This is to certify that the

thesis entitled

THE EFFECT OF TRANSIENT VIBRATION ON THE
TOP-TO-BOTTOM COMPRESSIVE STRENGTH OF UNITIZED
CORRUGATED SHIPPING CONTAINERS

presented by

ALAN ROBERT ADAMS

has been accepted towards fulfillment
of the requirements for

M.S. degree in PACKAGING

Bruce Harte

Bruce Harte
Major professor

Date October 27, 1987

THE EFFECT OF TRANSIENT VIBRATION ON THE TOP-TO-BOTTOM COMPRESSIVE STRENGTH OF UNITIZED CORRUGATED SHIPPING CONTAINERS

By

Alan Robert Adams

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

School of Packaging

1987

ABSTRACT

THE EFFECT OF TRANSIENT VIBRATION ON THE TOP-TO-BOTTOM COMPRESSIVE STRENGTH OF UNITIZED CORRUGATED SHIPPING CONTAINERS

By

Alan Robert Adams

The top-to-bottom compressive strength of corrugated shipping containers which had been subjected to a simulated transportation vibration environment was compared to the top-to-bottom compressive strength of non-vibrated boxes. The study was conducted on two sets of RSC boxes of different dimensions.

The containers were conditioned according to ASTM test standard D 685, and vibrated in compliance with ASTM test standard D 999. The compressive strengths of the boxes were determined according to ASTM test standard D 642. Moisture content of the box material was also determined as outlined in ASTM test standard D 644.

The mean top-to-bottom compressive strength of those boxes which did not fail in a simulated transient vibration environment was greater than the mean top-to-bottom compressive strength of non-vibrated boxes. The load at which failure occurred in the simulated transient environment was approximately one-third the value of the non-vibrated box top to bottom mean compressive strength.

A simple mathematical model was devised to explain the phenomenon and predict the maximum strength expected from an RSC box.

DEDICATION

This thesis is dedicated to my parents, Robert G. Adams and Rosalyn B. Adams, whose patience and support made this accomplishment possible.

ACKNOWLEDGEMENTS

I would like to thank my major advisor Dr. B.R. Harte for his support and guidance through the graduate program. I would also like to express my gratitude to the members of my graduate committee, Dr. R. Brandenburg, Dr. S.E.M. Selke, Mr. D.E. Young.

The assistance I received from, Dr. J. Gill with statistical design, Dr. J.W. Goff for package instrumentation, and Dr. G.J. Burgess in mathematical modeling, is also appreciated.

I am also indebted to the following companies for donating testing materials, Dow Chemical, Midland MI, Pillsbury, Minneapolis MN, and Lever Brothers, New York NY.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

It is generally accepted that a package has three main functions: (1) to contain and protect, (2) to provide some utility, and (3) to communicate. If one of the three functions is deficient the package is considered to have failed. In the transportation environment a package is subjected to the dynamic forces of vibration which could cause package failure. Very little research has been published on the effect of vibration on the ability of a package to fulfill these functions.

A tour through a typical warehouse will show that one of the most common packaging systems is the corrugated box. Observing a stack of boxes demonstrates that the bottom box is usually in the worst physical condition of the stack, with boxes at the top being in a less damaged state. When the boxe's physical condition is severe enough, it will collapse, thus failing to contain, protect, and to communicate. The determination of box top-to-bottom compressive strength is a common test procedure used to evaluate shipping containers. This test works satisfactorily for static loads, but the procedure is inadequate for dynamic testing.

Under normal, established testing procedures boxes are first preconditioned, conditioned, and lastly compression-tested empty with no correlation to dynamic environment testing. If dynamic testing is done, it is to determine if the package will survive a vibration resonance test for a set period of time. The actual strength of the container following repetitive shocks at resonance frequency may change from its non-vibrated state.

A reduction in top-to-bottom compressive strength may occur due to the dynamic vibration environment. If this occurs, a factor of some kind may be necessary to correct box top-to-bottom compressive strength to compensate for the loss due to vibration. If the factor is too low, a weak box results and damage occurs, or overpackaging could occur if the factor is too high. Either way results in an economic loss. A significant cost savings could result if an approximate value could be determined that would predict the strength reduction due to transient vibration.

Typically factors used to correct box top-to-bottom compressive strength have been developed based on experience, rules of thumb, or trial and error. These methods are inaccurate and inadequate in today's cost-competitive marketplace.

OBJECTIVES OF STUDY

This study was conducted:

1. To evaluate the change in top-to-bottom compression strength of corrugated shipping containers as a function of vibration.
2. To test different container systems to see if general top-to-bottom compressive strength patterns exist for corrugated shipping containers. Systems tested will be

varied according to size, number of boxes in the stack, weights in boxes, and types of dunnage.

LITERATURE REVIEW

COMPRESSIVE STRENGTH

Godshall in (1985) stated that the "corrugated container industry has been making board specifications that have little if any correlation with compression properties. These specifications are those set by the carrier classifications boards which, in the absence of other standards for grade classifications, have become the defacto standards for grade classification of corrugated fiberboard. The corrugating industry in the United States has continued to manufacture corrugated fiberboard using bursting strength and basis weight specifications, as set forth by the carrier industries, because it has been to their economic advantage to support these specifications. They have ignored the findings of the research community and the needs of shippers for compression strength. However, corrugated users are becoming more knowledgeable about the performance requirements of the transportation environment and are making stronger demands on their suppliers to meet their needs for greater box compressive strength."

Uniform Freight Classification Rule 41 (1978) and National Motor Freight Classification Item 222 (1978) require that single wall, corrugated fiberboard containers have a minimum bursting strength ranging from 125 psi. to 350 psi., with a required minimum combined weight of facings ranging from 52 lbs. to 180 lbs. allowing for a contents weight of 20 lbs. to 129 lbs. No mention is made of compressive strength in the standards.

McKee, Gander and Wachutta (1963) devised a formula to determine top-to-bottom compression strength of corrugated boxes. The expression is as follows:

$$\text{Top-to-bottom compression} = 5.8745\ Pm\ h^{0.5076}\ z^{0.4924}$$

where Pm = column crush in lb/inch; h = caliper of board in inches, and z = box perimeter (2L + 2W) in inches. This formula applies only to standard conditions, 73 degrees F (23 degrees C), 50% R.H.. There is no parameter to account for vibrational effects.

EFFECTS OF VIBRATION

Godshall (1968) reported that "failure (boxes which collapsed on a vibration table during testing) of containers appears to be due primarily to simple dynamic overloading (load on the top of the box was too great), and to dynamic overloading resulting from resonant amplification of vibrational input. Fatigue had no apparent effect on the top-to-bottom compressive strength of corrugated containers."

Goff (1974) reported on performance standards for parcel post packages, and concluded that vibration was shown to be of little consequence as a cause of damage in the parcel post system. Damage (boxes collapsing under load) could only be produced in the laboratory under very severe input conditions using very poorly constructed packages.

When the load was sufficient to cause damage, all similar packages tested under this load were damaged.

Guins (1975) found that an 8:1 amplification of the forcing vibration occurs during resonance, which induces bouncing in a stack of boxes. The acceleration value of the bouncing dynamic load will be 2-4 times the value of the static load. Therefore the dynamic load should only be 25 to 50 percent of the static load value.

CORRECTION FACTORS

Hanlon (1984) reports that a common rule of thumb for long-term storage is to use one-fourth of the compressive strength of a corrugated box as a safe load. He states that a more accurate method would be to calculate the fatigue factor for the length of time the material is expected to remain in storage. Factors are discussed for humidity and fatigue, but no reference is made to dynamic loading.

In the American Society for Testing and Materials standard (D 4169-82), the ability of a package to withstand the compressive loads that occur during vehicle transport or warehousing is considered an integral part of performance testing. Factors suggested range from 8.0 to 3.0 depending on which assurance level is desired (8.0 being the highest assurance level for extremely fragile products). The top-to-bottom compressive strength is divided by the factor for the estimated true value.

Young (1986) suggests that a factor of 3 to 6 be used to account for hazards in the transportation environment.

TRANSPORTATION ENVIRONMENT

Forest Products Laboratory (Report 22) describes vibration levels using a power spectral density envelope curve for typical trucks and railcars. Acceleration values in the envelope curves are considered typical of most vehicles if the occasional high peaks, not considered representative of continuous vibration, are excluded. For trucks 3 hz to 20 Hz is considered an average range at approximately 0.5 g's; for railcars the same frequencies have an average acceleration of 0.2 g's.

TEST METHODS

PREDICTING RESONANCE

Godshall (1973) attempted to predict resonant frequencies using spring factors obtained by repeated cyclic loading in a universal testing machine. The predicted resonant frequencies were all lower than the experimentally determined resonant frequencies; averaging only 81 percent of the actual values. He concluded that this was probably due to differences between static and dynamic spring factors and, for accuracy, an actual vibration transmissibility test should be used for precise determination of resonant frequencies.

Harris (1976) explained the jump phenomenon for a softening spring system (corrugated boxes are softening springs). "When the system is initially vibrated at a frequency higher than the natural frequency, followed by a decrease in frequency (continuously at a slow rate) the amplitude of the vibration increases, up to a point (this is resonance). In particular, at the point of vertical tangency of the response curve, a slight decrease in frequency requires that the system perform in an unusual manner; i.e., that it "jump" down in amplitude to the lower branch of the response curve" (this is not a smooth gradual decrease in amplitude). If the stack of boxes is initially vibrated from a lower frequency and gradually increased it will not have the same natural frequency. There is a portion of the response curve which is "unattainable". This is important to recognize in designing an experiment for determining resonance so that all samples are tested at the same natural frequency.

Kusza and Young (1974) discussed the vibration response of packages stacked in a column. They concluded that the greater the number of boxes in a stack, the lower the effective natural frequency of the stack. In this situation the oscillation of the top box was most severe. For this thesis the top box will be monitored to determine the natural frequency for the stack of boxes.

ESTABLISHED TEST METHODS

The American Society for Testing and Materials standard (D 685-73) includes conditioning of paper products and lists two steps in the conditioning process for knocked down shipping containers. First the samples must be preconditioned in an atmosphere of 1Ø to 35 % relative humidity at a temperature of 22 to 4Ø degrees C for a period of 5 to 1Ø hours. The second step is to condition in an atmosphere of 5Ø.Ø ± 2.Ø % R.H. and 23.Ø ± 1.Ø degrees C. for 5 to 8 hours.

The American Society for Testing and Materials standard (D 4169), which covers vibration performance testing, requires that for the highest assurance level, .5 g's and a dwell of 15 minutes for truck transport and .25 g's with a dwell of 15 minutes for rail transport be used.

The American Society for Testing and Materials standard (D 999-75) Method C, the unitized load or vertical stack resonance test, covers the effects of resonance in multiple-unit stacked loads, and recommends that if dwell time is not specified by other relevant ASTM test standards a dwell of 15 minutes be used.

The American Society for Testing and Materials standard (D 642-76) is the Standard Method of Compression Testing for Shipping Containers. The method suggests testing containers without contents, sealing the box to avoid distortions that may affect its load-bearing ability, and applying a preload of 5Ø lb force with the load being applied at a rate of .5 ± Ø.1 in./min..

In American Society for Testing and Materials standard (D 644-55) determination of the moisture content of paper products by oven drying is covered. The method requires the sample to be weighed, dried for 2 hours at 1Ø5 ± 3 degrees C then cooled in a desiccator for a period of one hour and reweighed. The percent moisture is determined by taking the difference in weight and dividing by the initial weight then multiplying by 100.

EXPERIMENTAL, MATERIALS AND PROCEDURES

SAMPLE CONTAINERS

Three sets of regular slotted containers (R.S.C.) were used in this study (figure No. 1).

Box Type 1. Specification

Corrugation - C flute, double faced.

Dimensions 18 1/4" x 11 1/4" x 11 3/4" (L x W x D)

Bursting Test - 200 lbs. per square inch.

Minimum Combined Weight Facings - 84 lbs per 1000 square feet.

Size Limit - 75 inches.

Gross Weight Limit - 65 lbs.

Manufactured by Container Corporation of America for Lever Brothers Company.

Box Type 2. Specification

Corrugation - C flute, double faced.

Dimensions 19 1/2" x 10 1/4" x 7 1/4" (L x W x D)

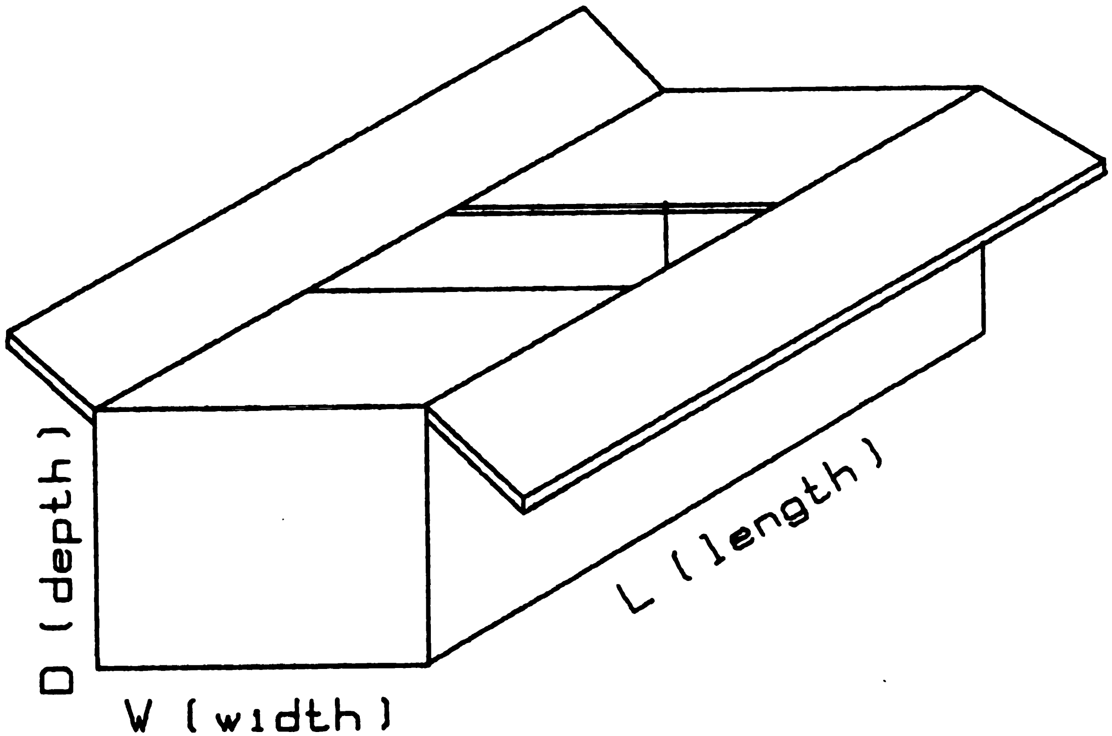
Bursting Test - 200 lbs. per square inch.

Minimum Combined Weight Facings - 84 lbs per 1000 square feet.

Size Limit - 75 inches.

Gross Weight Limit - 65 lbs.

Manufactured by Owens Illinois - Forest Products Division for the Pillsbury Company.



A Typical RSC

figure 1.

Box Type 3, Specification

Corrugation - B flute, double faced.

Dimensions 15 1/4" x 6 1/4" x 4 1/2" (L x W x D)

Bursting Test - 125 lbs. per square inch.

Minimum Combined Weight Facings - 52 lbs. per 1000 Square Feet.

Size Limit - 40 inches.

Gross Weight Limit - 20 lbs.

Manufactured by Weyerhaeuser Company for the Pillsbury Company.

CONDITIONING

Boxes were received knocked-down from Lever Brothers and Pillsbury. A glued manufacture's joint (glued by the corrugated box manufacture') was used on all boxes. Containers were first prebroke' and set up unsealed without bending flaps to allow for air circulation. The boxes were then preconditioned at 74 degrees F, and 30% R.H., for 24 hours, and, then, finally conditioned at 72 degrees F, at 50 ± 2% R.H., for 8 hours, in accordance with ASTM D 685 - 73. Temperature and relative humidity conditions were monitored using a Bendix recording Hygro-thermograph (model 594). The Hygro-thermograph was calibrated with a Bendix Psychron Psychrometer (model 566). After conditioning, empty containers were sealed top and bottom as outlined in ASTM Standard D 642 with 3M brand (3M - Minneapolis, MN) plastic sealing tape.

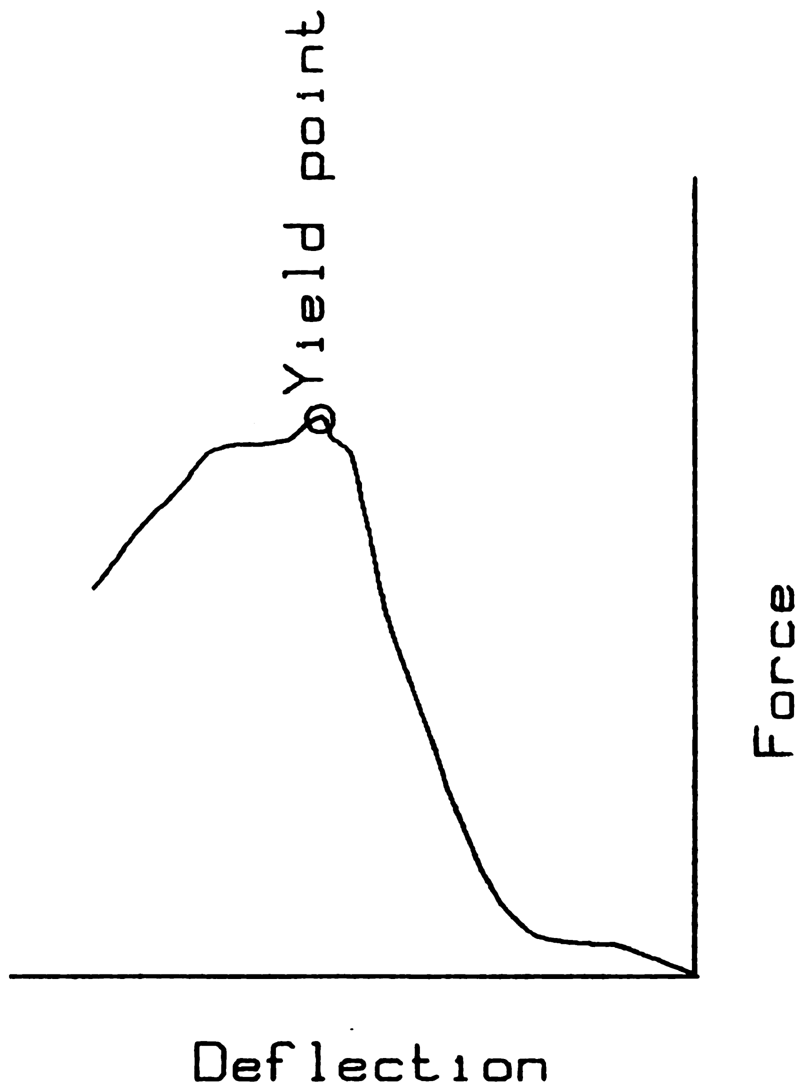
TESTING PROCEDURE

Testing sequence

Because all of the testing could not be performed during the same test-run, testing was divided into groups to avoid the combined effects of different moisture contents, different temperatures, and machine setup variability. For each test run one group of boxes was tested. One test group contains two boxes for each treatment performed; a treatment is each of the five different top loads and one control. Thus twelve boxes were tested during each run. Twenty samples for each treatment were needed (Gill 1986, see Appendix 2). Six treatments with twenty samples resulted in one hundred twenty boxes tested for each box size.

Compression Testing

Compression strengths of all the samples were evaluated using a Instron Universal Testing Machine Model TTC 2344642. A free floating platen apparatus was designed for this experiment and is discussed in Appendix 1. Crosshead speed used was Ø.5 inches per minute, as recommended in ASTM D 642-76 with the chart paper speed set at 5 inches per minute. Compressive strength was considered to be the yield point; the highest point on the force-deflection curve (figure 2). The compressive strength for each treatment category is reported as the average of twenty samples.



Yield point on force-deflection curve.

figure 2.

Vibration Testing

All vibration testing was performed using an MTS 840 Electro-hydraulic vibration test system. Samples were tested at 0.5 g's during resonance for 15 minutes as described in ASTM D 4169, for the highest assurance level for the worst ride in truck transportation. Resonance determination was calculated using a Hewllet-Packard X-Y plotter model 7034A, and a Kistler accelerometer model 815A5. The accelerometer was mounted in one of the boxes containing a load and placed on the top of the stack. "G" levels experienced in the package were plotted as a function of table frequency. Resonance was considered to be at the frequency where the package encountered the highest g level. The starting frequency of the vibration table was a lower frequency than the stack resonance frequency and was increased to the natural frequency of the stack to avoid a change in resonance frequency due to the "jump" phenomenon (Harris 1976).

Moisture Content

Determination of moisture content was performed on containers that were tested for compression strength. One box flap was cut off each box tested. The procedure followed was ASTM D 644 with one exception. Weighing containers are recommended when transporting samples from storage and testing location to avoid changes in moisture content due to differing atmospheres. These containers were not used because test samples were in the same conditioned atmosphere room during testing, and during moisture content determination. Samples were weighed, placed in a drying oven at 100 ± 3 degrees C for two hours, cooled for one hour in a dessicator, and then reweighed. Percent moisture was calculated for wet basis percent moisture by using the difference between the initial and final weights divided by the initial weight multiplied by 100.

RESULTS AND DISCUSSION

Two hundred eighty seven corrugated shipping containers were tested to determine if a change in compressive strength would result from transient vibration. All testing was done at 23 degrees C, 50% R.H.. Moisture content determination was performed for each test day.

Box No. 1 Obtained from the Lever Bros. Co.

Table one contains the results for this box at the various loads. For this test a stack of five boxes was chosen. The top four boxes contained evenly distributed weights. The bottom box was empty and supported the load. A stack, five boxes high was chosen because a typical truck trailer 40 feet long by 8 feet wide has 46080 square inches of floor space. If 90% space utilization is achieved there is 41472 square inches of usable space. Divided usable space by area per box of 205 square inches to calculate 202 boxes per layer. Normal truck trailers are capable of carrying 40,000 lbs. divided by 202 boxes per layer there would be 198 lbs per box if only one layer per truck is used. 198 lbs. per box is more weight than allowed by Uniform Freight Classification Rule 41 (1978). Rule 41 specifies a maximum allowable weight of 65 lbs. per container for 200 lbs test C-flute corrugated fiberboard. A range of 18 to 50 lbs per box was chosen to stay within the limits of Rule 41. Divide the lightest load 72 lbs. by 18 lbs. per box calculates 4 boxes are required to contain the

Table 1

Compressive Strength of Box No. 1

	Non-vibrated Box	Compression Strength (lbs) 72 lb load	88 lb load	104 lb load	112 lb load
1.	800	820	720	600	740
2.	800	720	760	700	720
3.	880	720	780	680	680
4.	820	800	700	660	740
5.	840	780	760	720	680
6.	820	900	800	700	640
7.	740	720	760	600	620
8.	720	720	720	680	720
9.	820	680	860	520	780
10.			700		600
mean	804.4	762.2	756.0	651.1	692.0
Std. dev.	48.8	68.9	49.7	64.9	58.3

load and one empty box on the bottom for a total stack of five boxes. The stack height should not be any taller than a truck door which is typically eight feet, the height for five boxes high is 4.9 feet.

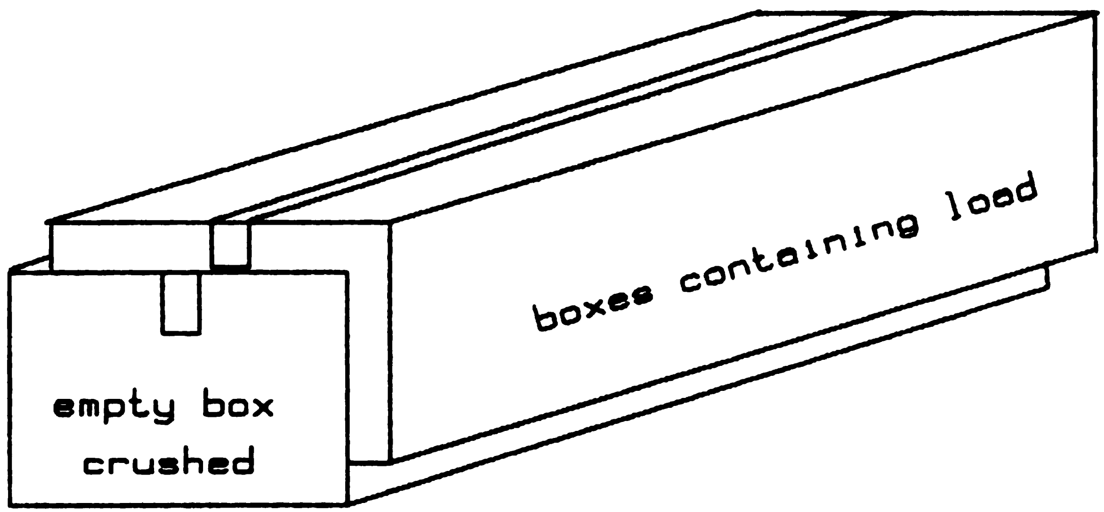
Non-vibrated average compressive strength for this box was 804 lb. As the top load was increased for each test run the compressive strength decreased from 762 lbs per box for a 72 lb. top load to 692 lbs. per box for a 112 lb top load. The standard deviation for the 72 lb. top load, which had the greatest variance, was within nine percent of the non-vibrated new box compressive strength. A possible conclusion would be that with an increase in top load the strength of a box will decrease. However several potential variables need to be considered. Vibration testing for this set of boxes was done on a weight by day basis; for example all of the 72 lb load tests were done on the same day. Machine setup, testing room atmospheres, test technician error are all factors that could change on a day-to-day basis. No provision was made to account for these variables. One way of investigating the changing test conditioning atmospheres would be to determine moisture content of the boxes. A change in moisture content possibly indicates that there was a change in the procedure or conditioning of the samples that could have skewed the results.

At loads higher than 112 lbs the boxes failed. However, this failure was not typical of failure patterns in the distribution environment. The boxes were crushed on two sides with the remaining sides still intact (figure 3). Observations in several warehouses demonstrated that typically a box will fail due to panels caving-in or out with development of a U shaped pattern (figure 4). This U shaped pattern is the same pattern that will occur in a typical compression test. In order to duplicate the same U shaped pattern during testing, a box cap was placed over the empty bottom box (figure 5) for the remaining sets of boxes. Placement of this cap over the top of the bottom box distributed the load over the entire box top surface and when failure occurred the same U shaped pattern resulted.

Box No. 2 Obtained from The Pillsbury Co.

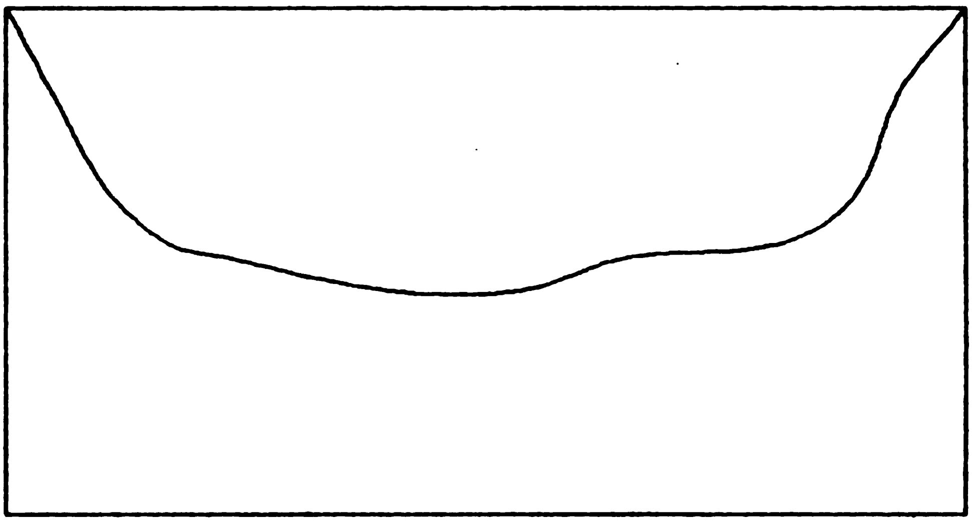
In table 2 are presented the results for box No. 2 tested under the various loads. Loading values were determined by a trial test. For test loadings over 215 lbs. the sample container was crushed in every trial. The loading was then decreased by 4 percent per loading to a load that was 21 percent of the non-vibrated box compressive strength. A loading of 21 percent of the non-vibrated box compressive strength is under the recommended safe limit of 25 percent as recommended by Hanlon (1984).

For this test the boxes were tested in groups as discussed previously. Rule 41, Uniform Freight Classification (1978) allows a maximum load of 65 lbs. per box for 200 lb test C-flute corrugated fiberboard. Loads



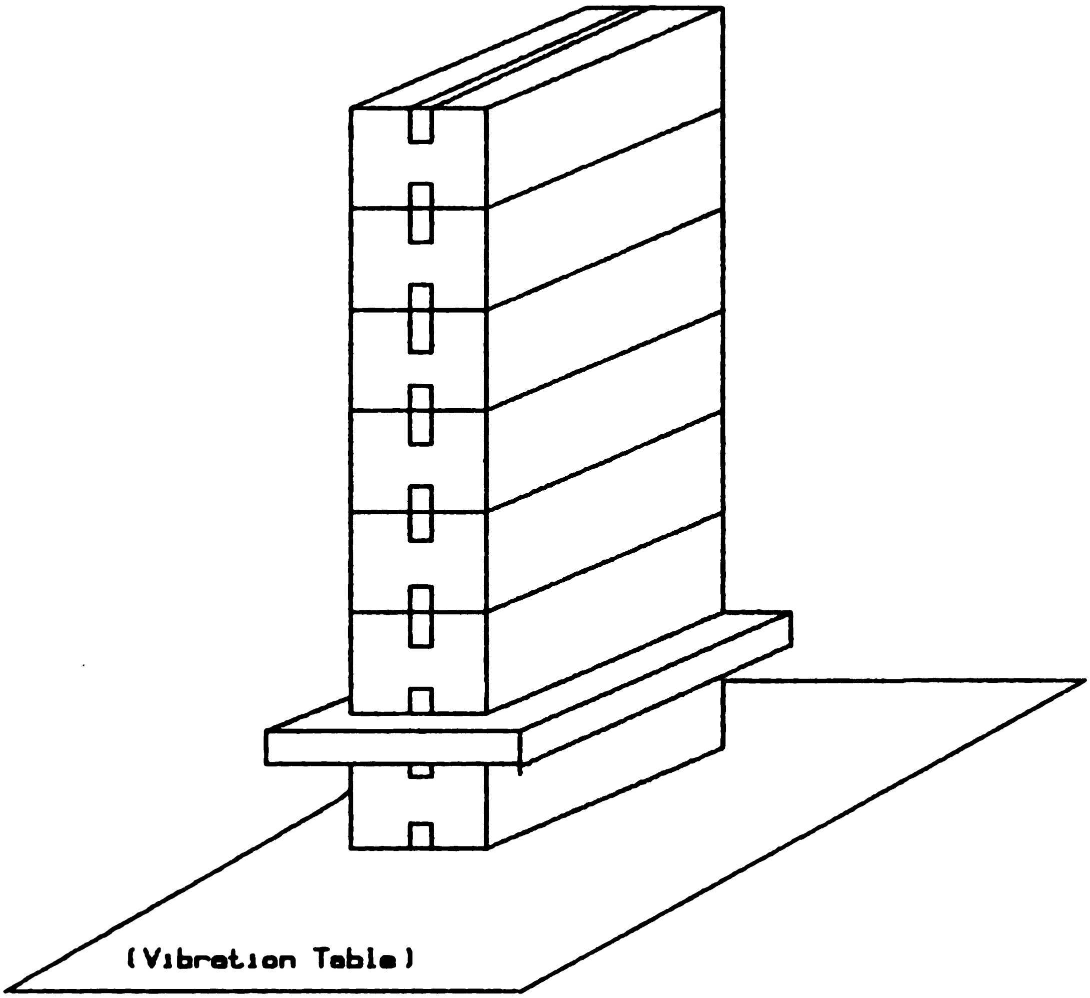
Two sides of the box
folding in rather than all
four sides buckling together

figure 3.



Typical "U" shaped pattern on the side of a corrugated box during compression.

figure 4.



Empty bottom box with
box cap in place

Figure 5.

Table 2

Compressive Strength of Box No. 2

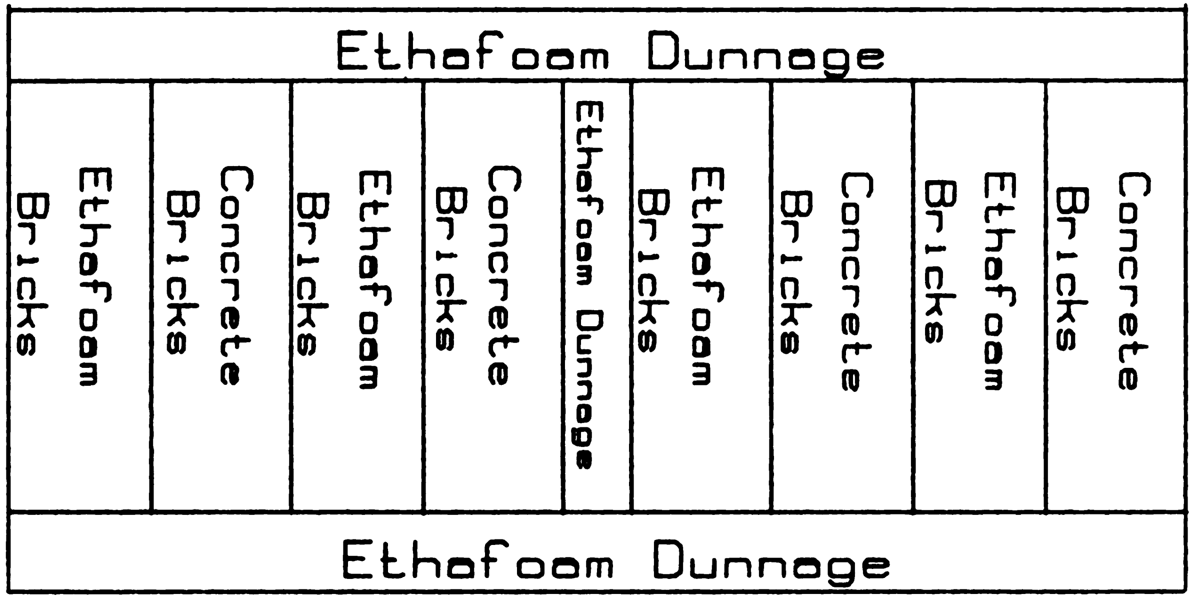
	Compression Strength (lbs)					
	Non-vibrated Box	125 lb load	146 lb load	168 lb load	191 lb load	215 lb load
1.	550	620	610	640	_____*	685
2.	610	480	620	610	590	_____
3.	560	610	660	620	630	670
4.	580	600	640	630	660	_____
5.	640	620	670	650	680	_____
6.	550	640	620	670	670	_____
7.	590	680	630	620	670	_____
8.	620	570	650	650	_____	_____
9.	570	640	620	650	_____	_____
10.	610	640	650	590	690	660
11.	540	590	680	660	700	_____
12.	600	660	620	680	660	_____
13.	620	630	650	660	_____	660
14.	580	620	660	670	650	630
15.	600	640	670	610	670	_____
16.	570	630	700	670	700	630
17.	620	690	660	650	_____	640
18.	540	610	650	660	_____	_____
19.	580	610	620	610	680	_____
20.	590	620	660	640	610	-----
mean	586	620	647	641	_____	_____
Std. dev.	28.4	42.2	23.5	24.6	_____	_____

_____* denotes failure of container

ranging from 21 lbs. to 36 lbs. were used to stay within limits of the rule. Six boxes containing 21 lbs each were used for a stack loading of 125 lbs. A box cap was placed over the empty bottom box supporting the load, bringing the total number of boxes in the stack to seven. Seven boxes have a height of 4 feet which is under the truck trailer door limit of 8 feet.

Concrete bricks were used as weights in the boxes with 9 lb density ethafoam as dunnage. To change weights in the boxes, bricks were added to and subtracted from each box as shown in figure 6. When a brick was removed a brick made of ethafoam replaced it, always positioned to keep the load evenly distributed. There was no resonance frequency interference between the brick, the ethafoam, and the stack, because both the brick and the ethafoam were determined to have a considerably higher resonance than the stack.

As shown in table 2 the boxes did not decrease in strength but increased. The first three loads resulted in a significant increase in strength compared to the non-vibrated box strength (Dunnett statistical test at 85 percent power (percent power is similar to confidence level) (Gill, Appendix 2)). Since the results from box No. 1 and No. 2 were different, it was decided to try a third test on a different container. The test was designed with a different size box, numbers of containers in the stack, and system for loading with weights.



Top view of corrugated box showing ethafoam and concrete brick placement.

figure 6.

Box No. 3 Obtained from The Pillsbury Co.

In Table 3 are shown the results for the third box with the various loadings. For this test B flute corrugated board was used instead of C flute, the box was approximately one-half the height dimension of the previous box, and eleven boxes were chosen for the stack height with ten boxes containing weights, the box cap, and the empty box on the bottom. The dimensions of the third box were too small to permit use of bricks for the load so lead weights were used. One and one-half pound weights were added and removed from a wooden frame placed in the corrugated box (figure 7). The wooden framework was necessary because there was no other dunnage used to fill the corrugated container. The resonance frequency of the wooden frame and bricks was checked and found to be higher than the resonance of the stack.

Using the Dunnett t-test, the compressive strength of the non-vibrated boxes and the 75 lb. loaded boxes were found to be significantly different at 85 percent power level. 85 percent power level was chosen so not to vary from the previous power levels. It is not obvious from table 3 that the compressive strengths of the non-vibrated boxes were found not to be significantly different than the 60 and 90 lbs. loaded boxes. Boxes loaded to approximately one third the non-vibrated compressive strength had a failure rate of thirty percent. Several factors may be of importance. In the second set of boxes, non-vibrated box

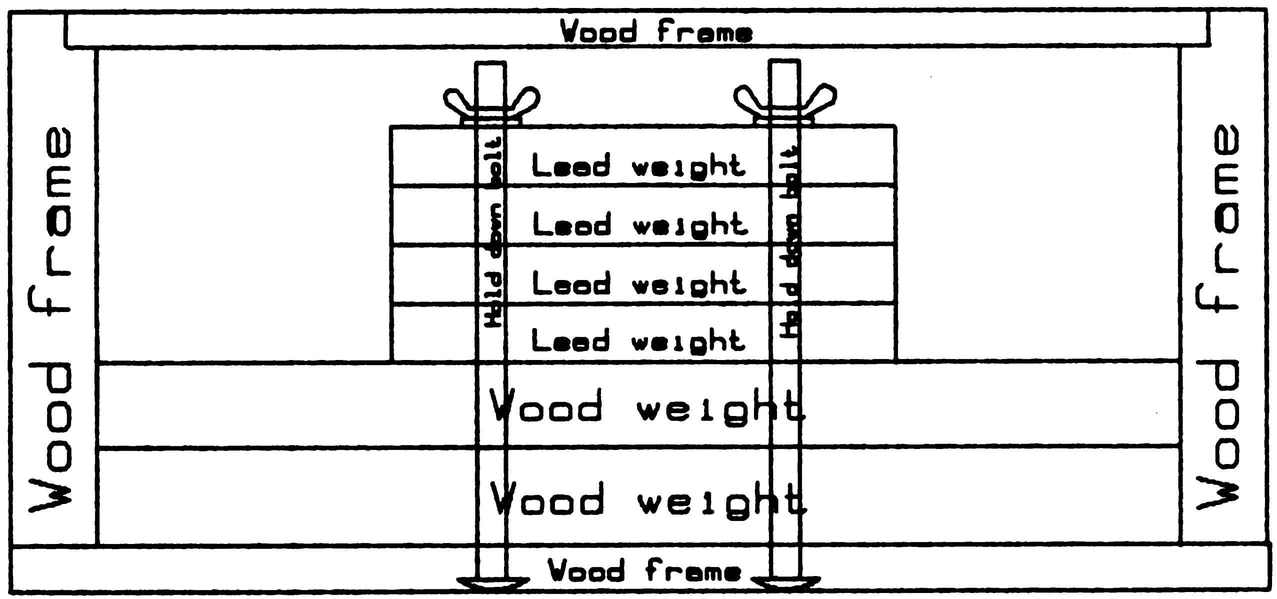
Table 3

Compressive Strength of Box No. 3

Compression Strength (lbs)

	Non-vibrated Box	6Ø lb load	75 lb load	9Ø lb load	1Ø5 lb load	12Ø lb load
1.	38Ø	34Ø	37Ø	31Ø	37Ø	_____*
2.	35Ø	36Ø	34Ø	32Ø	_____	_____
3.	32Ø	3ØØ	31Ø	32Ø	_____	_____
4.	26Ø	3ØØ	33Ø	28Ø	39Ø	38Ø
5.	31Ø	32Ø	33Ø	36Ø	38Ø	_____
6.	31Ø	33Ø	35Ø	33Ø	35Ø	33Ø
7.	33Ø	36Ø	37Ø	4ØØ	41Ø	_____
8.	38Ø	36Ø	42Ø	41Ø	_____	41Ø
9.	31Ø	34Ø	38Ø	_____	38Ø	_____
1Ø.	28Ø	32Ø	36Ø	33Ø	35Ø	_____
11.	27Ø	3ØØ	38Ø	34Ø	26Ø	_____
12.	29Ø	3ØØ	3ØØ	32Ø	26Ø	_____
13.	28Ø	33Ø	29Ø	37Ø	32Ø	_____
14.	27Ø	29Ø	24Ø	_____	_____	_____
15.	29Ø	34Ø	33Ø	35Ø	_____	_____
16.	3ØØ	36Ø	32Ø	34Ø	33Ø	4ØØ
17.	32Ø	28Ø	27Ø	37Ø	35Ø	_____
18.	3ØØ	3ØØ	31Ø	32Ø	4ØØ	33Ø
19.	33Ø	31Ø	35Ø	37Ø	32Ø	____
2Ø.	32Ø	38Ø	35Ø	31Ø	-----	-----
mean	31Ø	326	335	342	_____	_____
Std. dev.	33.2	28.4	41.7	33.3	_____	_____

_____* denotes failure of container



Wood frame with removable lead weights.

figure 7.

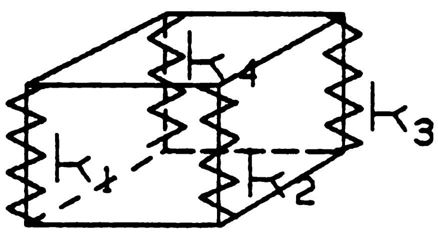
strength had a standard deviation of 3.3% of the mean compressive strength compared to the third set of boxes which had a standard deviation of 10.71% of the mean compressive strength. Included in the 90 lb load were two failures which were counted as zero.

Percent moisture content was determined for each group of boxes (tables 6-21 in appendix 3). A box flap was cut off from each individual box, weighed, dried, and reweighed to determine the difference. This number was then divided by the original weight times 100, to obtain the percent moisture content. The mean moisture content for the second group of boxes was equal to 7.25% with a standard deviation of .19%. The third group of boxes had a mean of 6.89% with a standard deviation of .1%.

In this study failure of the corrugated boxes was due to dynamic overloading, the weight of the load bouncing on the bottom container during resonance was too high. Most of the containers failed during the first four minutes of vibration. The top load at failure was one-third the mean value of the non-vibrated box top to bottom compressive strength. A factor of 3 should therefore be used when accounting for vibrational effects on corrugated box strength.

If for Box No. 3, 90 lb. load, the two failures that occurred are not counted when calculating Dunnett's t-test a significant statistical difference results. Graphing the Machine Compression Strength compared to Top load demonstrates the corrugated boxes tested had an 8-10% increase in top to bottom compressive strength after subjection to vibration (figures 8 & 9).

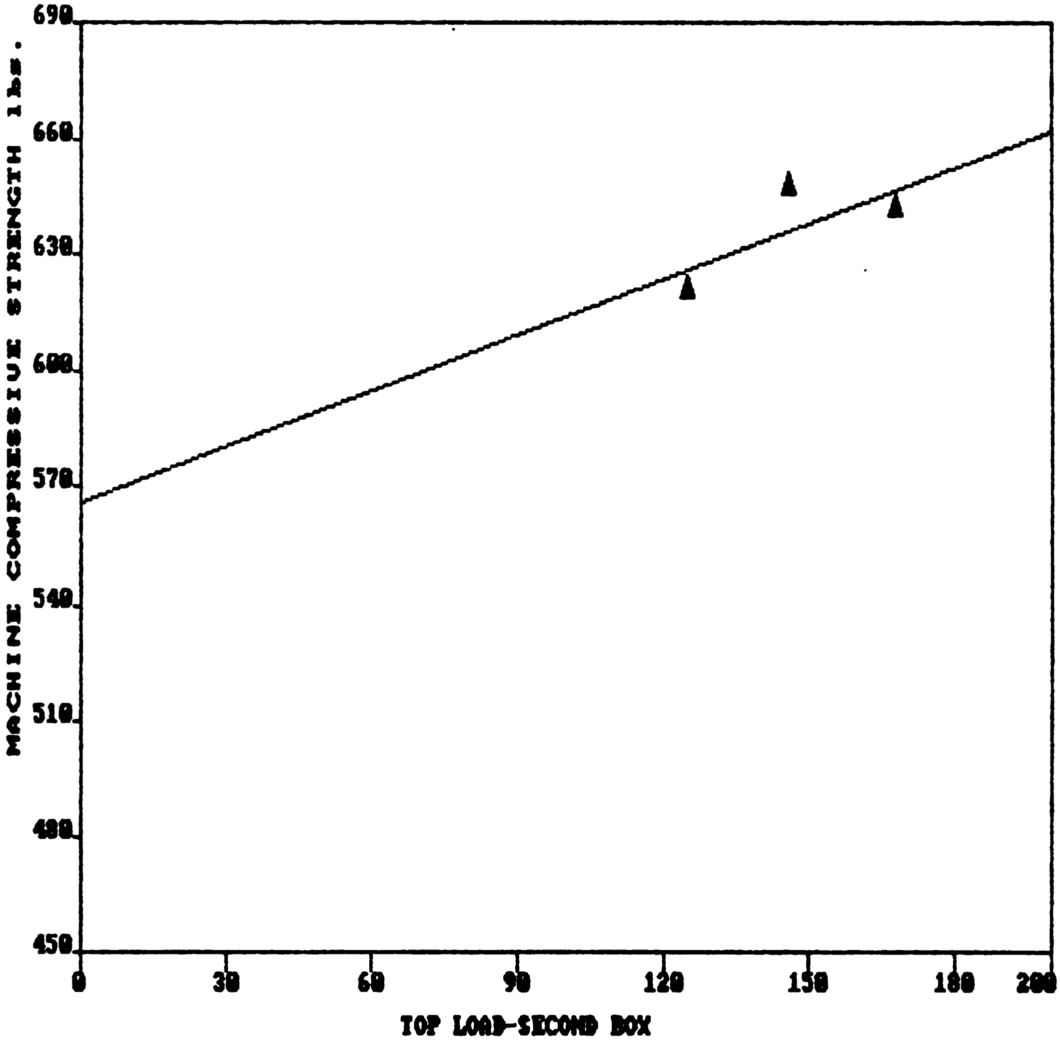
An explanation for this phenomenon is offered by Burgess (1987) where failure is due to a combination of side-wall buckling and corner-crushing. The dominant influence on compression strength is corner rigidity since buckling of corrugated sides takes place at relatively low loads. The RSC can then be modeled as a system of 4 springs of different lengths, each of which fails when the compression reaches some critical value. The function of the sides is to maintain the springs in an upright position (figure 10).



Four corners of a box acting as individual springs.

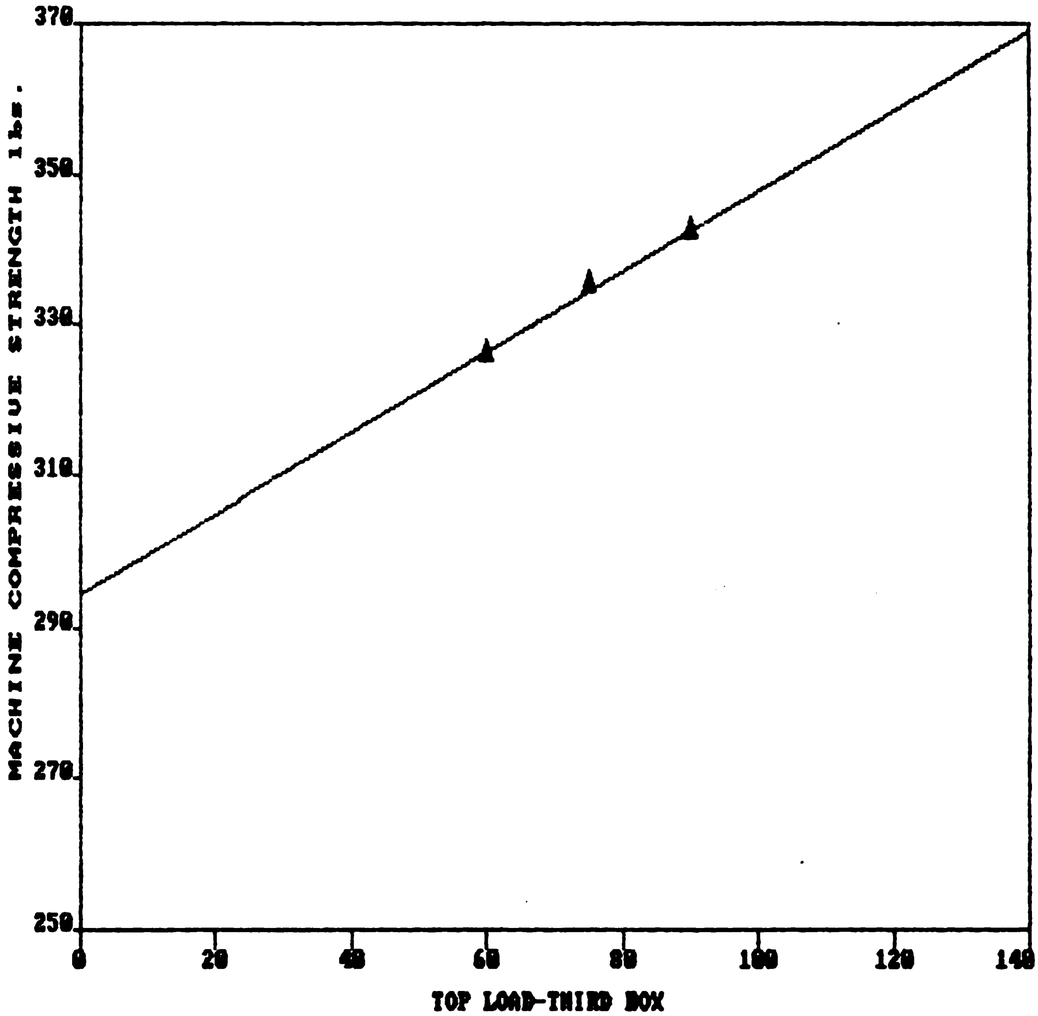
figure 10

When the floating platen begins to compress the RSC, it contracts only three of the 4 springs initially unless the four heights shown lie in a perfect plane. In this example "a" is equal to the distance between the platens and the uncontracted spring when the platen firsts contracts the other three. "k" is equal to the spring constant of <u>one</u> of the 4 identical corner springs. "x" is for compressions where the distance between the uncontracted spring and the



8.5 % increase in top-to-bottom compressive strength, Box No. 2

figure 8



7.8 % increase in top-to-bottom compressive strength,
Box No. 3

figure 9

platen are different than the optimum distance "a". For compressions "x" greater than "a" the force/deflection relation is:

$$F = (3k)x$$

For compressions x less than a, the platen has compressed three of the springs x and the fourth (x-a). So

$$F = 3kx + k(x-a) = 4kx - ka$$

Failure occurs when x is some critical value, say x_{cr}, at which time the load F becomes the compression strength C;

$$C = 4kx_{cr} - ka$$

If there was a perfect RSC where a = Ø, the compression strength would be as high as it would get: C_o = compression strength when a = Ø

$$C_o = 4kx_{cr}$$

Therefore,

$$C = C_o - ka = C_o - (C_o \div 4x_{cr})a$$

and

$$C \div C_o = (1 - a \div 4x_{cr})$$

This states that the ratio of the compression strength with the out of planeness distance "a" to the compression strength for a perfect RSC (C_o, which is unknown) is 1 - a ÷ $4x_{cr}$ where x_{cr} is the compression of the perfect RSC at failure (which is also unknown). (Sample data was collected for the box No. 2, see Table 4) Non-vibrated box (C,a) = (586, .Ø86), Vibration sample (C,a) = (642, .Ø16). now force fit these values into the above equation:

$$1).\quad 586 \div C_o = 1 - .Ø86 + 4x_{cr}$$

$$2).\quad 642 \div C_o = 1 - .Ø16 + 4x_{cr}$$

Solve simultaneously C_o = 655 lbs. and x_{cr} = .2 inches.

For box No. 2 the compression strength and corresponding deflection of a perfect RSC would be 655 lbs. at approximately .2 inches. Therefore,

$$C \div 655 = 1 - a + .8$$

or

$$C = 655\ (1 - 1.25a)$$

Sample data for box No. 3 (see table 5), Non-vibrated box (C,a) = (31Ø, .Ø485), Vibration sample (C,a) = (335, .ØØ8) force fit these values into the previous equation:

$$1).\quad 31Ø \div C_Ø = 1 - .Ø485 + 4x_{cr}$$

$$2).\quad 335 \div C_o = 1 - .ØØ8 + 4x_{cr}$$

Solve simultaneously $C_Ø$ = 34Ø lbs. and x_{cr} = .14 inches.

For box No. 3 the compression strength and corresponding deflection of a perfect RSC would be 34Ø lbs at approximately .14 inches. Therefore,

$$C \div 34Ø = 1 - a + .86$$

$$C = 34Ø\ (1 - 1.16a)$$

Determination of the "a" value for Box No. 2

The "a" value is the sum of the height measurement of two opposite corners subtracted from the sum of the height measurement from the two remaining corners. A 2Ø lb. weight on a plywood board was placed on the end of the box, a ruler measured the distance between a table surface and bottom of the board.

Table 4

Determining the "a" value for Box No. 2 test number 14. Measurements are clockwise around container in inches, two containers for each load were tested and averaged.

		Difference
Non	7 31/64, 7 27/64, 7 31/64, 7 31/64	.Ø625
vibrated	7 33/64, 7 29/64, 7 33/64, 7 31/64	.11Ø
box	Total ÷ 2 =	.Ø86
125 lb.	7 22/64, 7 22/64, 7 22/64, 7 21/64	.Ø16
load	7 24/64, 7 2Ø/64, 7 2Ø/64, 7 21/64	.Ø16
	Total ÷ 2 =	.Ø16
146 lb.	7 2Ø/64, 7 21/64, 7 24/64, 7 23/64	.ØØØ
load	7 21/64, 7 2Ø/64, 7 2Ø/64, 7 22/64	.Ø16
	Total ÷ 2 =	.Ø8Ø
168 lb.	7 23/64, 7 2Ø/64, 7 2Ø/64, 7 21/64	.Ø31
load	7 21/64, 7 22/64, 7 21/64, 7 2Ø/64	.ØØØ
	Total ÷ 2 =	.Ø16

Determination of the "a" value for Box No.3

Another method was used to obtain "a" values for box No. 3. A vernier caliper accurate to 1/1000" was used to measure the height of corners of the box. A statistically significant difference in strength existed between the non vibrated box and 75 lb. top load box and are the values presented.

Table 5

Determining the "a" value for Box No. 3 test number 2. Two sets of boxes were tested at the same time so there are four boxes per group. Measurements are in inches.

		difference
New Box	4.965, 5.074, 4.963, 5.000	.146
	4.990, 5.036, 5.036, 4.995	.005
	4.995, 5.020, 5.015, 5.021	.031
	5.040, 4.980, 4.995, 5.043	.012
	Total ÷ 4 =	.0485
75 lb.	4.981, 4.952, 4.975, 4.990	.014
	4.959, 4.960, 4.973, 4.971	.004
	4.961, 4.955, 4.970, 4.973	.003
	4.975, 4.961, 4.961, 4.965	.010
	Total ÷ 4 =	.008

This explanation states that if a box were perfectly square when manufactured it would have the greatest top to bottom compression strength. Boxes however are not perfectly square from the box manufacture. Some tolerances have to be allowed for the manufacturing process, but tighter the tolerances used when producing the corrugated box the higher the top to bottom compressive strength will be.

SUMMARY

Sets of different size corrugated boxes were tested to determine the effect of a simulated transient vibration environment on the mean top to bottom compressive strength. Moisture contents tests were performed on the sets of boxes and found to be similar. In summary:

1. Top to bottom mean compressive strength increased after subjection to vibration. This resulted in an 8 percent increase in top to bottom compressive strength
2. In this study failure of the corrugated box was due to dynamic overloading. Containers failed in the first four minutes of testing on the vibration table with a top load of one-third the value of the non-vibrated box mean compressive strength.
3. Higher tolerances followed during corrugated box manufacture will result in boxes having closer to equal box corner heights. Equal corner heights will increase top to bottom compression strength.
4. A safety factor of 3 should be used for calculation of the maximum top load a box can withstand in a transient vibration environment.

Areas for Future Study

1. Environmental considerations: All testing was performed at standard conditions ASTM D 685-73, temperature and relative humidity were not evaluated. Testing should

be done to see if these same trends hold true in severe conditions.

2. Pallet design and stacking patterns: What effect if any does the type of pallet used, and stacking pattern of boxes during vibration in transit have on the top to bottom compressive strength of corrugated shipping containers.

3. Load: All boxes tested for compressive strength were empty; Does a load in the container during vibration affect the top to bottom compressive strength.

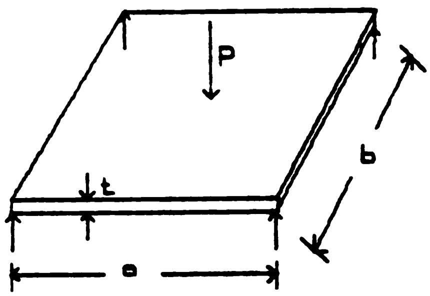
4. Test Burgess theory (1987): Corrugated boxes increase in top to bottom compressive strength after subjection to vibrational input because the corners of the non-vibrated box being unequal in heights, compared to a vibrated box where the corners are closer to equal heights due to settling effect of vibrational input.

APPENDICES

APPENDIX 1

From Den Hartog (1952) page 133 case 21.

Illustration of problem.



Rectangular plate supported on corners with a single concentrated force P in the exact center.

figure 11.

$$W_{max} = \epsilon \, (Pa^2 + Et^3)$$

a = 22", b = 28", b/a = 1.27

From page No. 133 for b/a = 1.27, ϵ = .153

Assume max force for platen = 1600 lbs.

Modulus of elasticity for aluminum = 9.9 - 10.3 x 10^6 lb/in^2

Maximum deflection for .75" thick plate = 0.023990"

One more consideration is weight of the platen. The weight should be less than the 50 lb pre-load required by ASTM Standard D 642 - 76 to account for slack in the platen mounting system. The density for aluminum is 168.5 lbs per cubic foot therefore .75" x 22" x 28" = 462 cubic inches ÷ 1728 inches per cubic feet = 0.27 cubic feet x 168.5 = 45.5 lbs.

APPENDIX 2

From Gill (1986) **Number of Boxes to Test**

$$d = c + \sigma \surd (r + 4)$$

r = number of boxes

σ = expected standard deviation

c = detectable change required

$d = 2.5$ value given by Gill from OC curves

$$2.5 = 50 + 40 \surd (r + 4)$$

$r = 16$ (plus 20% safety factor) = 20 boxes per treatment

93% Power

Analysis of Variance

Dunnett's test

$$t = (x_1 - x_2) + \surd (2(MS_e + r))$$

x_1 = mean of control group

x_2 = mean of treatment group

MS_e = Mean Squared Error

r = number per treatment

value of $t > 2.32$ for positive test of difference

value from Gill (1986) 85% power

APPENDIX 3

Table 6

Moisture Content of Box No. 2

Weight In Grams

First test day

No.	Initial Wt.	Final Wt.	moisture % content
1.	6.1559	5.7398	6.76
2.	6.3936	5.95Ø4	6.93
3.	6.Ø375	5.6345	6.67
4.	6.Ø68Ø	5.6574	6.77
5.	6.3323	5.8987	6.85
6.	6.1616	5.7445	6.77
7.	6.2212	5.7825	7.Ø5
8.	6.1156	5.7Ø27	6.75
9.	6.2726	5.8412	6.88
1Ø.	6.Ø432	5.6377	6.71
		Mean	6.81
		Std Dev.	Ø.11

Table 7

Moisture Content of Box No. 2

Weight In Grams

Second test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.1416	5.7Ø46	7.12
2.	6.Ø721	5.6469	7.Ø
3.	6.Ø911	5.6537	7.18
4.	6.Ø821	5.6798	7.17
5.	6.2853	5.8481	6.96
6.	6.1684	5.7346	7.Ø3
7.	6.1196	5.6781	7.21
8.	6.2441	5.7979	7.15
9.	6.1185	5.6798	7.17
1Ø.	6.2281	5.7776	7.23
		Mean	7.12
		Std Dev.	Ø.Ø9

Table 8

Moisture Content of Box No. 2

Weight In Grams

Third test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.1790	5.7108	7.58
2.	6.2460	5.7909	7.29
3.	6.1415	5.6952	7.27
4.	6.1565	5.6835	7.68
5.	6.1241	5.6656	7.49
6.	6.2252	5.7732	7.26
7.	6.1513	5.6929	7.45
8.	6.1479	5.7129	7.08
9.	6.2053	5.7455	7.41
10.	6.0745	5.6394	7.16
		Mean	7.37
		Std Dev.	0.19

Table 9

Moisture Content of Box No. 2

Weight In Grams

Fourth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.1300	5.6834	7.29
2.	6.1407	5.6889	7.36
3.	6.0687	5.6298	7.23
4.	6.1530	5.7150	7.12
5.	6.2689	5.8138	7.26
6.	6.2378	5.7861	7.24
7.	6.0623	5.6233	7.24
8.	6.1907	5.7576	7.00
9.	6.2775	5.8174	7.33
10.	6.1005	5.6801	6.89
		Mean	7.20
		Std Dev.	0.15

Table 10

Moisture Content of Box No. 2

Weight In Grams

Fifth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.1129	5.6556	7.48
2.	6.2448	5.7748	7.53
3.	6.3554	5.8715	7.61
4.	6.1932	5.7231	7.59
5.	6.0529	5.6194	7.16
6.	6.0982	5.6443	7.44
7.	6.1584	5.7122	7.25
8.	6.2664	5.8031	7.39
9.	6.1949	5.7283	7.53
10.	6.3051	5.8404	7.37
		Mean	7.44
		Std Dev.	0.15

Table 11

Moisture Content of Box No. 2

Weight In Grams

Sixth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.2216	5.7643	7.35
2.	6.3299	5.8633	7.37
3.	6.2574	5.7932	7.42
4.	6.2546	5.7849	7.51
5.	6.2174	5.7543	7.45
6.	6.3344	5.8583	7.52
7.	6.2177	5.7526	7.29
8.	6.3072	5.8473	7.40
9.	6.1946	5.7457	7.25
10.	6.3088	5.8478	7.31
		Mean	7.39
		Std Dev.	0.09

Table 12

Moisture Content of Box No. 2

Weight In Grams

Seventh test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.2768	5.8Ø74	7.48
2.	6.3316	5.8724	7.25
3.	6.3736	5.9Ø95	7.28
4.	6.1125	5.6735	7.18
5.	6.1399	5.6929	7.28
6.	6.1192	5.6661	7.4Ø
7.	6.1349	5.681Ø	7.4Ø
8.	6.3875	5.9212	7.3Ø
9.	6.3Ø88	5.8478	7.31
1Ø.	6.39Ø6	5.94Ø6	7.Ø4
		Mean	7.29
		Std Dev.	Ø.12

Table 13

Moisture Content of Box No. 2

Weight In Grams

Eighth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.2253	5.7865	7.05
2.	6.1840	5.7541	6.95
3.	6.3022	5.8522	7.14
4.	6.1641	5.7149	7.29
5.	6.1782	5.7158	7.48
6.	6.2712	5.7993	7.52
7.	6.2693	5.7875	7.69
8.	6.2703	5.8315	7.00
9.	6.2312	5.7733	7.35
10.	6.2626	5.8104	7.22
		Mean	7.27
		Std Dev.	0.24

Table 14

Moisture Content of Box No. 2

Weight In Grams

Ninth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.1355	5.6859	7.33
2.	6.2694	5.8136	7.27
3.	6.1659	5.7Ø39	7.49
4.	6.3ØØ6	5.8324	7.43
5.	6.3Ø33	5.8318	7.48
6.	6.2598	5.79Ø7	7.49
7.	6.2146	5.7584	7.34
8.	6.2775	5.8Ø59	7.51
9.	6.2415	5.7775	7.43
1Ø.	6.3242	5.8528	7.45
		Mean	7.42
		Std Dev.	Ø.Ø8

Table 15

Moisture Content of Box No. 2

Weight In Grams

Tenth test day

No.	Initial Wt.	Final Wt.	Moisture % content
1.	6.2993	5.8424	7.25
2.	6.1973	5.7519	7.19
3.	6.1648	5.7163	7.28
4.	6.1916	5.7467	7.19
5.	6.1295	5.7Ø61	6.91
6.	6.1479	5.7Ø31	7.23
7.	6.2Ø31	5.7627	7.1Ø
8.	6.Ø122	5.5963	6.92
9.	6.1Ø42	5.6675	7.15
1Ø.	6.1545	5.71Ø5	7.21
		Mean	7.14
		Std Dev.	Ø.13

Table 16

Moisture Content of Box No. 3

Weight In Grams

First and Second test groups

No.	Initial Wt.	Final Wt.	Moisture % content
1.	4.3002	4.0023	6.93
2.	4.4452	4.1492	6.66
3.	4.4096	4.1069	6.86
4.	4.3820	4.0808	6.87
5.	4.3686	4.0660	6.93
6.	4.4432	4.1326	6.99
7.	4.5551	4.2291	7.15
8.	4.3574	4.0621	6.78
9.	4.3978	4.0900	7.00
10.	4.4552	4.1458	6.95
		Mean	6.91
		Std Dev.	0.13

Table 17

Moisture Content of Box No. 3

Weight In Grams

Third test group

No.	Initial Wt.	Final Wt.	Moisture % content
1.	4.2356	3.935Ø	7.1Ø
2.	4.3971	4.Ø834	7.13
3.	4.2861	4.ØØ54	6.55
4.	4.3832	4.Ø827	6.86
5.	4.4756	4.1492	7.29
6.	4.4238	4.1Ø86	7.13
7.	4.66Ø2	4.3254	7.18
8.	4.3979	4.Ø868	7.Ø7
9.	4.45Ø5	4.1346	7.1Ø
1Ø.	4.39Ø7	4.Ø934	6.77
		Mean	7.Ø2
		Std Dev.	Ø.22

Table 18

Moisture Content of Box No. 3

Weight In Grams

Fourth test group

No.	Initial Wt.	Final Wt.	Moisture % content
1.	4.4157	4.1145	6.82
2.	4.2548	3.9594	6.94
3.	4.3694	4.0666	6.93
4.	4.4056	4.0979	6.98
5.	4.1693	3.8845	6.83
6.	4.3069	4.0101	6.93
7.	4.4320	4.1345	6.71
8.	4.4208	4.1167	6.89
9.	4.3865	4.0817	6.95
10.	4.3077	4.0279	6.50
		Mean	6.85
		Std Dev.	0.15

Table 19

Moisture Content of Box No. 3

Weight In Grams

Fifth test group

No.	Initial Wt.	Final Wt.	Moisture % content
1.	4.3424	4.0343	7.10
2.	4.3037	3.9925	7.23
3.	4.4565	4.1399	7.10
4.	4.6229	4.2838	7.34
5.	4.4502	4.1520	6.70
6.	4.4059	4.1076	6.77
7.	4.3851	4.0965	6.58
8.	4.2928	3.9895	7.07
9.	4.4159	4.1128	6.86
10.	4.4181	4.1157	6.84
		Mean	6.96
		Std Dev.	0.26

Table 20

Moisture Content of Box No. 3

Weight In Grams

Sixth and Seventh test groups

No.	Initial Wt.	Final Wt.	Moisture % content
1.	4.2644	3.9837	6.58
2.	4.3132	4.0243	6.70
3.	4.2885	3.9981	6.77
4.	4.3850	4.1127	6.42
5.	4.4264	4.3205	error
6.	4.4164	4.1216	6.68
7.	4.5493	4.2597	6.37
8.	4.2701	3.9826	6.73
9.	4.4268	4.1186	6.96
10.	4.4213	4.1263	6.67
11.	4.2538	3.9611	6.88
12.	4.4619	4.1310	7.41
13.	4.3356	4.0236	7.19
14.	4.0007	4.0652	error
15.	4.3058	4.0185	6.67
16.	4.3442	4.0518	6.73
17.	4.3418	4.0462	6.81
18.	4.4174	4.1278	6.56
19.	4.3900	4.1061	6.47
20.	4.3972	4.1086	6.56
Mean	6.73	Std Dev.	0.26

Table 21

Moisture Content of Box No. 3

Weight In Grams, Eighth, Ninth, and Tenth test groups

No.	Initial Wt.	Final Wt.	Moisture % contents
1.	4.4436	4.1398	6.90
2.	4.4897	4.1673	7.18
3.	4.3529	4.0464	7.04
4.	4.5260	4.2121	6.86
5.	4.3032	4.0001	7.04
6.	4.3437	4.0456	6.86
7.	4.4456	4.1447	6.77
8.	4.5013	4.1748	7.25
9.	4.2956	4.0059	6.74
10.	4.3634	4.0767	6.57
11.	4.4282	4.1229	6.89
12.	4.3993	4.0896	7.04
13.	4.5393	4.2269	6.88
14.	4.3418	4.0382	6.99
15.	4.4101	4.1033	6.96
16.	4.4028	4.1360	6.06
17.	4.4557	4.1504	6.85
18.	4.4099	4.1008	7.01
19.	4.4777	4.1585	7.13
20.	4.4860	4.2064	6.23

Mean 6.87, Std Dev. 0.29

LIST OF REFERENCES

American Society for Testing and Materials. 1983. Standard Test Methods of Compression Test for Shipping Containers. D642-76.

American Society for Testing and Materials. 1982. Standard Test Methods for Moisture Content of Paper and Paperboard by Oven Drying. D 644-55.

American Society for Testing and Materials. 1980. Standard Method of Conditioning Paper and Paper Products for Testing. D 685-73.

American Society for Testing and Materials. 1981. Standard Test Methods for Vibration Testing of Shipping Containers. D 999-75.

American Society for Testing and Materials. 1982. Standard Practice for Performance Testing of Shipping Containers and Systems. D 4169-82.

Burgess. G. 1987. Private Communication. Michigan State University. School of Packaging. East Lansing, MI.

Den Hartog, J.P. 1952. "Advanced Strength of Materials." 1st. ed. McGraw-Hill Book Company, Inc. New York, New York.

Gill, J.L. 1986. Private Communication. Michigan State University. Department of Dairy Science. East Lansing MI.

Godshall, W.D. 1968. "Effects of Vertical Dynamic Loading on Corrugated Fiberboard Containers", USDA Forest Service Research Paper. FPL 94.

Godshall, W.D. 1973. "Vibration Transmissibility Characteristics of Corrugated Fiberboard", USDA Forest Service Research Paper. FPL 211.

Godshall W.D. 1985. The Importance of Compression for Box Performance. presented at the Compression Symposium. Forest Products Laboratory, Madison, Wisconsin, October 1-3.

Goff J.W. 1974. "Development of Performance Standards for Parcel Post Packages", School of Packaging, Michigan State University, Project No. 3108 for U.S. Department of Commerce (NBS) Project No. 4-35711.

Guins, S.G. 1975. Notes on Package Design. Published by Guins, Okemos, Michigan.

Hanlon, J.F. 1984 "Handbook of Package Engineering." 2nd ed. McGraw-Hill Book Company. New York, New York.

Harris, C.M. and Crede C.E. 1976 "Shock and Vibration Handbook" 2nd ed. McGraw-Hill Book Company, New York, New York.

Kusza, T.J. and Young D.E. 1974. Testing. Package Development, November/December 1974, No 55.

McKee, R.C., J.W. Grander, and J.R. Wachuta. 1963. Compression Strength Formula for Corrugated Boxes. The Institute of Paper Technology, Sept.

National Motor Freight Classification 1978. Item 222, Fiber Box Handbook, Fiber Box Association, Chicago, Illinois 1979.

Ostrem F.E. and Godshall W.D. 1979. An Assessment of the Common Carrier Shipping Environment, USDA Forest Service General Technical Report. FPL 22.

Uniform Freight Classification 1978. Rule 41, Fibre Box Handbook, Fiber Box Association, Chicago, Illinois, 1979.

Young, D.E. 1986. Private Communication. Michigan State University. School of Packaging. East Lansing, MI.