Strength criterion for corrugated fiberboard under long-term stress

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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 where storage time is fixed. This study introduced multiple load levels and related them to the probability of time to failure. A statistical analysis of the logarithm of time-failure data varying with load level predicts the safe load corresponding to the lower fifth percentile of failure for any given storage time. Results were used to (a) quantify the performance of two corrugated fiberboards having significantly different components and (b) show that a safe-load-level test using multiple load levels and cyclic humidity is more sensitive to material strength differences than a dynamic edgewise compression test at standard atmospheric conditions. The average strength of the stronger material in a dynamic crash 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 hours in the cyclic-humidity environment was 115% greater than the weaker material.

Application:

A proposed test method for predicting fiberboard performance under long-term stress in environments where humidity is not controlled.

WHEN CORRUGATED BOXES with their contents are stacked and subjected to long-term storage, the bottom boxes can fail at loads far below the expected strength as measured in a dynamic compression test. Failure occurs when a container collapses, becomes unstable, or creeps to a critical deformation. Previous work has shown that creep tests of corrugated fiberboard in a cyclic relative humidity (RH) environment can detect material differences that are not apparent under constant atmospheric conditions *(1)*. This highlights the need to quantify the strength of boxes stored in different environments.

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. Because of the inherent variability among factors affecting strength, each strength criterion could lead to different rankings of materials.

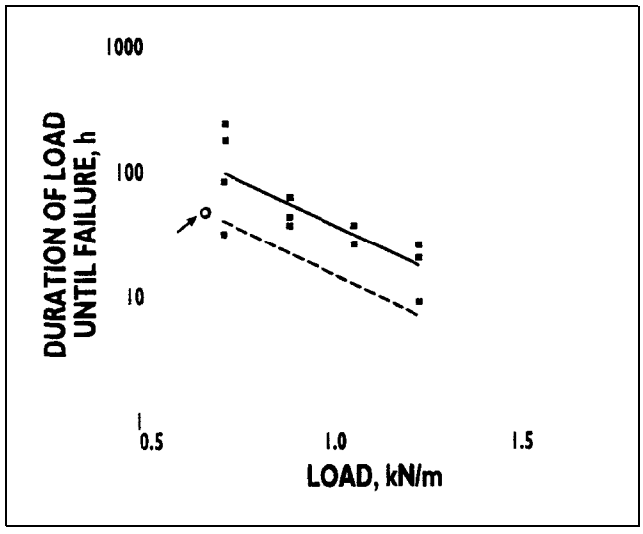
Containerboard is sensitive to moisture, which makes its storage environment critical and increases the effect of strength variation within the material. Users of general packaging materials have reported examples of severe storage environments such as ocean cargo, unconditioned warehouses in low-technology countries, and five years in isolated military warehouses *(2)*. Data from Kellicut and Landt's study *(3)* 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.

The conventional test method for determining the stacking life of a container subjects equivalent specimens to equal and constant loads until failure *(4)*. Various failure definitions can apply In such a test, it is generally observed that the logarithms of time to failure are normally distributed. Therefore, a small reduction in the logarithm-of-time variation significantly extends the time to 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.

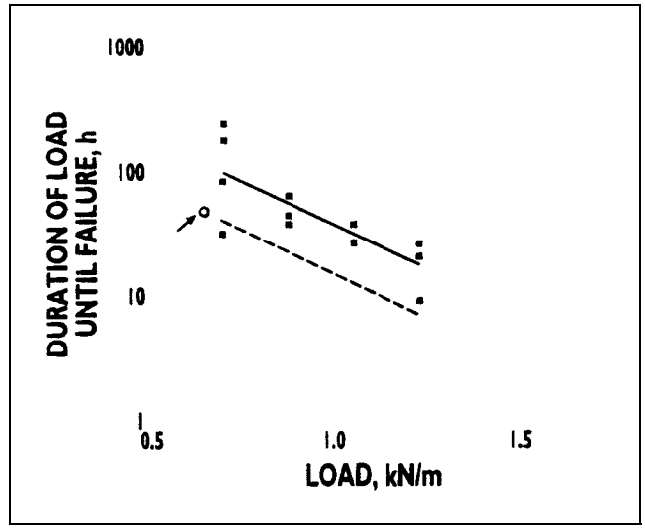
OBJECTIVE AND SCOPE

A test method to characterize corrugated fiberboard strength for general stress levels and storage times is particularly relevant with the use of containerboard made from recycled corrugated fiberboard and the so-called "high performance" containerboards. 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 corrugated fiberboard creep performance and increase the value of low-variability containerboard.

The objective of this study was to propose a criterion for quantifying the expected strength of corrugated fiberboard subjected to long-term stress. The criterion is established by acquiring time-to-failure data with varying loads. Conventional methods of statistical regression analysis for determining the lower fifth per-



1. Time to failure varying with edgewise compression load of nominal 220 × 115 × 220-glm² 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 ln T = 6.85 - 3.22P. The lower curve is the 5% boundary. The "o" on the 5% boundary is at a predicted safe load of 0.647 kN/m corresponding to 48 hours.



2. Time to failure varying with edgewise compression load of nominal 220 × 160 × 290-glm² C-flute corrugated fiberboard (Material B) in a cyclic-humidity chamber. Points represent data. The upper line is a linear regression of the data given by ln T = 8.74 - 3.20P. The lower curve is the 5% boundary. The "o" on the 5% boundary is at a predicted safe load of 1.39 kN/m corresponding to 48 hours.

	MATERIAL A			MATERIAL B		
Method	Mean	standard deviation	Lower 5% boundary	Mean	Standard deviation	Lower 5% boundary
Edgewise compression strength, kN/m	9.10	0.520	8.18	I1.8	0.497	10.9
Logarithm of time to failure at 1.40 kN/m*	3.59	0.216	3.2	5.20	0.249	4.76
Time to failure at I.40 kN/m, h	36.2	I.24	24.5	I81	I.28	II7
Residuals 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

*Mean, standard deviation, and lower 5% boundary are determined for the logarithm-of-time data, then converted to units of time.

1. Strength and life statistics of two corrugated fiberboards characterized by three methods

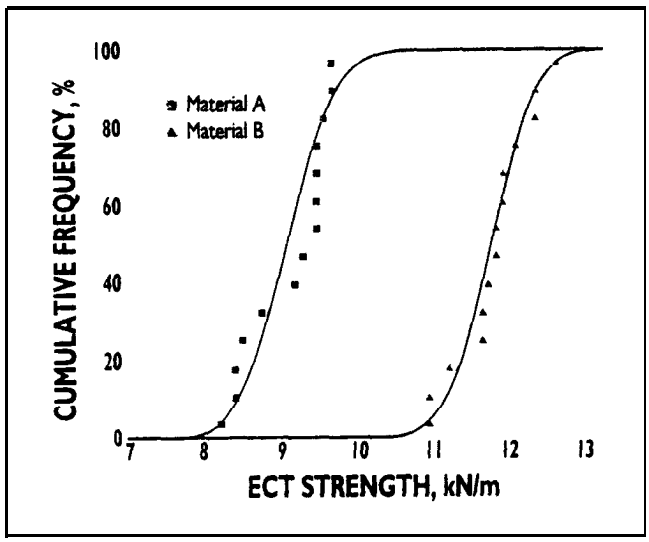
centile of predictions of the logarithms of time to failure are applied as a first step toward developing a more rigorous statistical characterization of the response. Then, strength is characterized as the load that predicts that no more than 5% of specimens will fail.

The methods of this study are limited to a test in which all specimens of all materials can be tested simultaneously in a single trial within the same environment. In previous creep research. eight corrugated fiberboards were ranked based on test results for subsets that were exposed to different trials at constant 50% RH, constant 90% RH, and nominal 50% to 90% cyclic-RH environments *(5).* Cyclic-RH 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.

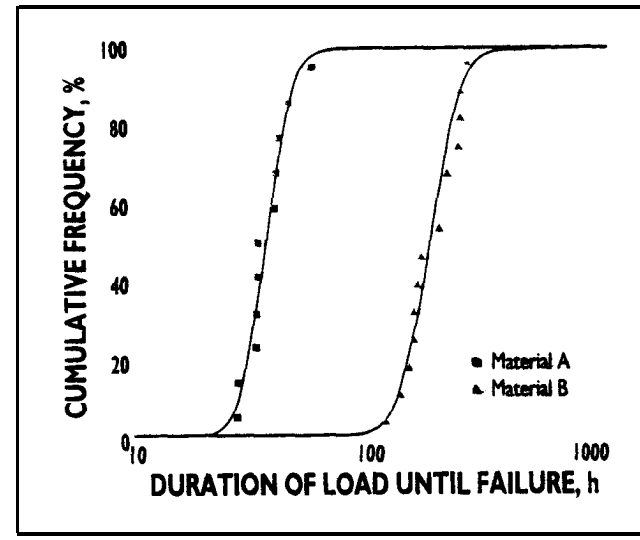
METHOD

If a batch of replicated test specimens of corrugated fiberboard is subjected to various constant load in the same environment, the logarithm of time to 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 *(6).* 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



3. Ordering of edgewise compressive strength of nominal 220 × 115 × 220-g/m² C-flute corrugated fiberboard (Material A) and nominal 220 × I60 × 290-g/m² C-flute corrugated fiberboard (Material B) used in the study. Points repesent data. The curves are the ordering of strength predicted by a normal probablility distribution of these data.



4. Ordering of time to failure of nominal 220 × 1I5 × 220-g/m² C-flute corrugated fiberboard (Material A) and nominal 220 × I60 × 290-g/m² C-flute corrugated fiberboard (Material B) subjected to 1.40 kN/m (8 lbf/in.) edgewise compression end 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

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 to failure *(7).* 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 time-to-failure. *T,* varying with load level. *P,* and the least-squares regression fits are shown in Figs. 1 and 2 for two different fiberboard materials. 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 Figs. 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.

Various statistical methods can be applied to such linearly varying data to characterize variability and predict a probable future response. A lower fifth-percentile boundary is plotted below each of the regression lines in Figs. 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.

EXPERIMENTAL

Two corrugated fiberboards made from conventional grade materials were characterized for strength by three methods: a dynamic edgewise crush test *(8),* an adaptation of the static creep test of a container under constant load *(4).* and the safe-load-level test proposed herein. Material A was a nominal 220 × 115 × 220-g/m² (45 × 24 × 45-lb/1000 ft²) C-flute construction used to build the lid component of a two-part produce container. Material B was a nominal 200 × 160 × 290-g/m² (45 × 33 × 59-lb/1000 ft²) 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. reinforced with paraffin, preconditioned, and conditioned to 50% RH in accordance with TAPPI T 811 *(8)* for all three test methods. The average edgewise compression strength *(8)* 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.) (i.e.. 30% stronger than Material A). Other variation statistics are given in Table I, and an ordering of the data for comparison with the frequency pre-

Load, kN/m	TIME TO FAILURE, h 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

11. Time-to-failure data varying with load level for two materials

dicted by a normal distribution is shown in Fig. 3. These dynamic strength data were used to establish load levels for static-compression life tests.

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.) in a cyclic-RH chamber. The humidity cycled sinusoidally between 39% RH and 93% RH during a 6-hour cycle, beginning at the lower 39% RH; temperature remained constant at 23°C. A test apparatus *(9)* 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.

KEYWORDS

Compression strength, corrugated boxes, creep test, environments, failure, fiber boards, loads, safety, storage, test methods.

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. Three specimens failed between 15 hours and 22 hours during an interruption in data acquisition and were not analyzed. 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 time to failure is shown in Fig. 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 hours for Material A and 181 hours for Material B. At these means, Material B survived 400% longer than did Material A.

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. This time, the humidity cycled sinusoidally between 38% RH and a virtual 100% RH during a 6-hour cycle beginning at 38% RH. 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. Time-to-failure data varying with load level are given in Table II and are plotted in Fig. 1 for Material A and in Fig. 2 for Material B. Table I gives statistics on the residuals associated with the y-values. From these, the lower fifth percentile boundary is plotted with each data set. The "o" on the boundary is at a time value of 48 hours. The corresponding load levels were at 0.647 kN/m (3.69 lbf/in.) for Material A and 1.39 kN/m (7.93 lbf/in.) for Material B. Thus, these 48-hour strength determinations predict the safe load that can be applied in the cyclic environment to limit failure for 48 hours to a 5% probability. By this criterion, Material B is 115% stronger than Material A.

The time of 48 hours was chosen somewhat arbitrarily to capture the effect of multiple 6-hour cycles and yet minimize extrapolation beyond data. The regression lines in Figs. 1 and 2 predict that Materials A and B would survive for 10.4 hours and 70.8 hours, respectively, at a load level of 1.4 kN/m. This 581% greater survival time at 38% to 100% RH compared with a 400% greater time at 39% to 93% RH predicts that the superiority of Material B over Material A broadens as the RH environment becomes more severe and is consistent with the difference between the 48-hour strength and the average dynamic strength.

The stronger Material B was more dimensionally sensitive to RH changes than was Material A. Average amplitudes of sinusoidal hygroexpansion occurring in response to the cyclic 38% to 100% RH were 0.114 mm (4.50 mil) and 0.121 mm (4.77 mil) for Materials A and B, respectively. The test for safe load level predicts the material creep sensitivity to real-world cyclic-RH environments and detects material differences not discernible from a strength test or a hygroexpansion test.

The results presented here, based on a small number of specimens, are also consistent with the results from Urbanik and others *(5)* that involved additional materials and creep environments.

CONCLUSIONS

This study proposes a strength criterion 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. In a conventional edgewise compression test at standard atmospheric conditions, a 790-

g/m^2 material was 30% stronger than a 606-g/m^2 material. When materials were subjected to various levels of long-term stress and cyclic humidity–and in accordance with the strength criterion proposed herein, corresponding to probable survival after 48 h–the heavier material was 115% stronger than the lighter material. 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 contamers at a fixed load level should be broadened to deal with multiple load levels. **TJ**

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