STRENGTH AND LIFE CRITERIA FOR CORRUGATED FIBERBOARD BY THREE METHODS

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ABSTRACT

The conventional test method for determining the stacking life of corrugated containers at a fixed load level does not adequately predict a safe load when storage time is fixed. This study introduced multiple load levels and related the probability of time at failure to load. A statistical analysis of logarithm-of-time failure data varying with load level predicts the safe load that would yield a 5% probability of failure for any given storage time. Results were used to (a) quantify the performance of two cormgated fiberboards having significantly different components and (b) ,show the differences obtained between a dynamic edgewise compression test at standard atmospheric conditions and a safe load level test using multiple load levels and cyclic humidity. The average strength of the stronger material in a dynamic crush test was 30% greater than that of the weaker material. However, the safe load level of the stronger material that would yield a 5% probability of failure after 48 h in the cyclic humidity environment was 115% greater than the weaker material.

INTRODUCTION

When corrugated boxes with their contents are stacked and subjected to long-term storage, the bottom boxes can fail at loads far below the strength determined in a dynamic compression test. Failure can occur when a container collapses, becomes unstable, or creeps to a critical deformation. The problem is how to choose from alternative box materials.

Following the methodology used for structural wood products, two stacking strength criteria can be applied. If the weight of the stack imposed on the bottom container is fixed, a material can be chosen to maximize stacking life. If the storage time is fixed, a material can be chosen to maximize a safe load level. As a result of the inherent variability among factors affecting strength, each strength criterion could lead to different rankings of materials.

The sensitivity of paper to moisture makes its storage environment critical and increases the effect of strength variation within the material. Users of general packaging materials have reported examples of severe storage environments such as Ocean cargo, unconditioned warehouses in low technology countries, and 5 years in isolated military warehouses (1). Data from Kellicut and Landt's study (2) are typical of the expected variation in the stacking life of corrugated boxes under controlled laboratory environments. Actual storage environments would further broaden the variation.

With the conventional test method (3) for determining the stacking life of a container, equivalent specimens are subjected to equal and constant loads until failure. Various failure definitions can apply. In such a test it is generally observed that the logarithms of times until failure are normally distributed. Therefore, a small reduction in the logarithm-of-time variation significantly extends the time until failure. Unfortunately, equal-load level tests are not very useful for service applications where the load or storage time is not known in advance. Such a test is not adequate for the general characterization of corrugated fiberboard, where the stress level during use is a function of container size.

OBJECTIVE AND SCOPE

A test method to characterize corrugated fiberboard strength for general stress levels and storage times is particularly relevant with the use of recycled corrugated fiberboard and the so called "high performance" papers. The safe load for a fixed storage time increases as material variability decreases. A general test method could be used to quantify the effects of quality control on fiberboard creep performance and increase the value of low variability papers.

The objective of this study was to propose a criterion for quantifying the expected strength of corrugated fiberboard subjected to long-term stress. Time-of-failure data varying with loads are acquired. Conventional methods of statistical regression analysis are applied as a first step toward characterizing the variation in the predictions of the logarithms of time-to-failure data. Then, strength is characterized as the load which predicts that no more than 5% of specimens will fail.

[1] This paper was previously submitted to Tappi Journal.

The methods of this study are limited to a test in which all specimens of all materials can, be tested simultaneously in one trial of the same environment. In previous creep research, eight corrugated fiberboards with subsets exposed to different trials of constant 50% relative humidity (RH), constant 90% RH, and 50% to 90% cyclic RH environments were ranked (4). Environment variability was found to reduce the certainty of the characterization of material performance. The study reported herein proposes a method for comparing two or more materials when all tests can be conducted together in the same environment.

METHOD

If a batch of replicated test specimens of corrugated fiberboard in the same environment are subjected to various constant loads, the logarithm of time until failure will generally vary linearly with load. This response has been observed for general wood and fiber materials and can be verified in terms of mechanistic principles for homogeneous materials (5). Deviations from linearity over the full range of loads can result from shifts in the mechanism of failure, depending on load or time. Such shifts could be caused by transitions between break-in and steady-state phases of creep, a progressive stress-dependent failure of specimen components, or time-varying changes in the test environment.

A condition for applying the principles of this report is that the load levels be controllable and remain independent of other test variables. Some researchers have unified data from multiple replicates of different corrugated containers by plotting the load ratio varying with the logarithm of time until failure (6). A specimen's load ratio is the ratio of the static load to the average dynamic compression strength of similar specimens. Although such data also exhibit linearity, the load ratio for a specific specimen varies statistically with its dynamic compression strength and neither the load ratio nor the time-to-failure data can be treated as an independent variable.

Typical data on failure time T varying with load level P and the least squares regression fits are shown in Figures 1 and 2. The regression lines predict the usual variation of y with x, but in this case the P-data are treated as x-values and transformations of T to the logarithm of T are the y-values. The response levels in Figures 1 and 2 are plotted using T-values and a logarithmic scale. The plot would look the same if y-values and a linear scale were used.

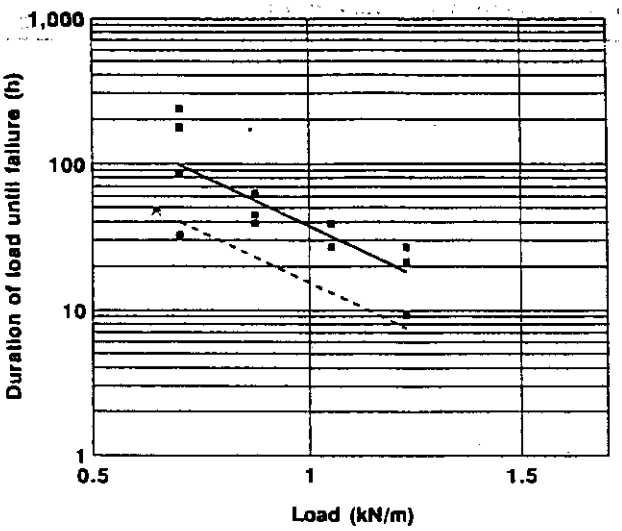

Figure 1: Failure time varying with edgewise compression load of nominal 220- by 115- by 220-g/m^2 C-flute corrugated fiberboard (material A) in a cyclic humidity chamber. Points represent data. The upper line is a linear regression of the data given by log T = 6.85 - 3.22 P. The lower curve is the 5% boundary. The "*" on the percentile boundary is at a predicted safe load of 0.647 kN/m corresponding to 48 h.

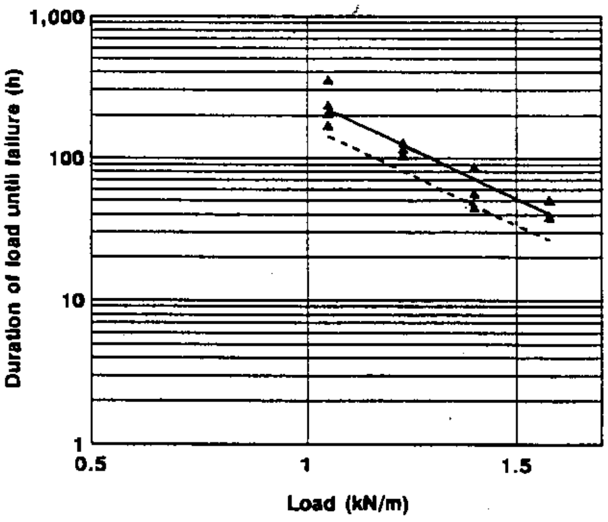

Figure 2: Failure time varying with edgewise compression load of nominal 220- by 160- by 290-g/m^2 C-flute corrugated fiberboard (material B) in acyclic humidity chamber. Points represent data. The upper line is a linear regression of the data given by log T = 8.74 - 3.20 P. The lower curve is the 5% boundary. The "*" on the percentile boundary is at a predicted safe load of 1.39 kN/m corresponding to 48 h.

Various statistical methods can be applied to such linearly varying data to characterize variability and predict a probable future response. A lower 5% boundary is plotted below each of the regression lines in Figure 1 and 2. The T-value along the lower percentile boundary is the prediction of a time beyond which specimens would fail with 5% probability. if loaded at the corresponding P-level. An upper percentile boundary yielding an opposite T-value could likewise be determined but would have little practical importance. The lower percentile boundary predicts a probable safe storage time and becomes more conservative as experimental variation increases.

EXPERIMENT

Two corrugated fiberboard materials were characterized for strength by three methods: a dynamic edgewise crush test (7). an adaptation of the static creep test of a container under constant load (3), and the safe load level test proposed herein. Material A was a nominal 220- by 115- by 220-g/m^2 · (45- by 24- by 45- × 10^{-3} lb/ft^2) C-flute construction used to build the lid component of a two-part produce container. Material B was a nominal 220- by 160- by 290-g/m^2• (45- by 33- by 59- × 10^{-3} lb/ft^2) C-flute board used to construct the body component of the container. Both materials were made by the same manufacturer using moisture-resistant adhesive.

Short column specimens, 51 mm (2 in.) wide by 38 mm (1.5 in.) high with height in the axis direction of flutes, were cut from each material. Top and bottom edges were reinforced with paraffin. The average edgewise compression strength of 14 specimens of material A at 23°C (73°F) and 50% RH was 9.10 kN/m (52.0 lbf/in.). Similarly, the average strength for material B was 11.8 kN/m (67.4 lbf/in.). Other variation statistics are given in Table I, and an ordering of the data for comparison with the frequency predicted by a normal distribution is shown in Figure 3. These dynamic strength data were used to establish load levels for static compression life tests.

Table I: Strength and life statistics of two corrugated fiberboards characterized by three methods

	Material A			Material B		
Method	Mean	Standard deviation	Lower 5% boundary	Mean	Standard deviation	Lower 5% boundary
Edgewise crush strength (kN/m)	9.10	0.520	8.18	11.8	0.497	10.9
Logarithm of compression life (h) at 1.40kN/m	3.59	0.216	3.2	5.20	0.249	4.76
Compression life (h) at 1.40 kN/m	36.2	1.24	24.5	181	1.28	117
Residuals (kN/m) of safe load level regression	0	0.504	-0.892	0	0.241	-0.426
48-h compression strength (kN/m)	0.924	-	0.647	1.52	-	1.39

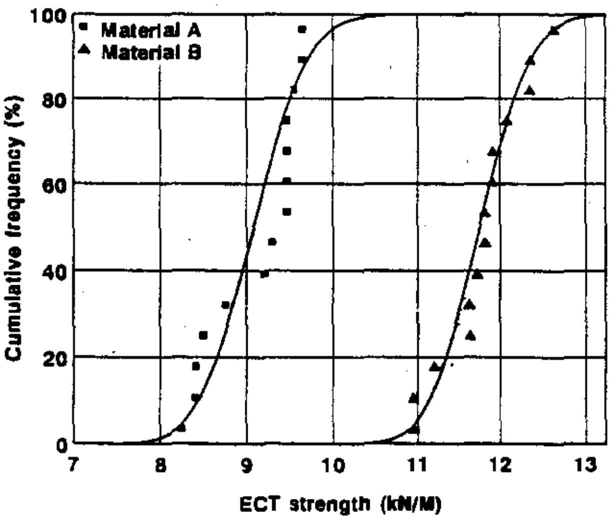

Figure 3: Ordering of edgewise compressive strength of nominal 220- by 115- by 220- g/m^2 C-flute corrugated fiberboard (material A) and nominal 220- by 160- by 290- g/m^2 C-flute corrugated fiberboard (material B) used in study. Points represent data. The curves are the ordering of strength predicted by a normal probability distribution of these data.

The compression life at a fixed stress level was determined next for the short column specimens. Fourteen specimens each of materials A and B were subjected to a load of 1.40 kN/m (8 lbf/in.), each in a cyclic RH chamber. The humidity cycled sinusoidally between nominal conditions of 50% RH and 90% RH during a 6-h cycle; temperature remained constant at 23°C. A. test apparatus (8) was used to apply constant edgewise compression and record specimen deformation as materials crept. All 28 specimens were tested in the same environment at the same time. The time at which a specimen ultimately collapsed was used to define its failure.

The hours to failure of 11 successful specimens of material A were 27.1, 27.4, 33.0, 33.0, 33.0, 33.3, 38.8, 39.4, 40.5, 44.6, and 56.9. The hours to failure of 14 specimens of material B were 117, 135, 147. 153, 153, 159, 166, 195, 195, 213, 238, 243, 243, and 256. The ordering of failure times is shown in Figure 4 and compared with the cumulative frequency predicted by a normal distribution of the logarithm-of-time data. Statistics on the logarithm-of-time data are given in Table I. The time corresponding to the mean of the logarithms is 36.2 h for material A and 181 h for material B.

A variation of the previous creep test was repeated in which 14 specimens of material A were subjected to loads of 0.70, 0.88. 1.05, and 1.23 kN/m (4,5,6, and 7 lbf/in.) in the cyclic RH chamber. Fourteen specimens of material B were subjected to 1.05, 1.23, 1.40, and 1.58 kN/m (6, 7, 8, and 9 lbf/in.) in the same environment. Failure time data varying with load level are given in Table II and are plotted in Figure 1 for material A and in Figure 2 for material B. Table I gives statistics on the residuals associated with the y-values. From these, the lower 5% boundary is plotted with each data set.

The "*" on the boundary is at a time value of 48 h. The corresponding load levels were at 0.647 kNm (3.69 lbf/in.) for material A and 1.39 kN/m (7.93 lbf/in.) for material B. Thus, these 48-h strength determinations predict the safe load that can be applied in the cyclic environment to limit failure for 48 h to a 5% probability.

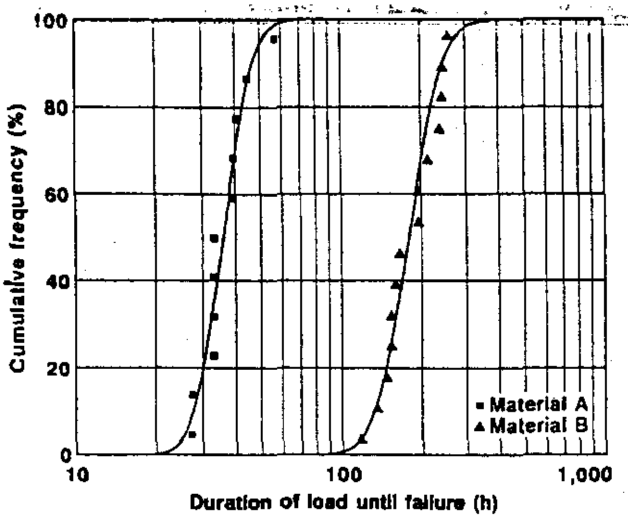

Figure 4: Ordering of failure times of nominal 220- by 115- by 220- g/m^2 C-flutecorrugated fiberboard (material A) and nominal 220- by 160- by 290- g/m^2 C-flute corrugated fiberboard (material B) subjected to 1.40 kN/m (8 lbf/in.) edgewise compression and 50% to 90% cyclic relative humidity. Points represent data. The curves are the ordering of times predicted by a normal probability distribution of the logarithm-of-time data.

The time of 48 h was chosen somewhat arbitrarily to capture the effect of multiple 6-h cycles and yet minimize extrapolation beyond data. The humidity environments cycled between target levels of 50% RH and 90% RH. Specimens in the compression life test survived longer than what would be predicted by the safe load level regression lines at the 1.40 kN/m load level. The actual cyclic humidity environments between the two tests differed from their target specifications and reflected the effect of trial variability. The results presented here. based on a small number of specimens, are consistent with the results from Urbanik and others (4) that involved additional specimens and various creep environments.

Table II: Time-of-failure data varying with load level for two materials

Load	**Failure time (h)**	
(kN/m)	**Material A**	**Material B**
0.701	239	
	177	
	86.8	
	32.9	
0.876	62.5	
	44.9	
	39.4	
1.05	38.9	357
	38.7	237
	27.2	207
		171
1.23	26.8	129
	21.3	117
	21.1	105
	9.18	
1.40		87.3
		57.0
		45.2
1.58		51.4
		51.0
		39.4
		38.6

CONCLUSIONS

In this study, a strength criterion is proposed for comparing the probable safe load levels of materials tested for creep life in the same environment at the same time. A safe load is the level at which failure would be limited to a 5% probability for a specified storage time. Results are used to compare two corrugated fiberboards known to have different material characteristics. A conventional edgewise compression test at standard atmospheric conditions yielded a 30% average strength difference between materials. When materials were subjected to various levels of long-term stress and cyclic humidity, the strength criterion proposed herein yielded a 1 15% strength difference, corresponding to probable survival after 48 h. Additional testing is needed to establish precision criteria for referee testing and to relate laboratory humidity environments to actual service conditions. The test method for determining the stacking life of containers at a fixed load level should be broadened to deal with multiple load levels.

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