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EDGEWISE COMPRESSION STRENGTH OF CORRUGATED BOARD

R. C. McKee, J. W. Gander, and J. R. Wachuta

ABSTRACT

The edgewise compression strength of corrugated board is a dominant factor in the compression strength of a box. Criteria are suggested for an adequate test of this property of combined board. Evidence is given to show that the "regular" (rectangular shape) column crush test now employed in the industry is inadequate because it evaluates the weakened loading edges of the specimen rather than the intrinsic board strength. A necked-down column test is described which exhibits a favorable mode of specimen failure and yields estimates of board strength significantly higher than the regular column crush test, on the average, for A-flute board in the cross-machine direction. It is believed that the necked-down test provides a more accurate estimate of the edgewise compression strength of corrugated board than does the regular column crush test.

Introduction

Of the several performance requirements of corrugated boxes, none perhaps has occupied a more prominent position of continuing interest and attention within the box and board industry than has box compression strength. The reasons are twofold: first, box compression strength is related to warehouse stacking performance and, secondly, the laboratory test of box strength is a useful tool in the box plant for evaluation of the over-all quality of the fiberboard materials and the efficiency of the conversion processes.

The laboratory box compression test, however, is of limited utility for several reasons. Coming, as it does, at the end of a sequence of manufacturing and conversion operations, it is an after-the-fact type of evaluation. In production runs of boxes, a considerable quantity of boxes may be manufactured before it is known whether they meet the required strength specifications. Moreover, the trend to larger boxes for shipment of major appliances not only increases the cost of the test but in some instances may exceed the capacity of the testing equipment, so that the test cannot even be performed in some laboratories.

Probably the most serious limitation of the box compression test is that it is generally not capable of distinguishing between the several factors which contribute to box strength. In a case of inadequate box strength, for example, it may not be apparent whether the fault lies with the component liners or corrugating medium, or the manufacture of the corrugated board, or the conversion operations. Closely allied with this lack of sensitivity to individual factors is the obvious shortcoming that the box test is so remote in time (and oftentimes location) from the manufacture of paperboard and corrugated board as to be of only limited value in the operations of the mill and corrugating plant.

These limitations of the box compression test have led the industry to a path of research whereby the compression performance of a container may be predicted in terms of its several governing factors: (a) quality of the basic materials, (b) box dimensions, (c) corrugating and conversion variables, and (d) environmental conditions. Separation of box compression performance into its constituent factors places proper emphasis on the relative importance of material quality, fabrication, conversion and box design. This approach offers the prospect that paperboard materials may be tested and evaluated in terms of those properties which are of direct importance to the performance of the box.

Evaluation of material quality, of course, may be approached at several distinct levels. In terms of the materials with which each must work, the box plant is concerned with the quality of the corrugated board which it produced and used in the manufacture of boxes and desires appropriate combined board tests which will be meaningful to box performance. The corrugating plant is also concerned with the quality of liners and mediums, again in terms of those properties which ultimately will affect box strength. Indeed, it may be visualized how greatly the paperboard mill could benefit if it could project fiber and processing variables to those sheet properties which, in turn, are related to performance of the finished container.

A great deal of interest is centered currently on the test properties of <u>corrugated</u> <u>board</u> which are pertinent to box compression strength. For reasons discussed in a following section of this paper, the edgewise compression strength of corrugated board is a property of major interest. The term <u>edgewise</u> refers to the direction of the applied load, namely, parallel to the plane of the liners, as contrasted with flat-wise compression as in the flat-crush test. Industry attention given to this board property is reflected most recently in McKinlay's advocacy of the column crush test (1) and an unpublished account of a round-robin study of this test conducted under the auspices of ASTM (2). The current interest in this property of combined board may be attributed to the fact that (a) box compression strength is dependent to a large degree on this property, (b) edgewise compression strength reflects certain fabrication effects of corrugating as well as the strength of the basic materials and therefore is a realistic measure of the quality of corrugated board, and (c) from a research standpoint, study of combined board strength is a first step in a chain of relationships linking box compression performance to fiber and sheet properties.

The Institute of Paper Chemistry has been conducting a fundamental research program since 1944 on behalf of the Fourdrinier Kraft Board Institute. Although the membership of the latter association is primarily concerned with the production of kraft linerboard and corrugating mediums, the scope of its research program embraces a wide variety of problems ranging from the production of kraft linerboard and corrugating mediums to their eventual performance in the finished container. A vital segment of this research program has been concerned with the relationship between combined board properties and box performance. In the course of developing information on this relationship, a body of experience on edgewise compression testing of combined board has been acquired during the past several years. The Fourdrinier Kraft Board Institute has requested that this information be made available in the hope that it may be of value to this industry as a whole.

Importance of edgewise compression strength

The top-to-bottom compression behavior of the majority of conventional, vertical flute, corrugated boxes may be described as follows. As the applied load is progressively increased, a load level is eventually reached where the side and end panels of the box become unstable and deflect laterally. The beginning of bowing of the panels may or may not be markedly evident, depending on whether the panel is initially nearly flat or, on the other hand, is warped or bowed due to box manufacture and set-up. Having become unstable, the central region of each panel suffers an appreciable decrease in its ability to accept further increase in load.

Bowing of the panels, however, does not usually coincide with the maximum load-carrying capacity of the box. The combined board near the vertical edges of each panel is constrained to remain essentially flat because of the adjacent panels of the box and thus is capable of accepting substantially greater load (by reason of its stable configuration) than the most centrally located regions of the panel (3).

An idealized profile of the distribution of load intensity around the perimeter of the box is diagrammed in Fig. 1. The total load carried by the container is proportional to the area beneath the load distribution curve. Based on experimental work cited in Reference (3), this diagram shows a difference in load-carrying capacity between the edges and the center of each panel at the perimeter. The centermost portions of the panel have been observed to carry only one-half to two-thirds the intensity of load sustained at the edges at the time the box fails.

Experiment shows (3) that the box reaches its maximum load when the *combined board at or near* a corner of a panel ruptures. Thus, the top-load strength of a container resides in large part in the combined board near the vertical edges of the box panels in the sense that (a) the edges carry the greatest intensity of load, and (b) rupture of the board at this location triggers failure of the entire box (3). It is presumed that the material near the edges fails at a load intensity equal or related to the intrinsic compression strength of the corrugated board. It should be noted, however, that the centermost portions of the panel make a significant contribution to the total box load.

Exact analysis of the behavior of a box in compression poses difficult problems in view of the nonuniform distribution of perimeter load illustrated in Figure 1. Kellicutt and Landt (4) and investigators at The Institute of Paper Chemistry (5) have formulated equations for box strength using empirical approaches widely applied to plate-type structures in compression. The latter theory may be expressed in the following generalized form for boxes which are not of extremely short depth and therefore bow under compression load:

$$P = a\, P_m^{\,b} \left(\sqrt{D_x D_y}\right)^{1-b} Z^{2b-1} \qquad (1)$$

where P = total box load, lb.

P_m = edgewise compression strength of combined board, lb./in.

D_x = in-machine flexural stiffness of combined board, lb.-in.

D_y = cross-machine flexural stiffness of combined board, lb.-in.

Z = perimeter, in.

a, b = empirical constants

This equation has been found to apply to boxboard cartons as well as corrugated boxes, and is appropriate to double- and triple-wall boxes as well as singlewall corrugated boxes. Ranger (6) has approached the box compression problem from the standpoint of an empirical distribution of load intensity around the perimeter, thereby leading to total box load by summation of the area under the load profile curve.

Pertinent to the present considerations is the observation that, in addition to box dimensions, each of the above-mentioned theories relates box strength to a compression strength property of the corrugated board in the cross-machine direction (i.e., compression load applied parallel to the flutes). Kellicutt and Landt employ the summation of the ring compression strengths of the liners and corrugating medium. The Institute and Ranger use the results of tests on short columns of combined board as estimates of its edgewise compression strength.

It should be mentioned that the latter two theories also introduce the flexural stiffnesses of the combined board because it is related to the significant though lesser load-carrying capacity of the bowed combined board away from the edges of the panels. It would be hazardous to base estimates of top-load compression on solely edgewise compression strength unless it could be shown that there is a precise correlation between edgewise compression strength and flexural stiffnesses over a wide range of fabrication and conversion conditions.

Of these two types of combined board properties, however, the edgewise compression strength of the corrugated board is the dominant one because it is this type of failure which triggers box failure in top-load compression.

Criteria for adequate test of edgewise compression strength--In view of the importance of combined board compression strength to box compression performance, it is desirable to formulate a definition of this property of combined board beyond what may appear as obvious. In this regard, it should be recognized that any material property test represents only an estimate, to some degree of accuracy and precision, of an inherent material property. A comparison of various test methods can become sidetracked on unimportant details unless there is an accepted definition of the property which they are supposed to evaluate.

Considering the region of box panel at the vertical edges, the combined board that eventually fails appears to be of elemental dimensions. That is, it has no definite boundaries. Rather, it is an arbitrary element of board, constrained by its neighboring elements and the over-all panel configuration to remain reasonably plane until rupture, as illustrated in Fig. 2. The intent of a test method is to determine the load intensity at which this element ruptures or otherwise fails to support <u>additional</u> load. The internal mechanism of rupture is open to conjecture and is not necessarily of immediate concern because the primary objective is to find the dimensions and method of testing of a combined board specimen which will most nearly duplicate the load behavior of the combined board element as it exists at the edges of a box panel.

It seems reasonable that the width of the element of combined board (or of a proposed specimen) is not a critical dimension, provided the width is not so small that the specimen loses its identity as a corrugated structure. It would appear also that the height of the combined board element in the container is not a crucial dimension; height of a compression member is a critical factor when the member buckles or bends, but in the region of the box under consideration the board remains essentially flat. An element height of the same order of magnitude as the flute width would probably suffice to preserve the essentials of the corrugated construction. It appears, therefore, that the ultimate compression strength of corrugated board, as it is manifested at the vertical edges of a box, is dependent only on the material properties of its components and its cross-section configuration.

The above reasoning leads to the following definition of edgewise compression strength of combined board:

Under a given set of environmental conditions, *there is an intrinsic maximum strength* (load per unit width) *of corrugated board, stressed in uniform edgewise compression parallel to the flutes, which depends on material properties and cross-section configuration and is independent of height and width provided these dimensions are large enough to preserve the characteristics of corrugated construction.*

Stated otherwise, the definition asserts that the maximum intensity of load capable of being sustained by the unbowed combined board at the edges of a box is not a function of the over-all box dimensions, but depends only on the material and cross-section properties of the board. Material properties may be considered as including any effect attributable to the corrugating adhesive.

When a specimen of combined board is tested in edgewise compression *apart from the box structure* it relinquishes the constraining influence of the neighboring elements of board in the box panel. The dimensions of the specimen then assume a more significant role in its compression behavior than do the dimensions of an arbitrary element within the box structure. If for a given mode of testing the specimen height is sufficiently great relative to its thickness, the specimen will bend and buckle and thus behave quite differently from its counterpart in the box structure. In this event, the peak load on the specimen will be considerably lower than the intrinsic compression strength of combined board.

This behavior is illustrated in Fig. 3, which is a graph of column compression load *vs.* column height obtained from 200-lb. series, A-flute board (cross-direction). The curve is representative of the behavior of many materials in addition to corrugated board. In the range of heights between A and B, the maximum load that the column can support is highly dependent on the height of the column; decreasing height increases the load. Column load is not a material property (as is edgewise compression strength) but rather is a property of the structure, the latter involving height (and width) dimensions.

If the column height is progressively decreased to B of Figure 3, the column load will increase. A further reduction in height in the range B to C may be expected to lead to no appreciable change in column load. In this range of heights, the column load is no longer sensitive to height but rather is limited only by the edgewise compression strength of the material. According to the aforementioned definition edgewise compression strength is dependent only on the strengths of the components of the combined board and the cross-section configuration of the corrugated board.

The proposed definition of edgewise compression strength and the column curve of Figure 3 suggest one criterion for determining the dimensions and method of testing of a specimen. If a series of combined board panels of progressively diminishing heights are tested, a specimen size should be reached eventually where further reduction in size will cause no further increase in compression load. Thus, a constant maximum attainable load over a range of specimen heights may be expected to furnish one criterion for selecting suitable specimen dimensions and modes of testing.

Other criteria for an adequate test of edgewise compression strength may be: (a) a characteristic strain (unit deformation) associated with peak load for a given sample of material; (b) visible rupture of the specimen similar to the rupture of combined board in the box; (c) a favorable correlation between the strength of the specimen and box compression strength. The last criterion, however, must be employed judiciously inasmuch as other material factors such as flexural stiffness may confound the comparison. For example, two containers of a given size and fabricated from boards of equal edgewise compression strength may exhibit differing compression loads because the combined boards have differing flexural stiffnesses.

It should be recognized that at the present time there are no absolute standards against which to judge the adequacy of a proposed test of edgewise compression strength. That is, no single test method has been widely enough accepted that it may be used as a yardstick to assess the validity of other tests. As a practical working criterion for purposes of test development, one can probably proceed on the assumption that the most accurate test of edgewise compression strength is one that exhibits the highest test load as long as it can be agreed that the strength level was not artificially achieved by the test fixtures or accessories.

<u>The column crush test</u>--One prominent type of test for estimation of the edgewise compression strength of corrugated board (cross-machine direction) is the column crush test. As employed by Kellicutt (<u>7</u>), the specimen is one-inch high (parallel to the flutes) and six inches wide. The specimen is tested with the six-inch long edges abutted directly against the testing machine platens; that is, load is applied parallel to the flutes. McKinlay (<u>1</u>) describes a specimen one-inch high and four inches wide. Three quarters of the height is clamped by means of a specimen holder, leaving one quarter inch of free height between the holder and the testing machine platen. The maximum load sustained

by these types of specimens is reported on a unit width basis.

Experimental work at the Institute casts doubt on the validity of this type of test as an estimate of the intrinsic edgewise compression strength of combined board. In the first place, visible failure of the column crush specimen is generally in the nature of a rolling or crushing of one or both loading edges, with no apparent damage to the remainder of the specimen. An end view of a specimen before and after testing is shown in the photograph of Figure 4. Kellicutt (7) provides a side-view photograph showing a similar type of failure. These pictures show clearly a highly localized region at a loading edge where the specimen has suffered a large amount of crushing, while the remainder of the specimen is free of visible failure.

This characteristic mode of failure leaves considerable question as to whether the column crush test duplicates the compression behavior of combined board as it exists in a box. If the column crush specimen is intended to simulate the behavior of any of a great number of small elements of board existing throughout the unbowed portions of a box panel, then it is an anomalous behavior that the specimen evidences failure at its loaded boundaries. The boundaries of the specimen are introduced by the test method and do not exist in the box structure. Any predisposition, therefore, for the specimens to fail at a boundary may be attributed to the test method rather than to an inherent property of corrugated board.

The existence of an edge failure is attributable to the inherent weakness of a prepared edge. The edge is a disruption of the continuity of the fibrous network and may be expected to be weaker than the remainder of the network because the fibers at the edge do not have the reinforcement of adjacent fibers. Moreover, the operation of cutting or sawing of the specimen may have the effect of weakening the fibrous network for some small distance into the specimen. For these reasons, the edge fails at a stress level less than that which will rupture the combined board throughout the remainder of the specimen depth.

If cutting weakens the fibrous network at the specimen edges, it may be anticipated that various methods of performing the cutting operation may cause varying degrees of damage and consequently differing strengths of the test specimens. A number of combined board specimens were prepared by means of various cutting tools. A double-bladed knife, Figure 5, was constructed to cut the parallel loading edges simultaneously; the specimen height was 0.7 inch. Samples of size fifteen were prepared in several widths for 200- and 275-series combined board by means of the knife and also with a sharp power-driven saw. As shown in Table I, the average strength of the saw-cut specimens was always substantially higher than that of the knife-cut specimens. Per cent differences ranged from 10 to 17%, based on the loads from the sawed specimens; on the average, the knife-cut specimens tested 13% lower than the saw-cut specimens. It is believed that, although knife-cut loading edges appear cleaner and neater than saw-cut specimens, the pressure of the knife blade rolls over the cut edge slightly and hastens failure at the edge. (It may be noted from Table I that there was a trend to increasing peak load as the specimen width was increased. This trend may be attributed to restraint of the lateral expansion of the specimen in the vicinity of the testing machine platens--an effect which increases with width of the specimen).

Along similar lines, samples of size fifteen were prepared from 69-26-69 lb./1000 ft.^{2} combined board by means of both a sharp saw and another saw which was in visibly dulled condition. These two-by-two-inch specimens gave an average peak load of 47.8 lb./in. when prepared with the sharp saw

Table I

Comparison of Column Crush Loads from Knife-Cut and Saw-Cut Specimens

Series, lb.	Basis Weight, lb./1000 ft.^{2}	Column Width, in.	Maximum Compression Load, lb./in.[a] Saw-Cut	Knife-Cut	Diff., %[b]
200	42-33-42	1	41.8	37.6	-10
		2	45.7	39.6	-13
		6	45.8(8)	40.8	-11
275	69-33-69	1	54.9	45.3	-17
				Av.	-13

Notes:

[a] Average from fifteen specimens except where noted by numeral in parentheses.

[b] Arbitrarily based on saw-cut loads.

but only 44.5 lb./in. when prepared with the dull saw--a significant difference of 7% (at the 5% level of significance).

It appears from these experiments that the maximum load levels obtained from column crush specimens tested flat-ended against the machine platens is markedly influenced by the nature of the cutting process employed in preparing the specimen. The test level apparently reflects the edge preparation and perhaps only indirectly the intrinsic compression strength of the corrugated board.

In analogy with the tensile properties of paper and paperboard, one might anticipate that corrugated board would exhibit a characteristic ultimate strain (i.e., deformation per unit length) as well as an intrinsic strength (i.e., load) in edgewise compression. To investigate this supposition, two-inch wide specimens of 42-33-42 lb./1000 ft.^{2}, A-flute board were saw-cut to various heights ranging from one-eighth to six inches. The deformation rate (in./min.) for each height was adjusted so that all samples were strained at a uniform apparent strain rate, namely, 0.025 in./in./min. Table II presents the average peak loads (lb./in.) and ultimate strain (in./in.) for these several samples of size fifteen. Ultimate strain was computed by dividing the total deformation at peak load by the specimen height. Replicate tests were performed for the one quarter and two inch high samples.

The specimens which were taller than three inches bowed visibly during test and thus were outside the scope of interest for edgewise compression testing. With regard to the peak loads, it may be seen that the columns with heights between 0.25 and 3.0 inches exhibited strengths within a range of 2-1/2 lb.

Table II

Maximum Load and Ultimate Strain from Column Specimens of Various Heights (Saw-Cut, 2-Inches Wide, 0.025 in./in./min. Strain Rate)

Specimen Height, in.	Maximum Load, lb./in.[a]	Ultimate Strain, in./in.[a]
0.125	37.3	0.121
0.25	46.6	0.057
0.25[b]	46.4	0.057
0.50	47.5	0.034
0.70	47.9	0.025
1.00	48.4	0.020
2.00	48.8	0.012
2.00[b]	48.9	0.012
3.00	48.7	0.011
3.50	43.6	0.008
4.00	44.4	0.007
6.00	36.2	0.005

[a] Average of fifteen specimens.

[b] Replication of preceding test conditions.

Except for the slight downward trend with decreasing height, the near constant loads over this range of heights is compatible with the concepts of column behavior discussed in a previous section. As the height of a column was decreased from six inches, a height was reached (namely, about three inches for these A-flute specimens) where there was no appreciable change in column load as the height was farther decreased--that is, the column load was limited only by the compression strength of the material.

The shortest column tested--one-eighth inch high--gave an extremely low load, namely, 37.3 lb./in. An explanation for this small load is not readily apparent, other than the possibility that for this short height imperfections in specimen preparation (such as unavoidable bevel and taper) become relatively more important than at the greater heights. Except for the one-eighth inch tall column, however, these samples exhibited the characteristic behavior expected of short columnseven though the maximum load was probably not the true edgewise compression strength of the combined board.

The average ultimate strains, on the other hand, varied widely, increasing from 0.011 to 0.121 over the range of column heights where no bowing occurred. The strain data are plotted in Figure 6, revealing the inverse relationship between apparent ultimate strain and column height. Thus, there was no single characteristic ultimate strain corresponding to the ultimate load for these specimens.

The strain behavior of these specimens may be explained in terms of the failure of the loading edge of the specimen. Assuming that preparation of the specimen weakens the fibrous network at and near the loading edges of the specimen, this region of the specimen may be expected to suffer a greater compressive unit strain than the combined board in the remainder of the specimen.

Inasmuch as the weakened region at the edgesis probably of constant depth for all heights of the specimen (depending only on the methods of cutting), its relative contribution to total deformation and to over-all unit strain would be greater for the shorter specimens than for the taller specimens. Thus, the large unit strains exhibited by the shorter specimens may be attributed to the existence of a large deformation at an edge due to preparation of the specimen.

In summary, it is doubtful that the column crush test reveals the intrinsic edgewise compression strength of corrugated board for three reasons: (a) failure of the specimen is localized at a prepared boundary of the specimen and therefore does not resemble rupture of the combined board in box compression; (b) the load levels are influenced by the methods employed in cutting the loading edges and therefore probably are indicative of the strength of the prepared edges rather than of the corrugated board throughout the remaining depth of the specimen; and (c) there is no characteristic ultimate strain corresponding to peak load on the specimen (such as in tension), reflecting the existence of large crushing deformations localized at the prepared edges of the specimen. In brief, it is believed that the column crush load is limited by the low strength of the prepared loading edges of the specimen.

Development of the necked-down column test--Studies were undertaken to develop a test method for evaluating the edgewise compression strength of corrugated board which would not suffer from the shortcoming of edge failure of the specimen. The investigation involved finding a way of retarding failure of the loading edges until the ultimate strength of the combined board elsewhere in the specimen could be attained. Possible approaches to this objective are: (a) strengthen the edges by some external means, and (b) reduce the stress intensity at the edges relative to the remainder of the specimen so that failure of the latter is reached before the edges fail.

Clamping the loading edges of the specimen or embedding them in some stiffer material probably involve both of the above-named approaches to retarding edge failure. Shaping the specimen so that there is more cross-section area at the edges than elsewhere throughout the specimen is an example of the second approach. A few preliminary trials involving clamped and shaped specimens suggested that the latter offered promise as an improved column test of corrugated board.

A shaped specimen which has been found to be satisfactory for column testing of A-flute board in the cross-machine direction is illustrated in Figure 7. The hourglass shape of the specimen will be referred to as <u>necked-down</u>, inasmuch as the width of the specimen progressively diminishes from about four inches at the loading edges to about one-and-a-half inches (4-1/2 flutes) at midheight. These widths are in the ratio of approximately 0.37, which means that the average load per unit width at the loading edge is only 37% of the load intensity at mid-height. This difference in load intensity is sufficiently great that the corrugated board at or near the cross section of minimum width reaches its failure stress before the crushing strength of the weak loading edges is exceeded.

The curved boundaries of the necked-down region of the specimen are semicircular and are cut with a five square inch, hand-operated, flat-crush cutter such as is available in most box plant laboratories. Equipment used in cutting the circular boundaries is shown in Figure 8. The plywood jig holds the specimen blank and locates the flat-crush cutter so that two circular cut-outs can be made. Various stages in the preparation of the specimen are diagrammed in Figure 9, where the dashed line indicates the final shape of the specimen. After the circular cuts are made the specimen is sawed to its finished shape.

The section of minimum width is prepared to include exactly 4-1/2 flute widths and their ten glue lines as illustrated in Figure 10. The plywood holding jig is dimensioned so that the minimum width will comprise exactly 4-1/2 flutes, provided the edges of the specimen blank (Figure 9a) are cut along flute glue lines. As individual operator's technique or variation in the flute-width dimension between box plants or variation in the diameter of the housing of the flat-crush cutter may necessitate some adjustment of this dimension of the holding jig. Choice of 4-1/2 flutes as the width at mid-height is somewhat arbitrary. At this cross section the fluted medium starts on one liner and ends on the other liner; it is believed that this type of symmetry may be desirable for combined board constructions having unbalanced liners. Test experience has not yet been exhaustive enough to reveal whether or not there is a significant difference between specimens with the fluted medium bonded at each end of the minimum cross section vs. a random distribution of flutes at mid-height. It is nearly as easy to cut the specimen to an exact number of flute widths, however, and it has the merit that an essential feature of corrugated construction is preserved.

The specimen is tested with the four-inch long edges abutted directly against the platens of a testing machine. Shallow metal strips affixed to the upper and lower platens on one side of the specimen are helpful and desirable in achieving initial alignment of the specimen. The specimen is tested to failure and the result is reported as maximum load divided by the minimum width of the specimen. Because of the varying width of the specimen, the unit strain varies along the height, being minimum near the loading edges and reaching a maximum at mid-height. Thus, ultimate strain cannot be computed by dividing the platen movement by the height of the specimen. Determination of strain requires special instrumentation which is capable of measuring the deformation over a short gage length at mid-height. This is not considered to be a serious shortcoming of the test at this time inasmuch as current theories of box compression performance are oriented almost solely to load rather than strain.

Table III presents a number of comparisons of the necked-down column test and a form of the column crush test which have been obtained over a period of several years with several grades of A-flute combined board. The necked-down specimens were of the shape illustrated in Figure 7, except that in some instances the section of minimum width was comprised of exactly five flutes rather than four and one-half. The column crush specimens were two inches high and six flutes wide. In each comparison the necked-down and column crush samples were prepared consecutively with the same saw by the same operator. Each sample contained fifteen specimens.

It may be seen in Table III that in every instance the necked-down columns sustained a greater average load than did the column crush specimens. The differences ranged from 6.3 to 25.8%, based on the necked-down column load; the composite average difference was 19.6%. Each difference shown in Table III was statistically significant at the 5% level or beyond. Clearly, no artificial strengthening of the corrugated board has been introduced by the necked-down test method.

Both the necked-down and column crush specimens exhibited no perceptible bowing during test. With but a very few exceptions, each of the column crush specimens failed along a loading edge, which is typical as discussed earlier. In all instances the necked-down columns ruptured at a location remote from the loading edges, usually at or near mid-height where the width of the specimen is least. Usually the rupture was within a zone of ± 3/4-inch

Table III

Comparison of Necked-down Column and Column Crush Test Results

Sample	Series, lb.	Basis Weight, lb./1000 ft.^{2}	Trial	Compression Load, lb./in. Necked-down	Compression Load, lb./in. Column Crush	Diff., %
1	200	42-26-42	1	41.5	35.9	-13.5
2	200	42-26-42	1	46.8	42.7	- 8.8
3	200	42-26-42	1	49.7	37.7	-24.1
			2	52.8	39.2	-25.8
			3	51.9	39.8	-23.3
4	200	42-33-42	1	52.7	49.4	- 6.3
5	275	69-26-69	1	60.8	47.6	-21.7
6	275	69-26-69	1	69.2	57.7	-16.6
7	275	69-26-69	1	65.0	51.1	-21.4
			2	71.8	59.3	-24.4
			3	72.2	54.2	-24.9
8	275	69-33-69	1	73.3	55.0	-25.0
9	350	90-26-90	1	69.7	57.9	-16.9
			2	82.2	61.9	-24.7
			3	77.0	63.9	-17.0
					Av.	-19.6

of mid-height. Over the depth of this zone the width of the specimen exceeds the minimum width by only a moderate amount; local weaknesses of the board may initiate rupture at a cross section even though it is not the absolute minimum width in the specimen.

The observations that the necked-down columns sustained the higher loads and failed remote from the loading edges indicate that these columns more nearly attained the intrinsic strength of the corrugated board than did the column crush specimens. In this sense, the necked-down column test may be regarded as a more accurate test of edgewise compression strength than is the column crush test.

There has not yet been an opportunity for a comprehensive comparison of the reproducibility of the necked-down and column crush tests. It may be seen in the data of Table III that replicate trials on 200-, 275- and 350-lb. boards showed rather large differences between trials for either type of test. It is believed, however, that these differences are not representative of either type of test inasmuch as during the sampling (which extended over several months), no attempt was made to "average out" variability in the material between trials. The data strongly suggest that the material tested in the second and third trials was actually stronger than in the first trial.

It is hoped that this laboratory and others will find it possible to compare these column test methods over a wider range of materials, both with regard to the load levels exhibited by the two tests and their variability. It should be recognized that the test data of Table III reflect a limited number of samples and therefore at this time cannot be claimed to be representative of commercial boards in general.

Based on the limited data of Table III, there appears to be a fair linear correlation between the necked-down column strength and the column crush strength. A scatter diagram is given in Figure 11. The correlation coefficient is 0.936. The line of best fit, as determined by the method of least squares, is

$$\underline{y} = -1.51 + 1.282\,\underline{x} \qquad (2)$$

where $\underline{y}$ = necked-down column strength, lb./in.

$\underline{x}$ = column crush strength, lb./in.

In view of the modestly small additive constant in Equation (2), namely, -1.51 lb./in., it may be noted that, in terms of the line of best fit, the necked-down column strength is about 28% greater than the column crush strength over the range of board combinations studied. Conversely, the column crush strength is (1/1.28) x 100= 78% of the necked-down column strength (that is, 22% lower), which agrees favorably with the average per cent difference shown in Table III.

That there may be a linear correlation between the two types of tests is perhaps explainable in that even though the column crush test appears to evaluate the strength of the weakened loading edges, the strength of these edges may reflect the intrinsic edgewise compression strength of the corrugated board. For these samples the loading edges apparently retained about 78% of the intrinsic board strength. The constant of proportionality between the two tests, however, may be quite variable between laboratories in view of the demonstrated sensitivity of the column crush test to the type and sharpness of the cutting tools used in preparing the specimen.

Although the necked-down column test is believed to give a superior estimate of the intrinsic board strength, there is nonetheless a possibility that the column crush test may be useful as a quality control test, provided a satisfactory correlation with a more accurate test can be established, and a reproducible cutting procedure and test jig can be devised. For purposes of quality control, it is of course necessary that the precision of the correlation be sufficiently good within a much narrower range of board strengths (say within a single series) than is included in Table III or Figure 11.

It may be of interest to mention that three necked-down configurations other than that illustrated in Figure 7 have been tried with A-flute combined board. These were prepared with a ten-square-inch flat-crush cutter (1.78-inch radius) and were shaped with various widths and heights and circular boundaries less than a semicircle in extent. These alternate shapes offered no improvement over the one diagrammed in Figure 7. It was noted, however, that when the width of the loading edge was decreased so that the minimum width cross section was about 70% of the width of the loading edge, edge failures occasionally occurred. This observation suggests that the loading edge should be at least 1.4 times wider than the minimum cross section to ensure failure of the corrugated board remote from the loading edges.

Exploratory trials indicate that B- and C-flute necked-down specimens of the size illustrated in Figure 7 may bow during test because of their lower caliper and hence lower bending stiffness. It is likely that use of a three-square inch flat-crush cutter (approximately one-inch radius) would suffice for these flute sizes inasmuch as the over-all specimen height would then be reduced from 3 to 2-1/2 inches. Alternatively, the specimen may be shaped so that the circular boundary is less than a semicircle in extent with a consequent decrease in over-all specimen height and therefore less tendency to bow. It must be kept in mind, however, that a favorably large ratio of the width of the loading edge and of the minimum cross section must be maintained in order to achieve the basic attribute of the necked-down specimen. The variations in specimen configuration described above also may be useful in accommodating the necked-down column test to testing machines where the distance between platens is small.

Finally, it should be remarked that very favorable column test results have been obtained with two-by-two inch specimens which have the loading edges dipped to a quarter-inch depth in a hot-melt paraffin wax or sodium silicate. After the dip solution hardened on the loading edges and thereby strengthened the edges, these specimens exhibited test loads as high as the necked-down specimen. The preparation time is about the same as with the necked-down specimen--the saving in cutting time being offset by the time required for dipping. Further investigation of this approach to the evaluation of edgewise compression strength is now going forward.

Summary

1. The dominant material factor governing the top-load compression strength of vertical flute boxes is the edgewise compression strength of the combined board in the cross-machine direction.

2. It is believed that the true edgewise compression strength of corrugated board is dependent on the material properties of its components and its cross-section configuration, and is independent of height and width provided these dimensions are large enough to preserve the characteristic features of corrugated construction.

3. Suggested criteria for an adequate test for edgewise compression strength are: (a) highest attainable load level, not artificially achieved; (b) a characteristic ultimate strain (analogous to stretch in tension); (c) rupture resembling failure of the combined board in the box; (d) absence of bending; and (e) favorable correlation with box compression strength.

4. It is doubtful that the column crush test currently advocated in the industry actually reveals the intrinsic compression strength of corrugated board, because the test apparently evaluates the strength of the loading edges which have been weakened by preparation of the specimen.

5. An edgewise compression test has been developed for A-flute corrugated board (cross-direction) which employs a specimen whose width at mid-height is less than the width at the loading edges. The necked-down shape prevents failure of the loading edges and permits the combined board near mid-height of the specimen to reach its maximum strength in the test.

6. In fifteen comparisons involving various grades of combined board it was found that the column crush strength was about 20% lower than the necked-down column strength, on the average.

7. In view of the favorable mode of specimen rupture and the higher column loads, it appears that the necked-down test specimen offers a more accurate estimate of the intrinsic edgewise compression strength of corrugated board than does a "regular" column crush test.

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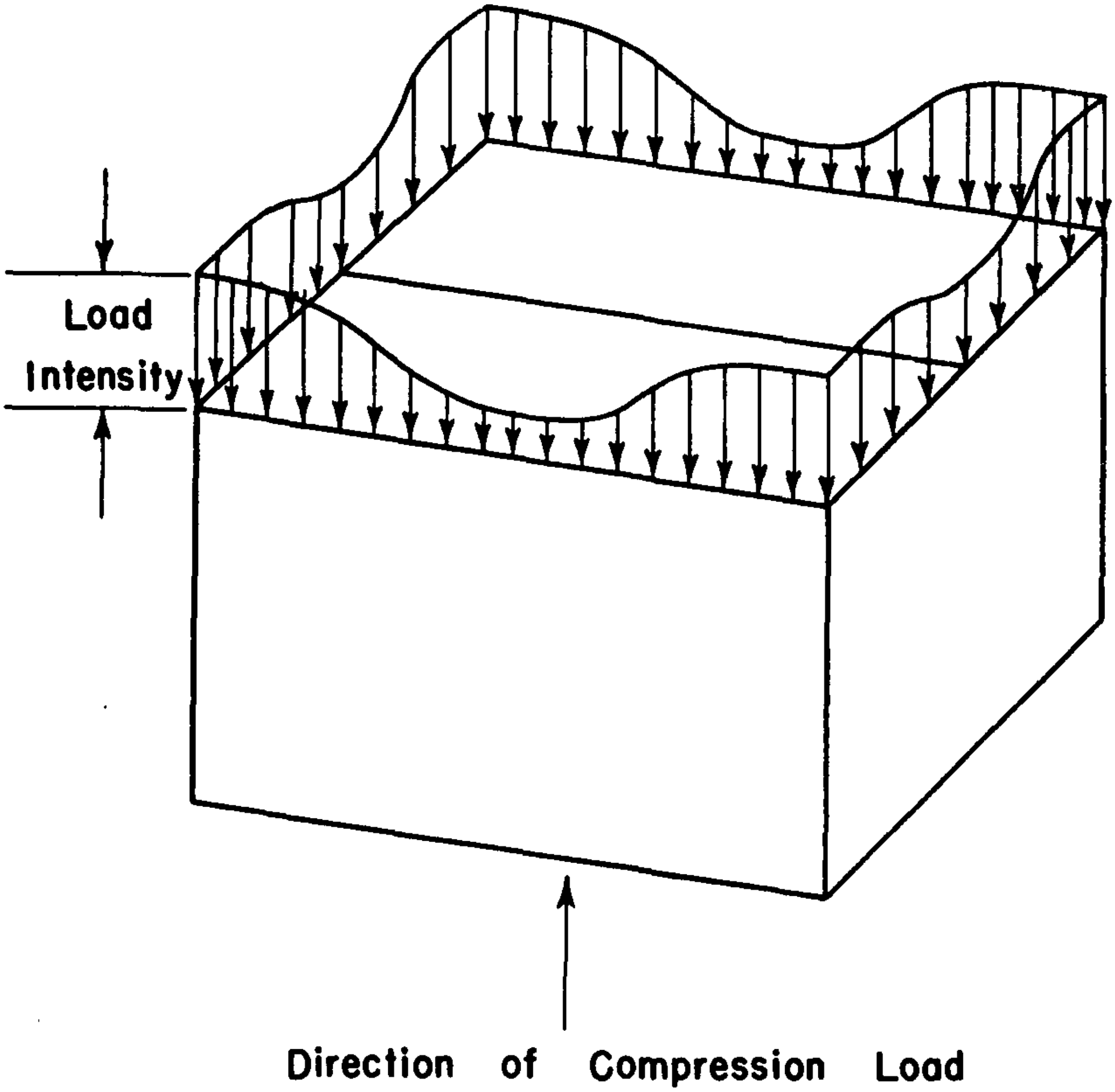


Figure 1. Distribution of Compression Load Around the Perimeter of a Box

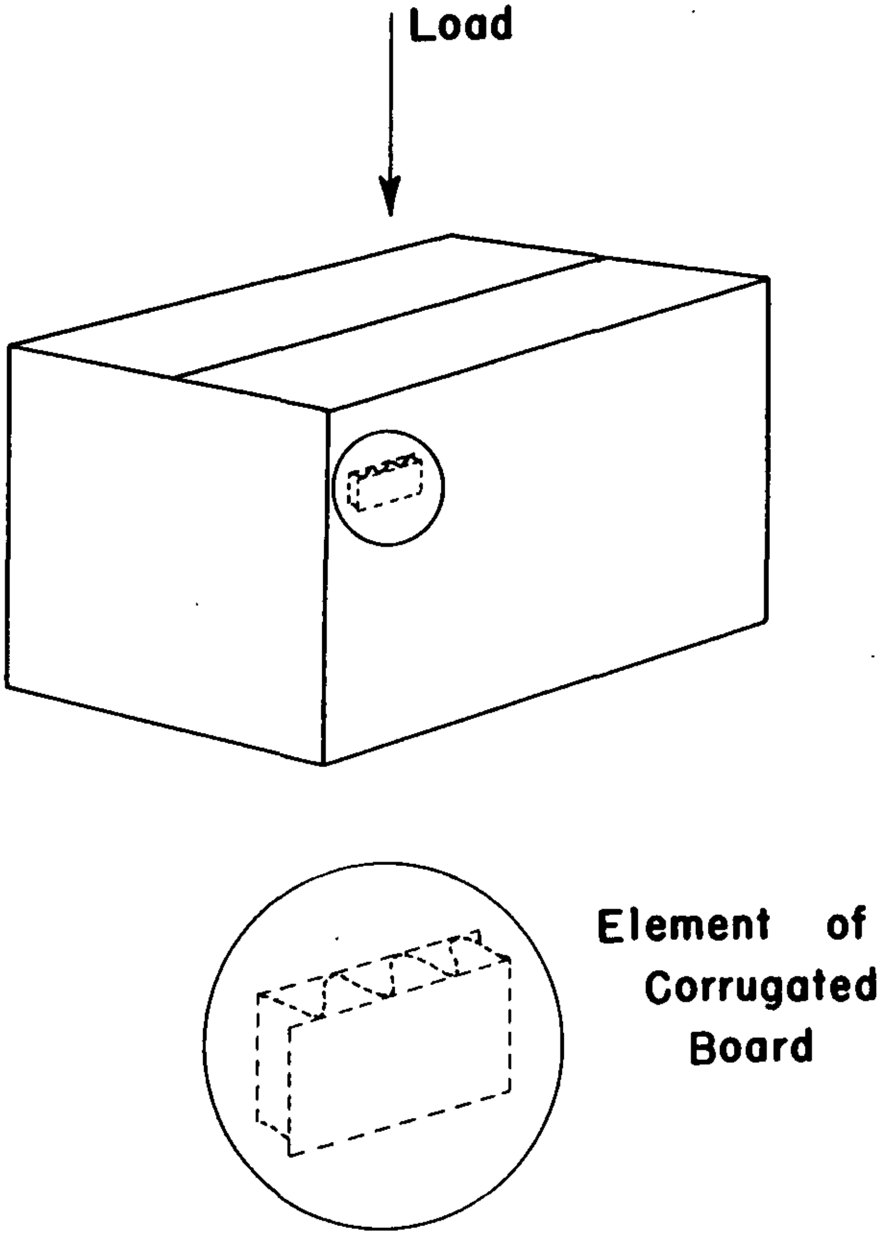


Figure 2. Element of Corrugated Board Subjected to Edgewise Compression Stress in Box Panel

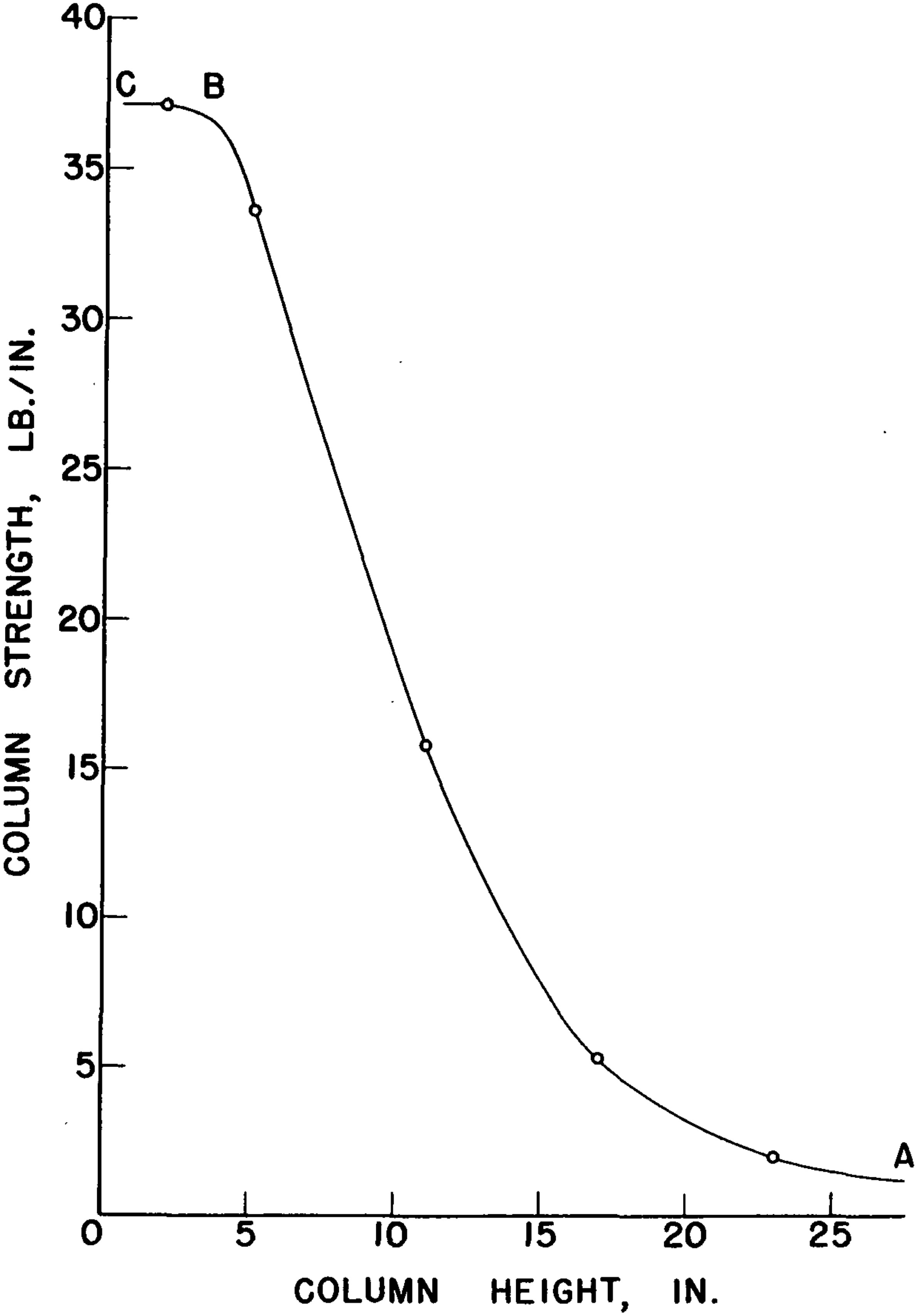


Figure 3. Experimental Column Curve of Three-Inch Wide Columns of 200-Series A-Flute Corrugated Board Tested Flat-Ended in the Cross-Machine Direction

PHOTOGRAPH

(Similar to Figure 7 of

Compression Report 64)

Figure 4. Nature on Failure in a Column Crush Specimen

PHOTOGRAPH

(Same as Figure 1 of
Compression Report 64)

Figure 5. Double-Blade Knife for Cutting 0.7-inch High Column Crush Specimens

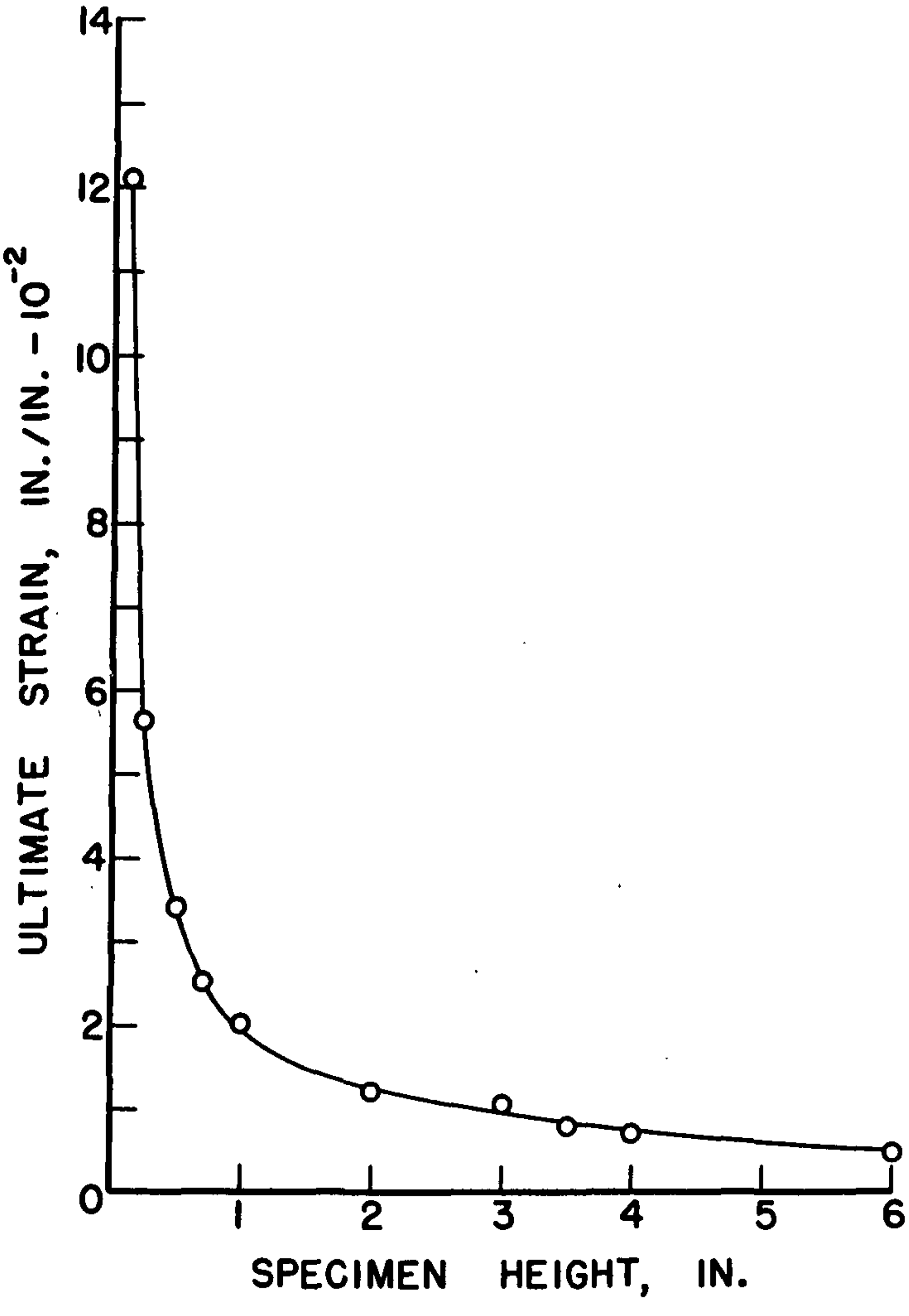


Figure 6. Apparent Ultimate Strain of Column Crush Specimens as a Function of Column Height

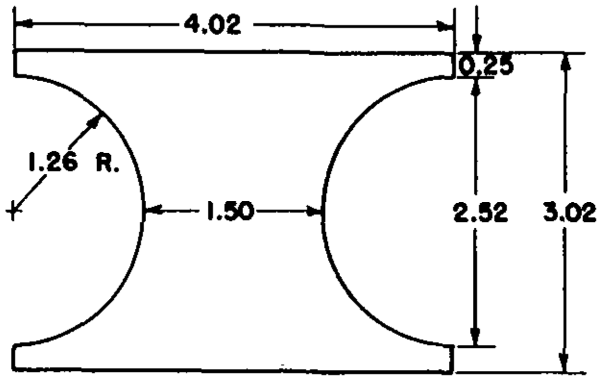


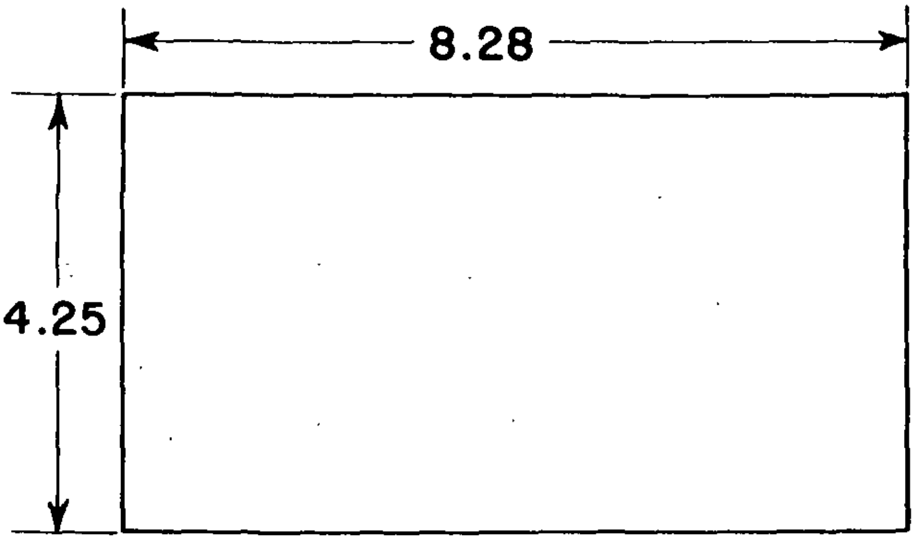
Figure 7. Configuration of Necked-Down Column Specimen for Cross-Machine Direction of A-Flute Combined Board

PHOTOGRAPH

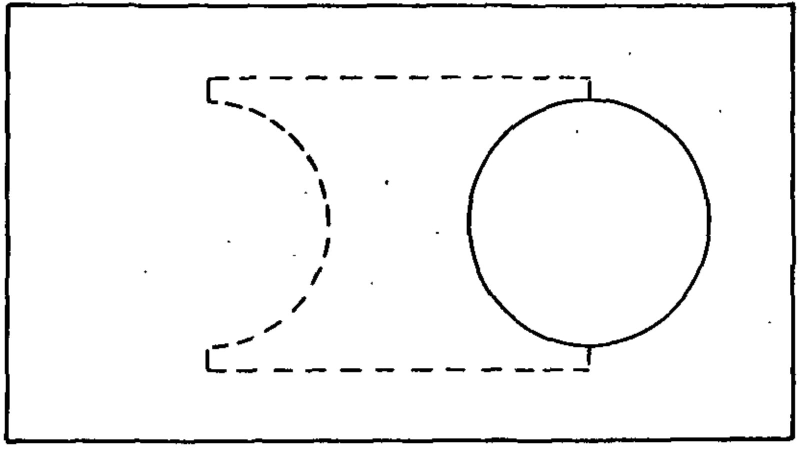
(Same as Figure 3

of Compression Report 73)

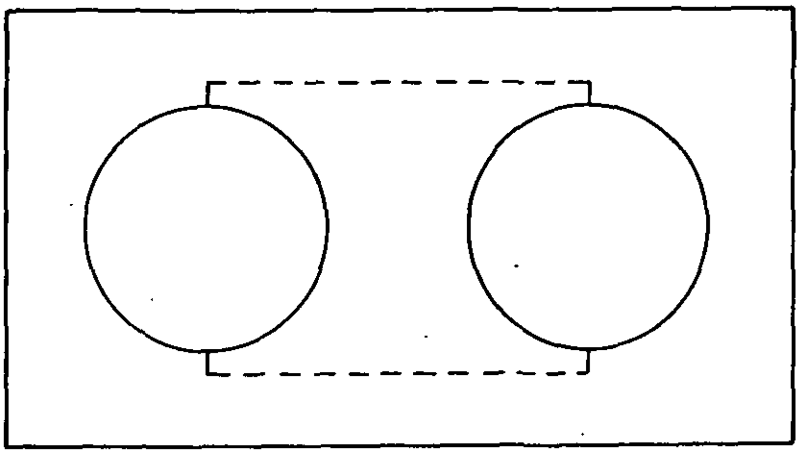
Figure 8. Equipment Employed to Prepare Circular Boundaries of the Necked-Down Column Specimen



(a) Specimen blank



(b) Cutting of right-hand fillet



(c) Cutting of left-hand fillet

Figure 6. Stages in Preparation of Necked-Down Column Specimen

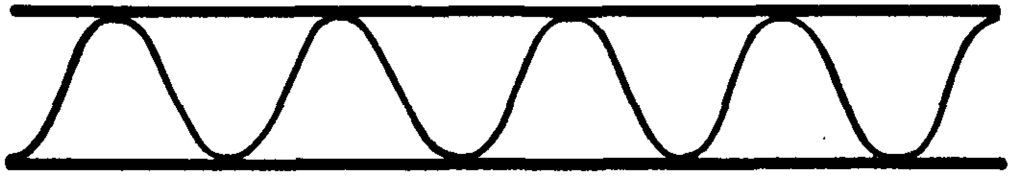


Figure 10. Cross Section of Minimum Width of Necked-Down Column Specimen

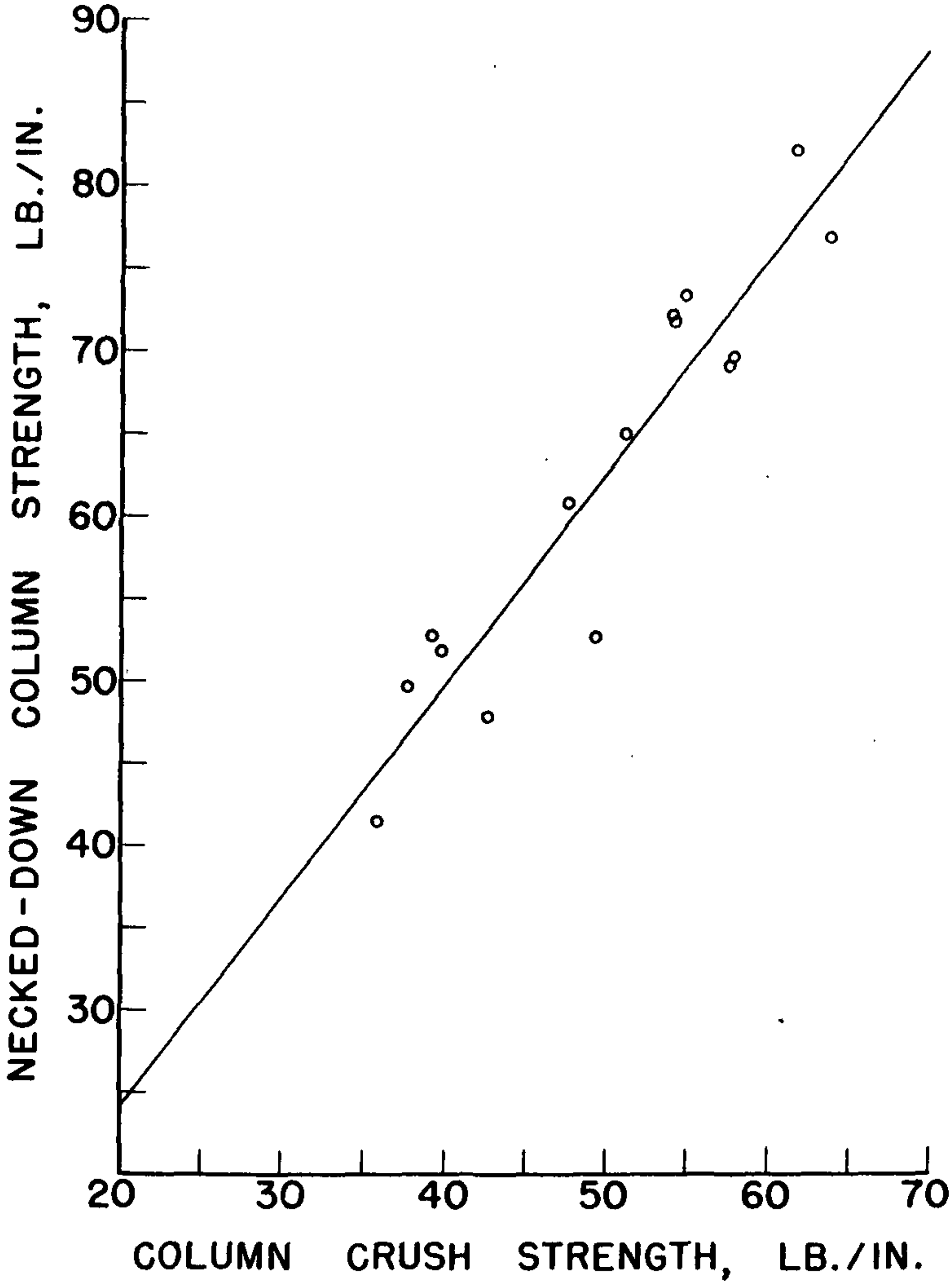


Figure 11. Correlation Between Necked-Down Column Strength and Column Crush Strength