BASIC DESIGN DATA FOR THE USE OF FIBERBOARD IN SHIPPING CONTAINERS

Box Strength Calculator

Information Reviewed and Reaffirmed

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Box Strength Calculator

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Introduction

Billions of corrugated and solid fiberboard shipping containers were manufactured in the United States from the 10,885,000 tons of paperboard produced for packaging purposes in 1951. Some of these containers were made on the basis of unrealistic rule-of-thumb methods; others were made on the basis of technical data resulting from the many container-evaluation studies that have been made and the experience of industry. To extend further the use of fiberboard and yet prevent waste and loss and damage in storage and shipment of goods more studies on the fundamental principles of design are needed. Design criteria are needed so that fabrication of containers for specific uses can be based on the physical characteristics and strength properties of the paperboard sheets used in fabricating the box board. Because of these needs, an investigation of the basic properties of fiberboard and its component paperboard sheets was initiated at the Forest Products Laboratory.

1This paper reports research undertaken in cooperation with the Quartermaster Food and Container Institute for the Armed Forces and has been assigned No. 404 in the series of papers approved for publication. The views or conclusions contained in this report are those of the authors. They are not to be construed as necessarily reflecting the views or endorsement of the Department of Defense.

2Developed by V. C. Setterholm, Technologist.

3Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

4Fibre Containers, Vol. 37, No. 8, 1952.
The investigation has been in progress, in cooperation with the Quartermaster Food and Container Institute for the Armed Forces, and as a result some design criteria have been developed. (1,2)

Primarily, formulas were evolved in which the test values of either the ring-crush test or the strip-column test of paperboard sheets are used to predict the compressive strength of corrugated as well as solid fiberboard boxes. In addition, the criteria include means of determining the compressive strength of fiberboard boxes for various moisture content values of the fiberboard and of determining the load that a fiberboard box could be expected to sustain for specific periods of time in storage (2).

The relationships between box strength and the properties of the component paperboard sheets were established and the initial design criteria were developed first for A- and B-flute corrugated fiberboard boxes made from corrugated fiberboard fabricated on the Laboratory's corrugator; the criteria then were extended to include C-flute boxes. Next, the basic relationships and the basis for design criteria were established for solid fiberboard boxes.

To simplify the use of the formulas that were developed for predicting the compressive strength of boxes, for determining the compressive strength at various moisture content values of the fiberboard, and for determining safe stacking loads for boxes in storage, alignment charts were constructed of each of the relationships involved (1).

Further simplification of the design criteria resulted in the development of the Forest Products Laboratory Box Strength Calculator. The calculator combines the information contained in the several alignment charts and makes possible the solution of various design problems after simple manipulations of the calculator. The answers can be obtained in a few seconds.

This article discusses the relationships upon which the calculator is based and illustrates its use as a tool in the solution of design problems involving either corrugated or solid fiberboard boxes.

Tests and Procedures

Several forms of material and test methods were used in the development of design criteria (1, 2). Only the ring-crush test and strip-column test of the component paperboard sheets and the compression test of the finished fiberboard box will be discussed in this article, however.

5Underlined numbers in parentheses refer to Literature Cited at the end of this article.
Ring-crush Test

The ring-crush test consisted of testing 1/2- by 6-inch strips of paperboard formed into a ring in a metal specimen holder. The strips were supported on the inner surface by one of several removable islands, such that a column of paperboard 1/4 inch high extended above the holder; the selection of appropriate islands depended upon the thickness of the paperboard. The strips thus supported were crushed in a testing machine (3). The test yielded a single value, that of maximum load.

Specimens were so cut from the sample sheets that the crushing load could be applied parallel to either the "with-machine" or "across-machine" direction of the paperboard. Both liner boards and corrugating mediums used in the construction of the corrugated fiberboards were tested in this procedure.

Strip-column Test

The strip-column test was essentially used for tests of the components of the solid fiberboard. The test specimens were of the same size and cut by the specimen cutter used for preparation of the ring-crush test specimens. The strips were held straight between two clamp supports so as to provide a column 1/8 inch high. As in the ring-crush test, only a single value of maximum load was obtained when the column was crushed in a testing machine.

Compression Tests of Boxes

The compression tests of boxes were made in a universal testing machine that had a mechanism for making an autographic load-compression curve of each test.

Conditioning of Specimens Prior to Tests

The specimens for the ring-crush and strip-column tests were conditioned before test in an atmosphere maintained at 75° F., 64 percent relative humidity. The boxes were conditioned in several different atmospheres, so that the relationship of compressive strength of the box and moisture content of the fiberboard could be established.

Discussion of Results

One of the main objectives of the basic investigation of fiberboard was to develop a method of expressing the crushing strength of a fiberboard box, fabricated from either corrugated or solid fiberboard, using the test values from a simple test of the component paperboard sheets.
In the development of this method, the tube, which is primarily a box without top or bottom, was used as the intermediate link between tests of the components and of the box. Also, the tube represents the ultimate compressive strength that can be obtained from any given combination of component materials, and through its use the upper limits of compressive strength for a box could be established.

Development of a Design Formula for Corrugated Fiberboard Boxes

After evaluating the simple ring-crush test and the strip-column test by means of a more precise test, the modified ring-crush test (3), it appeared that the test values from either of the tests could be used in an appropriate formula for calculating the compressive strength of fiberboard tubes and boxes.

The Forest Products Laboratory has applied the thin-plate theory of mechanics to design of panels of plywood (4, 5, 6, 7). Since fiberboard and plywood are both nonisotropic materials, it was believed that the design information for plywood could be used as a guide in evolving a formula for fiberboard. Several tentative formulas were developed, and each in turn was modified for simplification. The several tentative formulas resulted in the following formula for calculating the top-to-bottom compressive strength of the finished fiberboard box with A-, B-, or C-flutes vertical in side walls:

\[ P = \left( \frac{a}{x^2} \right)^{1/3} \left( \frac{2}{x^2} \right) \]

in which

\[ P = \text{total compressive strength of box in pounds} \]

\[ P_x = \text{composite ring-crush load of built-up board (pounds per inch)} \]

\[ P_{rQ} = \text{single face} + P_{rQ} \text{ double back} + a x P_{rc} \]

\[ P_{rQ} = \text{ring-crush load in pounds per inch of a 1/2- by 6-inch strip of liner either in the with- or across-machine direction, dependent upon P} \]

\[ P_{rc} = \text{ring-crush load in pounds per inch of a 1/2- by 6-inch strip of corrugating medium in the across-machine direction} \]
\[ a = \text{ratio of length of corrugating medium when flat to its length when corrugated (A-flute = 1.523, B-flute = 1.361, C-flute = 1.477)} \]

\[ a^2 = \text{either 8.36, 5.00, or 6.10 for A-, B-, or C-flute, respectively} \]

\[ Z = \text{perimeter of box in inches} \]

\[ J = \text{box factor for the appropriate kind of fiberboard} \]

- A-flute = 0.59
- B-flute = 0.68
- C-flute = 0.68
- Solid = 0.70

To simplify the use of the formula, alinement charts were constructed for A-, B-, and C-flute boxes (1) as well as for boxes made of solid fiberboard.

**Development of a Design Formula for Solid Fiberboard Boxes**

The results of tests on solid fiberboard tubes and components indicated that the same method that was used for expressing the compressive strength of corrugated boxes could be used, with slight modification, for solid fiberboard boxes. Essentially, the modification consisted of including a factor representing the grain direction of the fiberboard in respect to the applied load and a box factor for solid fiberboard in the formula for \( P \), the total compressive strength, and using values from the strip-column test rather than the ring-crush test for determination of the \( P_x \) quantities.

As with corrugated boxes, an alinement chart was constructed to simplify the calculations of compressive strength of solid fiberboard boxes.

**Development of Duration-of-load Information for Fiberboard Boxes**

To determine the information deemed necessary for establishing the load limits for specific periods of storage, long-time loading tests were made of several kinds of corrugated boxes in several controlled atmospheres (2). From these tests the relationship between the compressive strength of a box and the amount of dead load, corresponding to the stacking loads in a warehouse, that a box could support for specific periods of time was established. For example, a dead load that approached the maximum compressive strength of a box caused failure usually within minutes, but dead loads that were equivalent to about 60 percent of the compressive strength of the box extended the time to about 30 days. The relationship between compressive strength and duration of load can be expressed by a curve that is based on the ratio of the dead load to the static compressive strength of the box. This relationship applies for all boxes, both corrugated and solid fiberboard, and for all moisture conditions of the fiberboard.

Rept. No. R1911-A

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Relation of Moisture Content of Fiberboard to Compressive Strength

In determining the relationship of duration of load and compressive strength of the box, several controlled atmospheres were employed. From this investigation, a relationship between moisture content of the fiberboard and compressive strength of the box was found (2). The relationship became apparent from curves for various lots of boxes in which the compressive strength of the box was plotted against moisture content. Examination of the curves showed that they all had about the same slope, and for practical purposes it appeared that a curve representing an average slope could be used to represent the relationship. Hence, if the compressive strength of a box at one moisture content is known, the compressive strength of the box can be interpreted at other moisture contents of the fiberboard.

A formula was derived for expressing the relationship between moisture content and box strength, and to simplify its use, an alinement chart was constructed (1).

Development of a Box Strength Calculator

In the basic investigation of fiberboard and its component parts, for each relationship that was established an alinement chart was constructed to facilitate its use. In the development of each relationship, however, it was found that all phases of the investigation were related. For example, after the relationship between the compressive strength of the component paperboard sheets and the compressive strength of the box was established, duration of load was found to be directly related to compressive strength. Both the duration of load and the compressive strength were in turn related to the moisture content of the fiberboard. Hence, it became apparent that if the several alinement charts could be consolidated a useful tool would result -- one that could be used by the laboratory technician in quality-control work, by the packaging engineer in design applications, and by the fiberboard box salesman, and that could be used for calculating the requirements of specifications for all fiberboard boxes.

As a result of the consolidation of the alinement charts, the tool was developed and was designated as a Box Strength Calculator. The calculator is shown in figure 1 and can be used for the following: (1) To calculate the top-to-bottom compressive strength of an A-, B-, or C-flute corrugated fiberboard box or a solid fiberboard box having a perimeter up to 400 inches; (2) to calculate the dead load that a box can be expected to sustain for a specific period of time in storage; (3) to interpret the compressive strength of a box at one moisture content of the fiberboard in terms of other moisture contents; and (4) to determine what strength properties are required of the component sheets in order to provide a box that meets specific use requirements.

The use of the calculator can best be explained by the solution of a hypothetical example.
Solution of a Problem with the Calculator

For purposes of illustrating the use of the calculator it is assumed that a regular slotted B-flute box 12 by 12 by 12 inches is desired for a specific container in which the gross load is to be 65 pounds. The commodity for which the box is intended is being manufactured during an off-season period, and it will be stored in a warehouse until the appropriate time to market it. The warehouse facilities are limited, and it is expected that the length of storage will be about 100 days. Boxes will be stacked five high during the period, and it is expected that the moisture content of the fiberboard during this period will approach but not exceed 14.0 percent.

The manufacturer desires to provide as good a box as will be needed to meet the requirements, but he knows that over-design is a waste of materials and wants to avoid this condition. He also knows the boxes will be handled several times before they reach the storage warehouse, and each handling will result in some reduction of compressive strength. For this reason, he is going to allow a safety factor of 20 percent.

The problem therefore is to select the proper combination of paperboard materials from which to make the board for the box. This selection can be made simply and in a matter of seconds by using the box strength calculator to determine the combined ring-crush strength of the components for the moisture content of 9.5 percent (laboratory test conditions).

The problem is solved as follows:

(1) Aline the hair-line of the indicator with 260 pounds (load on bottom box) on the outer scale (compressive strength of boxes).

(2) Orient 100 days of the duration scale (small top disk) with the hair-line of the indicator.

(3) With the small and large disks fixed in position, move the hair-line to 0 on the duration scale. With the indicator in this position, it may be seen from the outer scale that a box having a compressive strength of 480 pounds will be needed. This strength is needed at a moisture content of 14.0 percent if the box is to support 260 pounds for 100 days or less. It is desired, however, to know the corresponding compressive strength of the box at 9.5 percent moisture content (laboratory test conditions).

(4) With the hair-line indicator set at 480 pounds on the outer scale, aline the 14.0 percent figure of the moisture-adjustment scale with the hair-line indicator. Hold the smallest and largest disks in a fixed position and turn the indicator to coincide with 9.5 percent on the moisture adjustment scale. In this position 660+ pounds is read on the outer scale (compressive strength of box). Hence, the box desired has a compressive strength of 480 pounds in the warehouse conditions with an expected moisture content of 14.0 percent and 660+ pounds in the laboratory where 9.5 percent moisture content is expected.
Since a safety factor of 20 percent was allowed, the compressive strength required becomes 792 pounds.

The second portion of the problem is to determine the combined ring-crush strength of the components of the box and is accomplished by the following settings:

(5) With the indicator set at 792 pounds on the outer scale (compressive strength of box), arrange the board index of the second largest disk opposite of the B-flute index of the largest disk.

(6) Next, move the box-factor scale so that 0.68 is aligned with the hairline of the indicator.

(7) Move the box-perimeter scale until 48 inches on that scale coincides with perimeter index of the box-factor scale.

With the disks thus arranged, 43.5 pounds may be read at the component crushing-strength index of the middle disk.

Any combination of paperboard sheets that can be put together in a B-flute board to give a combined crushing strength value of 43.5 pounds will satisfy the requirements. Part of the solution to the problem is shown on the calculator of figure 1.

Further, similar manipulations of the calculator show that the 792-pound test box could be attained with a solid fiberboard box in which the load is perpendicular to the machine direction, a C-flute corrugated box, and an A-flute corrugated box. For these boxes the combined crush values would need to be 47.0, 38.0, and 35.0 pounds, respectively.

Assembly of Calculator

The disks of the calculator have been printed on heavy paper and included in this report following figure 1. From these disks and a hair-line indicator, a calculator can be assembled for use. Cut out the individual disks on the heavy black circle lines. Punch a hole of a size appropriate for a pivot pin through the center of each disk, which is marked with a cross. Assemble the disks in order of increasing size with the smallest disk on top and the largest disk on the bottom, as follows: Disk No. 1 (smallest disk)—moisture-adjustment scale and duration-of-load scale; disk No. 2—box-factor scale and box-perimeter index; disk No. 3—component crushing strength index and box-perimeter scale; disk No. 4—scale for combined crushing strength of components (values above line for solid fiberboard boxes; values below line for corrugated boxes) and board index; disk No. 5 (largest disk)—index settings for solid fiberboard boxes in which the applied load is parallel to the machine direction, solid fiberboard boxes in which the applied load is perpendicular to the machine direction, and B-flute, C-flute, and A-flute corrugated boxes, and the scale for compressive strength of boxes.
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Box factors for use in calculating top-to-bottom compressive strength of boxes

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<th>Flutes</th>
<th>Box factor 1</th>
<th>Grain direction factor 2</th>
<th>Box factor 1</th>
<th>Grain direction factor 2</th>
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<td>Parallel</td>
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<tr>
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<td>Perpendicular</td>
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<tr>
<td>C</td>
<td>0.68</td>
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1 Flutes parallel to direction of calculated load.
2 In relation to direction of calculated load.

Combined crushing values of components corresponding to Mullen and combined basis weight values of built-up board as specified in Consolidated Freight Classification, Rule 41

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<th>P. s. i.</th>
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<th>Lb. /in.</th>
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1 Not including corrugating medium.
2 Flutes parallel to direction of calculated load.
Figure 1.--The Box Strength Calculator consists of five circular disks with various scales and indexes and a hair-line indicator.

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