EVALUATION OF SOME EXISTING EMPIRICAL EQUATIONS FOR TOP-TO-BOTTOM COMPRESSION STRENGTH OF CORRUGATED FIBREBOARD BOXES

THESIS FOR THE DEGREE OF M. S.

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By

Salustiano S. Mirasol, Jr.

AN ABSTRACT

Submitted to
Michigan State University
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The top-to-bottom compression test of corrugated fibreboard container is widely used to evaluate the performance of boxes subjected to stacking load. It often discloses from the nature of the failures and the capacity to withstand loading, deficiencies in design, construction, or fabrication. On the basis of the engineering properties of the components and the box dimensions, quite a number of empirical equations have been developed to estimate the top-to-bottom compression strength of a corrugated fibreboard box.

Four empirical equations which the author believes have made distinct and valuable advances in the determination of compression strength of boxes were evaluated. The equations involved are those of Kellicutt and Landt; Maltenfort; McKee, Gander and Wachuta. McKee, Gander and Wachuta formulated two interrelated equations which were evaluated in this study.

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The experiment was designed for a 200 lb. single wall and C-flute construction corrugated fibreboard. All the test board blank sheets and the components of the board used throughout the study came from the same roll of liners and corrugating medium and were produced in a single production run on one corrugating machine. The study involved the making of 900 boxes of 225 sizes in a sample making equipment. The box sizes were such that the dimensions were all dependent on three parameters, namely, depth to perimeter ratio, perimeter, and length to width ratio.

With the manner in which the dimensions of the boxes were determined, an analysis was undertaken with respect to individual parameters in addition to the primary objective of the experiment.

The test procedures employed satisfied either the TAPPI Standards or the ASTM Standards in the preparation of test samples and the actual testing. Due to unavailability of standard test procedure for the determination of the Column Crush Test, the author devised a method which to him seemed satisfactory. On the other hand, the Concora Liner Test value for the test board was not determined because a special fixture needed for the test was not available. However, on account of the linear nature of the equation, further evaluation was still undertaken.

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Based on the data compiled from the actual testing of fibreboard components, corrugated fibreboards and RSC boxes made of a single wall C-flute, 200 lb test board, the major findings of the study are:

1. Except for the Maltenfort Empirical Equation, theoretical values for top-to-bottom compression strength are all low. If the Concora Liner Test result on the liners used would fall within the range 28.3 lb. to 45.6 lb., the equation by Maltenfort would equal the test result values on certain range.

2. The empirical equation of Kellicutt and Landt as well as Maltenfort's are closely correlated although the increment could not be determined. Similarly, the two equations of McKee, Gander and Wachuta are highly correlated.

3. Varying the length to width ratio changes slightly the compressive strength. Boxes with L/W = 1.25 and L/W = 1.50 give higher compressive strength than square boxes. On boxes with L/W = 1.75 and L/W = 2.00 the resultant compressive strengths are lower than on a box with an L/W = 1.00 or a square box.

Dr. James W. Goff
Adviser

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INTRODUCTION

The top-to-bottom compression test of empty boxes is perhaps one of the most commonly used today for evaluating the performance of corrugated fibreboard containers. The test is used to determine the ability of different boxes to withstand stacking load. Furthermore, it often discloses from the nature of the failures and the capacity to carry load, deficiencies in design, construction or fabrication, which are of vital information to the manufacturer.

During the past two decades, quite a number of empirical equations have been developed to estimate the top-to-bottom compression strength of a corrugated fibreboard box on the basis of the engineering properties of the components and the box dimensions. The parameters involved maybe one or more of the following: box perimeter; Young's modulus of elasticity (E); flexural stiffness; transverse shear stiffness; short column crush test; ring crush test (liners and medium); Concora Liner Test (CLT); caliper; basis weight; and flute type.

Four empirical equations which the author believes have made distinct and valuable advances in the determination of compression strength of boxes will be the equations to be evaluated. The fifth equation by Banger (1)* which also deserves equal merit will not be included because a parameter which was based on experimental data introduce doubts at the start, due to the use of a different conditioning standard prior to testing. The test materials were conditioned at 68°F and 65% relative humidity for 48 hours before testing which would be outside of the allowable limits for conditioning set by TAPPI (TAPPI Standard T402-m-49 for conditioning: 73 ± 3.5°F temperature and 50 ± 2% relative humidity).

The equations involved are those of Kellicutt and Landt; Maltenfort; and McKee, Gander and Wachuta. McKee, et al formulated two interrelated equations which will be evaluated in this study. With the required parameter values determined (except the Concora Liner Test which was not included due to unavailability of test fixtures) to satisfy the empirical equations, the compression strengths are computed. Correlation is then made with the actual compression test values of boxes.

Aside from correlating the theoretical values for compression strength with actual results, an analysis will be made on the tested corrugated boxes on the basis of variations in perimeter, depth to perimeter ratio, and length to width ratio. This analysis is brought about by

* Reference listed in the bibliography.

choosing box sizes which follow a pre-determined set of parameters.

With no set standard for determining the short column crush test (sometimes called edgewise compression strength) of corrugated fibreboard as of this writing, the author devised a method which to him seemed very satisfactory. The full detail of the method is included in the section on test methods.

The entire evaluation is based on 200 lb. single wall test board with only one type of flute, C-flute. All the corrugated fibreboard blanks on this study were made on a single production run which used the same liners and medium throughout, sufficient to make 900 boxes of 225 sizes.

DEVELOPMENT OF CORRUGATED FIBREBOARD BOX (2)*

The first appearance of a corrugated form of some relationship to the present corrugated box is believed to have appeared in England. On July 7, 1856, a patent was granted to Edward Charles Healey and Edward Ellis Allen covering the fluting of paper or other materials to be used as a cushioning or lining for the sweat bands of hats. At that time it is believed that corrugating was achieved by first wetting the material and then passing it between a heated pair of corrugated or embossed rollers or between a heated pair of corrugated dies. Although this invention had cushioning as its primary function, it is not given a great deal of direct credit on the eventual development of corrugated boxes because little or no progress was made with the idea towards the packaging field.

The breakthrough was on December 19, 1871 when the first real patent for corrugated material that is directly traceable to the present corrugated boxes was granted to an American, Albert L. Jones for an "improvement in paper for packing". A portion of Mr. Jones' claims were:

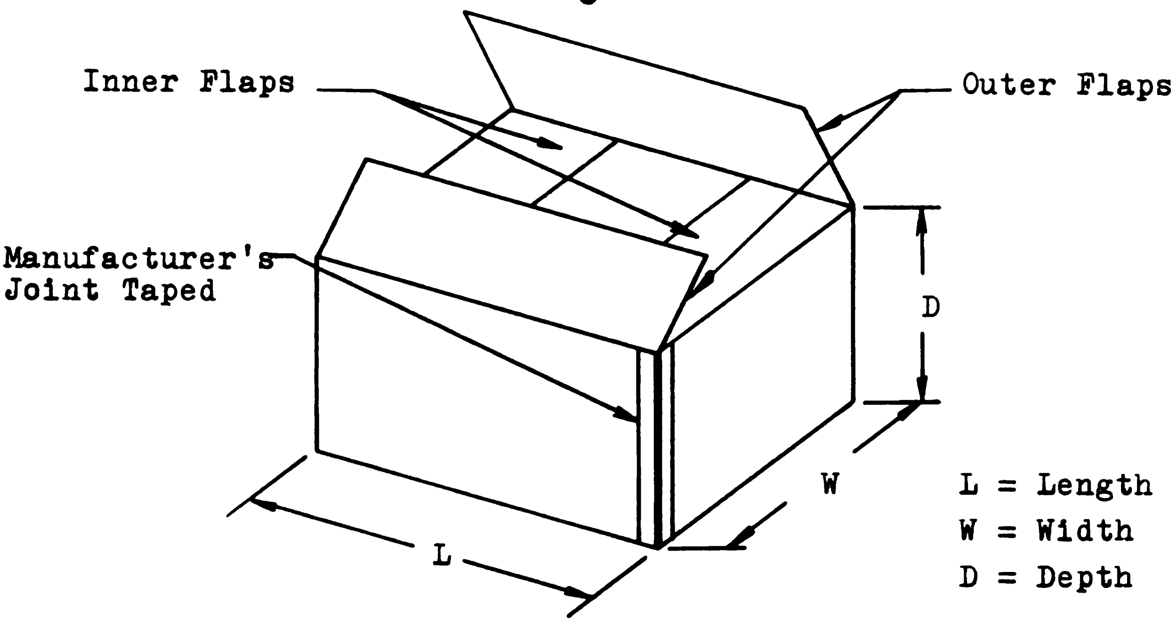
"The subject of this invention is to provide means for securely packing vials and bottles with a single

*Material for this topic was taken from the book "Paperboard and Paperboard Containers. A History." by H. J. Bettendorf.

> thickness of the packing material between the surface of the article packed: and it consists in paper, card-board, or other suitable material, which is corrugated, crimped, or bossed, so as to present an elastic surface ....instead of wrapping the vials or bottles with the corrugated material, the latter may be made into packing-boxes....".

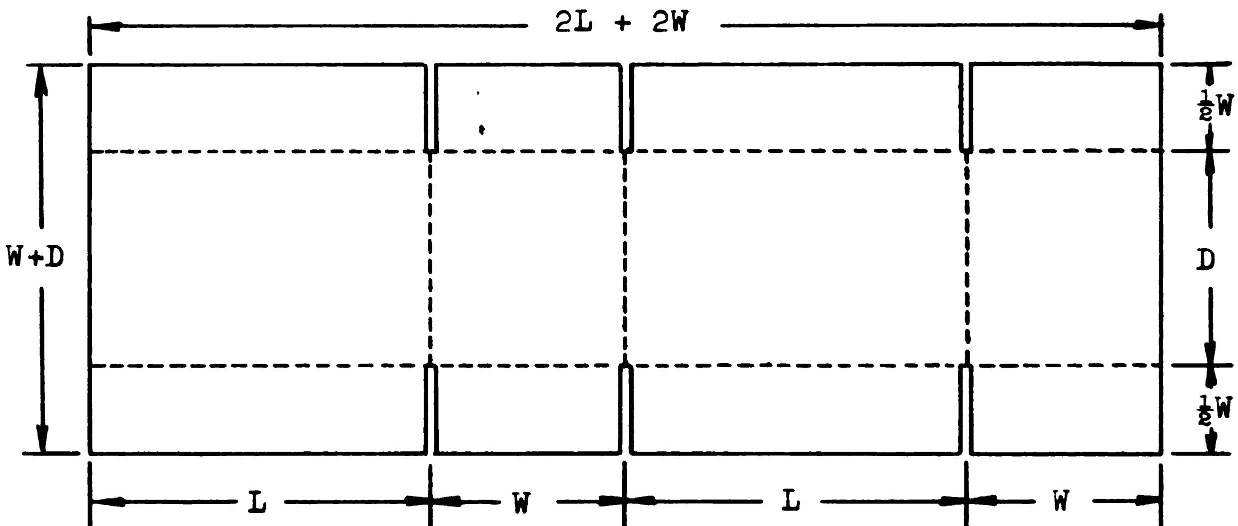
Rights to Jones' patent apparently were obtained by Henry D. Norris, who started making the corrugated material for packing glass bottles. In the meantime, in 1874, Oliver Long obtained a patent on lined corrugated fibreboard (single face and double face) for packing purposes, a vast improvement to the original corrugated material alone. The use of the unlined materials replaced straw, sawdust and excelsior in packing glass bottles and glass lamp chimneys in wooden boxes and barrels. With the invention of lined corrugated fibreboard, boxes were made for express shipments and then as freight shipping containers.

Corrugated fibreboard arose as a cushioning material and then became a large shipping container due to the savings in freight and handling costs. The corrugated container, originally designed for light express shipments, had in the meantime been developed and most of the present day styles were available. Notably there was the so-called regular slotted container shown in Figure 1, a box made of one blank, scored so as to form the four side panels of the box, joined with tape or stitches to form a tube, slotted in from both ends of the tube to form closure flaps, and scored around the tube to permit the flaps to close.



Regular Slotted Container (RSC)

The dimensions given are the inside dimensions of the box.



Blank Size of RSC Box

"A" Scores = horizontal dotted lines

"B" Scores = vertical dotted lines

Perimeter = Z = 2L + 2W

Figure 1

Nomenclature

This type of container is characteristic of 90% of shipping containers made today. The RSC boxes were very attractive to the cereal manufacturers because they were delivered collapsed ready to be set up as boxes and they were compatible with the cartons of cereals on account of its lightness, smoothness and printability. The demand for corrugated shipping boxes grew fast due to the extended use of these boxes into many lines of products other than for cereal food products. Corrugated fibreboard containers provide strong, resilient, and lightweight packaging at low cost.

TECHNICAL ADVANCEMENT

The first recorded laboratory tests for the improvement of shipping containers were made in 1905 by the Forest Service (3) in cooperation with Purdue University. The purpose of these tests was to determine the merits of different kinds of wood as box material. Corrugated fibreboard material was excluded from the tests due to its limited use on cereals alone on a special permit from the Official Classification Committee during that period.

In 1910, the Forest Products Laboratory was established at Madison, Wisconsin (3). The Laboratory's objective in connection with shipping containers was to develop fundamental principles of design and relationships of the various details necessary to produce containers that are balanced in strength. Although actual testing of corrugated fibreboard containers at the Forest Products Laboratory started even before World War I, and in spite of the development of the hexagonal testing drum, thorough study on the scientific design of fibreboard boxes started only in the early thirties.

The early manufacturers and users were apparently concerned on how the corrugated boxes could withstand rough handling. They resorted to such tests as dropping the box off the tailgate of a truck, bouncing it down a flight of stairs, sliding it down a chute or actually shipping and then checking at the point of destination. With emphasis on rough handling, the revolving drum became a widely used test for determining corrugated box performance.

In the late thirties, universal acceptance was achieved in the use of corrugated fibreboard boxes as shipping containers which provided adequate protection to its content. For this reason, increased consideration was given to the strength of the corrugated boxes. An extensive evaluation was made by McCready and Katz (4) on the corrugated fibreboard as an engineering material in connection with a study of adhesive on the strength of corrugated fibreboard. They may be the first to formulate an empirical equation for compression strength as a function of modulus of elasticity based on the thin plate theory of mechanics.

At about the same period, Carlson (5,6) published his findings on some factors that would affect the determination of engineering properties' values for corrugated fibreboard as well as the significance of these factors to the compressive strength of the box made of the same material.

In 1943, Little (7) developed an equation for box compression strength based on the engineering column strength formula by Rankine. The assumption was that corrugated fibreboard is uniform in its properties and that the same laws could be applied to it which govern other elastic materials.

From 1951 to the present, several attempts were made to formulate empirical equations which could predict the compressive strength of the corrugated fibreboard box. At this point, four of those empirical equations will be discussed in more detail and from thereon, actual evaluation would be made.

EMPIRICAL EQUATIONS

Using the principles of engineering mechanics and statistics, simplified formulae were developed relating top-to-bottom compression strength of boxes with its combined corrugated fibreboard properties, component properties that comprise the fibreboard, and box dimensions. The empirical equations that are involved will be discussed according to their chronological order of publication and not due to preference.

I. Kellicutt and Landt's (8) Empirical Equation

$$P = (r_{sf} + r_{df} + \alpha\, r_{cm}) \left[\frac{K^2}{(Z/4)^2} \right]^{1/3} ZJ \qquad \text{(I)}$$

Where:

P = total box compressive strength in lbs.

r_{sf} = ring crush of single face liner in cross machine direction, lb/in.

r_{df} = ring crush of double face liner in cross machine direction, lb/in.

r_{cm} = ring crush of corrugated medium in cross machine direction, lb/in.

α = take-up factor of corrugating medium:

A-flute --- 1.523 B-flute --- 1.361

C-flute --- 1.477

K = Constant: A-flute --- 8.36 B-flute --- 5.00

C-flute --- 6.10

Z = box perimeter, in.

J = box factor: (for laboratory made and taped)

A-flute --- 0.717 B-flute --- 0.752

C-flute --- 0.717

The empirical equation (I) in the preceding page evolved from the basic formula developed at the Forest Product Laboratory, U.S. Department of Agriculture, for the design of plywood panels by applying the thin plate theory of mechanics. Fibreboard being a nonisotropic material is comparable to plywood. The main objective was to develop a method of expressing the compressive strength of a corrugated fibreboard box using test data obtained from simple tests on the components of the fibreboard. In the development a tube made of corrugated fibreboard consisting of four panels representing a box without top and bottom was used as the intermediate link between tests of the fibreboard components and of the box.

In the equation, three constants are involved. First, the take-up factor, α, which is actually a corrugated fibreboard trade constant corresponding to the length in feet of the corrugating medium that comprises a foot of corrugated fibreboard, and it differs for every type of flute used. Secondly, the constant K is defined as the ratio of the combined ring crush value on the cross machine direction in pounds per inch (liners and medium) and the compressive strength of a specific size of cubical tube with the vertical crushing load parallel to the flute. Different values were determined for each specific flute construction. Finally, box factor, J, is the ratio of box compressive load to tube compressive load for various cross sections with height 12 inches and greater found to be reasonably constant. On heights less than 12 inches, considerable divergence between the box and tube loads existed. Specific box factor applies to a type of flute and the kind of joint used in the manufacturer's joint.

II. Maltenfort's (9) Empirical Equation

$$P = 5.8L + 12W - 2.1D + K + k(CLT-O) \qquad (II)$$

Where:

P = total box compressive strength in lbs.

L = box length, in.

W = box width, in.

D = box height, in.

K = Constant: A-flute --- 365 B-flute --- 212
C-flute --- 350

k = Constant: A-flute --- 6.5 B-flute --- 5.4
C-flute --- 6.5

CLT-O = average Concora Liner Test - across machine direction of single face and double face liners, in lbs.

The empirical equation was developed by applying linear regression analysis, a statistical method, on series of test data for top-to-bottom compression strength of single wall corrugated fibreboard boxes. On the basis that the relationship of dimensions to compressive strength is linear, an equation was formulated using the dimensions and liners strength without regard for the corrugating medium.

The equation (II) in the preceding page is actually a simplified form of: $P = 4.45(2L + 2W) - 3.1(L - W) - 2.1D + K + k(CLT\text{-}O)$. The constants, with the values in the quantity $(2L + 2W)$ excluded, were the values determined using statistical method.

Concora Liner Test (CLT) is a straight crush test on a 6 inches by ½ inch strip of liner instead of a ring crush. The advantages over the ring crush test as claimed are: (a) on heavy liner grades, damage resulting in trying to form a ring is avoided; (b) it avoids the effect on the strength of the material by the circular configuration of the test specimen; (c) a straight crush test corresponds with the kind of loading experienced by liners on box compression testing.

III. McKee, Gander and Wachuta's (10) First Empirical Equation

When $D/Z \geqq 1/7$,

$$P = 2.028\ P_m^{0.746}\ (\sqrt{D_x D_y})^{0.254}\ Z^{0.492} \qquad \text{(III)}$$

Where:

P = total box compressive strength in lbs.

P_m = edgewise compressive strength of plate material, lb/in.

D_x = flexural stiffness of combined board in machine direction per unit width, lb-in.

D_y = flexural stiffness of combined board in cross-machine direction per unit width, lb-in.

Z = box perimeter, inch.

The empirical equation is based on the assumption which relates the ultimate compressive strength of a plate to the instability load and the edgewise compression strength of the material of the plate by means of a power function.

Basic Equation:

$$P_z/P_{cr} = C\ (P_m/P_{cr})^b$$

or

$$P_z = C\ P_m^b\ P_{cr}^{1-b} \qquad \text{(a)}$$

Where:

P_z = ultimate strength of the plate per unit width, lb/in.

P_{cr} = instability load, lb/in.

C, b = Constants

From the theory of buckling of initially flat plates,

$$P_{cr} = 12\, k_{cr} \sqrt{D_x D_y}/W \qquad \text{(b)}$$

Where:

k_{cr} = buckling coefficient

$$= (\pi^2/12) \left[(r^2/n^2) + (n^2/r^2) + 2K \right]$$

$r = (\sqrt[4]{D_x D_y})\ (D/W)$

n = number of halfwaves in buckled panel in the direction of load

$n = i$, if $\sqrt{i(i-1)} \leq r \leq \sqrt{i(i+1)}$

K = a plate parameter dependent on mechanical properties and cross-section geometry of the combined fibreboard, dimensionless.

W = width, inch.

D = depth, inch.

By approximation, $K = 0.5$, $\sqrt[4]{D_x D_y} = 7/6$, $W = Z/4$.

Equation (b) then becomes

$$P_{cr} = \frac{(4\pi)^2 \sqrt{D_x D_y}}{Z^2} \left[\frac{196D^2}{9n^2 Z^2} + \frac{9n^2 Z^2}{196D^2} + 1.0 \right] \qquad \text{(c)}$$

Where:

$n = 1, \quad \text{if} \quad D/Z \leq 3\sqrt{2}/14$

$n = 2, \quad \text{if} \quad 3\sqrt{2}/14 \leq 3\sqrt{6}/14$

$n = i, \quad \text{if} \quad 3\sqrt{i(i-1)}/14 \leq 3\sqrt{i(i+1)}/14$

Denoting the modified buckling coefficient within the bracket as k in equation (c) and substituting in equation (a), then multiplying by Z to obtain the total compression load, the resulting equation is:

$$P = C\,(4\pi)^{2-2b}\,P_m^{\,b}\,(\sqrt{D_x D_y})^{1-b}\,Z^{2b-1}\,K^{1-b} \qquad \text{(d)}$$

The modified buckling coefficient is assumed to be $K^{1-b} = K^{.24}$, and being a constant, equation (d) is further simplified into:

$$P = aP_m^{\,b}\,(\sqrt{D_x D_y})^{1-b}\,Z^{2b-1} \qquad \text{(e)}$$

The experimental constants a and b of the simplified box formula were determined by a logarithmic plotting of the load ratios $\left[\dfrac{P/Z}{\sqrt{D_x D_y}/Z^2} \text{ vs. } \dfrac{P_m}{\sqrt{D_x D_y}/Z^2}\right]$ of actual test results wherein a straight line was fitted by the method of least squares which gave values for a = 2.028 and b = 0.746, thus the empirical equation.

IV. McKee, Gander and Wachuta's (10) Second Empirical Equation

When $D/Z \geqq 1/7$,

$$P = 5.874\ P_m^{0.746}\ h^{0.508}\ Z^{0.492} \qquad \text{(IV)}$$

Where:

h = combined fibreboard caliper, inch.

The empirical equation was actually derived from the first equation of the same authors. On the basis that correlation of composite flexural stiffness, edgewise compression strength, and combined fibreboard caliper existed, equation $P = 2.028\ P_m^{0.746}\ (\sqrt{D_x D_y})^{0.254}\ Z^{0.492}$ was further simplified.

Designating the ordinate as $\sqrt{D_x D_y}$ in lb-in. and the abscissa, the product of edgewise compression strength, multiplied by caliper squared ($P_m\ h^2$) in lb-in., test data were plotted. Fitting a line on the points plotted, a correlation was achieved which gave the relation, $\sqrt{D_x D_y} = 66.1\ (P_m\ h^2)$ and by substituting this relation in equation (III), gives the empirical equation (IV).

DESIGN OF EXPERIMENT

The experiment was designed for a 200 lb. single wall and C-flute construction corrugated test board.* All the corrugated fibreboard blank sheets and the components of the board used throughout the study came from the same roll of liners and corrugating medium and were produced in a single production run on one corrugating machine. At the start of production, quality checks were done on the test board before getting the set of blanks needed.

With the evaluation of the empirical equations as the primary objective on the basis of actual test results on top-to-bottom compression strength of RSC boxes, different sizes were considered. The box sizes** were such that the dimensions were all dependent on three parameters, namely, depth to perimeter ratio (D/Z), perimeter (Z), and length to width ratio (L/W). The parameter values involved are:

D/Z Ratio	Perimeter (inches)	L/W Ratio
.08	30	1.00
.16	34	1.25
.24	38	1.50
.32		

* See Appendix A for test material description

** See Appendix B

D/Z Ratio	Perimeter (inches)	L/W Ratio
.40	42	1.75
.48	48	2.00
.56		
.70	56	

The D/Z = .08 was not used in combination with perimeters 30 inches, 34 inches, and 38 inches on account of the very low resultant box depth (range: 2-13/32" - 3-1/32") which was not practical especially with the presence of flaps. In spite of the combinations being reduced by 15, there were still 225 combinations and thus sizes. With four samples for each size, the total number of boxes tested was 900. All of these boxes tested were made individually in the laboratory on a sample maker equipment.

With the manner in which the dimensions of the boxes were determined, an analysis will be undertaken with respect to individual parameters in addition to the primary objective of the experiment.

TEST METHODS

Tests on the fibreboard components and the combined board were performed under controlled conditions of temperature and humidity, and the test pieces were made after the sample materials had been adequately exposed to test conditions. Similarly, the RSC test boxes were compression tested in the same controlled conditions although the actual box making was done under ordinary room conditions. All the sample materials and test boxes underwent preconditioning for at least 24 hours at 100°F temperature (TAPPI Standard T402-m-49: not to exceed 140°F). After preconditioning they were then transferred into the conditioning room where the temperature is controlled at 72°F and relative humidity at 50% (TAPPI Standard T402-m-49 for conditioning: Temperature = 73 ± 3.5°F, Relative Humidity = 50 ± 2% and for not less than 24 hours). The purpose of preconditioning the boxes is to approach the moisture content at equilibrium under standard conditions from a drier state. The moisture content, if necessary, is reduced to less than half the value under standard conditions during preconditioning, then raised to standard conditions in the controlled room.

With the above standard conditions satisfied, the basis weights and calipers for corrugated fibreboard and its components were determined by using the TAPPI Standard

T410-m-45 and TAPPI Standard T411-m-44, respectively.

Material Test

Ring Crush Test - (ASTM Designation: D1164 - 60)

Test specimens are cut 6 inches long and ½ inch wide. Since cross machine ring crush values for liners and medium are required, the machine direction of the specimens should be lengthwise. Each test specimen is inserted in the specimen holder and positioned at the center between the two platens of the compression tester. The maximum load required to collapse the specimen is the desired value. A minimum of ten specimens for each principal direction of the fibreboard is recommended. The compression tester used on this particular test is an H & D Crush Tester.

Concora Liner Test (9)

The same test specimens for the ring crush test are used in this determination. The only difference lies on the configuration of the specimen when placed between the platens. The CLT specimen is straight instead of in the form of a ring and thus, a special jig consisting of a platen and sample holder had to be fitted on an H & D Crush Tester. Due to unavailability of a fixture, the CLT-0 value will be excluded but the empirical equation will still be evaluated on account of the linear nature of the equation.

Static Bending Test

Six 13 inches by 2 inches specimens with the corrugations parallel to the length and six 13 inches by 3 inches with corrugations perpendicular to the length were clean cut with extra care in order not to damage the flutes. On each set, three specimens were tested with the load applied to the single face and the other three to the double face.

The set-up is such that the board specimen is supported near its ends by two ½ inch wooden dowels 12 inches apart with an overhang of ½ inch on both ends. Two points loading was used with the points spaced 4 inches apart. The rate of loading was 0.05 inch per minute while the center deflection of the beam was measured in 0.001 inch. Simultaneous readings were made at intervals of 0.2 pound until failure occurred. Tests were performed on a Baldwin-Emery SR-4 testing machine.

With the data on load and corresponding deflection plotted, the slope of the curve at the origin was determined and this would correspond to the load deflection ratio, $\frac{P}{y}$. Using the equation, $EI = \frac{23PL^3}{1296y}$ for two point loading (11) and with the slope and the length L of the beam between supports known, the flexural stiffness was computed. To obtain the value of flexural stiffness per inch width, the computed EI is divided by the width in inches of the tested specimen.

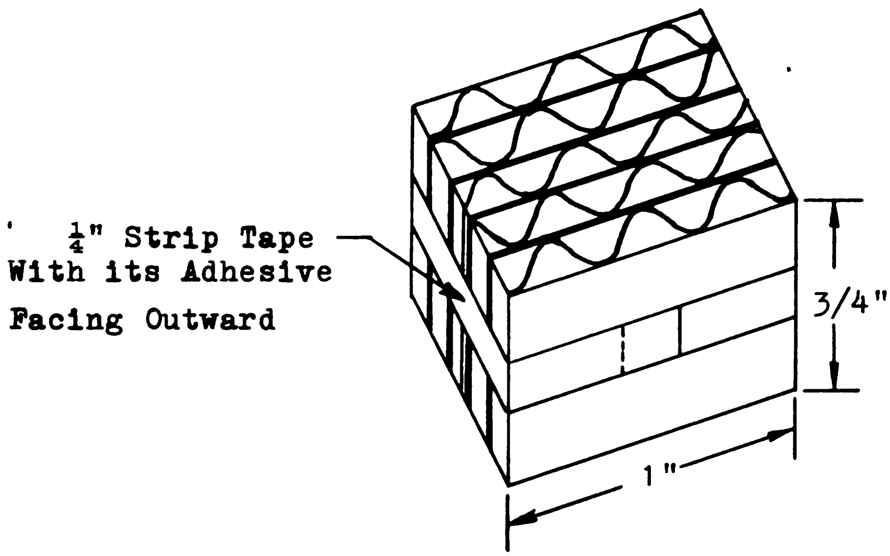
Column Crush Test

The column crush test was utilized to measure the structural resistance of corrugated fibreboards when loaded as columns. On this specific test, no standard as yet has been set by either the American Society for Testing Materials (ASTM) or the Technical Association of Pulp and Paper Industry (TAPPI). It is for this reason that the author devised his method of testing.

In the design of the method, difficulties in the preparation of the specimens, the propping of the specimen perpendicular to the platens of the compression tester, and the distribution of compressive load on the specimen edges were considered.

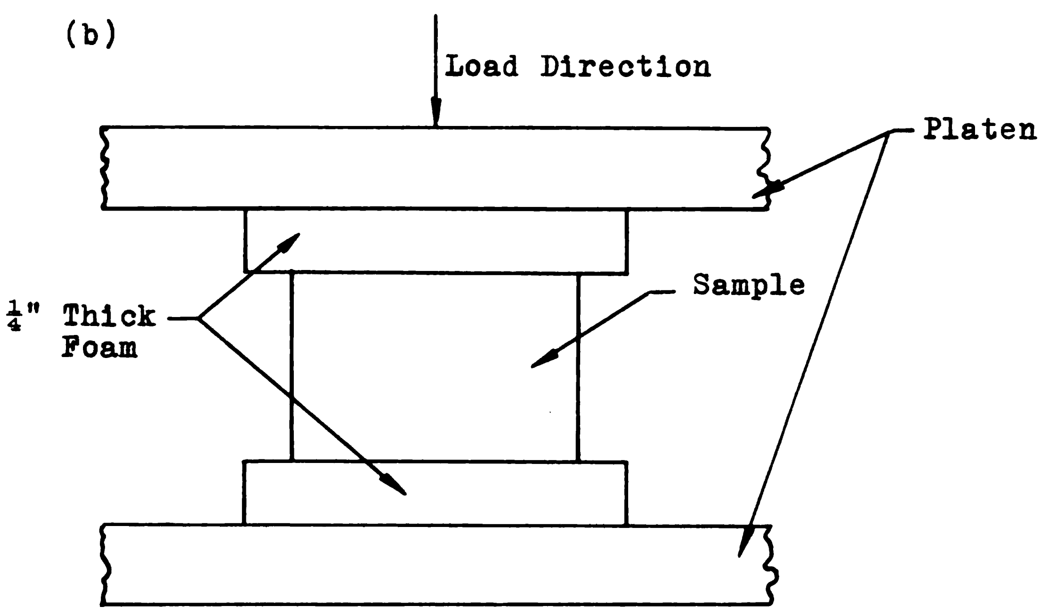
The procedure is to clean out rectangular specimens of 1 inch long and 3/4 inch wide with the flute parallel to the width without damaging the flutes. A number of specimens are placed side by side and a ½ inch strip of tape with its adhesive facing outward is used as a loose band just to gather them together, in such a way that specimens would slip if it were free to do so. This is illustrated in Figure 2(a). The choice of the specimen size was based on earlier trials, and the convenience that an inch length gives in the determination of the edgewise compression strength per inch width is realized by merely dividing the total compressive load by the number of specimens used. The number of specimens needed in a sample is

(a)



A set of five specimens in a sample loosely banded by a tape with its adhesive facing outward (not touching the samples) ready for compression test.

(b)



A sample (five specimens with its flutes vertical) with foams on its bearing surface in-between platens of a compression tester.

Figure 2

Column Crush Test

arbitrarily determined. As a guide, the corrugated fibreboard caliper multiplied by the number of specimens should be approximately or slightly less than an inch. This would give a loading area which is almost a square.

To counteract the difficulty in the distribution of the bearing load due to the nature of the material tested, two $\frac{1}{4}$ inch thick foam cut $1\frac{1}{2}$ inches by $1\frac{1}{2}$ inches are placed on the bearing areas as shown in Figure 2(b). This would also minimize the effect of the slight irregularities which exist when the specimens are cut to their specified size.

The results of the column crush test using the proposed method are shown in Appendix C.

RSC Box Compression Test

TAPPI Standard method T804-m-45 specifies glued flaps on compression testing of corrugated shipping containers. Any other method of sealing the flaps is also satisfactory provided the method followed does not leave anything inside the box which would influence the compression test.

With the above condition imposed, the RSC test boxes were made with a provision to facilitate the stapling of the flaps. This is to prevent the bracing action brought

about by the lowering of the flaps during compression when the wider panels break inward. During the box making, the flaps were made narrow so that upon closure an access hole is available for the stapler to clinch with four staples the inner and outer flaps together.

The compression testing of all the RSC test boxes was performed on the Tinius-Olsen Compression Tester at a platen speed of 0.5 inch per minute and with fixed platen. (TAPPI Standard T804-m-45 on platen speed = 0.5 ± 0.25 inch per minute with either fixed or floating platen.)

RESULTS AND DISCUSSION

All the data necessary to satisfy the objectives of the experiment had been compiled. These would take the form of tables, figures and graphs. In the succeeding discussion, the equations will not be referred to by their author's names but rather by the Roman numbers designated to each specific equation.

Evaluation of Empirical Equations:

In evaluating the four empirical equations considered in this study, two tables, 1 and 2, and two graphs, Figures 3 and 4, were utilized. On Table 1, computed values based on the empirical equations (except Maltenfort's equation wherein no definite conclusion could be formulated in the absence of the Concora Liner Test) were found to be low. The variations are shown on Table 2 which gives the trend as to how close the computed compressive values are to the experimental values.

Since Equation (II) does not have the 6.5 (CLT-O) value which is a constant and with the variations given on Table 2, the range of values that CLT-O would have to limit the variation to a minimum was computed. The CLT-O value for the component materials used in the experiment should be within the range: 28.3 to 45.6. If the value

Table 1. Actual and Theoretical Compression Strengths for Different Perimeters

Author and Equation	P for Z = 30" lb.	P for Z = 34" lb.	P for Z = 38" lb.	P for Z = 42" lb.	P for Z = 48" lb.	P for Z = 56" lb.
Test Data	650*	682*	702*	763**	820**	868**
I. Kellicutt and Landt $P = (r_{sf} + r_{df} + \alpha r_{cm}) \cdot \left[\frac{K^2}{(Z/4)^2}\right]^{1/3} ZJ$	562	586	608	625	657	692
II. Maltenfort $P = 5.8L + 12W - 2.1D + 350 + 6.5\,(CLT-O)$	466⊖ + 6.5 (CLT-O)	482⊖ + 6.5 (CLT-O)	497⊖ + 6.5 (CLT-O)	516⊖ + 6.5 (CLT-O)	540⊖ + 6.5 (CLT-O)	572⊖ + 6.5 (CLT-O)
III. McKee, Gander and Wachuta $P = 2.028\, P_m^{0.746} \sqrt{D_x D_y}\, Z^{0.492}$	469	499	527	554	591	638
IV. McKee, Gander and Wachuta $P = 5.874\, P_m^{0.746}\, h^{0.508}\, Z^{0.492}$	457	486	513	539	575	621

* - Average of 140 tests
** - Average of 160 tests
⊖ - Average of the entire set of dimensions for each test series. See Appendix F.

Table 2. The Compressive Load Difference in Pounds Between the Experimental Results and the Theoretical Computed Values.

Per.	I Kellicutt & Landt	II Maltenfort	III McKee, Gander & Wachuta	IV McKee, Gander & Wachuta
30	88	184*	181	193
34	96	200*	183	196
38	94	205*	175	189
42	138	247*	209	224
48	163	280*	229	245
56	176	296*	230	247

* - These figures would vary if CLT-0 value was available. Thus, the figures would assume lower values and/or negative values if the computed compressive load with CLT-0 value included exceed that of the actual test values.

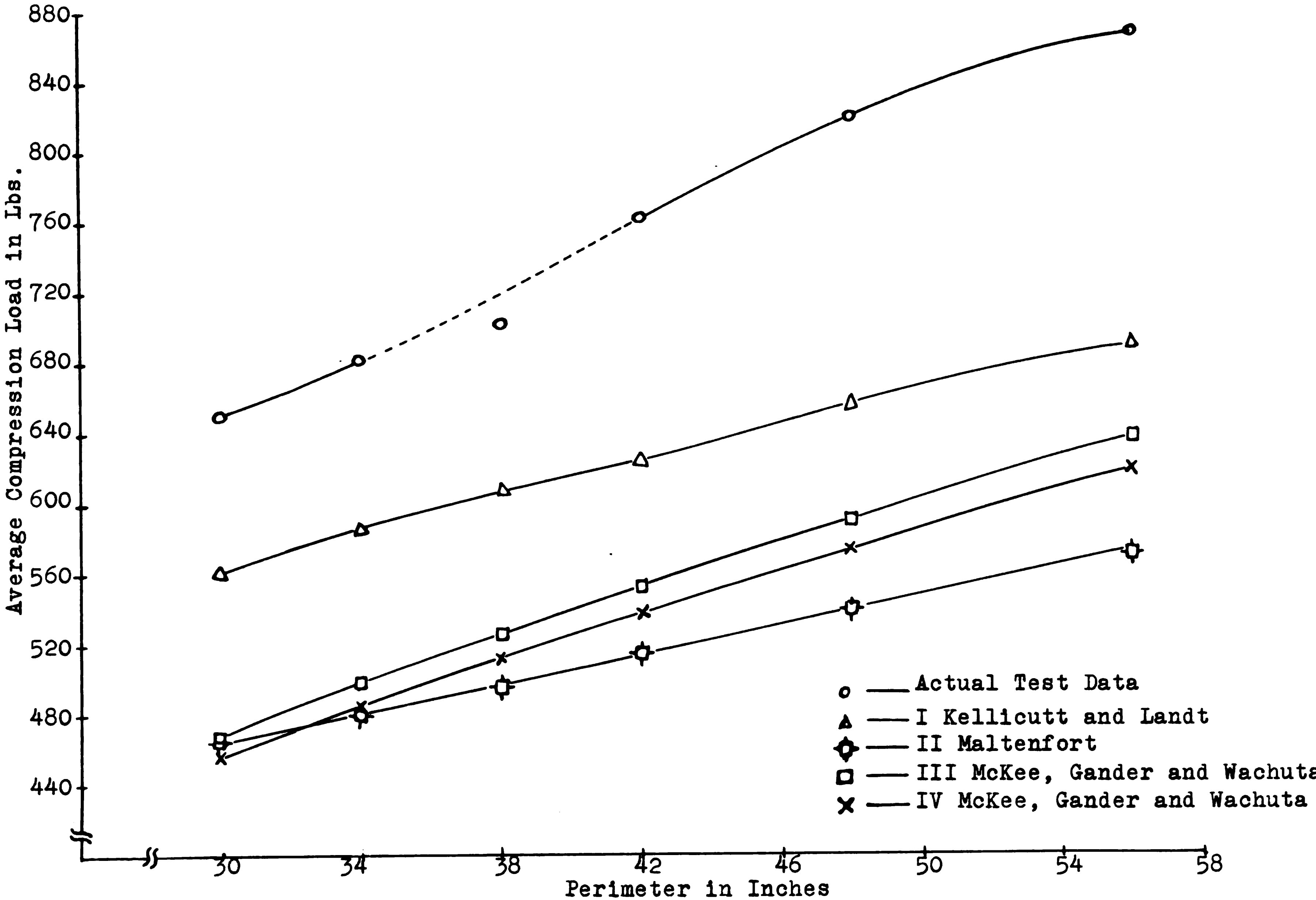

Average Compression Load in Lbs.
880
840
800
760
720
680
640
600
560
520
480
440
30
34
38
42
46
50
54
58
Perimeter in Inches
Actual Test Data
I Kellicutt and Landt
II Maltenfort
III McKee, Gander and Wachuta
IV McKee, Gander and Wachuta

Figure 3

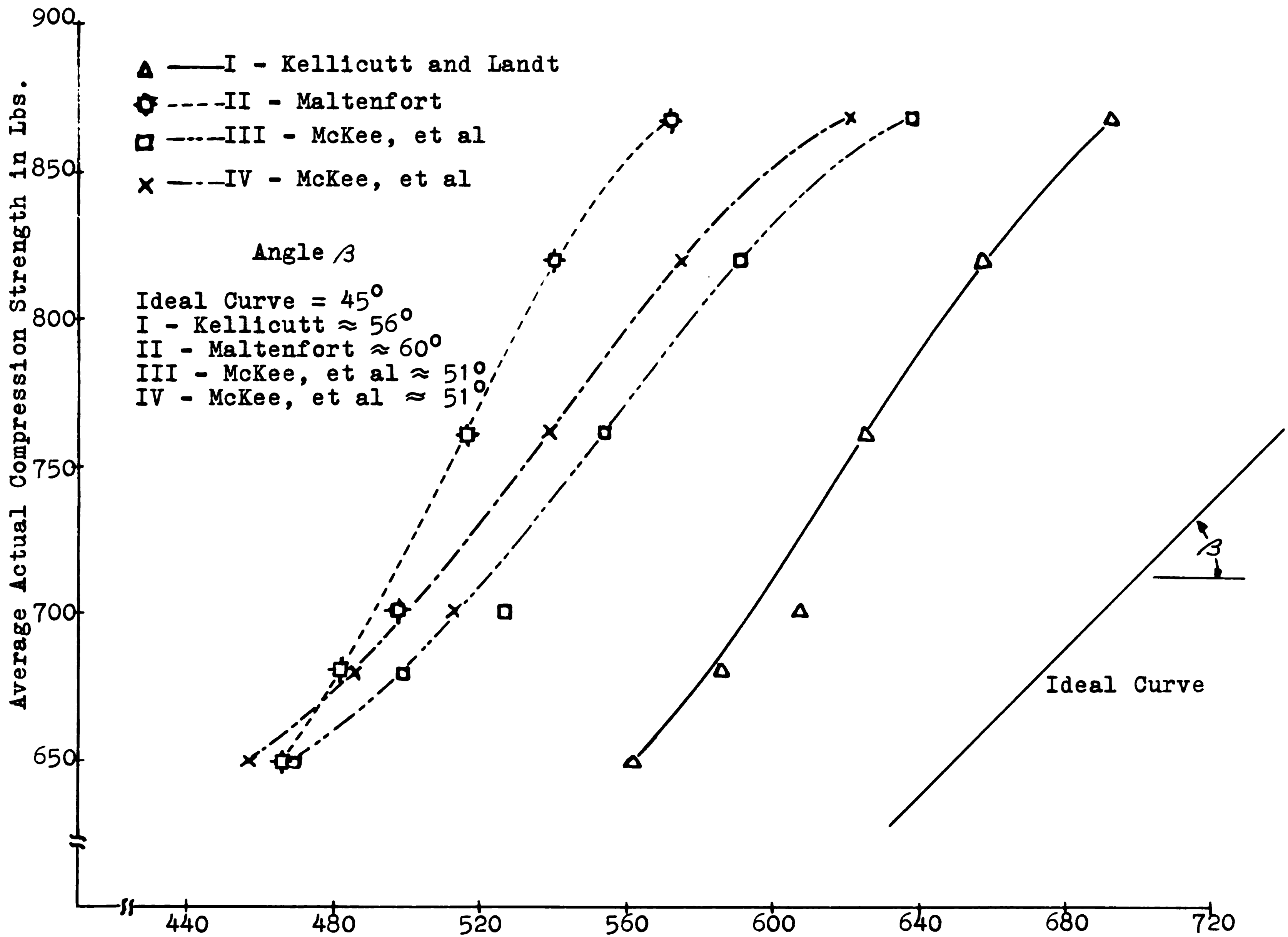

900
850
800
750
700
650
Average Actual Compression Strength in Lbs.
440
480
520
560
600
640
680
720
Theoretical Compression Strength in Lbs.
I - Kellicutt and Landt
II - Maltenfort
III - McKee, et al
IV - McKee, et al
Angle β
Ideal Curve = 45°
I - Kellicutt ≈ 56°
II - Maltenfort ≈ 60°
III - McKee, et al ≈ 51°
IV - McKee, et al ≈ 51°
Ideal Curve
β

Figure 4

determined falls near the lower limit, it would approach the first three low perimeters but would still give a low value on the remaining perimeters. Similarly, if CLT-O value is near the upper limit of the range it would satisfy the higher perimeters considered. However, it would have in turn a high compression value exceeding the actual compression test value for the low perimeters. At this point, it is worth mentioning that the constant shown in Table 1 which has been determined for Equation (II) is an average, using an entire range of depth, length, and width variations for each set of perimeter used.*

Upon analyzing Figures 3 and 4, distinct patterns are noted. It appears correlations among the equations are in pairs. Equations (I) and (II) are highly correlated throughout the entire range of perimeters. The difference could not be determined for the reason mentioned earlier. Similarly, Equations (III) and (IV) are highly correlated on the perimeters considered with slightly lower values for Equation (IV). The two equations differ only by 12-16 pounds on the entire range.

The plotted test data in Figure 3, on the other hand, seemed to show some slight correlation on the first three lower perimeters but abruptly changed its pattern in the

* See Appendix F.

remaining perimeters. The pattern is a widening of the gap with respect to the theoretical curves. Figure 4 shows how close the correlation between an ideal curve and the theoretical-actual curves are. By approximating the slope of the curves and comparing with the ideal curve, inferences could be made that Equations (III) and (IV) are more closely correlated with respect to the overall range of perimeters than Equations (I) and (II) without regard to the variation constants. The constants could be easily altered without difficulty to bring the theoretical value to that of the actual test values. A general trend exists on all the equations in that as the perimeter is increased, the theoretical values decreased when actual test values increased more rapidly.

Analysis of RSC Corrugated Boxes

A general knowledge could be restated that as the box perimeter is increased, top-to-bottom compressive strength correspondingly increases. As to the resultant increase, many attempts have been made but no conclusive evidence have been published so far. The succeeding discussion will not pinpoint the relationship but rather would analyze the effects on the compressive strength of the corrugated box when one parameter is varied while the other parameters are held constant.

Constant Parameter

The given curves on Figures 5 and 7 were plotted based on the tabulated data on Table 3. Similarly, Figure 6 used the data on Table 4. With the perimeters constant and with the depth to perimeter ratio varied, definite patterns were observed on Figure 6. These observed patterns support an earlier statement that the compressive strength increases with an increase in perimeter. The curves are such that the four lower perimeters are very unstable within the D/Z = 0.08 to D/Z = 0.32 and similarly, applies to Figure 7 on the height range of from 3-3/8 inches to 12 inches. The upper two perimeters have the same characteristics although the range of instability was reduced by one-half. The remaining portions of the curves taper down gradually but not at the same rate. This shows that no definite relationship exists as the perimeter is changed at a set interval with variable D/Z ratio and height.

Figure 6 shows the effect of D/Z ratio with load per inch perimeter and with the perimeter constant. The curve is very much similar to Figure 5 but the arrangement now is in reverse; that is, as the perimeter is increased the load capacity per inch perimeter is reduced.

Table 3. Average Compression Strength in Pounds for Different Perimeters With Depth to Perimeter Ratio Constant Based on 20 Samples.

D/Z	30"	34"	38"	42"	48"	56"
.08				842	864	934
.16	684	734	749	780	814	869
.24	620	647	686	739	814	872
.32	662	690	733	762	822	880
.40	641	671	704	766	833	853
.48	652	672	686	723	810	866
.56	640	699	675	748	820	852
.70	653	660	679	743	784	818

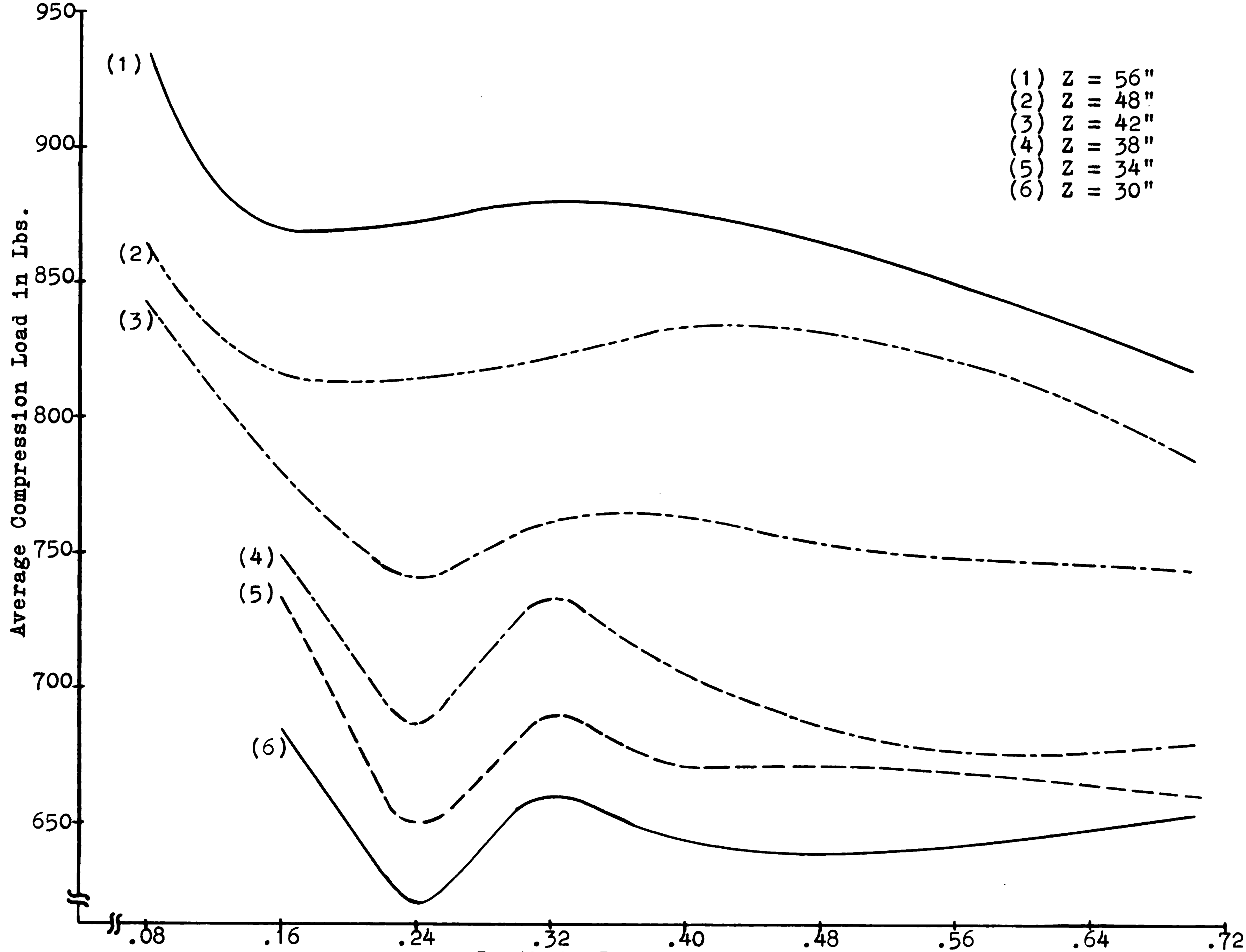

950
900
850
800
750
700
650
Average Compression Load in Lbs.
(1)
(2)
(3)
(4)
(5)
(6)
(1) Z = 56"
(2) Z = 48"
(3) Z = 42"
(4) Z = 38"
(5) Z = 34"
(6) Z = 30"
.08
.16
.24
.32
.40
.48
.56
.64
.72
Depth to Perimeter Ratio

Figure 5

Table 4. Average Compression Strength in Pounds Per Inch Perimeter for Different Perimeters With Depth to Perimeter Ratio Constant Based on 20 Samples.

D/Z	30"	34"	38"	42"	48"	56"
.08				20.05	18.00	16.68
.16	22.80	21.59	19.71	18.57	16.96	15.52
.24	20.67	19.03	18.05	17.60	16.96	15.57
.32	22.07	20.29	19.29	18.14	17.13	15.71
.40	21.37	19.74	18.53	18.24	17.35	15.23
.48	21.73	19.77	18.05	17.21	16.88	15.46
.56	21.33	20.56	17.76	17.81	17.08	15.21
.70	21.77	19.41	17.87	17.69	16.33	14.61

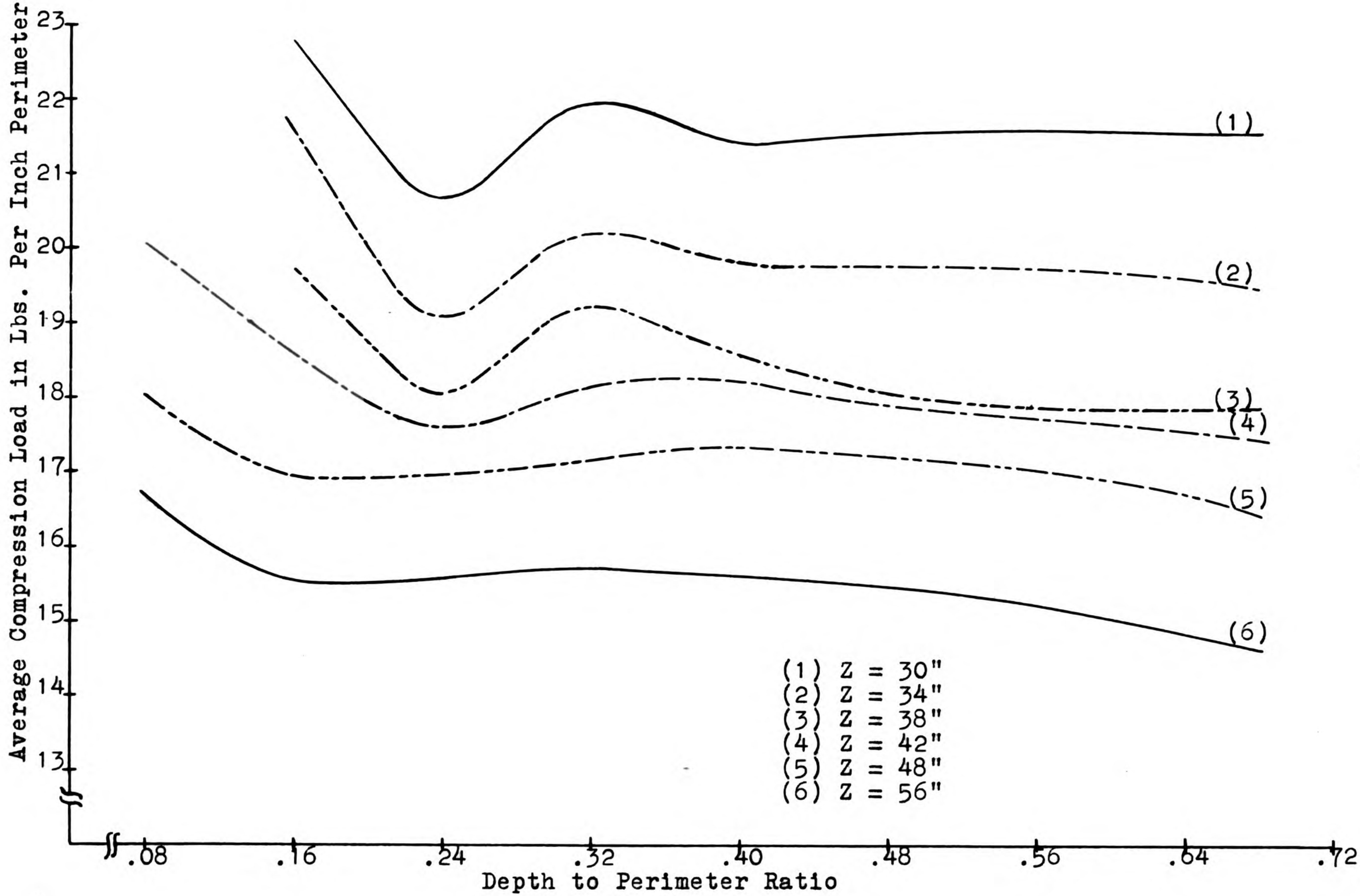

Average Compression Load in Lbs. Per Inch Perimeter
23
22
21
20
19
18
17
16
15
14
13
.08
.16
.24
.32
.40
.48
.56
.64
.72
Depth to Perimeter Ratio
(1)
(2)
(3)
(4)
(5)
(6)
(1) Z = 30"
(2) Z = 34"
(3) Z = 38"
(4) Z = 42"
(5) Z = 48"
(6) Z = 56"

Figure 6

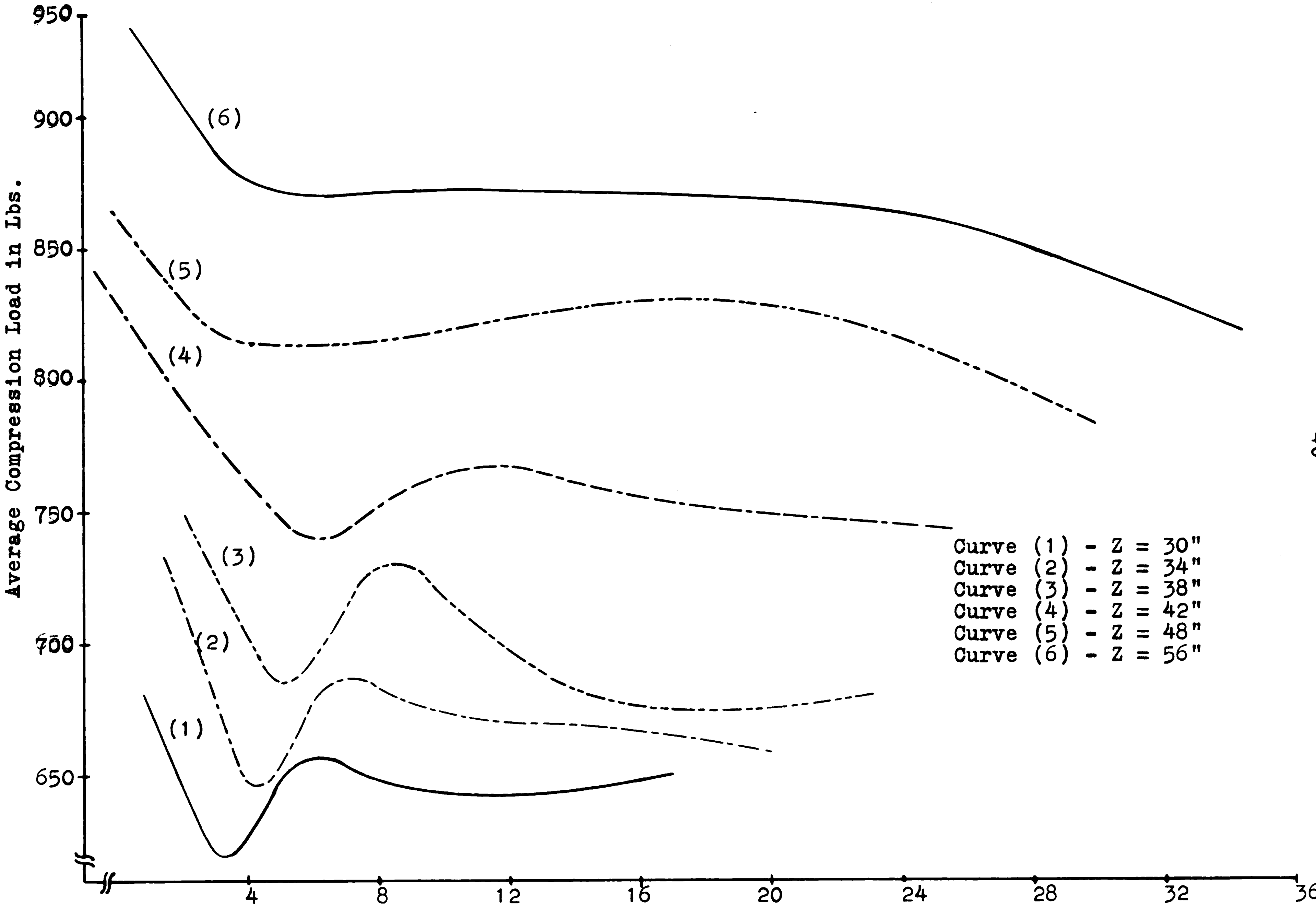

Average Compression Load in Lbs.
950
900
850
800
750
700
650
(1)
(2)
(3)
(4)
(5)
(6)
4
8
12
16
20
24
28
32
36
Height in Inches
Curve (1) - Z = 30"
Curve (2) - Z = 34"
Curve (3) - Z = 38"
Curve (4) - Z = 42"
Curve (5) - Z = 48"
Curve (6) - Z = 56"

Figure 7

Depth to Perimeter Ratio - Constant

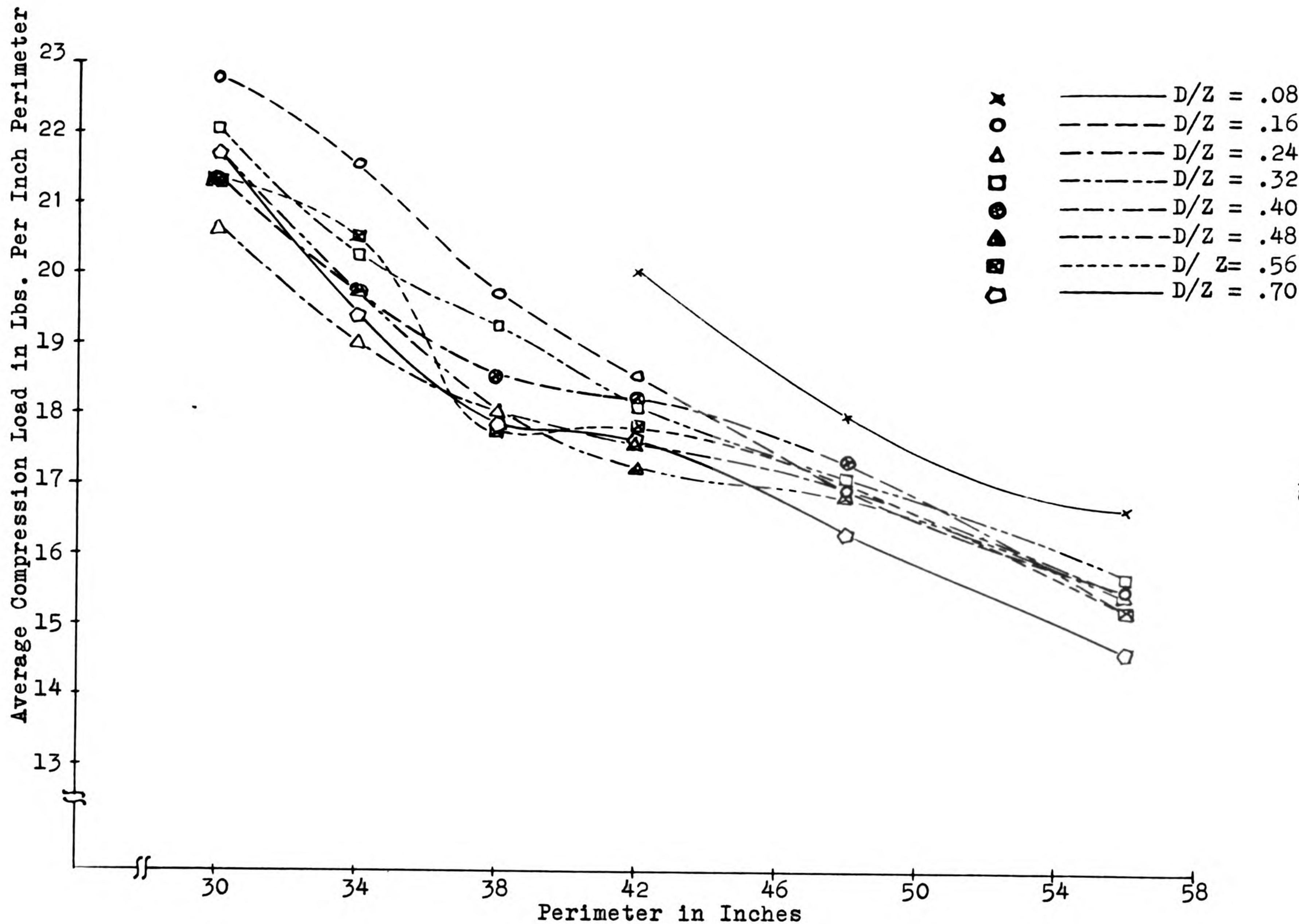
Figure 8 clearly shows that for $D/Z < 1/7$, compressive strength would be relatively high, which is the case for $D/Z = 0.08$. The effects on the compressive strength upon varying the D/Z ratio is to vary more on lower perimeters, then gradually variation is decreased as the perimeter is increased.

Length to Width Ratio - Constant

Data on Tables 5 and 6 were used to plot the curves on Figures 9 and 10, respectively. Tests showed that varying the length to width ratio affected the compression load but not on a large scale. It was found that boxes tested with an $L/W = 1.25$ and $L/W = 1.50$ gave a higher compressive load than square boxes. Furthermore, boxes tested with an $L/W = 1.75$ and $L/W = 2.00$ presented values lower than an $L/W = 1.00$ would give.

The RSC Box

With the varied sizes of corrugated box tested, an observation was made with regards to the buckling characteristics of the vertical panels. Three distinct types of buckling were noticed. The first is a halfwave, as shown in Figure 11, which is characteristic of short depth boxes. This actually occurs just before failure. Figures 12 and 13



Average Compression Load in Lbs. Per Inch Perimeter
23
22
21
20
19
18
17
16
15
14
13
Perimeter in Inches
30
34
38
42
46
50
54
58
D/Z = .08
D/Z = .16
D/Z = .24
D/Z = .32
D/Z = .40
D/Z = .48
D/ Z= .56
D/Z = .70

Figure 8

Table 5. Average Compression Strength in Pounds for Different Perimeters with Length to Width Ratio Constant Based on 28-32 Samples.

L/W	30"	34"	38"	42"	48"	56"
1.00	660	688	711	761	822	861
1.25	656	692	710	780	847	891
1.50	648	694	714	784	825	888
1.75	658	678	681	759	812	844
2.00	629	657	694	730	794	856

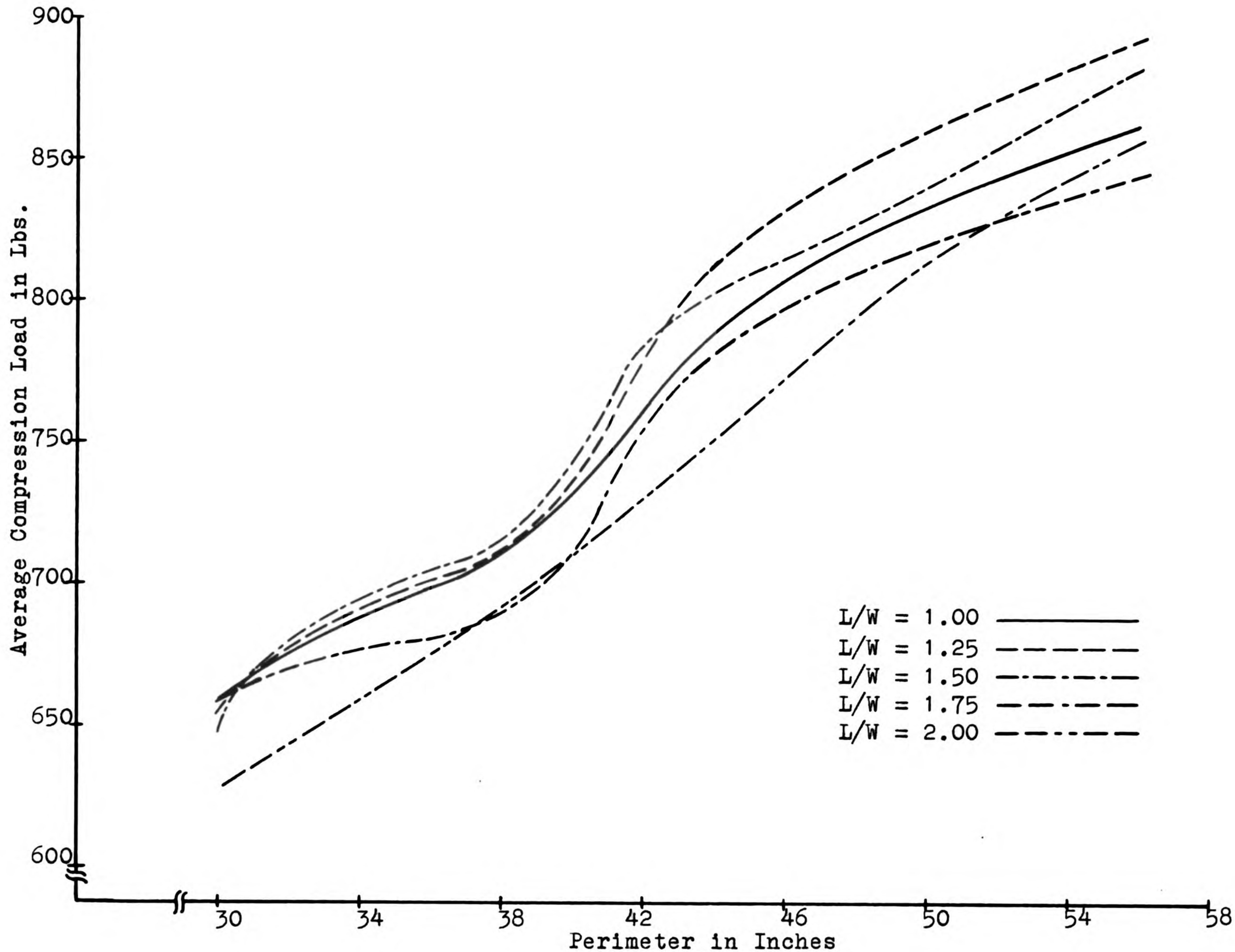
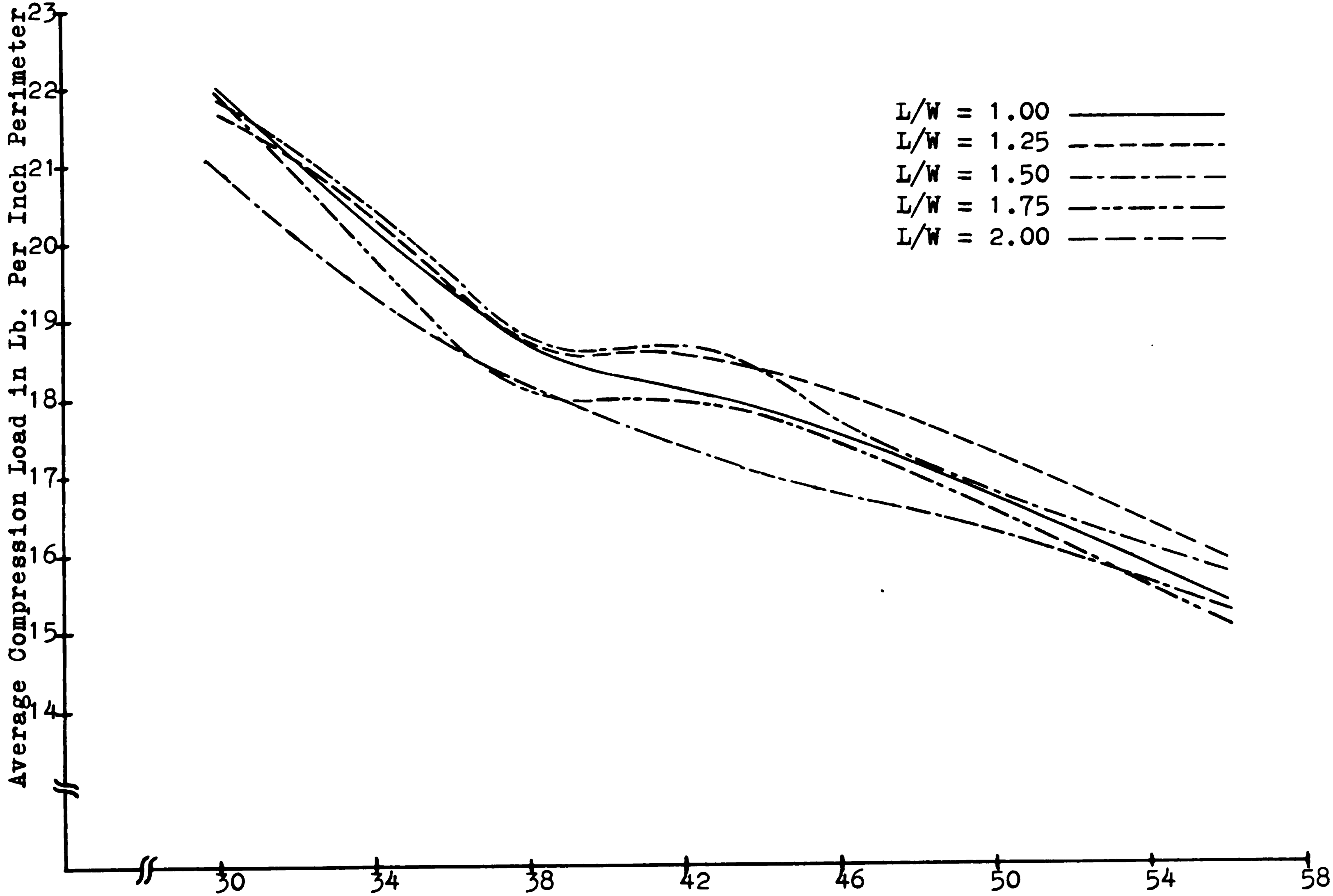

Average Compression Load in Lbs.
900
850
800
750
700
650
600
30
34
38
42
46
50
54
58
Perimeter in Inches
L/W = 1.00
L/W = 1.25
L/W = 1.50
L/W = 1.75
L/W = 2.00

Figure 9

Table 6. Average Compression Strength in Pounds Per Inch Perimeter for Different Perimeters With Length to Width Ratio Constant Based on 28-32 Samples.

L/W	30"	34"	38"	42"	48"	56"
1.00	22.00	20.24	18.71	18.12	17.13	15.38
1.25	21.87	20.35	18.68	18.57	17.65	15.91
1.50	21.60	20.41	18.79	18.67	17.19	15.86
1.75	21.93	19.94	17.92	18.07	16.92	15.07
2.00	20.97	19.32	18.26	17.38	16.54	15.29



Average Compression Load in Lb. Per Inch Perimeter
23
22
21
20
19
18
17
16
15
14
30
34
38
42
46
50
54
58
L/W = 1.00
L/W = 1.25
L/W = 1.50
L/W = 1.75
L/W = 2.00
Perimeter in Inches

Figure 10

illustrate two halfwave and three halfwave buckling, respectively, with the panels alternately buckling on each halfwave.

No definite boundary could be determined but rather occurrence on some D/Z range are somewhat consistent. For the two and three halfwaves buckling, a stipulation that the panels should not be warped before testing does not necessarily have to be followed inasmuch as the side panels would still buckle as mentioned and therefore, would eliminate the effect of warping. As for the short depths, warped vertical panels would induce the direction of buckling.

A further observation was made in that failures of the boxes tested occurred mostly in panel number 1, the wider vertical panel as shown in Figure 14. This may be due to the presence of the manufacturer's joint which lessens the bearing capacity of the corner. All failures no matter what the height of the box may be (on boards without fabrication defects) always occur either on the bottom or on the top areas near the score line. The line of failure comes from the corners in contact with the platen, then forms a curve concave upwards for upper failure (convex upward for lower failure). This type of failure may be inwards or outwards depending upon the box configuration.

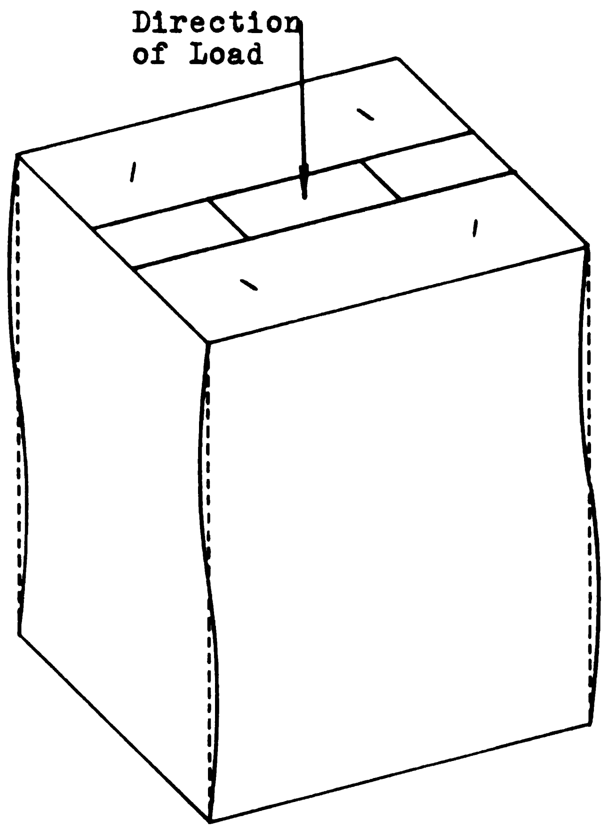


Figure 12

Condition of a relatively medium height corrugated box buckling as shown when under compression just before failure.

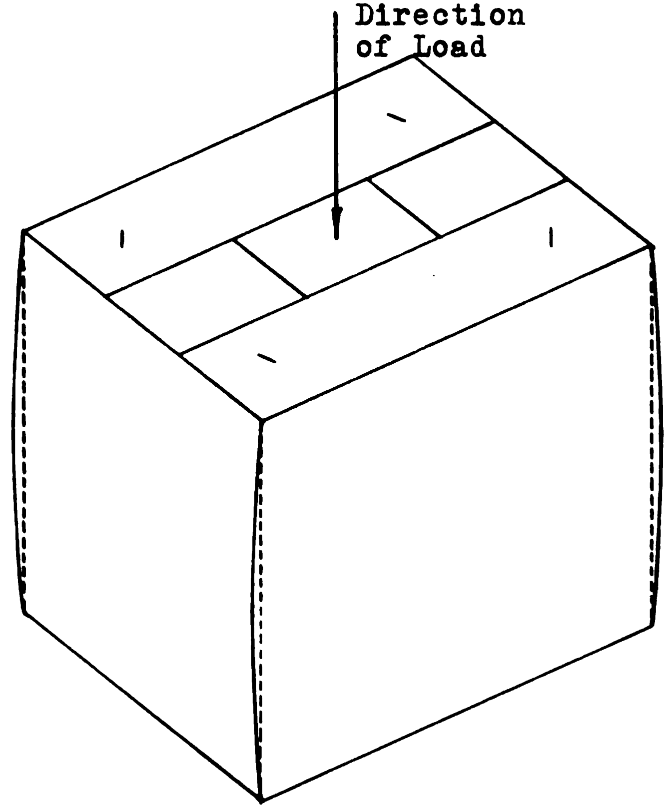


Figure 11

Condition of a relatively short height corrugated box buckling outward on some instances inward, under compression just before failure.

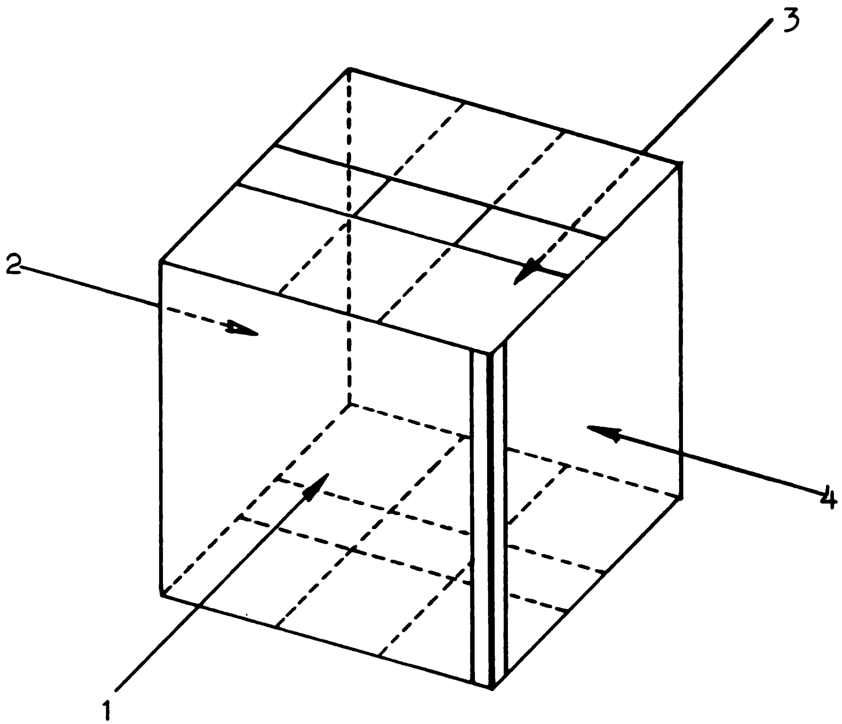


Figure 14

A typical corrugated box with its vertical sides in relation to the manufacturer's joint, are assigned numbers for reference.

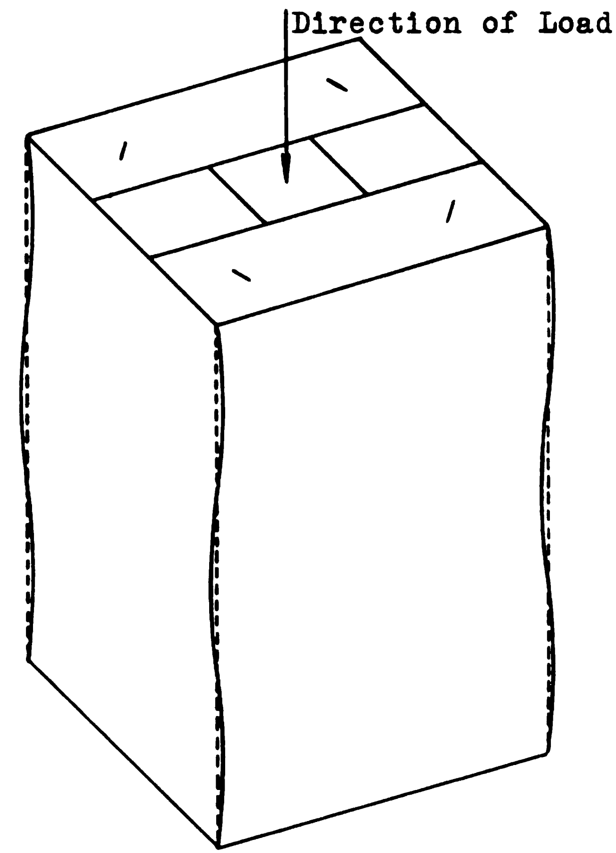


Figure 13

Condition of a relatively tall corrugated box buckling as shown when under compression just before failure.

CONCLUSIONS

The conclusions are based on the data compiled from the actual testing of fibreboard components, corrugated fibreboards and RSC boxes made of a single wall C-flute, 200 lb. test board.

The following conclusions are:

1. Except for the Maltenfort Empirical Equation, theoretical values for top-to-bottom compression strength are all low. If the Concora Liner Test result on the liners used would fall within the range 28.3 lbs. to 45.6 lbs., the equation by Maltenfort would equal the test result values on certain range.

2. The empirical equation of Kellicutt and Landt as well as Maltenfort's are closely correlated although the increment could not be determined. Similarly, the two equations of McKee, Gander and Wachuta are highly correlated. No correlation exists between the first two equations and the two latter equations. On the lower perimeters slight correlation exists between test results and the theoretical values but diverges on higher perimeters.

3. Varying the length to width ratio changes slightly the compressive strength. Boxes with L/W = 1.25 and L/W = 1.50 give higher compressive strength than square boxes. On boxes

with L/W = 1.75 and L/W = 2.00 the resultant compressive strengths are lower than on a box with an L/W = 1.00.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Ranger, A. E.
   1960 The Compression Strength of Corrugated Fibreboard Cases and Sleeves. Paper Technology, Vol. 1(5) : 531-541.

2. Bettendorf, H. J.
   1946 Paperboard and Paperboard Containers, A History. Board Products Publishing Co., Chicago, Illinois.

3. Kellicutt, K. Q.
   1959 F P L (Forest Products Laboratory) Structural Design Work Rests on 50 Years Research. Package Engineering, Vol. 4(2) : 60-63.

4. McCready, D. W. and D. L. Katz
   1939 A Study of Corrugated Fibreboard - The Effect of Adhesive on the Strength of Corrugated Board. University of Michigan, Engineering Research Bulletin No. 28 (1939).

5. Carlson, T. A.
   1940 Bending Tests of Corrugated Board and Their Significance. Paper Trade Journal, Vol. 110, No. 8 : 123-127.

6. Carlson, T. A.
   1941 Some Factors Affecting the Compressive Strength of Fiber Boxes. Paper Trade Journal, Vol. 112, No. 23, 35-38.

7. Little, J. R.
   1943 A Theory of Box Compressive Resistance in Relation to the Structural Properties of Corrugated Paperboard. Paper Trade Journal, Vol. 116, No. 24, 31-34.

8. Kellicutt, K. Q. and E. F. Landt
   1951 Basic Design Data for the Use of Fibreboard in Shipping Containers. U. S. Department of Agriculture, Forest Service, Forest Products Laboratory Bulletin D1911, 39 pp.

9. Maltenfort, G. G.
1956 Compression Strength of Corrugated Containers-Parts I and II. Fibre Containers and Paperboard Mills, Vol. 41(7) : 44,49,50,52,57, Vol. 41(9) : 60-62,67,68,72,74.

10. McKee, R. C., J. W. Gander and J. R. Wachuta
1963 Compression Strength Formula for Corrugated Boxes. Paperboard Packaging, Vol. 48(8) : 149-159.

11. Marin, J. and J. A. Sauer
1954 Strength of Materials. The Macmillan Company, New York. P. 151.

12. McKee, R. C. and J. W. Gander
1957 Top-Load Compression. TAPPI, Vol. 40(1) : 57-64.

APPENDIX

APPENDIX A

Test Materials

Components of corrugated fibreboard

Single Face Liner:

Basis Weight = 45 lb/MSF

Caliper = 0.0128 in.

Mullen = 106 lb/sq.in.

Ring Crush Test -

MD = 14.41 lb/in width

OD = 10.13 lb/in width

Double Face Liner:

Basis Weight = 44 lb/MSF

Caliper = 0.0129 in.

Mullen = 120 lb/sq.in.

Ring Crush Test -

MD = 14.48 lb/in width

OD = 11.69 lb/in width

Corrugating Medium:

Basis Weight = 27 lb/MSF

Caliper = 0.010 in.

Mullen = 37.5 lb/sq.in.

Ring Crush Test -

MD = 6.30 lb/in width

OD = 5.53 lb/in width

Combined corrugated fibreboard

200 lb. test board

C-flute = 42 flutes/ft

Basis Weight = 132 lb/MSF

Caliper = 0.160 in.

Mullen = 214 lb/sq.in.

Flexural stiffness = 103 lb-in. (machine direction)

Flexural stiffness = 47 lb-in. (cross-machine direction)

Column Crush Test = 37.0 lb/in width

APPENDIX B

Box Sizes

Perimeter = 30"

Code*	D/Z	L/W	W (in.)	L (in.)	D (in.)
112	.16	1.00	7½	7½	4-13/16
122	.16	1.25	6-11/16	8-5/16	4-13/16
132	.16	1.50	6.0	9.0	4-13/16
142	.16	1.75	5-15/32	9-17/32	4-13/16
152	.16	2.00	5.0	10.0	4-13/16
113	.24	1.00	7½	7½	7-7/32
123	.24	1.25	6-11/16	8-5/16	7-7/32
133	.24	1.50	6.0	9.0	7-7/32
143	.24	1.75	5-15/32	9-17/32	7-7/32
153	.24	2.00	5.0	10.0	7-7/32
114	.32	1.00	7½	7½	9-5/8
124	.32	1.25	6-11/16	8-5/16	9-5/8
134	.32	1.50	6.0	9.0	9-5/8
144	.32	1.75	5-15/32	9-17/32	9-5/8
154	.32	2.00	5.0	10.0	9-5/8
115	.40	1.00	7½	7½	12
125	.40	1.25	6-11/16	8-5/16	12
135	.40	1.50	6.0	9.0	12
145	.40	1.75	5-15/32	9-17/32	12
155	.40	2.00	5.0	10.0	12

Perimeter = 30"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
116	.48	1.00	7½	7½	14-13/32
126	.48	1.25	6-11/16	8-5/16	14-13/32
136	.48	1.50	6.0	9.0	14-13/32
146	.48	1.75	5-15/32	9-17/32	14-13/32
156	.48	2.00	5.0	10.0	14-13/32
117	.56	1.00	7½	7½	16-13/16
127	.56	1.25	6-11/16	8-5/16	16-13/16
137	.56	1.50	6.0	9.0	16-13/16
147	.56	1.75	5-15/32	9-17/32	16-13/16
157	.56	2.00	5.0	10.0	16-13/16
118	.70	1.00	7½	7½	21
128	.70	1.25	6-11/16	8-5/16	21
138	.70	1.50	6.0	9.0	21
148	.70	1.75	5-15/32	9-17/32	21
158	.70	2.00	5.0	10.0	21

Perimeter = 34"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
212	.16	1.00	8½	8½	5-7/16
222	.16	1.25	7-9/16	9-7/16	5-7/16
232	.16	1.50	6-13/16	10-3/16	5-7/16
242	.16	1.75	6-3/16	10-13/16	5-7/16
252	.16	2.00	5-11/16	11-5/16	5-7/16

Perimeter = 34"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
213	.24	1.00	8½	8½	8-5/32
223	.24	1.25	7-9/16	9-7/16	8-5/32
233	.24	1.50	6-13/16	10-3/16	8-5/32
243	.24	1.75	6-3/16	10-13/16	8-5/32
253	.24	2.00	5-11/16	11-5/16	8-5/32
214	.32	1.00	8½	8½	10-7/8
224	.32	1.25	7-9/16	9-7/16	10-7/8
234	.32	1.50	6-13/16	10-3/16	10-7/8
244	.32	1.75	6-3/16	10-13/16	10-7/8
254	.32	2.00	5-11/16	11-5/16	10-7/8
215	.40	1.00	8½	8½	13-19/32
225	.40	1.25	7-9/16	9-7/16	13-19/32
235	.40	1.50	6-13/16	10-3/16	13-19/32
245	.40	1.75	6-3/16	10-13/16	13-19/32
255	.40	2.00	5-11/16	11-5/16	13-19/32
216	.48	1.00	8½	8½	16-5/16
226	.48	1.25	7-9/16	9-7/16	16-5/16
236	.48	1.50	6-13/16	10-3/16	16-5/16
246	.48	1.75	6-3/16	10-13/16	16-5/16
256	.48	2.00	5-11/16	11-5/16	16-5/16

Perimeter = 34"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
217	.56	1.00	8½	8½	19-1/32
227	.56	1.25	7-9/16	9-7/16	19-1/32
237	.56	1.50	6-13/16	10-3/16	19-1/32
247	.56	1.75	6-3/16	10-13/16	19-1/32
257	.56	2.00	5-11/16	11-5/16	19-1/32
218	.70	1.00	8½	8½	23-13/16
228	.70	1.25	7-9/16	9-7/16	23-13/16
238	.70	1.50	6-13/16	10-3/16	23-13/16
248	.70	1.75	6-3/16	10-13/16	23-13/16
258	.70	2.00	5-11/16	11-5/16	23-13/16

Perimeter = 38"

312	.16	1.00	9½	9½	6-3/32
322	.16	1.25	8-7/16	10-9/16	6-3/32
332	.16	1.50	7-19/32	11-13/32	6-3/32
342	.16	1.75	6-29/32	12-3/32	6-3/32
352	.16	2.00	6-11/32	12-21/32	6-3/32
313	.24	1.00	9½	9½	9-1/8
323	.24	1.25	8-7/16	10-9/16	9-1/8
333	.24	1.50	7-19/32	11-13/32	9-1/8
343	.24	1.75	6-29/32	12-3/32	9-1/8
353	.24	2.00	6-11/32	12-21/32	9-1/8

Perimeter = 38"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
314	.32	1.00	9½	9½	12-5/32
324	.32	1.25	8-7/16	10-9/16	12-5/32
334	.32	1.50	7-19/32	11-13/32	12-5/32
344	.32	1.75	6-29/32	12-3/32	12-5/32
354	.32	2.00	6-11/32	12-21/32	12-5/32
315	.40	1.00	9½	9½	15-7/32
325	.40	1.25	8-7/16	10-9/16	15-7/32
335	.40	1.50	7-19/32	11-13/32	15-7/32
345	.40	1.75	6-29/32	12-3/32	15-7/32
355	.40	2.00	6-11/32	12-21/32	15-7/32
316	.48	1.00	9½	9½	18¼
326	.48	1.25	8-7/16	10-9/16	18¼
336	.48	1.50	7-19/32	11-13/32	18¼
346	.48	1.75	6-29/32	12-3/32	18¼
356	.48	2.00	6-11/32	12-21/32	18¼
317	.56	1.00	9½	9½	21-9/32
327	.56	1.25	8-7/16	10-9/16	21-9/32
337	.56	1.50	7-19/32	11-13/32	21-9/32
347	.56	1.75	6-29/32	12-3/32	21-9/32
357	.56	2.00	6-11/32	12-21/32	21-9/32

Perimeter = 38"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
318	.70	1.00	9½	9½	26-5/8
328	.70	1.25	8-7/16	10-9/16	26-5/8
338	.70	1.50	7-19/32	11-13/32	26-5/8
348	.70	1.75	6-29/32	12-3/32	26-5/8
358	.70	2.00	6-11/32	12-21/32	26-5/8

Perimeter = 42"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
411	.08	1.00	10½	10½	3-3/8
421	.08	1.25	9-11/32	11-21/32	3-3/8
431	.08	1.50	8-13/32	12-19/32	3-3/8
441	.08	1.75	7-21/32	13-11/32	3-3/8
451	.08	2.00	7.0	14.0	3-3/8
412	.16	1.00	10½	10½	6-3/4
422	.16	1.25	9-11/32	11-21/32	6-3/4
432	.16	1.50	8-13/32	12-19/32	6-3/4
442	.16	1.75	7-21/32	13-11/32	6-3/4
452	.16	2.00	7.0	14.0	6-3/4
413	.24	1.00	10½	10½	10-3/32
423	.24	1.25	9-11/32	11-21/32	10-3/32
433	.24	1.50	8-13/32	12-19/32	10-3/32
443	.24	1.75	7-21/32	13-11/32	10-3/32
453	.24	2.00	7.0	14.0	10-3/32

Perimeter = 42"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
414	.32	1.00	10½	10½	13-7/16
424	.32	1.25	9-11/32	11-21/32	13-7/16
434	.32	1.50	8-13/32	12-19/32	13-7/16
444	.32	1.75	7-21/32	13-11/32	13-7/16
454	.32	2.00	7.0	14.0	13-7/16
415	.40	1.00	10½	10½	16-13/16
425	.40	1.25	9-11/32	11-21/32	16-13/16
435	.40	1.50	8-13/32	12-19/32	16-13/16
445	.40	1.75	7-21/32	13-11/32	16-13/16
455	.40	2.00	7.0	14.0	16-13/16
416	.48	1.00	10½	10½	20-5/32
426	.48	1.25	9-11/32	11-21/32	20-5/32
436	.48	1.50	8-13/32	12-19/32	20-5/32
446	.48	1.75	7-21/32	13-11/32	20-5/32
456	.48	2.00	7.0	14.0	20-5/32
417	.56	1.00	10½	10½	23-17/32
427	.56	1.25	9-11/32	11-21/32	23-17/32
437	.56	1.50	8-13/32	12-19/32	23-17/32
447	.56	1.75	7-21/32	13-11/32	23-17/32
457	.56	2.00	7.0	14.0	23-17/32

Perimeter = 42"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
418	.70	1.00	10½	10½	29-13/32
428	.70	1.25	9-11/32	11-21/32	29-13/32
438	.70	1.50	8-13/32	12-19/32	29-13/32
448	.70	1.75	7-21/32	13-11/32	29-13/32
458	.70	2.00	7.0	14.0	29-13/32

Perimeter = 48"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
511	.08	1.00	12	12	3-27/32
521	.08	1.25	10-21/32	13-11/32	3-27/32
531	.08	1.50	9-19/32	14-13/32	3-27/32
541	.08	1.75	8-3/4	15¼	3-27/32
551	.08	2.00	8.0	16.0	3-27/32
512	.16	1.00	12	12	7-11/16
522	.16	1.25	10-21/32	13-11/32	7-11/16
532	.16	1.50	9-19/32	14-13/32	7-11/16
542	.16	1.75	8-3/4	15¼	7-11/16
552	.16	2.00	8.0	16.0	7-11/16
513	.24	1.00	12	12	11-17/32
523	.24	1.25	10-21/32	13-11/32	11-17/32
533	.24	1.50	9-19/32	14-13/32	11-17/32
543	.24	1.75	8-3/4	15¼	11-17/32
553	.24	2.00	8.0	16.0	11-17/32

Perimeter = 48"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
514	.32	1.00	12	12	15-3/8
524	.32	1.25	10-21/32	13-11/32	15-3/8
534	.32	1.50	9-19/32	14-13/32	15-3/8
544	.32	1.75	8-3/4	15¼	15-3/8
554	.32	2.00	8.0	16.0	15-3/8
515	.40	1.00	12	12	19-7/32
525	.40	1.25	10-21/32	13-11/32	19-7/32
535	.40	1.50	9-19/32	14-13/32	19-7/32
545	.40	1.75	8-3/4	15¼	19-7/32
555	.40	2.00	8.0	16.0	19-7/32
516	.48	1.00	12	12	23-1/16
526	.48	1.25	10-21/32	13-11/32	23-1/16
536	.48	1.50	9-19/32	14-13/32	23-1/16
546	.48	1.75	8-3/4	15¼	23-1/16
556	.48	2.00	8.0	16.0	23-1/16
517	.56	1.00	12	12	26-29/32
527	.56	1.25	10-21/32	13-11/32	26-29/32
537	.56	1.50	9-19/32	14-13/32	26-29/32
547	.56	1.75	8-3/4	15¼	26-29/32
557	.56	2.00	8.0	16.0	26-29/32

Perimeter = 43"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
518	.70	1.00	12	12	33-5/8
528	.70	1.25	10-21/32	13-11/32	33-5/8
538	.70	1.50	9-19/32	14-13/32	33-5/8
548	.70	1.75	8-3/4	15¼	33-5/8
558	.70	2.00	8.0	16.0	33-5/8

Perimeter = 56"

611	.08	1.00	14	14	4½
621	.08	1.25	12-15/32	15-17/32	4½
631	.08	1.50	11-7/32	16-25/32	4½
641	.08	1.75	10-3/16	17-13/16	4½
651	.08	2.00	9-11/32	18-21/32	4½
612	.16	1.00	14	14	8-31/32
622	.16	1.25	12-15/32	15-17/32	8-31/32
632	.16	1.50	11-7/32	16-25/32	8-31/32
642	.16	1.75	10-3/16	17-13/16	8-31/32
652	.16	2.00	9-11/32	18-21/32	8-31/32
613	.24	1.00	14	14	13-15/32
623	.24	1.25	12-15/32	15-17/32	13-15/32
633	.24	1.50	11-7/32	16-25/32	13-15/32
643	.24	1.75	10-3/16	17-13/16	13-15/32
653	.24	2.00	9-11/32	18-21/32	13-15/32

Perimeter = 56"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
614	.32	1.00	14	14	17-15/16
624	.32	1.25	12-15/32	15-17/32	17-15/16
634	.32	1.50	11-7/32	16-25/32	17-15/16
644	.32	1.75	10-3/16	17-13/16	17-15/16
654	.32	2.00	9-11/32	18-21/32	17-15/16
615	.40	1.00	14	14	22-13/32
625	.40	1.25	12-15/32	15-17/32	22-13/32
635	.40	1.50	11-7/32	16-25/32	22-13/32
645	.40	1.75	10-3/16	17-13/16	22-13/32
655	.40	2.00	9-11/32	18-21/32	22-13/32
616	.48	1.00	14	14	26-7/8
626	.48	1.25	12-15/32	15-17/32	26-7/8
636	.48	1.50	11-7/32	16-25/32	26-7/8
646	.48	1.75	10-3/16	17-13/16	26-7/8
656	.48	2.00	9-11/32	18-21/32	26-7/8
617	.56	1.00	14	14	31-3/8
627	.56	1.25	12-15/32	15-17/32	31-3/8
637	.56	1.50	11-7/32	16-25/32	31-3/8
647	.56	1.75	10-3/16	17-13/16	31-3/8
657	.56	2.00	9-11/32	18-21/32	31-3/8

Perimeter = 56"

Code	D/Z	L/W	W (in.)	L (in.)	D (in.)
618	.70	1.00	14	14	39-7/32
628	.70	1.25	12-15/32	15-17/32	39-7/32
638	.70	1.50	11-7/32	16-25/32	39-7/32
648	.70	1.75	10-3/16	17-13/16	39-7/32
658	.70	2.00	9-11/32	18-21/32	39-7/32

* - code legend

CODE LEGEND

1XX - Perimeter 30"

2XX - Perimeter 34"

3XX - Perimeter 38"

4XX - Perimeter 42"

5XX - Perimeter 48"

6XX - Perimeter 56"

XX1 - D/Z = 0.08

XX2 - D/Z = 0.16

XX3 - D/Z = 0.24

XX4 - D/Z = 0.32

XX5 - D/Z = 0.40

XX6 - D/Z = 0.48

XX7 - D/Z = 0.56

XX8 - D/Z = 0.70

X1X - L/W = 1.00

X2X - L/W = 1.25

X3X - L/W = 1.50

X4X - L/W = 1.75

X5X - L/W = 2.00

APPENDIX C

Column Crush Test

Results on C-flute corrugated fibreboard:

Values based on 5 specimens per sample in pounds per inch width.

33.4	35.6	36.6	37.6	38.2
34.2	35.8	36.8	37.6	38.8
34.8	36.0	36.8	37.6	38.8
35.0	36.2	37.0	37.6	39.0
35.2	36.2	37.0	38.0	39.2
35.4	36.2	37.2	38.0	39.4
35.4	36.4	37.2	38.0	41.5
35.6	36.4	37.4	38.0	

Average = 37.0 lbs./in. width

APPENDIX D

Average Compressive Load on Four Samples in Lbs.

Code*	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
12X	686	727	730	677	600
13X	583	606	630	656	625
14X	675	642	642	678	672
15X	672	636	638	625	636
16X	669	666	616	659	650
17X	664	666	620	647	602
18X	669	652	660	667	619
22X	719	780	739	744	691
23X	642	642	655	666	633
24X	683	702	700	698	667
25X	694	686	663	664	650
26X	670	670	713	647	659
27X	730	703	710	678	642
28X	650	664	682	649	657
32X	800	702	820	725	700
33X	608	685	713	712	711
34X	714	750	741	713	749
35X	767	746	699	628	682
36X	736	716	647	656	674
37X	690	672	672	684	657
38X	661	699	705	646	686

* See code legend on Appendix B

Code	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
41X	841	836	859	861	812
42X	758	825	805	758	755
43X	684	772	800	722	717
44X	778	802	739	736	755
45X	784	763	794	749	743
46X	769	750	758	691	647
47X	731	763	754	795	698
48X	745	731	764	761	712
51X	836	865	853	874	894
52X	878	837	802	800	750
53X	803	863	810	827	770
54X	800	886	824	803	797
55X	850	825	825	850	900
56X	817	822	813	786	809
57X	828	855	864	797	755
58X	761	819	794	765	781
61X	953	965	936	822	995
62X	851	888	873	839	893
63X	872	908	885	833	815
64X	865	939	917	844	833
65X	867	850	872	849	830
66X	850	859	942	850	827
67X	832	885	877	844	825
68X	795	836	800	826	830

APPENDIX E

Average Compressive Load on Four Samples in Lbs. Per Inch Perimeter

Code	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
12X	22.87	24.23	24.33	22.57	20.00
13X	19.43	20.20	21.00	21.87	20.83
14X	22.50	21.40	21.60	22.60	22.40
15X	22.40	21.20	21.27	20.83	21.20
16X	22.30	22.20	20.53	21.97	21.67
17X	22.13	22.20	20.67	21.57	20.07
18X	22.30	21.73	22.00	22.23	20.63
22X	21.15	22.94	21.74	21.88	20.32
23X	18.88	18.88	19.26	19.59	18.62
24X	20.09	20.65	20.59	20.53	19.62
25X	20.41	20.18	19.50	19.53	19.12
26X	19.71	19.71	20.97	19.03	19.38
27X	22.35	20.68	20.88	19.94	18.88
28X	19.12	19.53	20.06	19.09	19.32
32X	21.05	18.47	21.58	19.08	18.42
33X	16.00	18.03	18.76	18.74	18.71
34X	18.79	19.74	19.50	18.76	19.71
35X	20.18	19.63	18.40	16.53	17.95
36X	19.37	18.84	17.03	17.26	17.74
37X	18.16	17.68	17.68	18.00	17.29
38X	17.39	18.40	18.55	17.00	18.05

Code	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
41X	20.02	19.91	20.45	20.50	19.33
42X	18.05	19.64	19.17	18.05	17.98
43X	16.29	18.38	19.05	17.19	17.07
44X	18.52	19.10	17.60	17.52	17.98
45X	18.67	18.17	18.90	17.83	17.69
46X	18.31	17.86	18.05	16.45	15.41
47X	17.41	18.17	17.95	18.93	16.62
48X	17.74	17.40	18.19	18.12	16.95
51X	17.42	18.02	17.77	18.21	18.63
52X	18.29	17.44	16.71	16.67	15.63
53X	16.73	17.98	16.88	17.23	16.04
54X	16.67	18.46	17.17	16.73	16.60
55X	17.71	17.19	17.19	17.71	18.75
56X	17.02	17.13	16.94	16.38	16.85
57X	17.25	17.81	18.00	16.60	15.73
58X	15.85	17.05	16.54	15.94	16.27
61X	17.02	17.23	16.71	14.68	17.77
62X	15.20	15.86	15.59	14.98	15.95
63X	15.57	16.21	15.80	15.77	14.55
64X	15.45	16.77	16.38	15.07	14.88
65X	15.48	15.18	15.57	15.16	14.82
66X	15.18	15.34	16.82	15.18	14.77
67X	14.86	15.80	15.66	15.07	14.73
68X	14.20	14.93	14.29	14.75	14.82

APPENDIX F

Computed Values Using the Maltenfort Equation:=

P = 5.8L + 12W - 2.1D + 350 + 6.5 (CLT-0).*

Code**	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
12X	473	478	483	486	489
13X	468	473	478	481	484
14X	463	468	473	476	479
15X	458	463	467	471	474
16X	453	458	463	466	469
17X	448	453	457	461	464
18X	439	444	449	452	455
Ave.	458	463	467	470	473
Overall Average = 466					
22X	490	495	500	504	507
23X	484	490	495	499	501
24X	479	484	489	493	496
25X	473	479	483	487	490
26X	467	423	478	481	485
27X	461	467	472	476	479
28X	451	457	462	466	469
Ave.	472	478	483	486	490
Overall Average = 482					
32X	506	513	518	522	526
33X	500	507	512	516	520
34X	494	500	505	510	513
35X	487	494	499	503	517
36X	481	487	493	497	500
37X	474	481	486	491	494
38X	463	470	475	479	483
Ave.	486	493	498	503	506
Overall Average = 497					

* All the given figures exclude the 6.5 (CLT-0) value.

** See Appendix B for code legend.

Code	L/W 1.00	L/W 1.25	L/W 1.50	L/W 1.75	L/W 2.00
41X	530	537	543	547	552
42X	523	530	536	540	544
43X	514	521	527	532	536
44X	509	516	522	527	530
45X	506	509	515	519	523
46X	495	502	508	512	516
47X	488	495	500	505	509
48X	475	482	488	493	497
Ave.	504	511	517	522	526
Overall Average = 516					
51X	556	564	571	576	580
52X	547	556	562	568	572
53X	539	548	554	560	564
54X	531	540	546	551	556
55X	523	532	538	544	548
56X	515	524	530	535	540
57X	507	515	522	527	532
58X	493	501	508	513	518
Ave.	527	535	541	547	551
Overall Average = 540					
61X	590	599	607	613	619
62X	580	590	598	604	609
63X	571	580	588	595	600
64X	562	571	579	585	590
65X	552	561	569	576	581
66X	543	552	560	566	572
67X	533	543	550	557	562
68X	517	526	534	541	546
Ave.	556	565	573	580	585
Overall Average = 572					