	
Box 1	18%	35%	52%
Box 2	33%	46%	60%
Box 3	31%	44%	61%
Box 4	28%	45%	53%

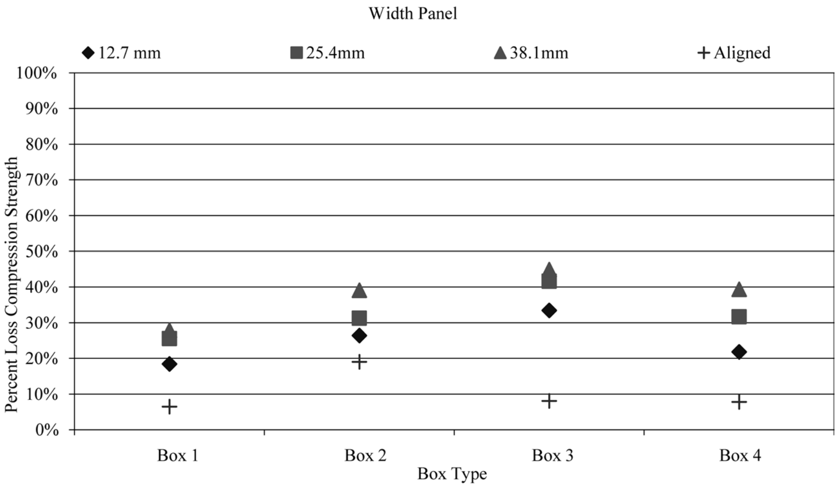

Figure 11. *Percent Loss in box compression strength of mis-aligned stack along the wide edge.*

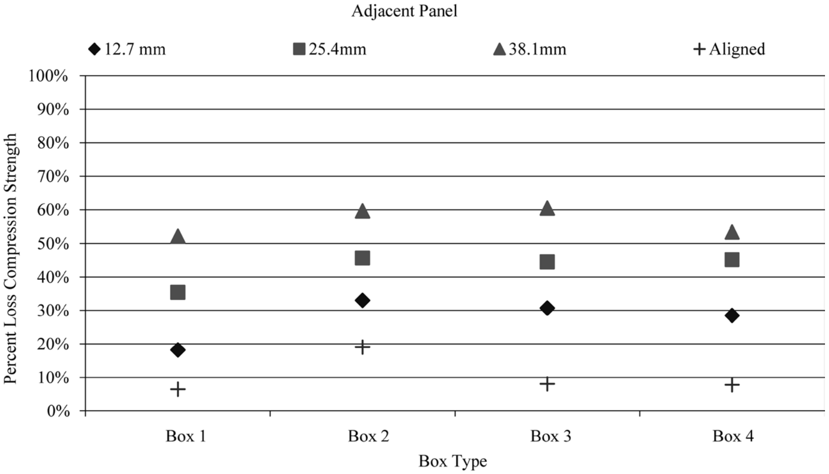

Figure 12. *Percent Loss in box compression strength of mis-aligned stack along the adjacent edges.*

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Determine Natural Frequencies of Stacked Corrugated Boxes Using a Roving Hammer

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ABSTRACT: Stacked vibration test is a conventional method to identify natural frequencies of stacked shipping units, using broad ranged ASTM D 4169 test. This study aims to determine the dynamic properties of stacked corrugated boxes using a roving hammer. The mathematical model of a four (4)- layer stacked corrugated boxes was established first to determine the natural frequency of the corrugated box. Experimental modal analysis based on roving hammer and sweep vibration testing were then carried out for the stacked shipping units. In order to distinguish the structure frequency of the stacking layers from the natural frequency of the corrugated box, experimental modal analysis was conducted for stacked boxes for one to four layers. The results of the experiments were compared with each other and led to the conclusion that roving hammer impact testing provides an effective method to determine the structure frequencies of a stacked unit on site.

INTRODUCTION

THE unitized shipping units are usually stacked on a single pallet or slip sheet for transportation in a tractor trailer. The rough road surface, unbalanced tire system and flexing of the trailer causes the unitized shipping units to experience vertical impact and vibration. In order to identify the natural frequency of the stacked shipping units, pre shipments tests such as ASTM D4169 or ASTM D 999 are usually used to replicate the distribution hazards by vertically stacked shipping units in a single column on a laboratory based vibration table. The frequency response function (FRF) and natural frequency are measured when the vibration table generates vibration with a variety of frequencies. Running such a test requires an investment in vibration tester, and the testing is extensive and resource–consuming.

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Although the stacked corrugated boxes are multiple degree of freedom and have some degree of non linearity, they can generally be represented as a superposition of single degree of freedom (SDOF) linear models. Urbanik [2] developed the analytical model for a four layers of stacked corrugated boxes and developed the max transmission ability and amplification based on the three single degree of freedom (SDOF). Natural frequency was predicted in his model using the formula $\omega = (k/m)^{1/2}$. Where k is the linearized stiffness from the compression test of the corrugated boxes. And m is the weight of the product and corrugated box. Vincent *et al.* [3] developed a metal spring based, single degree-freedom series physical system, representing single, vertical stacked units. A Numeric model was developed based on Simulink. Frequency response function (FRF) generated by the numeric model was compared to the physical model. Wang [4] also developed the three layer physical model based on a combination of the metal springs. The measured frequency response function (FRF) based on the physical model and computed FRF based on simulation software were investigated. The coupled stiffness was also predicted based on the numerical model. Both studies showed a good agreement in FRF between the physical model and numerical model.

This study introduces experimental modal analysis to identify dynamic properties of stacked corrugated boxes. Experimental modal analysis has been used by industries for many years in determining dynamic properties of a structure. The method is not reliant on large testing equipment and can be performed on site. The natural frequencies of the system are easily determined with an accelerometer and amplifier and the collected data can be quickly converted to the frequency domain by FFT analysis.

MATHEMATICAL MODEL OF STACKED CORRUGATED BOXES

A mathematical model for the stacked corrugated boxes used can be determined by treating each box as a single spring- damped system equivalent to the other boxes used. The mass of each box in this study is equal to the mass of the weighted wooden box inside, the foam packaging used in each corner of the box, and the cardboard box itself.

When only a single box is being tested, the mathematical equation for the box is the same as that of a mass damped system in free vibra-

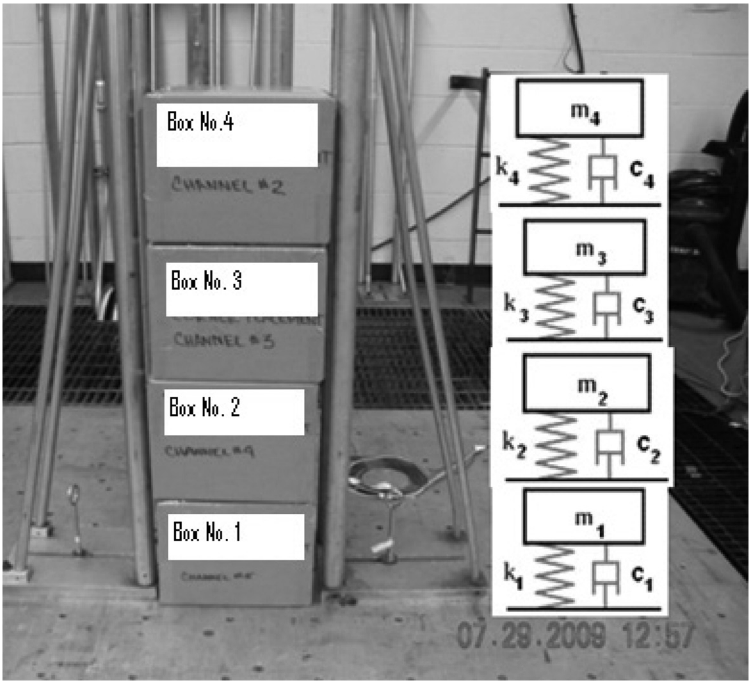


Figure 1. *Stacked corrugated boxes on the vibration tester and the mathematical model.*

tion, $m\ddot{x}+c\dot{x}+kx=0$. When there are two boxes, this results in two equations.

When three or four boxes are used, the resulting equations are in the same form as with only two boxes. When a force *f*(*t*) is applied to the base of the system, the right hand side of the equation will be equal to the input force. The mathematical model of the Figure 1 can be described in matrix form as follows:

$$[\mathrm{M}]\ddot{X}+[\mathrm{C}]\dot{X}+[\mathrm{K}]X=0 \tag{1}$$

Where [M] is the mass matrix, [C] is the damping coefficient matrix. [K] is the matrix of stiffness, and [F] is the force matrix. The four layer stacked corrugated boxes act as a base exciting system when the base force [F] is applied.

A measured mass, spring constant and damping coefficient must be experimentally derived in order to determine the frequency response function of the system. The formulas derived for each box in the stack should correlate closely to any experimentally data collected from each box.

Below is the mass matrix for the four box stack modeling described in Equation (1) .

$$[\mathrm{M}]=\begin{bmatrix} m1 & 0 & 0 & 0 \\ 0 & m2 & 0 & 0 \\ 0 & 0 & m3 & 0 \\ 0 & 0 & 0 & m4 \end{bmatrix} \tag{2}$$

The spring constant matrix for the four box stack is below. The natural frequency of the system can be determined by taking the square root of [K]/[M] or by solving $[\mathrm{K}] - \omega^2[\mathrm{M}] = 0$.

$$[\mathrm{K}]=\begin{bmatrix} k1+k2 & -k2 & 0 & 0 \\ -k2 & k2+k3 & -k3 & 0 \\ 0 & -k3 & k3+k4 & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix} \tag{3}$$

The damping coefficient matrix for the four box stack is below.

$$[\mathrm{C}]=\begin{bmatrix} c1+c2 & -c2 & 0 & 0 \\ -c2 & c2+c3 & -c3 & 0 \\ 0 & -c3 & c3+c4 & -c4 \\ 0 & 0 & -c4 & c4 \end{bmatrix} \tag{4}$$

It is being assumed that the mass, spring constant for each box was the same in the study. Each shipping unit in the four layer stacked was an identical corrugated box, the box was uniform in 0201 type and size and contained a 6.8 kg wooden box filled with sand, cushioned in all eight corners with 0.085 kg of foam. 32 lb. C-flute corrugated board was used to construct the corrugated box. In this study, the wooden box cushioned with foam was taken as a combined product. And, the spring constant and damping between the wooden box and corrugated box are not considered in the mathematic model. The mass of each box, *m* is the sum of the cardboard box (0.312 kg), the eight foam corners (0.085 kg each), the wooden box (2.27 kg), and the sand filling the wooden box (4.54 kg), for a total weight of 7.8 kg.

[K] and [C] in this model are the static stiffness matrix and the damping coefficient matrix of the stacked corrugated boxes. [K] was derived from the compression-strain curve. In the static compression-

Table 1. Static Stiffness Obtained from Compression Test.

Static Stiffness from Compression Tests			
Sample	**Δf (N)**	**Δx (m)**	**k (N/m)**
1	489	–0.0019	257368.42
2	525	–0.0019	276315.79
3	578	–0.0019	304210.53
4	512	–0.0019	269473.68
5	756	–0.0019	397894.74
Average	**572**	**–0.0019**	**301052.63**
St Deviation	**96.62**	**0**	**50851.69**

strain curve, the linear portion of the stress-strain curve was taken as the static stiffness. The stacked units vibrates in the elastic region during the transportation. The following table illustrated the static stiffness from five box samples. The averaged static stiffness for each box was determined to be 301.05 kN/m using a Lansmont compression testing machine under the ambient environment at 23°C and 50% RH.

Having derived the static stiffness of the corrugated board boxes, the four layer stacked corrugated boxes can be described in a matrix. The natural frequency can then be computed theoretically using the measured mass, stiffness of the system. Solving for the matrix $[K] - \omega^2[M] = [0]$ allows the natural frequency of the system to be determined. According to values to be placed in M are:

$$[M] = \begin{bmatrix} 7.8 & 0 & 0 & 0 \\ 0 & 7.8 & 0 & 0 \\ 0 & 0 & 7.8 & 0 \\ 0 & 0 & 0 & 7.8 \end{bmatrix} \tag{5}$$

The values for the stiffness K are:

$$[K] = \begin{bmatrix} 602{,}105.26 & -301{,}052.63 & 0 & 0 \\ -301{,}052.63 & 602{,}105.26 & -301{,}052.63 & 0 \\ 0 & -301{,}052.63 & 602{,}105.26 & -301{,}052.63 \\ 0 & 0 & -301{,}052.63 & 301{,}052.63 \end{bmatrix} \tag{6}$$

The natural frequency of the systems can be calculated from [K] and [M], using the equation $[K] - \omega^2[M] = 0$ and solving a zero filled matrix.

$$\begin{bmatrix} 602{,}105.26-7.8\varpi^2 & -301{,}052.63 & 0 & 0 \\ -301{,}052.63 & 602{,}105.26-7.8\varpi^2 & -301{,}052.63 & 0 \\ 0 & -301{,}052.63 & 602{,}105.26-7.8\varpi^2 & -301{,}052.63 \\ 0 & 0 & -301{,}052.63 & 301{,}052.63-7.8\varpi^2 \end{bmatrix} = 0 \tag{7}$$

Solving the matrix equation for zero results in a ω value of 196 radians, which is equal to 31.2 Hertz. This corresponds to the natural frequency of the corrugated box. And it does not take into account the stiffness of the wooden box that the cushion foam contained within because the system is taken as SDOF.

DETERMINE THE NATURAL FREQUENCIES USING A ROVING HAMMER

Experimental modal analysis refers to the relationship between vibration theory and measured quantities. Experimental modal is obtained from the Frequency Response Function (FRF) measurement that is usually represented by a matrix of differential equations as shown in the Figure 2 as F(ω) = H(ω)X(ω), where F(ω) is the exciting force as input, X(ω) is the output in the form of displacement, velocity or acceleration, and H(ω) is the FRF representing the dynamic properties of the structure. An experimental modal analysis is typically carried out by exciting a structure in one location using a roving hammer and measuring the response at other locations of the structure.

After a frequency response function is determined, it is easier to analyze if it is broken up into modes. Each mode will have a single peak which corresponds to a natural frequency of the system, and the sum of the modes is the FRF of a structure. When using an impulse hammer as shown in Figure 2, the recorded frequency response for each test is placed in a matrix for the Fast Fourier Transform (FFT) of the system. In the diagram, the frequency response for each point corresponding to H(ω) at that point, which leads to a specific response X, given each input F at striking point 9. The Fourier transform is computed by an oscilloscope and the output X(ω) is charted. Changing the response sensors locations accordingly from sampling location 1 to 8, an array of output modes of $X(t)\ddot{X}(t)$ can be derived, $\ddot{X}_{19}(t)\ \ldots\ \ddot{X}_{89}$.

The mechanical system H(ω) transforming input F(ω) into output X(ω) is not measured in this experiment because the input force is not

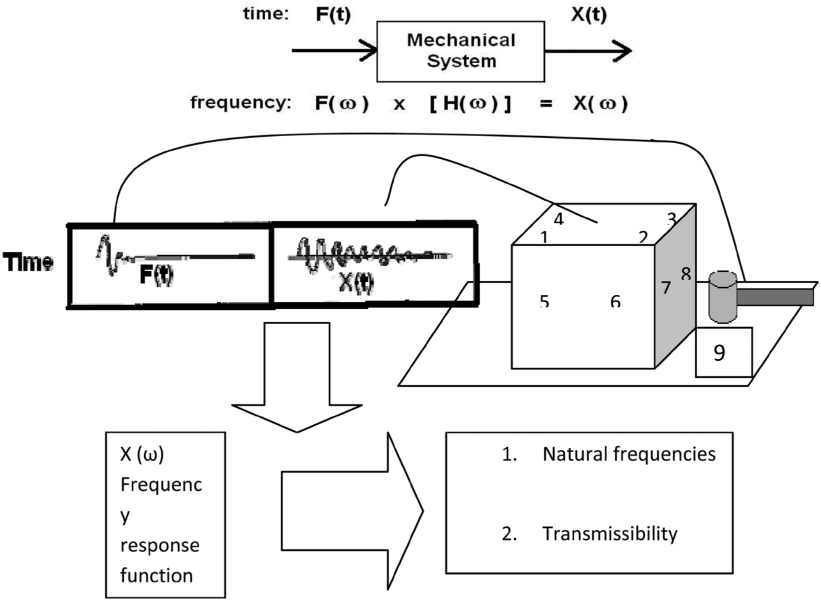


Figure 2. *Illustration of a roving hammer impact test.*

being calculated for each hammer strike. Computer simulation would be necessary to characterize the mechanical system H(ω) using the measured input force and output frequency responses at each point on the box.

A Kistler SN 2003532 K-SHEAR8704B50M1 accelerometer was attached to the box for accelerometer tests. The accelerometer was attached to a Kistler 5114 amplifier which was then attached to an oscilloscope.

Tests were performed with between one and four boxes in the stack with the hammer being used to excite the platform or the top box in the stack. In order to place the accelerometer in the direction within the boxes, a small hole was created in the foam cushion. The accelerometer was then threaded through the hole after it was carefully attached to the flap inside the corrugated box. The roving hammer is made of the hard rubber. The material of roving hammer depends on weather the impacted system can be excited or not. The testing condition is 23°C and 50% RH.

Average 2000 Data points after each impact were collected on the oscilloscope over a 40 millisecond period using the single sequence function. These data points were processed using fast fourier transform (FFT) function available on the oscilloscope. From Natural frequencies were determined by identifying the frequenct at peak points on the FFT curve.

All data gathered on the oscilloscope was saved to a floppy disk and transferred to a spreadsheet in excel format for further analysis.

The frequency spectrum resulting from applying a Fourier Transform to the acceleration data is stated in Figure 5. The first peak frequency seen in the spectra is at 9–10 Hz, representing c1-k1 structure in Figure 1. The second peak frequency is at 20 Hz. This frequency represents the natural frequency of substructure c2- and k2 in Figure 1. The third peak frequency is at 27 Hz, representing c3-k3 substructure, the last peak frequency is at 38 Hz representing the c4-k structure in Figure 1.

STACKED VIBRATION TEST

In order to verify the dynamic properties of the stacked corrugated boxes, stacked vibration test was carried out in accordance to both ASTM D 4169 standard (Figure 1). Sweep test with profile of 0.5G/3–100 Hz was carried out to identify the natural frequency of the system (Figure 1). The accelerometer sensor was installed in the inner flap of the corrugated board. The accelerometer was tested in the locations underneath the inner flap of the corrugated box, the same locations as the experimental modal analysis.

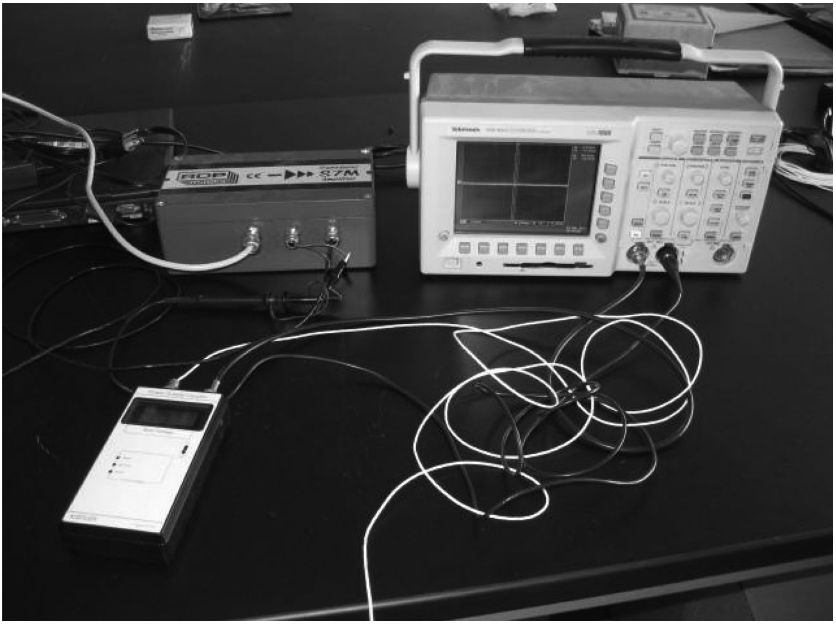


Figure 3. *5114 Amplifier and Oscilloscope used in the experiment.*

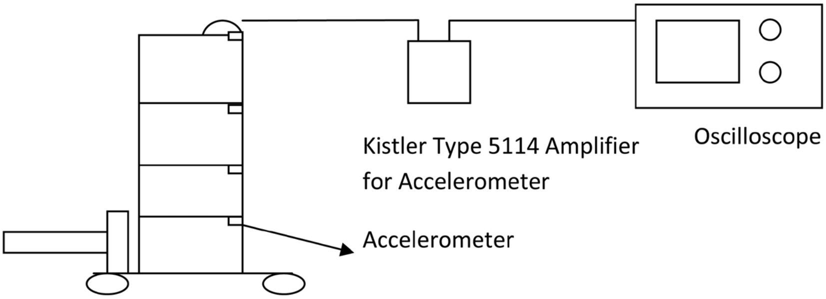


Figure 4. *Experimental set up of roving hammer excitement for a four (4)–layer stacked corrugated boxes.*

ANALYSIS

Table 2 summarizes the peak frequencies obtained from three the different methods. The 1st peak natural frequency derived from the experimental modal analysis (Figure 6) is close to the natural frequency 9–10 Hz identified by the sweep vibration testing. The 2nd peak natural frequencies varied from 32.5–35.5 Hz for boxes in the middle and 41.5–43.5 Hz for the top and bottom box. The peak frequencies 32.5–35.5 Hz are close to the from the vibration test and the calculated frequency from the Equation (7) as well.

In order to distinguish the natural frequencies and their represented structure, experimental modal analyses were performed again for the

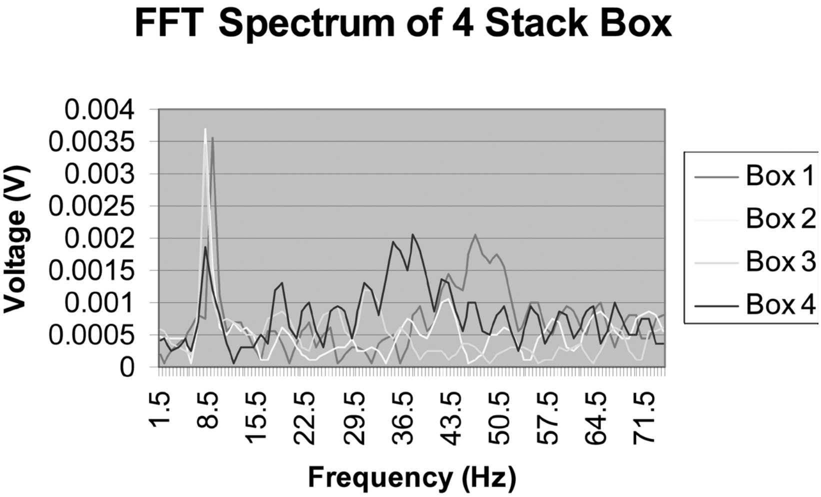
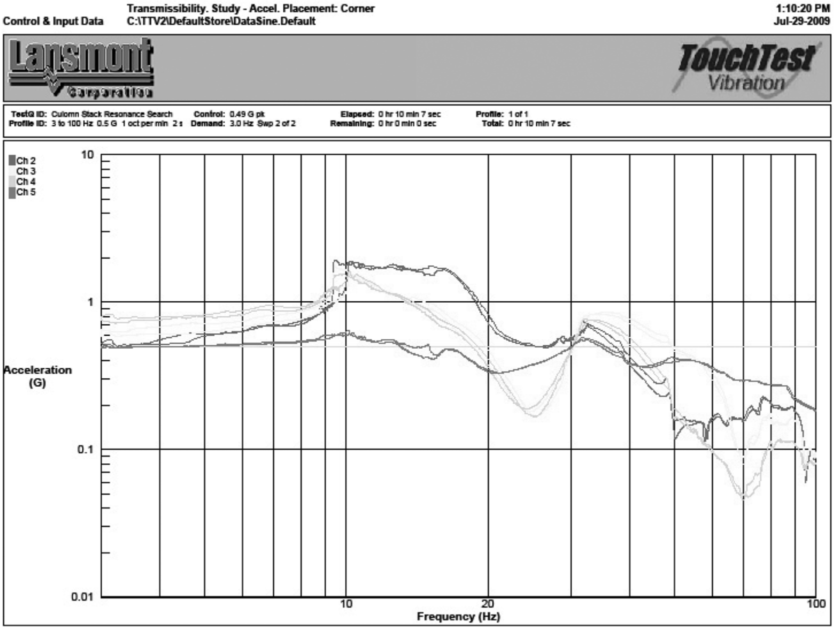


Figure 5. *FFT and the natural frequencies measured on each box for four (4)-stacked stacking corrugated boxes.*



Control & Input Data
Transmissibility. Study - Accel. Placement: Corner
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1:10:20 PM
Jul-29-2009

TestQ ID: Culomn Stack Resonance Search
Profile ID: 3 to 100 Hz 0.5 G 1 oct per min 2 s
Control: 0.49 G pk
Demand: 3.0 Hz Swp 2 of 2
Elapsed: 0 hr 10 min 7 sec
Remaining: 0 hr 0 min 0 sec
Profile: 1 of 1
Total: 0 hr 10 min 7 sec

Figure 6. *The FFT spectrum derived from the sweep test based on ASTM D 4169 (Ch 5–Box. 1; Ch 4–Box 2; Ch 3–box 3; Ch 2–box 4).*

one (1)–stack, two (2)–stack, three (3)–stack and four (4)–stack corrugated boxes respectively. The Figure 7 shows a summary of FFT analysis for the four measurements. In the FFT chart, the 1st peak frequency demonstrates a shift to a lower side when stacking layer increases from 1-layer to 4-layer stacking. The peak 9.5 Hz appears only in the 4-stacking layer FFT chart which leads the conclusion that the 9–10 Hz is the structure frequency of the four (4)–stacked boxes, and the frequency range of 31–35.5 Hz is the natural frequency of the corrugated box.

Table 3. Peak Frequencies Obtained from Three Methods.

Position of the Corrugated Box in the Stacking	Peak Frequencies from 3–100 Hz Sweep Test, 0.5 G Base Excitation	Peak Frequencies from Experimental Modal Analysis	Natural Frequency ω Calculated from $[K] - \omega^2[M] = 0$
Top	9 Hz–18 Hz; 33 Hz	8.5 Hz,43.5 Hz	31.2 Hz
2nd from the top	9 Hz, 33 Hz	8.5 Hz, 32.5 Hz	
3rd from the top	9 Hz, 33 Hz	8.5Hz, 35.5 Hz	
Bottom	10 Hz, 33 Hz	9.5 Hz, 41.5 Hz	

CONCLUSION

Three different methods were used in this paper to obtain the natural frequencies and structure frequency for a stacked corrugated boxes: the calculation method based on the mathematical model, the experimental modal analysis and the actual vibration test. The calculated natural frequency of the corrugated box is in good agreement with the actual vibration test. The experimental modal analysis was able to identify the structure frequency related to the stacking layer that was also identified in the actual vibration test. The natural frequency obtained from the experimental modal analysis are in partial good agreement with the actual vibration test.

Comparing the vibration test, equipments involved in experimental modal analysis are small and light equipment. The testing can be carried out on site. If the purpose of the actual vibration test is to identify the structure and natural frequencies of the system, the experimental modal analysis provides an effective method to determine the structure frequencies of a stacked unit on site.

The FFT chart from experimental modal analysis showed a clear and sharp peak than the FFT spectrum from the vibration test due to its simple excitement created by hammer impact. Further study is required to study the response difference between the actual vibration test and experimental modal analysis in certain frequency range.

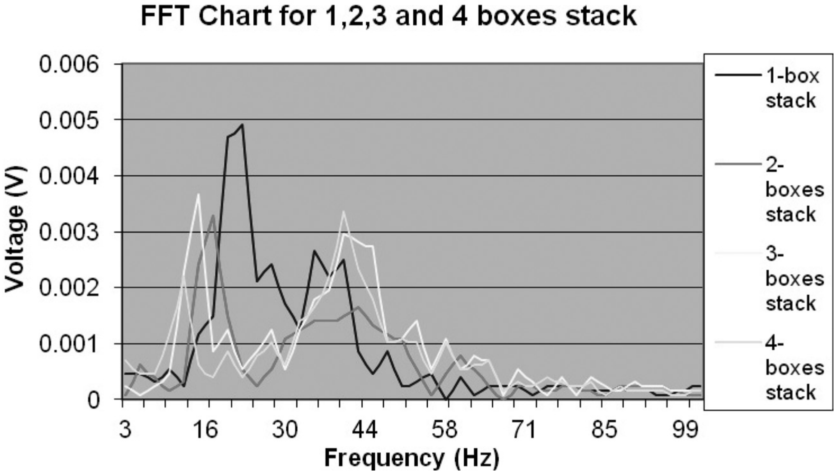

Figure 7. FFT chart for 1, 2, 3 and 4 boxes stack.

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Effect of Palletized Box Offset on Compression Strength of Unitized and Stacked Empty Corrugated Fiberboard Boxes

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ABSTRACT: The purpose of this study was to evaluate the effect of pallet type, tie-sheet and stack configuration on compression strength of a palletized load of boxes. Four boxes made from similar board grade and different dimensions were selected for this study. The column stack configuration which represented the control was compared with the 3 stack configurations either on a CHEP® or GMA pallet. The unitized load either had a tie-sheet in between layers or no tie-sheet between layers of boxes on the respective pallets, for compression strength comparison with the control unitized load represented by a column stack configuration. This is the first of a series of two papers.

1.0 INTRODUCTION

THE compression strength of corrugated fiberboard shipping containers is affected by various factors including temperature, moisture content, humidity, flute size and the basis weight of linerboard and medium of a corrugated container. These factors can contribute towards the natural variation in board characteristics eventually affecting the variation in box compression strength of two identical boxes.

Corrugated shipping containers containing goods are typically stacked on a pallet that are unitized using a stretch wrap film or banding for distribution and storage in a warehouse. Stack configurations, to make a unitized load of the shipping containers on a pallet, typically depend on their size and dimensions. The two commonly practiced stack configuration in the packaging industry are 'column' and 'interlocked'.

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Stacking operations in a manufacturing plant can be either automated or manual depending on the volume of the production. Irrespective of the method of stacking a common issue that is generally faced is that a unitized load may not be completely situated on top of the pallet deck boards. Sometimes the bottom layer of boxes overhangs slightly off the pallet. The magnitude of this overhang may compromise the load bearing strength of the bottom layer, eventually causing pallet instability.

To address this issue a study was performed where the effect of various magnitudes of overhang and stack configurations was evaluated [1]. It was discovered that the percent strength loss for a palletized box compression strength varied considerably depending on the box geometry and possibly by board grade and flute size [1]. This study showed that the percent loss in palletized box compression strength as an effect of overhang can range between 23–49% depending on the magnitude and direction (length, width or adjacent panel) of overhang [1]. Similarly, palletized box compression strength was also observed to be affected by the stacking configuration of the unitized load of boxes [1]. It was ascertained that there was a 45% loss in palletized box compression strength compared to an interlocked configuration [1]. These losses in palletized box compression strength can drastically affect pallet stability during distribution, handling or storage in a warehouse.

A research study was conducted where three palletized loads of two-piece plastic cans were stacked in various staggered positions to evaluate the effect of off-set on stack stability [2]. It was discovered that a 153 mm (6 in) pallet offset in the middle pallet and a 204 mm (8 in) pallet offset on the top pallet made the 3 high palletized load unstable resulting to a tip-over of the top two stacked pallet loads [2]. This can have very detrimental reparations in a warehouse environment where workers carry out their daily operations. This makes it necessary to ascertain the effect of overhang and stack configurations on palletized box compression strength to assess pallet stability during transportation and handling. Therefore, the focus of this study was to evaluate the effect of pallet type, tie-sheet and stack configuration on compression strength of a palletized load of boxes with different dimensions.

In 1975, Phil M. Ziegler, sent results of findings of a major research study conducted by the Container Corporation of America to all designers of corrugated packaging on behalf of the Technical Services of the Container Divisions. The report stated various factors that resulted in loss in top-to-bottom box compression strength due to pallet overhang, box misalignment and interlocking. It also stated that *"Without* *exception our customers underestimate the deterioration in top to bottom compression of containers when they are improperly handled and stacked in the distribution system"* [3]. The study further concluded that as much as 29% loss in compression strength is due to misalignment vertically and a 45% loss of compression is due to an interlocking pattern on a three high pallet unit. Data and test details on this extensive testing done on empty boxes was discussed by Ievans [3].

The results from this study were further presented in a Fibre Box Association document called "*CORRU~FACTS*" that summarized "corrugated facts for users of corrugated packaging" [4]. This document summarized the results of the study as:

1. Pallet Overhang can reduce top to bottom compression up to 32%.
2. Wooden pallets can reduce top to bottom compression up to 32%.
3. Interlocked patterns can reduce top to bottom compression up to 55%.

In addition, this document stated that to provide load stability of stacked corrugated boxes in transit a shipper had four options. These were reported as:

1. Use of anti-skid treatment on the flaps of the containers to increase the coefficient of friction.
2. Spot-gluing the tiers of a pallet load
3. Use of a plastic or corrugated shroud.
4. Use of a Master Pack

It also concluded that "whenever possible make sure that you utilize 'vertical (columnar) stacking rather than interlocked stacking' ".

The test methods that have been widely accepted and used globally to test empty box compression strength for over forty years are ASTM D642 "Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components and Unit Loads" [5] or its International Standards Organization (ISO) equivalent ISO 12048 "Packaging—Complete, Filled Transport Packages—Compression and Stacking Test Using a Compression Tester" [6].

It has been a standard practice for corrugated fiberboard boxes to be tested with no contents (empty) to compare their expected performance in actual conditions after they are filled and stacked in warehouses. The test methodology was originally developed by the paper industry through Technical Association of Pulp and Paper Industries (TAPPI). TAPPI standard T804 was the original standard for "Compression Testing of Fiberboard Containers" [7]. The authors caution readers of this paper that while this has been the most used and internationally accepted test method to measure strength of a fiberboard box, testing of filled containers typically have a significantly different performance. Bulk liquids and bulk granular products when filled in a corrugated fiberboard boxes cause them to bulge and most likely loose strength, whereas semi-rigid and rigid contents tend to enhance overall package (box and contents) strength.

Box compression strength can be measured by using either a floating platen or a fixed platen on a compression testing machine [8]. A past study has shown that there was no significant differences in single box compression strength between the two methods of compression testing for several types of boxes [8]. This was more than likely because the natural variation in the compression strength of two identical boxes masked the difference between the two test methods. However, corrugated board and box manufacturing processes have improved considerably over the years in order to reduce the natural variation in box compression strength.

2.0 MATERIALS AND METHODS

Four corrugated fiberboard regular slotted containers (FEFCO 0201) of varying dimensions and made from the same board grade (ECT of 5.71 Kgf/cm) were selected for this study (Table 1). The test samples were obtained from three different suppliers in Michigan. These boxes were erected, closed without any contents and sealed using hot melt glue, and pre-conditioned at 23°C (73°F) and 50% RH (standard conditions) for at least 72 hours prior to compression testing.

This study selected two types of standard wooden pallets measuring 1219 × 1016 × 127 mm (48 × 40 × 5 in). The first type of pallet was in conformance to the requirements of the Grocery Manufacturers Association (GMA). The second type of pallet was manufactured per the specifications of the Commonwealth Handling Equipment Pool organization (CHEP®). CHEP® is the world's largest container and pallet leasing company and issues, collects, repairs and reissues about 300 million pallets and containers to assist manufacturers, distributors and retailers to transport their products safely and efficiently [9]. GMA pallets are amongst the most commonly used pallet styles in North America

Table 1. Sample Box Specifications.

Type	ECT (Kgf/cm)	Length (m)	Width (m)	Height (m)	Fiberboard Box Supplier
Box 1	5.71	0.48	0.38	0.25	Coastal Container, MI
Box 2	5.71	0.48	0.33	0.15	Coastal Container, MI
Box 3	5.71	0.38	0.25	0.25	South Haven Packaging, MI
Box 4	5.71	0.41	0.30	0.25	Michcor Container, MI

and accounts for 30% of all new wood pallets produced in the United States [9]. ISO also recognizes the GMA pallet footprint as one of its six standard sizes. The major application of these pallets is for grocery distribution in North America. The CHEP® pallet has a larger top deck surface coverage than the GMA pallet.

The study was designed to determine the effect of pallet type, tie-sheet and stack configuration on the compression strength of a unitized load. The four stack configurations considered for this study were column stack (control), interlocked, overhang and interlocked overhang stack as shown in Figures 2–5. Four corrugated fiberboard regular slotted containers (FEFCO 0201) of varying dimensions were selected to capture the deviation contributed by the different box sizes towards the palletized box compression strength.

The unitized load compression strength was performed on all four stack configurations with a tie-sheet between each layer and repeated without tie-sheet between the layers. Three replicates were performed for each test set up. The experimental design for this study is shown in Table 2. The column stack configuration which represented the control was compared with the 3 stack configurations with either tie-sheet in between layers or no tie-sheet between layers. Compression testing was done in accordance with ASTM D642 on a box compression tester (Lansmont, Monterey, CA) under standard conditions.

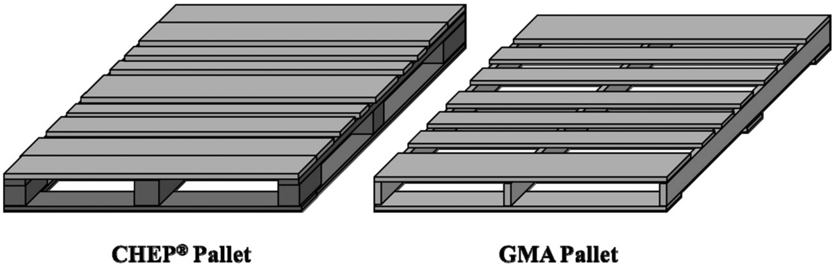

Figure 1. *Pallet types used in study.*

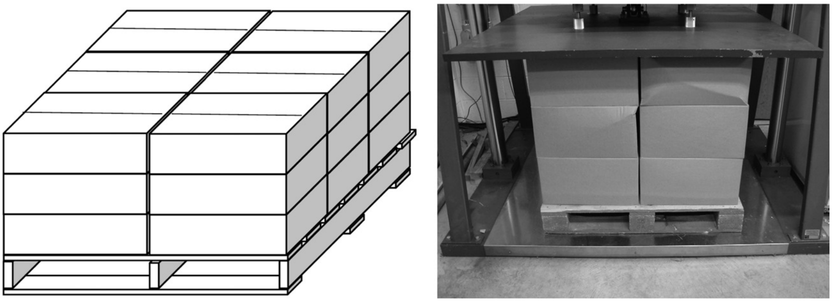

Figure 2. *Palletized box stack configuration for control—column pattern.*

3.0 RESULTS AND DISCUSSION

Palletized box compression strength of the column stack configuration (control) was observed to have the highest compression strength compared to the three-stack configurations on CHEP® or GMA pallets, with or without tie-sheet between layers for all box dimensions.

Column stack configuration of palletized boxes was expected to have the highest compression strength as they perfectly aligned along the edges and corners, therefore providing the maximum compressive resistance during vertical top to bottom compression testing (Tables 3–6).

The interlocked stack configuration showed lower palletized compression strength than the column stack overhang stack configuration (Tables 3–6). This trend was observed on both types of pallets with or without ties sheet between layers. This shows that an interlocked stacking pattern has a larger effect on reducing overall unitized load box compression strength rather than a column stack with a 25.4 mm overhang as shown in Figure 3. An interlocked pattern provides a more stable configuration however, as the boxes are not aligned along the edges and corners between layers therefore the load bearing area pro-

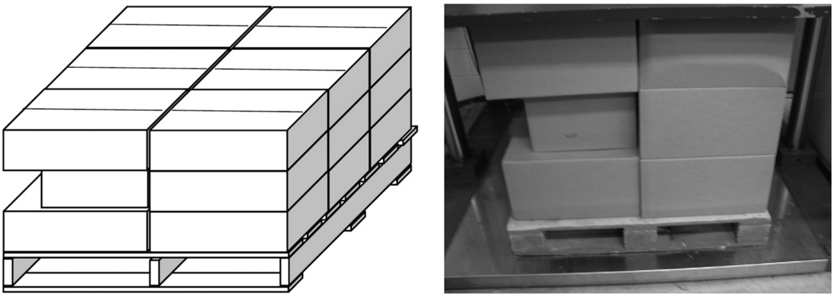

Figure 3. *Palletized box stack configuration for interlocked pattern.*

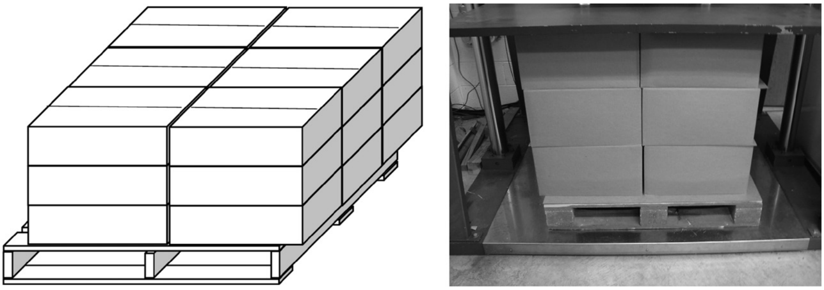

Figure 4. *Palletized box stack configuration for overhang pattern.*

vides lesser compressive resistance compared to a column stack configuration.

From the results shown in Tables 3–6, it is evident that an overhang of 25.4 mm is not a large enough magnitude to compromise palletized box compression strength compared to an interlocked pattern. However, when an interlocked stack configuration is combined with an overhang of 25.4 mm (Figure 3), the results indicate that there was a greater reduction of palletized box compression strength for all combinations of pallets and tie-sheets (Tables 3–6). This explains that the effect of an interlocked stack pattern is considerably magnified by an overhang of 25.4 mm while measuring palletized box compression strength compared to a column stacked pattern with a 25.4 mm overhang.

Overall the CHEP® pallets provided a higher palletized box compression strength than boxes placed on a GMA pallet. The spacing between the top deckboards on a CHEP® pallet is relatively less compared to standard GMA pallets. Therefore the bottom layer (load bearing layer) without tie-sheet on a CHEP® pallet is not damaged considerably during compression testing, thus enabling the bottom layer to provide higher compressive resistance compared to a bottom layer on GMA Pallet.

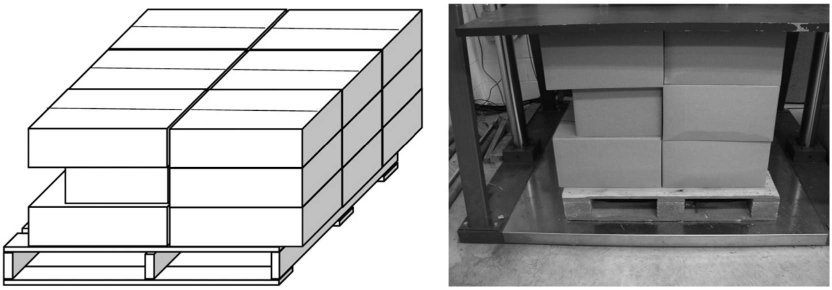

Figure 5. *Palletized box stack configuration for interlocked overhang pattern.*

Table 2. Experimental Design for Different Test Treatments.

Type of Box	Pallet Type		Stack Configuration			
Box 1	CHEP®	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 1	CHEP®	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 1	GMA	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 1	GMA	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 2	CHEP®	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 2	CHEP®	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 2	GMA	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 2	GMA	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 3	CHEP®	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 3	CHEP®	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 3	GMA	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 3	GMA	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 4	CHEP®	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 4	CHEP®	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 4	GMA	Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang
Box 4	GMA	No Tie-sheet	Control	Interlocked	Overhang	Interlocked Overhang

The palletized box compression strength of boxes between respective stack configurations on CHEP® and GMA pallets with or without tie-sheets between layers was compared. It was observed that tie-sheets between layers had a positive effect on the palletized box compression strength. The data in Tables 3 and 4 indicate that the load bearing layer is able to sustain higher compressive resistance when a tie-sheet is placed between the bottom layer and the top deck for both CHEP® and GMA pallet.

This is more evident when the percent loss in palletized box compression strength data shown in Tables 7 and 8 are compared between the CHEP® pallets with tie-sheet and without tie-sheet between layers. It was observed that the percent reduction in box compression strength

Table 3. Palletized Box Compression Strength on CHEP® with Tie-sheet.

	Control (Kg)	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	1124	933 ± 60.7	1 097 ± 29.0	858 ± 3.2
Box 2	1195	1028 ± 38.3	1258 ± 79.9	997 ± 86.6
Box 3	613	588 ± 10.4	574 ± 43.0	498 ± 13.4
Box 4	963	661 ± 100.3	934 ± 58.1	753 ± 7.4

Table 4. Palletized Box Compression Strength CHEP® with No Tie-sheet.

	Control (Kg)	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	1050	773 ± 37.1	1126 ± 53.1	764 ± 9.5
Box 2	1100	827 ± 24.1	1204 ± 121.9	890 ± 17.0
Box 3	461	345 ± 111.4	387 ± 36.6	345 ± 15.8
Box 4	1002	796 ± 90.3	949 ± 44.0	811 ± 23.6

Table 5. Palletized Box Compression Strength on GMA with Tie-sheet.

	Control (Kg)	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	1228.8	897.2 ± 89.3	1067.1 ± 93.9	820.2 ± 77.5
Box 2	1367.1	938.1 ± 26.2	1030.4 ± 79.7	859.5 ± 39.8
Box 3	584.2	492.6 ± 21.6	582.8 ± 32.1	520.2 ± 10.6
Box 4	927.1	801.1 ± 19.1	915.5 ± 107.7	754.1 ± 14.7

Table 6. Palletized Box Compression Strength on GMA with No Tie-sheet.

	Control (Kg)	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	1055	762 ± 77.3	854 ± 31.5	692 ± 55.6
Box 2	932	714 ± 143.4	877 ± 61.4	704 ± 34.8
Box 3	549	467 ± 5.9	496 ± 39.2	396 ± 37.9
Box 4	965	623 ± 80.2	803 ± 68.7	636 ± 101.3

Table 7. Percent Loss of Palletized Box Compression Strength on CHEP® with Tie-Sheet.

	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	17%	2%	24%
Box 2	14%	–	17%
Box 3	4%	6%	19%
Box 4	31%	3%	22%

Table 8. Percent Loss of Palletized Box Compression Strength on CHEP® with No Tie-Sheet.

	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	26%	–	27%
Box 2	25%	–	19%
Box 3	25%	16%	25%
Box 4	21%	5%	19%

Table 9. Percent Loss of Palletized Box Compression Strength on GMA with Tie-Sheet.

	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	27%	19%	34%
Box 2	31%	6%	24%
Box 3	14%	10%	28%
Box 4	14%	17%	34%

is larger when boxes were placed on a CHEP® pallet without tie-sheet on the top deck board.

A similar trend was not observed for the boxes palletized on a GMA pallet (Tables 9 and 10). It was observed that the palletized box compression strength for boxes placed on a GMA pallet with tie-sheet and without tie-sheet between layers was very similar for most of the stack configurations and type of boxes. However, comparing Table 5 and Table 6 it is evident that tie-sheet does provide a positive effect on the palletized box compression strength on GMA pallets.

4.0 CONCLUSIONS

This study evaluated the effect of pallet type, tie-sheet and stack configuration on compression strength of a palletized load of four sizes of boxes. The following conclusions were reached in this study:

1. The compression strength of empty stacked boxes in an inter-lock pattern is lower than that of column stacked boxes on a wood pallet.
2. The compression strength of palletized empty corrugated boxes on a CHEP® pallet is higher than compression strength of similar stacked boxes on a Grocery Manufacturers Association specified wood pallet.
3. The loss in compression strength with no tie-sheet between layers

Table 10. Percent Loss of Palletized Box Compression Strength on GMA with No Tie-Sheet.

	Interlocked (Kg)	Overhang (Kg)	Interlocked Overhang (Kg)
Box 1	28%	19%	34%
Box 2	23%	6%	24%
Box 3	15%	10%	28%
Box 4	35%	17%	34%

is more than with a tie-sheet when comparing stacked empty and palletized boxes.

4. The average loss in compression strength due to three-high palletization is 25% or boxes retain 75% of their original empty box compression strength.
5. The average loss in compression strength due to over-hang on a three high stacked boxes on a pallet is 13% or boxes retain 87% of their original empty box compression strength.
6. Loss of strength in stacked configurations affects the overall stability of stacked loads during warehousing and storage and can result in fatal results in the form of damage or injury.

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Effect of Diameter on the Openability of Threaded Closures

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ABSTRACT: Bottles are the widely used packaging medium for processed fruit products such as jams, jellies, juices, syrups and squashes. Other vital food products such as honey, jellies made from nuts and many forms of edible oil are also packed in bottles. Bottle is preferred due its ease of formability, ease of handling and storage. The product filled in bottles are said to be safe, if and only if, the closure protects the product effectively. Packages are designed aiming at protecting the product and are successful in doing so, but compromises the comfort of the consumer. This issue turns more problematic if the consumer is weak or aged, since ageing is coupled with reduced muscle strength. Moreover, if the consumer fails to open the package then the package fails its ultimate purpose of delivering the product to the consumer.

The work of this project is centred at finding the root cause behind the difficulty in opening the threaded closures. Diameter of the threaded closures, age factor of the consumers and the force exerted by the wrist on closures of various diameters are the factors to be considered.

The use of the torque wrench for measuring the opening torque was found to be the most effective method for the work. A torque wrench with a capacity range of 1–20 Nm was suggested for this work. Age range and diameter of the closures for testing have been classified and the tests have been done according to the classification. The torque range which the sample population fails to open comfortably is taken as the maximum torque generated by the sample. The actual tightening torque set for the bottled packages is obtained from previous studies.

All the data obtained have been correlated by means of graphs and statistical means to arrive at the optimal tightening torque for the threaded closures. 30 mm, 75 mm, 85 mm closures were found to be more difficult to open and most women and men above 70 found it difficult to open almost every bottle.

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INTRODUCTION

General

VALUE addition to the agricultural products has become the ultimatum in the current situation. For self reliance in food security and alleviating poverty, every single grain produced must be preserved. Wastages caused to agricultural production is due to its nature of perishability, seasoned excess production, lack of proper storage, ineffective transport, rodents, poor packages and mechanical damages.

To enhance the global competitiveness of Indian agriculture the two areas of immense importance are value addition and post-harvest processing. At present, only 7% of the output of the agricultural sector is value added and 2% of the volume of perishables is processed. Although India is the largest producer of fruits in the world the production per capita is only about 100 gms per day. It is estimated that more than 20–22% of total production of fruits is lost due to spoilage at various post harvest stages. Thus the per capita availability of fruits is further reduced to around 80 gms per day which is almost half the requirement for a balanced diet. It is estimated that the loss of fruits and vegetable in the post harvest stage is 20–40% in Asia and far east, 10–40% in middle east, 10–50% in Africa and 10–40% in Latin America causing significant food loss to consumers and economic loss to producers and traders [1].

At every stage of processing of agriculture produce, viz primary and secondary-tertiary processing, value is added to the produce. The estimated value addition to the raw food materials through primary, secondary-tertiary processing in India are 75% and 25% respectively. The food processing sector in India has gained importance due to consumer preferences for ready to cook (RTC) and ready to eat (RTE) foods besides, increased demand for snack foods and beverages [1].

As far as India is concerned 42% of food industry is in the organized sector and 33% in the small scale, tiny and cottage sectors. The total production of fruits and vegetables in India is over 45 million tons and 85 million tons respectively. The losses are estimated to the extent of 20–30% due to lack of proper harvesting, processing, packaging and storage facilities which is valued at Rs.230 billion. ‘A grain saved is a grain produced’ [1].

The percentage production of processed foods and vegetables in different forms are fruit juices and fruit pulp contributing up to 25%, jams and jellies up to 10%, pickles up to 12%, ready to serve beverages up to 3%, synthetic syrups up to 8%, squashes up to 4%, tomato products up to 4%, canned vegetables up to 4%, and others to 18% [2].

The aerated soft drinks industry in India comprises over 100 plants across all states. Next to packed tea and packed biscuits, soft drinks constitute the third largest packaged food, regularly consumed.

Given the statistics and the cost involved a successful value addition to agricultural produce is incomplete without a proper packaging technology. Packaging is a continuous entity right from the field to the consumer which involves storage and transport. The value added agriculture produces and other aerated beverages in India are mostly reaching the consumers in bottled packs with either narrow or wider mouths protected with crown caps or threaded closures. Crown caps are suitable only to narrow mouthed bottles and it requires another tool for opening. Due to its limitations, threaded closures are dominating over the crown closures. The bottled packs with threaded closures meet out the basic function of a package to contain, to protect and to inform but it compromises with the comforts of the consumers to access the product with comfortable opening torque especially with the wider closures.

Even though the package was perfect to its definition, there had been incidents of hospitalization in the consumer end while trying to access the products packed in bottles. Many of the aged and healthily week consumers try to access the bottled produce even with sharp knives to open the tamper evident threaded closures and also fail to open thereby causing mechanical injuries to themselves and also to others nearby. Many consumers fail to open the lug closures and also invite heart problems by creating self pressure. Some consumers while facing openablity problems, try to access the product even by making damages to the pack. This may create possibilities to consume certain dangerous produce which are caused due to the spillage of package material into the ultimate product. Though the ultimate product is of high quality, many consumers who have faced with openability problems tend to avoid buying the product subsequently, thus making the production industry sick.

With the probable increase in the population of the senior citizens and the impact of modern lifestyle, there is a decline in the average strength characteristics. Therefore, while designing the packages of consumer products, comfort of these consumers are to be taken care of who are weaker in their muscular strength.

Taking into account the above facts it is imminent to evolve an optimal tightening torque which is suitable to meet out the functions of packaging and also comfortable to the consumer to access the ultimate product. This paper is aimed at solving the openability problem of the threaded closures. Extensive real time data collection on the strength characteristic of the consumer is to be performed for establishing comfortable opening torque for the closures.

Need for the Study

According to the European Demographic Statistics (EUROSTAT 1998) by the year 2010 about 25% of the European Union population (currently 374 million) will be aged 60 years and over and this will rise to 30% by 2020. In the USA the corresponding population projection figures are 19% and 23% (US Census Bureau 2000). Total life expectancy has also been increasing, with average longevity in the European Union currently at 81 years for women and 75 years for men [8].

Age-related physical and cognitive changes have been well documented elsewhere (Bromley 1988, Aiken 1995). However, the increase in numbers of older people living alone brings a challenge to those involved in design of products. There is a requirement to provide strength data and information to ensure that products are designed for use by all. Taking simple and necessary products such as food packaging, there is a clear need to design such packaging to allow everyone access to it. Steenbekkers and Beijsterveldt (1998) found, in a survey of 750 participants, that for problems such as difficulties with opening jars, women reported more problems than men. However, comparing the list of psychomotor activities used, jar opening came only second to opening child-resistant packaging as a source of problems (Steenbekkers and Beijsterveldt 1998) [8].

The UK Department of Trade and Industry (DTI) published a report in 1999 with regard to age-related changes and packaging, which identified three functions that impact on the interface between the individual and the packaged product (DTI 1999a). In terms of the visual function, issues such as increasing the contrast and size of lettering need to be addressed; in terms of cognitive function issues of child resistant closures can be a source of problems and finally in terms of muscle function, hand torque and pinch strength reduction in older adults have not been fully addressed by industry (DTI 1999a) [8].

When examining injuries in the UK for 1994, it was found that the majority of accidents related to glass containers occur after use (DTI 1997). The number of accidents in 1994 were 550 at initial opening of glass bottles and 610 for the initial opening of plastic bottles. The injury mechanism was not specific in this report, but it was appreciated that knives were used to open difficult containers or to remove tamper-evident bands. The Department of Trade and Industry reports that for guidance in the UK, industry uses a `Rule of Thumb' where opening torque (Nm) is equated directly to cap diameter (mm) (DTI 1999b). This report does state that it is unlikely that such a rule will be acceptable for older adults (DTI 1999b). Other research in this area had found that assistance was required to unscrew metal top closures used on glass jars (DTI 1997) [8].

This indicates that even with simple products such as jars and their lids, there is a need to consider the older and weaker users in the population. Studies have been carried out to examine torque exertion and hand strength in both younger and older adults. These have included studies of different shapes and sizes of lids and interactions between these factors. For example, Imrhan and Loo (1988), using commercially available lids of diameters 31 mm, 51 mm, 74 mm and 113 mm, concluded that diameter influenced the application of torque. For rough textured lids, torque increased as diameter increased, but for smooth-surfaced lids, torque decreased between 74 mm and 113 mm. Opening strength measured during the study ranged between a mean of 5.01 Nm for the rough-textured lid of 113 mm diameter and 0.6 Nm for the smooth-textured lid of 31 mm diameter for a sample of 42 adults between the ages of 60 and 97 years (Imhran and Loo 1988) [8].

Though considerable study on the injuries caused due to opening of packages have been done, the study on the design of safer packages is meagre. One such design parameter is the tightening of threads used in closures. Furthermore all the research has been done with reference to the European demographics. It is acceptable that the European demographics is far more distinct than the Indian demographics. It is more important to perform similar such studies in India. This helps to design packages with Indian consumers safety and ease of usage in mind.

METHODOLOGY

The summary of the method followed in the work as follows

- Step 1: Measurement of human wrist torque exertion
- Step 2: Actual tightening torque used in bottled packages
- Step 3: Graphically relating the values

Step 1: Measurement of Human Wrist Torque Exertion

Measurement of the maximum torque exerted by human wrist was measured. For this purpose a torque wrench was used. The details of the torque wrench are

- Manufacturer—Norbar (U.K)
- Measuring range—1–20 Nm
- Tolerance at 20°C—< ±1%

To make use of the torque wrench an extra setup was required on the regular closures. The setup included a bolt and nut fastened at the center of the closures

The torque wrench was used to tighten the closure to a predetermined torque. The bottle with the tightened closure was given to the sample population to open. The torque value which the consumer failed to open comfortably was noted as the maximum strength value of the sample. Similar such data were collected with varying closured diameters and age range. Six bottles with closures of diameter 30 mm, 55 mm (two closures for round and square shaped bottle), 65 mm, 75 mm and 85 mm were used for the test. The age group of the population were classified as 15–30, 30–40, 40–50, 50–60, 60–70, 70–80 and 80–90. A total of 125 samples of which 65 were male while 60 were female. The break up of sample with respect to age and sex is given in Table 1.

Step 2: Actual Tightening Torque Used in Bottled Packages

The actual tightness in which the closures are fastened to the bottles

Figure 1. *Torque wrench.*

Table 1. Break Up of Samples.

Age Range	No. of Male	No. of Female
15–30	14	16
30–40	7	7
40–50	9	10
50–60	11	9
60–70	8	8
70–80	9	5
80–90	7	5
Total	**65**	**60**

available in the market were obtained from previous work done by Yoxal *et al.* [3].

Step 3: Graphically Relating the Values

Graphical representation of the measured values i.e. the maximum torque value, age and the actual tightening torque were done to clearly demonstrate the relation between the three.

RESULTS AND DISCUSSIONS

It can be inferred from the graphs that the force exerted on the closures with diameters 55 mm and 65 mm lie mostly in the measured

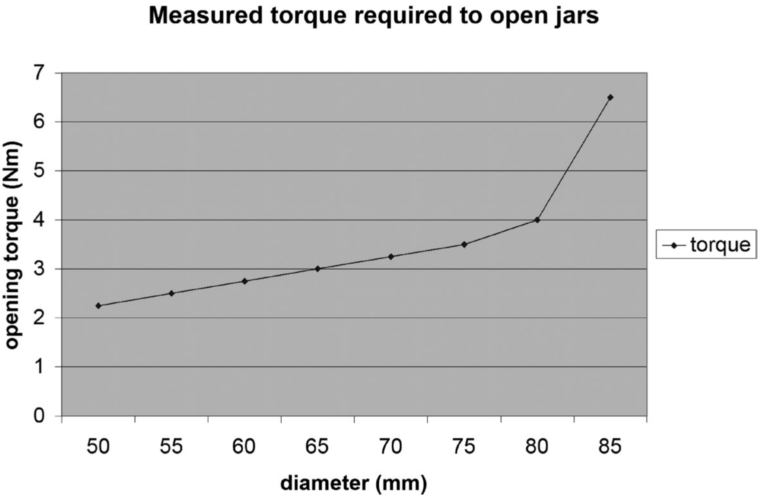

Figure 2. *Force required to open the closures.*

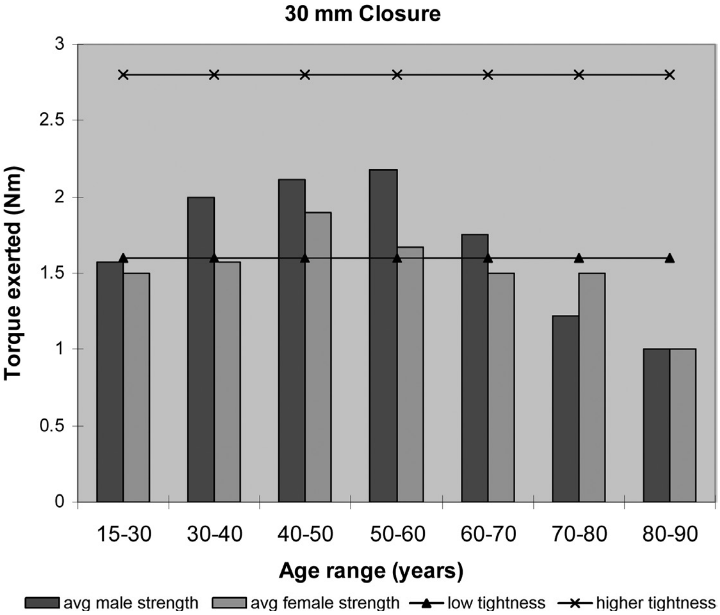

Figure 3. *Graph of torque against age for 30 mm diameter jar closure.*

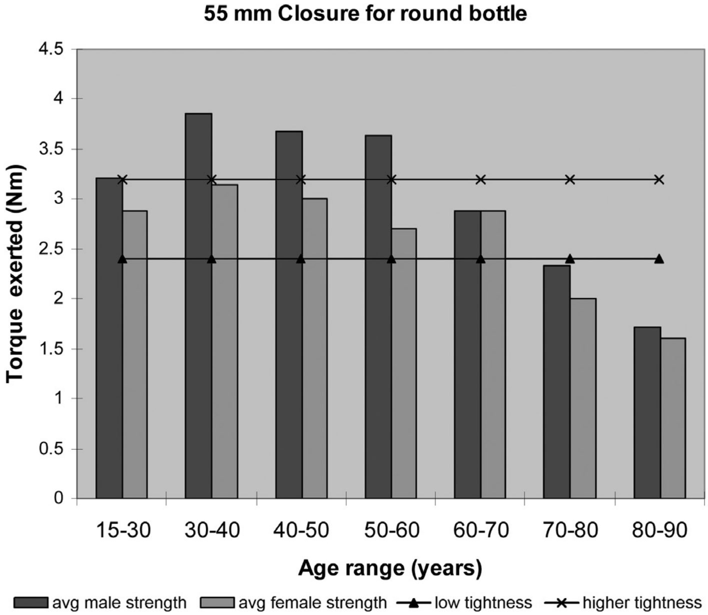

Figure 4. *Graph of torque against age for 55 mm diameter round jar closure.*

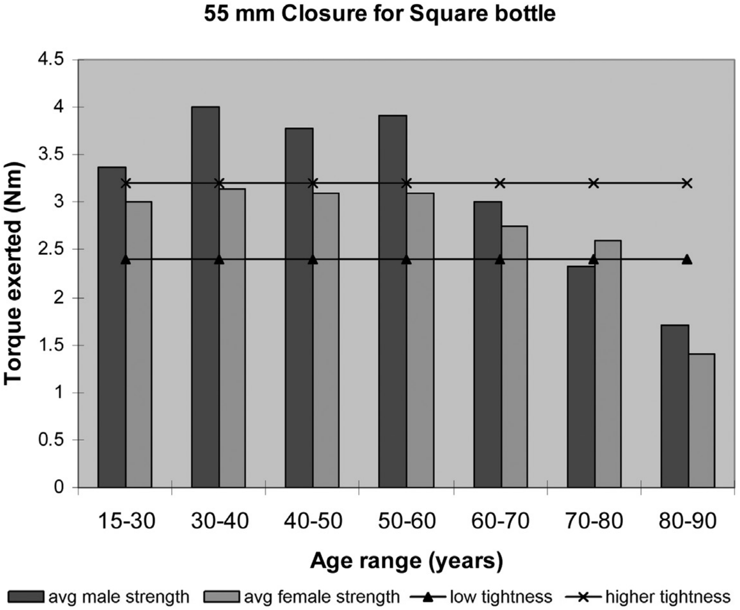

Figure 5. *Graph of torque against age for 55 mm diameter square jar closure.*

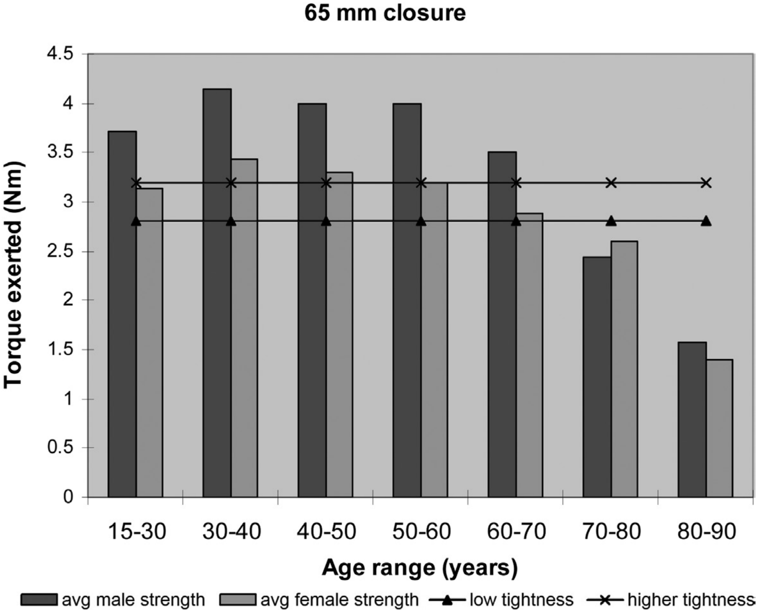

Figure 6. *Graph of torque against age for 65 mm jar closure.*

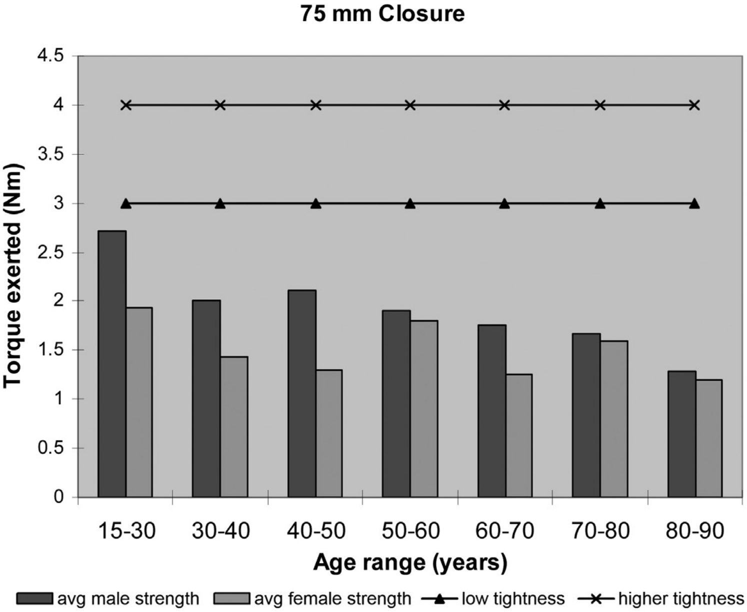

Figure 7. *Graph of torque against age for 75 mm jar closure.*

Figure 8. *Graph of torque against age for 85 mm jar closure.*

opening torque range. The narrower closure i.e. 30 mm closure and the wider ones (75 mm and 85 mm) are found to be more difficult to open.

The generalized reason is that the 55 mm and 65 mm closures were more comfortable for the consumer to hold on or to grip it, while the 30 mm, 75 mm and 85 mm closures were not that comfortable to grip.

Technically analyzing, torque is the product of the force applied and the perpendicular distance between its point of application and the axis of the closure ($T = N*x$ where N = force, x = distance).

In 30 mm closures the 'x' value is low (15 mm) and to overcome the actual tightening torque (1.6 Nm to 2.8 Nm) the force applied has to be in the range of 106.66 N to 186.66 N which is very high. Adding to this is the size which is difficult to grip. Female population above 60 and below 30 fall below the lower tightness range and male population above 70 fall in the failure range.

In 55 mm closure the '*x*' value is moderate i.e. 25.25 mm and the actual tightness value is in the range of 2.4 Nm to 3.2 Nm. In such conditions the force required to open the closures will be in the range of 95.04 N–126.73 N which is relatively low and is easier to open. Female and male population above 70 failed to exert even the lower tightening torque.

Torque exerted on another 55 mm closure for a square bottle was calculated to see if the shape of the bottle had a considerable impact on the gripping. The 50–60, 70–80 female population shows a mild improvement in the torque exerted.

Similar to the 55 mm closures the 65 mm closure had a tightness range of 2.8 Nm to 3.2 Nm. Force required is in the range of 86.15 N to 98.46 N which is a moderate value. Female population above 60 and male population above 70 failed to exert the lower tightening torque.

In the case of 75 mm closures the force required to open the closures varies from 40 N to 53.3 N. For 85 mm closures the tightness ranges from 6 Nm to 7.5 Nm and the force required would be from 141.17 N to 176.47 N. Almost all of the sample population failed to open or exert the force

CONCLUSIONS

The presented data suggest that bottles currently available on the market are likely to be difficult for some women and the elderly, in particular, to open. Larger sizes of jars are especially hard to open, with almost all users unable to open containers with 85 mm lids. The smaller lids generally fare better, but many elderly users will struggle to open all sizes of jars. In the case of 30 mm closures even young women below 30 found it much hard to open. This is because the small size was difficult to grip on and the 30 mm closures had to be gripped only using the thumb and index fingers. The bottles with 55 mm and 65 mm closures were found to be much easier to open. This is because these closures were comfortable enough to hold onto and hence more efficient to grip. The 75 mm closure used in this study is tapered to the top like a cone. This shape was the most difficult to grip on and hence only reduced opening torque could be exerted. The 85 mm closure was way too big considering the palm of the samples and were difficult to open. On concluding, many samples were not able to exert the torque required to open the bottled packages and hence the initial tightness range set by the package designers must be revised and reduced to the openable limits.

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Sensory Evaluation of Fresh Cut Mangos Packaged in Rigid Containers Subjected to Mechanical Abuse by Transport Vibration

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ABSTRACT: There has been an increasing demand for tropical fruits in particular mango in the recent years. This study was undertaken to compare the quality of fresh cut mango in modified atmosphere package in a rigid container with 'Continuous film' and a 'Snap-fit' lid, subjected to transport vibration. Whole mango (*Mangifera indica*) were cut into 1-inch cubes pieces and dipped in 3% NatureSealTM containing calcium ascorbate for two minutes. This was followed by filling approximately 160 ± 20grams of mango pieces in three types of containers 'Snap fit PET (polyethylene-terephthlate)' container, 'Continuous film PET' container, and 'Continuous film PLA'. Fresh cut mangos packed in 'Snap fit' PET containers were vibrated for 60 minutes using ASTM D4169, Truck Assurance Level II test method. A qualitative comparison of fresh cut mangos were performed between 'Control' samples packed in 'Snap fit' PET containers, 'Continuous film PET' container, 'Continuous film PLA' container and 'Snap fit' PET containers subjected to transport vibration. Quality evaluation (Sensory quality, color analysis and TSS) of cut mangos were done at Day 1, 4, 7 and 10. In-package gas composition (O_2 and CO_2) was observed during storage to monitor effect of in package gas composition on cut mango quality. Accumulation of higher level of CO_2 in 'Continuous film' rigid container led to rapid quality deterioration of cut mango compared to 'Snap-fit' PET container. The physically abused mango samples packed in 'Snap-fit' PET container showed acceptable aroma, color, sweetness and firmness intensity till at Day 7 compared to the cut mangos packaged in 'Continuous film' rigid containers (PET and PLA). The overall quality of fresh cut mango packed in 'Snap-fit' PET container exposed to vibration was found to be better than cut mangos packed in 'Continuous film' rigid containers during storage. These findings indicate that quality preservation of fresh cut mango can be achieved by selecting an appropriate package system to withstand physical abuse during transportation.

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INTRODUCTION

RIPE mangos (Mangifera indica) are among the most delectable tropical fruits in the world. World mango production in 2005 was estimated to be at 28.51 metric tons, where India was the leading producer at 38.6% followed by China and Thailand at 3.61 million metric tons (12.9%) and 1.73 million metric tons (6.2%) [1]. The majority of the mango fruit imported into the U.S. is from Mexico, Brazil, Peru, Ecuador, and Haiti. Even though the U.S. is not a major mango producer, it is the largest importer of fresh mangos. For the period between 2003 and 2005, U.S. imported nearly 32.7% of total mango import [1] showing a growing trend in mango consumption in the U.S. market. Since mangos are imported both over road and sea it is exposed to logistical adversities which can degrade the quality of mango by the time it arrives at the point of purchase. It is well known that whole fruits like mango, banana, tangerine and papaya get bruised and quality deteriorates more rapidly. Such spoilage is dependent on road conditions and type of trucks used to transport fruits [2]. Recently, fresh cut mangos have been gaining popularity as a value added product among retail and food service customers. Since average consumers in U.S. are not well versed with the attributes of a good and ripe mango in a retail store, a way to offer this delicious fruit to consumers without having to speculate its quality is to provide ready to eat fresh cut mangos in trays or clamshell packaging with all the qualitative attributes maintained at a level making it a delectable fruit.

Fresh cut fruits (FCF) are increasingly becoming popular in the marketplace. The FCF is a $300 million industry, projected to reach $1 billion by 2010 [3]. With growing health concerns, consumers are resorting to more nutritional options in their diet, such as consuming FCF [3]. It is well known from prior research that fresh cut fruits are more perishable than intact fruits [4] as a result of chemical and physical stresses during processing, handling and storage. Undesirable exposure to temperature, humidity, atmosphere and sanitary conditions can deteriorate product quality [4] in appearance, flavor and purging at the bottom of the package. Respiration rates of FCF are normally higher than intact fruit, and they increase with temperature [4]. Therefore it is recommended that FCF should be stored at low temperatures unless there is a risk of chilling injuries. Fresh cut mango quality can be maintained at good quality by determining appropriate harvest time [5] and using modified atmosphere packaging. Modified atmosphere packaging of fresh cut fruits has been a popular area of research utilizing continuous film and/or 'Snap-fit' style of containers. The packaging material often used for the container base is PET (polyethylene-terephthlate) which contributes substantially towards solid waste in a landfill. To combat this issue, biodegradable containers made from PLA (Poly lactic acid) are increasingly becoming popular in the fresh cut fruit industry. Research has shown that replacing PET with PLA containers have comparable results in maintaining fresh cut fruit quality. It is also known that transportation abuses can have a significant effect on the quality of fresh cut fruits [6]. Therefore it is essential to ascertain the effect of physical abuse during transportation on quality of fresh cut mangos in a modified atmosphere package. Consumers expect to buy cut fruits fresh and without any defects at grocery stores [7]. Therefore, one of the ongoing challenges is to reduce physical abuse and extend the shelf life of fresh cut mangos. Thus, the objective of this study was to compare different packaging systems to ascertain the quality of fresh cut mangos, after being subjected to transportation.

MATERIALS AND METHODS

Mango Dice Processing

Commercially produced whole mango was procured from a bulk supplier based in Texas. The whole mango was washed and dipped in a commercial sanitizer- Fruit & Vegetable Wash (SC Johnson Professional, Sturtevant, WI) (100-ppm chlorine) for five minutes. This was followed by storage at 4°C ± 0.3°C in a chamber for a period of twelve hours prior to cutting. Once mangos equilibrated to the desirable temperature, they were cut in a 22°C ± 4°C environment. The mangos were cut into 16.3 cm^3 cubes (1-$inch^3$) using a sharp stainless steel knife (Figure 1) cleaned in 100pm chlorine solution (Figure 2) Mango pieces were dipped in an anti-browning solution: (3% NatureSeal™ containing calcium ascorbate) for two minutes. This was followed by filling approximately 160 ± 20 g of mango pieces in three types of containers: 'Snap fit PET (polyethylene-terephthlate)' containers, 'Continuous film PET' containers, and 'Continuous film PLA (poly(lactide))' containers. The 'Snap fit PET', PET and PLA container with inside dimensions of approximately 12.1 × 12.1 × 4.4 cm with a capacity to hold 236 grams of cut fruit (Figure 2) model number 47-15 were obtained from Packaging Direct Inc. (Gladwin, Michigan). The film rolls used as lid

Figure 1. Fresh cut mango dicing operation.

material (PET and PLA film) was procured from Clearlam Packaging, Inc (Elk Grove, IL). The container and film specification are shown in Table 1.

A semi automatic tray sealer (Multivac Model T-200, Inc., Kansas City, MO, USA) was used to heat seal a continuous polymeric film PET (Heat seal layer- Ethylene Vinyl Acetate) and PLA films on filled PET and PLA containers respectively as seen in Figure 4. One layer of cut

Figure 2. Sanitizing and anti-browning dipping solution.

Table 1. Container and Film Specification.

	Type of Container		
	Snap Fit PET	**Continuous Film PET**	**Continuous Film PLA**
Thickness	Lid—0.36 mm Container—0.51 mm	Film—0.03 mm Container—0.51 mm	Film—0.04 mm Container—0.55 mm
Weight	25.6 gm	22.6 gm	21.7 gm

mango filled and sealed containers were packaged in C-flute corrugated fiberboard boxes (Case code-FEFCO 0306) which had a board combination of 215/162/215 g/m^2, with a burst strength of 12.70 kgf/cm^2 and a ECT of 8.09 Kgf/cm. The inside dimensions of the box were 40.6 × 38.1 × 3.2 cm (Figure 5). These boxes were then subjected to random vibration for 60 minutes to represent an approximate 800 kilometer trip using ASTM D4169, Truck Assurance Level II, on a vibration table (Lansmont Model 10000-10, Inc, Monterey, CA, USA). In addition to the vibration tested samples, control samples were placed in a refrigerated chamber at 4°C ± 0.3°C for a period of 24 hours for further examination.

QUALITY EVALUATION

Fresh cut mangos were evaluated during storage for, sensory quality, color, total soluble solids (TSS), and in-package atmosphere at Days 1, 4, 7 and 10. All experiments were done in triplicate. Sensory evaluation was done by five trained panelists on an unstructured line scale 1–15 (1 = Very Bad and 15 = Very Good) for aroma, color, firmness, sweetness

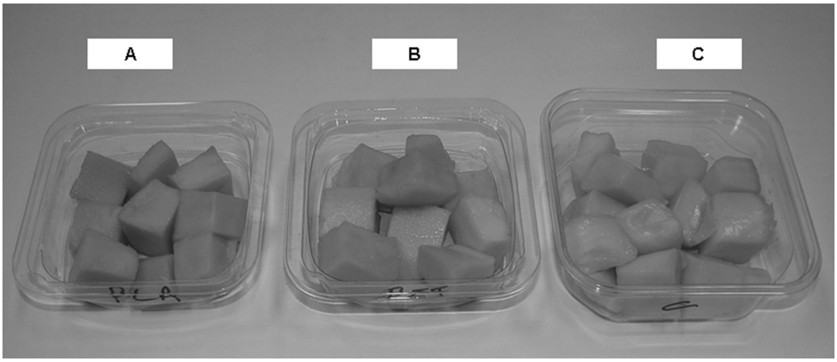

Figure 3. *Fresh cut mango packaging containers (A) PLA Continuous film container, (B) PET Continuous film container, (C) Snap-fit container.*

Figure 4. *Semi automatic tray sealer (Multivac Model T-200, Inc, Kansas City, MO, USA).*

and overall acceptability. Total soluble solid contents of fresh-cut fruits were measured using hand refractometer (Model: Atago PAL-1, Atago Co. Ltd., Tokyo, Japan). Tristimulus reflectance colorimetery was used to assess the extent of browning in mango dices (Saper and Douglas, 1987). The color of dices (L*, a*, and b* values) was obtained from the center of each dice using a LabScan XE, (Hunter Associates Laboratory, Inc, Virginia, USA). A decrease in L* value indicates a loss of brightness, and a more positive a* value indicates browning, whereas a more positive b* indicates yellowing or discoloration. The changes of in-package O_2 and CO_2 concentrations were measured using a headspace analyzer (6600 O_2/CO_2 Headspace Analyzer, Illinois Instrument, Illinois, USA).

STATISTICAL ANALYSIS

The collected data was analyzed using statistical software Minitab 13.1 (Minitab Inc., State College, PA, USA). Analysis of variance was performed on sensory and firmness data and the means were separated using Fisher's least squares difference at a significance level of $p < 0.05$.

RESULTS AND DISCUSSION

Quality Evaluation

Fresh cut mango quality was evaluated by five trained panelists on a line scale 1–15 (1 = Very Bad and 15 = Very Good) for aroma, color, firmness, sweetness and overall acceptability at Day 1, 4, 7 and 10.

The intensity of aroma showed a decreasing trend over the ten days of storage (Figure 6). There was a significant difference in aroma ($p < 0.05$) between cut mango samples packed in 'Control' container and 'Continuous film' PET, PLA container at Day 4, 7 and 10 (Table 2). An intensity score of 7 and below was deemed to be of unacceptable quality. Based on this conjecture it was found that fresh cut mangos did not have an acceptable aroma level after Day 4 for cut mangos packed in PET and PLA container with a 'Continuous film' as lidding material. Upon further analysis it was ascertained that the physically abused (vibrated) container samples had the highest aroma intensity followed by control samples, PET and PLA continuous film container samples. The panelists detected off odors in cut mangos packaged the PET and

Figure 5. *Fresh cut mango containers packaged in shipping containers made from corrugated fiberboard.*

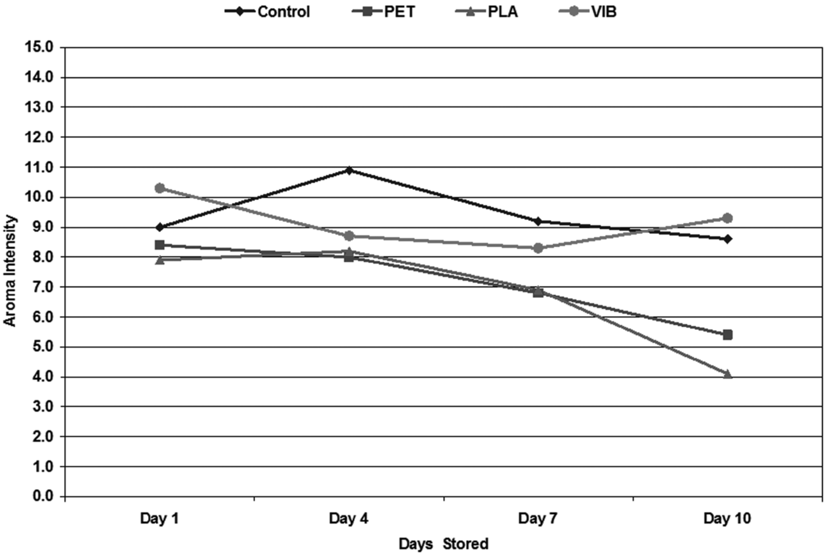

Figure 6. *Sensory scores for fresh cut mango aroma during storage period. 1 = Very Bad; 15 = Very Good.*

PLA sample, which was expected, as off odors were trapped in the head space of PET and PLA containers with a continuous film. Since the film was effectively sealed along the lip of the container therefore accumulated off odors was unable to escape. Where as, head space accumulation of off odors in the 'Snap-fit' PET containers were able to permeate through the container as it was not hermetically sealed. Therefore, the physically abused mango samples packed in 'Snap-fit' PET container showed acceptable aroma intensity even at Day 10 compared to the cut mangos packed in 'Continuous film' PLA and PET containers. This also goes to show that physically abused cut mango possibly releases more aroma volatiles compared to un-abused mangos stored in a continuous film container. Moreover, off odors released by cut mangos in a container with continuous film are trapped in the head space therefore over-powering the mango aroma volatiles.

A yellow mango flesh color is an indication of ripeness [5], as mango deteriorates over time it tends to fade to pale yellow and eventually has a brownish color. Yellow color of cut mangos stored in PET and PLA containers was significantly higher than control and vibrated samples at Day 1 (Figure 7) and by Day 10 the samples showed extensive browning (Figure 8).

This indicates that cut mango samples stored in PET and PLA containers with continuous film ripen at a faster rate than the control and vibrated samples. Comparing the L* values during the storage period (Table 3) for all the samples it can be seen that the cut mango samples in the PET and PLA containers had significantly lower values than the control and vibrated samples, indicating that the PET and PLA samples had rapid browning reaction than the other samples. Similarly, the a* and b* values indicate that control and vibrated samples maintain significantly higher yellow color than the PET and PLA samples (Table 3). The control and vibrated samples packed in 'Snap-fit' PET containers maintained higher color intensity (yellow) than the PET and PLA samples at Days 4, 7 and 10. This shows that there is rapid browning of cut mango samples packed in the PET and PLA containers with continuous film compared to physically abused cut mango packed in 'Snap-fit' PET containers.

Table 2. Effect of Treatments on Sensory Attributes for Fresh Cut Mango During Storage.

		Days Stored			
Attributes	**Treatments**	**Day 1**	**Day 4**	**Day 7**	**Day 10**
Aroma	Control	*9.0 ± 1.17ab	10.9 ± 1.24a	9.2 ± 1.10a	8.6 ± 1.85a
	PET	8.4 ± 0.89b	8.0 ± 1.41b	6.8 ± 1.30b	5.4 ± 0.65b
	PLA	7.9 ± 1.43b	8.2 ± 1.30b	6.9 ± 1.25b	4.1 ± 0.89b
	VIB	10.3 ± 1.79a	8.7 ± 1.67b	8.3 ± 1.10ab	9.3 ± 1.30a
Color	Control	8.0 ± 1.24ab	10.3 ± 1.30a	7.6 ± 1.78ab	8.8 ± 1.94a
	PET	9.6 ± 1.34b	7.2 ± 0.55b	8.1 ± 1.30c	9.0 ± 2.17b
	PLA	9.0 ± 0.44b	7.8 ± 1.14a	6.8 ± 1.09bc	9.8 ± 1.87b
	VIB	9.6 ± 1.30a	8.6 ± 1.30a	9.6 ± 1.58a	8.6 ± 1.00a
Firmness	Control	8.0 ± 1.58a	10.3 ± 1.30a	7.6 ± 1.08b	8.8 ± 1.30a
	PET	9.6 ± 0.89a	7.2 ± 0.84b	8.1 ± 0.89b	9.0 ± 2.65a
	PLA	9.0 ± 1.22a	7.8 ± 0.45b	6.8 ± 1.09b	9.8 ± 1.76a
	VIB	9.6 ± 1.14a	8.6 ± 1.52b	9.6 ± 1.34a	8.6 ± 1.34a
Sweetness	Control	10.2 ± 0.83a	8.7 ± 1.30a	7.7 ± 1.48a	7.9 ± 2.55a
	PET	8.1 ± 1.34ab	7.0 ± 1.41a	4.9 ± 1.43b	4.0 ± 1.00b
	PLA	7.2 ± 1.78b	7.9 ± 2.88a	5.3 ± 2.38b	3.3 ± 1.53b
	VIB	8.9 ± 2.35ab	7.9 ± 0.89a	8.0 ± 2.58a	9.1 ± 1.52a
Overall	Control	10.2 ± 1.09a	9.6 ± 1.52a	8.7 ± 1.72a	8.4 ± 1.67a
	PET	8.0 ± 1.00b	6.7 ± 1.72b	6.2 ± 1.30b	4.4 ± 1.79b
	PLA	9.0 ± 1.41ab	8.3 ± 2.11ab	5.1 ± 1.95b	3.3 ± 1.44b
	VIB	9.9 ± 1.14a	8.0 ± 1.23ab	9.3 ± 1.98a	9.2 ± 0.75q

Different letters following the values within a column indicate differences according to the Fisher's LSD at $p \leq 0.05$.

*Line scale 1–15 (1 = Very Bad and 15 = Very Good).

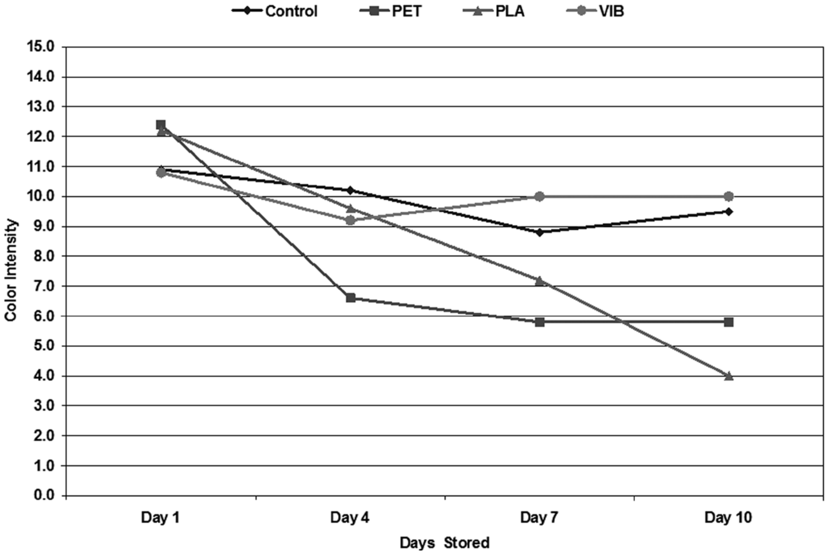

Figure 7. *Sensory scores for fresh cut mango color during storage period. 1 = Very Bad; 15 = Very Good.*

Mango tissue deterioration can be assessed by the firmness rating provided by the trained panel. The firmness rating of cut mango did not show a general trend, however the control and vibrated samples showed significantly higher firmness rating at Day 4 and 7. However, by the end of the storage period, all samples had similar firmness rating (Figure 9).

It was observed that sweetness scores decreased during the ten day storage period (Figure 10). The control and vibrated samples had higher ratings than the PET and PLA samples at Day 1, 4, 7 and 10 (Table 2). The control and vibrated samples had significantly higher sweetness scores at Day 7 and 10, compared to PET and PLA samples. Sweetness scores for PET and PLA samples were below the acceptability score 7

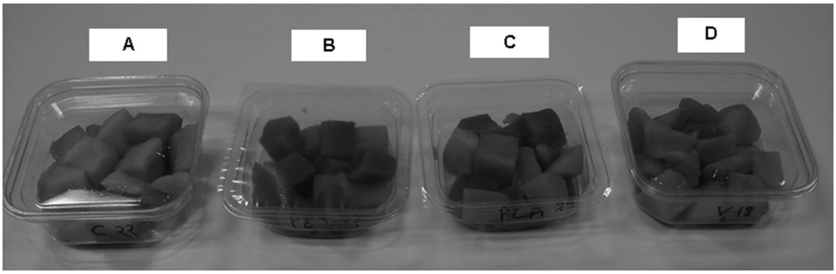

Figure 8. *Change in color of Fresh cut mango stored in different container at Day 10 (A) Control-Snap-fit Pet Container (B) PET Continuous film container (C) PLA Continuous film container (D) Vibrated cut mango-Snap-fit PET container.*

Table 3. Effect of Treatments on CIE L* a* b* Parameters for Fresh Cut Mango During Storage.

		Days Stored			
Attributes	**Treatments**	**Day 1**	**Day 4**	**Day 7**	**Day 10**
L*	Control	63.9 ± 1.62a	60.7 ± 2.87a	58.6 ± 3.01a	56.5 ± 3.23a
	PET	48.0 ± 5.80c	44.8 ± 6.45c	43.7 ± 6.73c	40.5 ± 4.81c
	PLA	42.5 ± 1.34d	40.5 ± 2.78c	39.2 ± 3.53c	38.1 ± 3.17c
	VIB	58.0 ± 2.05b	53.9 ± 2.75b	51.9 ± 1.94b	50.7 ± 2.42b
a*	Control	17.1 ± 2.36a	17.8 ± 2.34a	18.3 ± 2.19a	18.2 ± 2.47a
	PET	13.0 ± 1.89b	14.2 ± 2.18b	14.3 ± 1.75b	13.9 ± 2.07b
	PLA	12.0 ± 1.72b	13.2 ± 1.85b	13.8 ± 0.94b	13.1 ± 1.13b
	VIB	18.7 ± 0.42a	19.6 ± 0.75a	19.6 ± 0.50a	18.8 ± 0.94a
b*	Control	66.9 ± 2.31a	60.8 ± 3.77a	58.1 ± 2.35a	53.6 ± 4.25a
	PET	47.1 ± 9.52c	41.7 ± 12.13bc	46.9 ± 10.57b	43.3 ± 5.43b
	PLA	40.7 ± 5.27c	38.1 ± 7.73c	42.9 ± 7.02b	40.1 ± 5.82b
	VIB	58.4 ± 4.42b	51.5 ± 3.55ab	47.9 ± 4.03b	45.1 ± 5.70b

Different letters following the values within a column indicate differences according to the Fisher's LSD at $p \leq 0.05$.

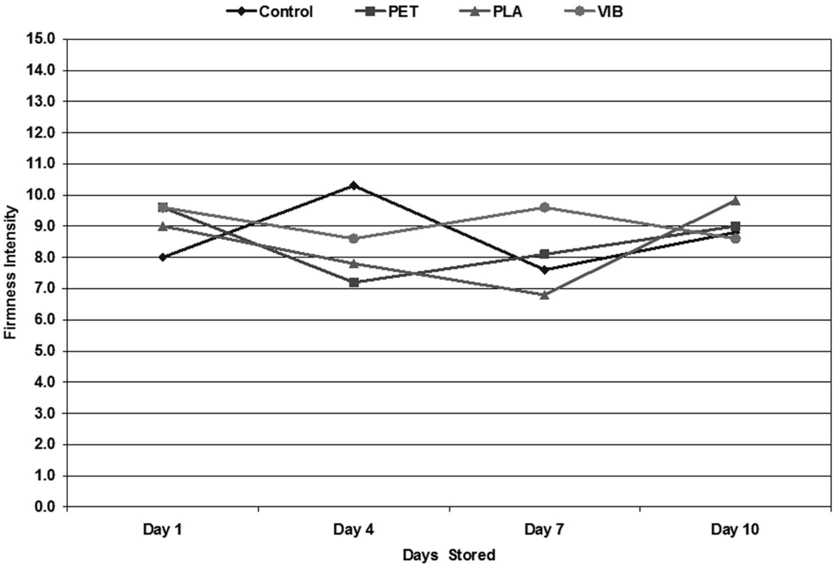

Figure 9. *Sensory scores for fresh cut mango firmness during storage period. 1 = Very Bad; 15 = Very Good.*

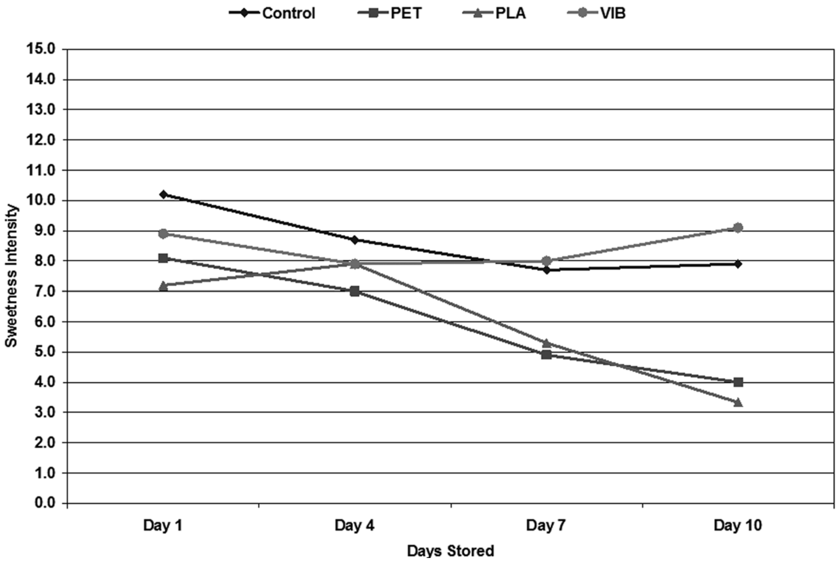

Figure 10. *Sensory scores for fresh cut mango sweetness during storage period. 1 = Very Bad; 15 = Very Good.*

at Day 7 as the panelists detected off flavors. The control and vibrated samples were rated higher than 7 even at Day 10 and did not detect a considerable amount of off-flavor.

Cut mango samples showed a decreasing trend for the 'Overall Acceptability' scores (Figure 11). The panelists deemed the cut mango samples stored in PET and PLA containers unfit for consumption at Day 7 , they were rated to have significantly lower overall ratings than control and vibrated samples (Table 2). The control and vibrated samples were rated by panelists to have overall ratings higher than 7 deeming it acceptable for consumption at Day 10.

Table 4. Effect of Treatments on Total Soluble Solids for Fresh Cut Mango During Storage.

		Days Stored			
Attributes	**Treatments**	**Day 1**	**Day 4**	**Day 7**	**Day 10**
TSS	Control	15.2 ± 0.058a	16.0 ± 0.26a	15.7 ± 0.058a	15.2 ± 0.34a
	PET	14.6 ± 0.058b	13.9 ± 0.10c	15.0 ± 0.15b	13.2 ± 0.15c
	PLA	13.8 ± 0.0c	14.9 ± 0.10b	15.2 ± 0.11b	14.1 ± 0.40b
	VIB	13.9 ± 0.25c	13.8 ± 0.25c	13.9 ± 0.00c	13.6 ± 0.10bc

Different letters following the values within a column indicate differences according to the Fisher's LSD at $p \leq 0.05$.

The total soluble solids for all cut mango samples showed an increasing trend till Day 7 then reducing at Day 10. The results showed that TSS of control samples were significantly higher than the vibrated cut mango samples packaged in the 'Snap-fit' PET container and cut mango samples packaged in 'Continuous film' PLA container by Day 10 (Table 4). This indicates that cut mango was ripening as it converted starches to sugar [8] during the initial period until the sugars started to degrade after Day 7, as sweetness ratings (Figure 10) of cut mango samples packed in 'Continuous film' containers dropped drastically after day 7.

In-Package Atmosphere

In package gas composition was monitored for the storage period of ten days. The optimal controlled atmosphere condition for fresh cut mangos were 2–4% O_2 and 10% CO_2 [9]. Package headspace Oxygen and Carbon-dioxide composition is shown Table 5. It was observed that O_2 and CO_2 composition for the control and vibrated samples stored in 'Snap-fit' PET containers ranged from 18–19% and 3–5% respectively for ten days of storage. This suggests that the 'Snap-fit' PET containers were not an effective barrier to control the O_2 gas concentration to an optimum level. However, the CO_2 concentration was limited within the optimal concentration level of 10%. This was not the case when the

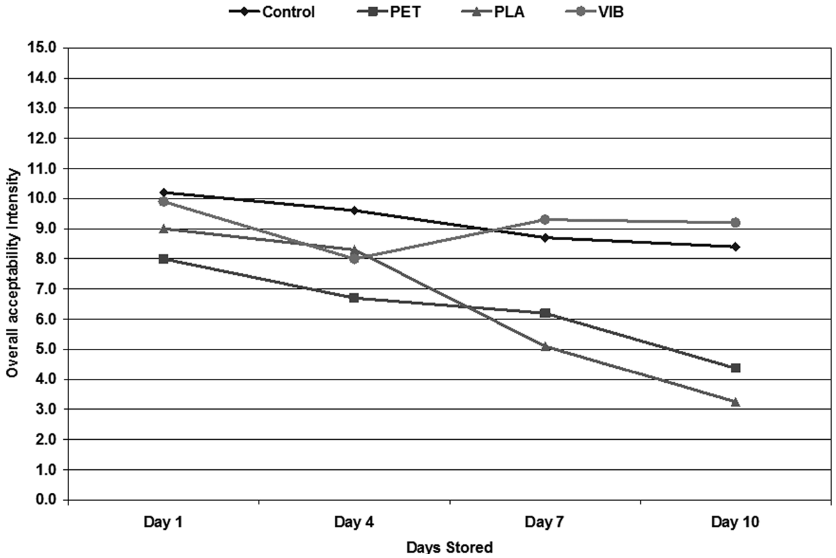

Figure 11. *Sensory scores for fresh cut mango overall acceptability during storage period. 1 = Very Bad; 15 = Very Good.*

Table 5. Effect of Treatments on In-package Gas Composition for Fresh Cut Mango During Storage.

In package Gas Composition	**Treatments**	**Days Stored**			
		Day 1	**Day 4**	**Day 7**	**Day 10**
Oxygen*	Control	18.4 ± 1.07a	17.5 ± 2.37a	19.1 ± 0.56a	18.8 ± 2.80a
	PET	8.54 ± 1.21b	21.2 ± 18.53a	10.8 ± 5.84b	13.6 ± 5.87b
	PLA	7.83 ± 0.83b	1.4 ± 0.35b	0.96 ± 0.29c	0.63 ± 0.6c
	VIB	18.45 ± 1.05a	17.9 ± 0.83a	17.85 ± 2.55a	18.9 ± 0.35a
Carbon dioxide	Control	3.5 ± 1.45b	5.1 ± 4.71 c	2.9 ± 0.781c	2.9 ± 3.71c
	PET	20.7 ± 2.84a	28.1 ± 15.45ab	28.7 ± 17.24b	16.3 ± 18.14b
	PLA	19.9 ± 2.18a	41.1 ± 4.12c	46.8 ± 6.48a	45.6 ± 4.14a
	VIB	3.4 ± 1.60b	12.4 ± 18.93bc	4.8 ± 3.79c	2.5 ± 0.53bc

Different letters following the values within a column indicate differences according to the Fisher's LSD at $p \leq 0.05$.

cut mango samples were packed in 'Continuous film' containers. The O_2 concentration for cut mango samples stored in PLA container with continuous film decreased from 7% to less than 1% by Day 10 (Table 5) and the CO_2 concentration increased from 20% to 45.6% by Day 10 (Table 5). Similarly, The O_2 concentration for cut mango samples stored in PET container with continuous film increased from 8% to 13% by Day 10 (Table 5) and the CO_2 concentration ranged from 20% to 16% by Day 10 (Table 5). Therefore, a container sealed with a continuous film may not be effective to maintain optimum in-package gas composition profile (O_2 and CO_2 concentration) during a 10 day storage period. This explains degradation of cut mango quality during storage, as seen in Figures 6–7 and Table 3 where quality loss was primarily due to off-odor (loss in aroma), color loss, sweetness and flesh softening.

CONCLUSIONS

Passive modified atmosphere packaging with appropriate levels of O_2 and CO_2 levels are successful in maintaining quality of fresh cut mango exposed to physical abuse during transportation. A rigid container with a continuous film (PET or PLA) is not a suitable packaging option as compared to a 'Snap-fit' PET container. Undesirable gas composition (O_2 and CO_2) during storage in 'Continuous film' rigid container induced anaerobic respiration leading to fruit decay and quality degradation. This resulted in undesirable quality attributes during storage as seen in aroma, color, sweetness and overall acceptability ratings from sensory evaluation. The findings of this study suggest that fresh cut mango packaged in 'Snap-fit' PET containers is better suited to maintain desirable headspace O_2 and CO_2 composition during transportation than 'Continuous film' rigid containers.

ACKNOWLEDGEMENTS

The authors will like to thank National Mango Board, USA and United States Department of Agriculture for their financial contribution. We would like to thank fresh produce distributor Coast Tropical for providing fresh whole mangos. Also, we would like to acknowledge the contribution from Department of Food Science, Sensory Analysis Lab at Michigan State University for providing their facilities to conduct this study.

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Table 5. Comparison of state-of-the-art matrix resins with VPSP/BMI copolymers.

Resin System	Core Temp. (DSC peak)	Char Yield, %
Epoxy (MY720)	235	30
C379: H795 = 14	285	53

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