THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

EFFECT OF FINGERLINES ON CROSS-DIRECTION EDGEWISE COMPRESSION STRENGTH OF COMBINED BOARD

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SUMMARY

The cross-direction edgewise compression strength of combined board, which is the dominant factor in top-load box compression, can be expected to depend upon fabrication variables as well as component strength and flute geometry. Among the fabrication factors of possible consequence are adhesion, fractured flutes, high-lows, fingerlines, and pressure, temperature, and moisture during corrugating.

An exploratory study was undertaken to determine the effect of fingerlines on edgewise compression strength. The following conclusions may be drawn from the work:

1. Inspection of 546 boxes following the top-load compression test revealed that about 7% definitely failed at a fingerline and about 30% definitely did not fail at a fingerline. The latter figure indicates that in about 70% of the boxes, failure either started at a fingerline or eventually found its way to a fingerline. This result suggests that, as expected, the fingerline may be a zone of weakness in edgewise compression.

2. Evaluation of edgewise compression on areas of combined board with and without fingerlines from 22 samples of commercially-manufactured combined board revealed that, on the average, the edgewise compression strength in areas of the board having fingerlines was 3.5% lower than without fingerlines.

3. There is considerable variation in the apparent effect of fingerlines on edgewise compression. This probably shows that the influence of

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fingerlines is a matter of the degree of adhesion at the fingerline, which in turn varies between samples of combined board. Further studies are proposed to identify more positively the importance of fingerlines in edgewise compression and box compression.

INTRODUCTION

The cross-direction edgewise compression strength, P_m, is the most important property of combined board relative to top-to-bottom compression strength of a corrugated container (1). To a first approximation, P_m is the sum of the strengths of its three components – two liners and corrugating medium (accounting for draw) – although closer investigation reveals an effect of flute size and shape (2).

The aforementioned dependence on component strength and flute geometry is an idealization. It presumes that the three components are perfectly bonded together into a structural entity (namely, combined board) and furthermore that the strengths of the components are the same as evaluated from the roll. In reality the situation may be far different. Adhesion may be spotty or at a low level allowing the liners to buckle away from the flutes. In extreme cases flutes may be fractured during corrugating, whereupon the contribution of the medium to P_m would be less than anticipated from evaluation of the parent roll. "High-lows" may result in inadequate adhesion at alternate flute tips on the double-face side. Lack of adhesive at the fingerlines possibly may cause a weak zone on the single face side of the board. In addition to these observable defects in combined board, it seems likely that the extremes of pressure, temperature, and moisture during corrugating may alter the strength of the liners and medium as evaluated from the parent rolls.

Thus, it seems evident that fabrication effects should be considered along with component strength and geometry as a factor governing the edgewise compression strength of corrugated board.

To help clarify the relative importance of one of these fabrication factors, an exploratory study was performed relative to the effect of fingerlines. Fingerlines are marks left on the corrugating medium by the grooves in the top corrugating roll. These grooves accommodate the tips of the metal fingers which hold the fluted medium in mesh with the lower corrugating roll. They occur at two to four-inch intervals across the web of board, depending on the design of the corrugator.

The presence of fingerlines is manifested in two ways. First, as a result of the grooves in the upper corrugating roll, there is usually a local increase in thickness of the fluted medium because this zone is not under the high pressure to which the remainder of the medium is subjected in the labyrinth. For this reason there will be a change in cross section of the medium at the fingerline and moreover, it can be anticipated that the strength of the medium at the fingerline may differ from the remainder of the medium, although the net effect on edgewise compression can only be speculated at this time.

Second, and probably more important, there may be a lack of adhesion at the fingerline. This arises because the adhesive transfer roll is also slotted to accommodate the fingers and adhesive is not applied directly to the flute tips at the fingerline. By careful adjustment of the adhesive applicator, finger design, etc., it is possible to cause a flow of adhesive into the fingerline area from the sides of the fingers. In general, however, the fingerline is a zone of reduced, or absence of, adhesive and it is not uncommon to find combined board with complete lack of adhesion over the approximately 1/8-inch width of the fingerline.

The fingerline runs perpendicular to the direction of the applied load in top-to-bottom box compression or in the cross-direction edgewise compression test of corrugated board. Compression load must "pass" through this zone in both the liner and the medium. It seems likely that the aforementioned change in cross section of the medium may give rise to stress concentrations at the fingerlines, thereby making this point of the medium the most highly stressed and in effect the weakest point in the medium. Moreover, in cases of poor adhesion due to fingerlines, the liner and medium are not attached to each other and do not offer support to each other. It may be visualized that in the case of lightweight liners, the unsupported height of liner at the fingerline may be sufficiently great, relative to the liner thickness, to permit buckling of the liner away from the flute and consequent failure. In this event, the structural principles favoring corrugated board are not operative and a sacrifice of strength may be incurred.

An exploratory study was performed to determine whether fingerlines per se have a discernible effect on box compression and on the edgewise compression strength of combined board. Recommendations are given for further work to clarify this matter.

EFFECT OF FINGERLINES ON LOCATION OF BOX COMPRESSION FAILURE

During the test program on commercially manufactured boxes which led to development of the simplified box compression formula (1), a large number of box specimens were inspected following the top-load compression tests to determine the location of failure relative to fingerlines in the combined board. Each box specimen was dissected at the location of compression failure on each vertical edge and it was noted whether or not the failure line coincided with a fingerline in the combined board. It may be recalled that box compression failure typically initiates at one or more vertical edges and then progresses into the side panels.

In the interest of gaining an over-all picture of the coincidence of failure and fingerlines, the composite data from the inspection are presented in Table I. For example, of 173 A-flute boxes inspected, six boxes failed at a fingerline at all four vertical edges of the box. In these instances it is certain that failure initiated at a fingerline of the combined board. As shown in the table, 12 of the A-flute boxes failed on a fingerline at three vertical edges; however, at the fourth vertical edge of each of these 12 boxes, failure did not coincide with a fingerline. Inasmuch as the inspection was made after the compression test and the vertical edge at which failure started was not known, it is inconclusive for these 12 boxes whether or not compression failure originated at a fingerline. However, the fact that failure at least eventually involved a fingerline at three out of four edges indicates that fingerlines may indeed have been a zone of weakness of the combined board.

TABLE I

COINCIDENCE OF FAILURE LINE AND FINGERLINE IN BOX COMPRESSION

	No. of Boxes with Fingerline Failure at					
Flute	4 edges	3 edges	2 edges	1 edge	No edge	Total
A	6	12	48	54	53	173
C	18	24	56	65	94	257
B	12	26	38	30	10	116
Total	36	62	142	149	157	546
Per cent of total boxes	6.6	11.3	26.0	27.3	28.8	100.0

It may be seen in Table I that in 53 of the 173 A-flute boxes, the compression failure did not coincide with a fingerline at any vertical edge. It may be definitely stated for these boxes that failure did not originate at a fingerline.

The relative frequency of fingerline failures with B- and C-flute boxes is similar to A-flute except that somewhat more fingerline failures occurred in B-flute boxes. This may be a result of the increased number of fingerlines per width of B-flute board; B-flute fingerlines are two inches apart, while A- and C-flute fingerlines are three or four inches apart.

The composite experience with A-, B-, and C-flute boxes is shown in the last line of Table I. In 6.6% of the boxes inspected, compression failure definitely initiated at a fingerline. In 28.8% of the boxes, failure definitely did not originate at a fingerline. In the remaining 64.6% of the boxes it is inconclusive whether or not failure originated at a fingerline.

By way of summary, it may be stated that top-load compression failure did not always start at a fingerline. However, in approximately 70% of the boxes, compression failure either initiated at a fingerline or found its way to a fingerline, suggesting that the fingerline may be a zone of reduced compression strength of the combined board.

EFFECT OF FINGERLINES ON EDGEWISE COMPRESSION AND BOX COMPRESSION FAILURE

The data of Table I do not speak directly to the question of whether or not box failure occurred at a fingerline as a result of the combined board being weaker at the fingerline than elsewhere. To study this matter, a number of box samples were studied in greater detail. In addition to noting coincidence of fingerlines and box compression failures, the edgewise compression strength was evaluated in the presence of a fingerline in the short column specimen. These data for short columns with fingerlines may be compared with the previously published data for short columns without fingerlines; the simplified box compression formula is based on the latter. The "standard" wax-reinforced, rectangular, cross-direction column specimen was employed for both types of tests (10 specimens per sample), the only difference being that a fingerline was included at midheight in one set of specimens. In general, the fingerline columns were prepared and tested at a later date than the standard columns.

The results of this comparison are shown in Table II along with data on the frequency of fingerline failures in top-load compression. For example, with Sample 2307 (B-flute, 200-lb. series) three out of 10 boxes exhibited fingerline failures at all four vertical edges, five boxes at three vertical edges, etc. This is the same system used in Table I. In addition a "severity index" has been computed in order to represent the frequency of fingerline failures in the box by a single number. The "severity index" is the number of vertical edges in 10 boxes exhibiting failure at a fingerline. For Sample 2307 the index may be calculated as:

$$(3 \times 4) + (5 \times 3) + (2 \times 2) + (0 \times 1) + (0 \times 0) = 31.$$

The index may range from 40 (all vertical edges suffer fingerline failure) to 0 (no edge exhibits fingerline failure). The index is calculated on the basis of 10 boxes even though only 9 boxes were inspected for some samples. The samples are listed in Table II according to decreasing frequency of fingerline failures.

TABLE II

CORRELATION BETWEEN FINGERLINE FAILURE IN BOX COMPRESSION AND FINGERLINE STRENGTH IN EDGEWISE COMPRESSION

			Fingerline Failures in Boxes		Edgewise Compression Strength, lb./in.		
Code	Flute	Series	No. of Each Type[a]	Severity Index[b]	No Fingerline	Fingerline	Diff., %[c]
2307	B	200	3-5-2-0-0	31	49.7	48.8	- 1.8
2137	C	350	3-2-1-3-1	23	72.7	65.6	- 9.8
2054	A	275	1-0-7-1-0	21	59.9	57.0	- 4.8
2176	C	200	2-0-4-3-1	19	40.6	40.6	0.0
1176	A	200	1-2-1-4-1	18	44.0	41.3	- 6.1
2182	B	275	0-2-4-2-2	16	64.2	59.2	- 7.8
2009	B	200	0-1-3-4-1	14	46.0	41.6	- 9.6
2315	A	200	0-2-2-4-2	14	45.7	44.1	- 3.5
2050	C	275	0-2-1-5-1	14	71.1	66.4	- 6.6
2219	C	175	0-1-5-0-4	13	43.9	41.0	- 6.6
1172	A	200	0-1-3-0-5	10	42.4	39.3	- 7.3
2111	C	275	0-1-0-4-5	7	57.1	56.9	- 0.4
2115	A	275	0-0-3-1-6	7	56.0	58.3	+ 4.1
2167	C	175	1-0-0-2-7	6	40.8	36.6	- 10.3
2177	C	200	0-0-1-4-5	6	41.7	44.2	+ 6.0
1180	A	275	0-0-0-0-9	0	50.5	48.3	- 4.4
2095	A	275	0-0-0-0-9	0	63.7	59.8	- 6.1
						Av.	- 4.4

[a]Number of boxes exhibiting failure coincident with fingerline at 4, 3, 2, 1 and no vertical edges, respectively.

[b]Number of vertical edges in 10 boxes exhibiting failure at fingerline.

[c]Based on values for no fingerline.

The right-hand portion of Table II gives the comparison of edgewise compression strength of combined board with and without fingerlines. With Sample 2307 the average strength with a fingerline present was 1.8% lower than in the absence of a fingerline. Considering all samples, the edgewise compression strength was reduced because of the fingerline by as much as 10.3% and on the average by 4.4%. In two samples the fingerline columns tested 4 and 6% higher than without a fingerline. Since it is difficult to conceive that a fingerline strengthens the board, this result is indicative of variability in material and testing and should temper the remaining comparisons. Nonetheless, the over-all trend is toward a decrease of about 4% in edgewise compression strength because of fingerlines.

It might be anticipated that the greater the reduction in edgewise compression due to fingerlines, the more frequently will compression failures occur at a fingerline in a box. In other words, it is expected that there should be a positive correlation between the severity index and the per cent loss in edgewise compression due to fingerlines. This relationship is shown graphically in Fig. 1. It may be seen that there is little evidence of a significant correlation. This result was unexpected because it means that even though the fingerline area is appreciably weaker in compression than the adjacent combined board, the box need not necessarily exhibit a high frequency of fingerline failures. Conversely, some boxes for which the fingerline area was only slightly less strong than adjacent board exhibited a high frequency of fingerline failures.

In summary, the data of Table II and Fig. 1 indicate that, in general, the fingerline tends to reduce the edgewise compression strength of the board

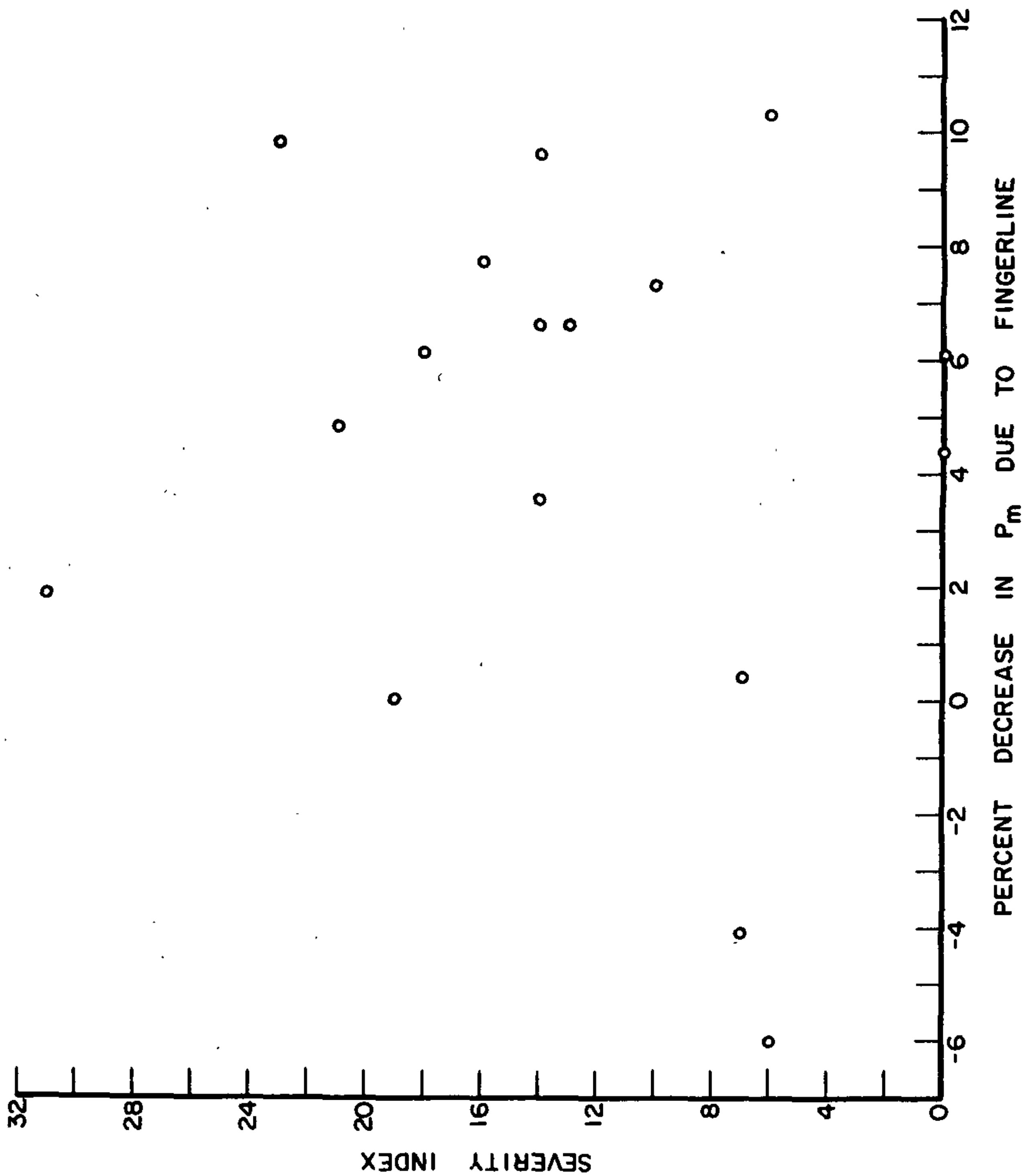

Figure 1. Relationship Between the Number of Vertical Edges per 10 Boxes Exhibiting Fingerline Compression Failure (Severity Index) and the Decrease in Edgewise Compression Strength of Combined Board due to Fingerlines

slightly. However, there is not a clear-cut relationship between the frequency of fingerline failures in box compression and the strength of the fingerline areas relative to the adjacent board.

FURTHER STUDY OF THE EFFECT OF FINGERLINES ON EDGEWISE COMPRESSION

The data of Table II regarding the effect of fingerlines on edgewise compression may be viewed with some reservations because of a lapse of time between the tests of columns with and without fingerlines. Experimental variability due to sampling, operators, and test equipment may confound the comparison. Moreover, the frequency of failures along the fingerline in the short column was not recorded and thus the cause of the observed reductions in strength is not documented.

To overcome these objections, a better controlled comparison was made between short columns with and without fingerlines. Five samples of A-flute, commercially-manufactured combined board were selected, namely one sample of 125-lb. series, two of 200-lb. series and two of 275-lb. series. (It would be desirable to expand this sampling to include more samples with lightweight liners, in keeping with the discussion in the Introduction. Only one sample in the 125-lb. series was available at the time of this study.)

Fifteen short column specimens (cross-direction, wax-reinforced loading edges, two inches by two inches) were prepared without fingerlines from each sample of combined board and fifteen with a fingerline at approximately midheight. The specimens were paired during preparation; that is, one specimen with a fingerline and one specimen without a fingerline were cut immediately adjacent to each other. Subsequent statistical analyses of the data were carried out by the method of paired variates. This method of sampling and data analysis should minimize the effect of variation in strength over the area of the base sheet of combined board.

The results of this study are shown in Table III along with the pin adhesion strength of the combined board which was evaluated for reference purposes. For example, with the 125-lb. series board (A-3) the edgewise compression strength of 15 specimens without fingerlines was 38.38 lb./in. and the strength with fingerlines was 38.61 lb./in. In this instance, the strength with fingerlines was slightly higher than without fingerlines, although the difference was not statistically significant at the 0.05 level. In three of five samples, the fingerline strength was lower than that of board without fingerlines, although the differences are small and none were statistically significant. On the average, the edgewise compression with fingerlines was 0.3% lower than without fingerlines.

Not all of the specimens possessing fingerlines failed along the fingerline. It may be of interest to examine the strengths of those short columns which failed at a fingerline to determine whether the strength is appreciably lower under these circumstances or whether the fingerline failure is mainly a chance occurrence. As shown in the lower portion of Table III, nine specimens of Sample A-3 failed along the fingerline; if any portion of the failure line included the fingerline it was counted as a fingerline failure. On the average, the strength of these nine fingerline specimens was 38.56 lb./in. The average strength of the corresponding nine specimens without fingerlines was 38.88 lb./in. Thus, in this instance, short columns which failed at a fingerline did so at a slightly lower load (0.8% lower) than columns without fingerlines. This indicates that failure at the fingerline was not simply a chance occurrence but probably was attributable to lower strength at the fingerline. Analogous results were obtained in four of

TABLE III

COMPARISON OF EDGEWISE COMPRESSION STRENGTH WITH AND WITHOUT FINGERLINES

(Cross direction)

Code	Series	Pin Adhesion, lb./6 sq. in.		No. of Specimens	Edgewise Compression Strength, lb./in.		Diff., %[a]	Significance[b]
		S.F.	D.F.		Without Fingerline	With Fingerline		
					All Specimens			
A-3	125	83	104	15	38.38	38.61	+0.6	No
A-23	200	93	99	15	49.87	49.69	-0.4	No
2406	200	76	80	15	50.70	49.68	-2.0	No
2467	275	73	89	15	57.82	57.43	-0.7	No
2504	275	63	99	15	65.45	66.03	+0.9	No
						Av.	-0.3	
					Specimens Exhibiting Fingerline Failures			
A-3	125	--	--	9	38.88	38.56	-0.8	No
A-23	200	--	--	5	50.59	49.28	-2.6	No
2406	200	--	--	8	50.70	48.59	-4.2	Yes
2467	275	--	--	8	58.38	57.22	-2.0	No
2504	275	--	--	4	67.25	67.50	+0.4	No
						Av.	-1.8	

[a]Based on values without fingerlines.

[b]Significance at the 0.05 level.

the five samples of combined board, although none of the differences in strength are very large and only one was statistically significant. On the average, the strength of columns failing at fingerlines was 1.8% lower than that of columns without fingerlines.

The data in Table III are interpreted to mean that for these particular five samples of commercially manufactured combined board there was only a slight decrease in edgewise compression strength at the fingerlines relative to the remainder of the corrugated board. While the fingerline appears to be a zone of reduced strength, it was not sufficiently lower in these samples to guarantee failure at the fingerline zone. Reference to the pin adhesion data in Table III suggests that the rather low adhesion of the single-face liner in several of the samples may have minimized the influence of the fingerlines.

Combining the data in the upper part of Table III with the data of Table II, it may be stated that for these 22 samples of commercial combined boards, the edgewise compression strength in the presence of fingerlines was 3.5% lower than without fingerlines. This indicates that, on the average, the fingerline region is somewhat less strong that the remainder of the board in commercial combinations.

As a matter of possible interest, the variability in column strength with and without fingerlines is shown in Table IV in terms of coefficient of variation. Only the paired specimens are considered for which columns containing a fingerline actually failed at a fingerline. It may be seen that there is no marked difference in variability for the two types of specimens.

TABLE IV

VARIABILITY IN EDGEWISE COMPRESSION STRENGTH

Code	Series	No. of Specimens	Coefficient of Variation, % Without Fingerlines	With Fingerlines
A-3	125	9	1.9	2.4
A-23	200	5	3.2	3.1
2406	200	8	3.7	3.6
2467	275	8	4.5	4.7
2504	275	4	1.4	1.8
		Av.	2.9	3.1

FUTURE WORK

The results of this study are rather inconclusive in that the strongest statements that can be made are of a negative character, such as: not all boxes fail at a fingerline under top-load compression, and not all commercial combined boards show marked reductions in a strength at a fingerline. The reason for these rather indefinite conclusions is that classifying short columns or portions of boxes as either having or not having fingerlines is superficial. The heart of the matter is whether or not there is insufficient adhesion at the fingerline which will cause a reduction in edgewise compression strength. The influence of fingerlines is probably a matter of degree. Undoubtedly, there are boards where the fingerline is not a zone of significant weakness relative to the remainder of the board. And undoubtedly there are others where the fingerline is indeed significantly weaker than adjacent board.

It is believed that a more definitive study is required to place the matter of fingerlines in proper perspective. It is proposed that as a first step a controlled experiment should be performed to establish the sensitivity of edgewise compression to lack of adhesive at the fingerline. It is visualized that this may be accomplished by controlled runs on the Institute single-facer, giving varying degrees of adhesion at the fingerline while maintaining "uniform" adhesion over the remainder of the area of combined board fabricated from a given set of components. The results of this work should reveal the influence of varying degrees of fingerline adhesion on edgewise compression. The study should also encompass a range of component grades, for example, lightweight and heavyweight liners.

Secondly, consideration should be given to methods for evaluating the degree of adhesion at the fingerline. It is doubtful whether the conventional pin adhesion test is sensitive enough for this, and in any event it does not separate the influence of fingerlines from the influence of adhesion over the adjacent board.

Ultimately, the question which should be answered is whether or not to include a fingerline in the short column specimen in routine evaluations of the edgewise compression strength of combined board. In principle it would seem desirable to do so. If the fingerline is a zone of weakness, it should be reflected in box compression performance and accordingly the column test should be performed to reveal this. In cases where the fingerline is of no consequence, there is nothing lost by including it in the column specimen. On the other hand, if further study were to reveal that fingerlines are of little consequence in general, they could be ignored in column testing and the extra labor of locating fingerlines during preparation of columns would be avoided.

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